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The April 1973 earthquake was the first one for which strong motion accelerograms were obtained in Hawaii. Ground motion in the volcanic ash turned out to be quite different from the ground motion of the lava rock. This was evident not only from the damage picture but also from the recorded aftershocks. Volcanic ash remained stable during this earthquake; it is not necessarily true that the volcanic ash would not liquefy during an earthquake of longer duration. Damage was not as great as found in other earthquakes of this magnitude (6.2). This can be attributed to several facts; the earthquake was very deep-seated (41 km); the duration of the strong motion was short (7 sec); and the island of Hawaii is sparsely populated (its total population is 70,000, of whom 30,000 live in Hilo). There are very few tall buildings in Hilo; most are one- or two-story residential units. A significant portion of the damage was to public roads and bridges. Seismometric data and preliminary strong-motion instrumental results and aftershocks are presented. Soil mechanics and foundations, soil dynamic analyses, and earthquake damages are discussed.

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THE HONOMU, HAWAII, EARTHQUAKE

report of inspection

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Commission on Sociotechnical Systems
NATIONAL RESEARCH COUNCIL

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NOTICE

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This report has been reviewed by a group other than the authors according to the procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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FOREWORD

The National Academy of Engineering formed the Committee on Natural Disasters to foster study of the engineering aspects of disasters such as earthquakes, floods, windstorms, and major fires. The objective of the studies is to improve the level of protection against these hazards and to stimulate the research needed to understand their nature.

This report is sponsored by the Committee's Panel on Earthquakes and contains results of inspection and study of the Honomu, Hawaii, earthquake of April 26, 1973.

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PREFACE

Shortly after it was learned that the April 26, 1973, earthquake on the island of Hawaii had caused damage in the millions of dollars, the National Research Council's Committee on Natural Disasters asked for an investigation and report on damage caused by the earthquake. After a preliminary inspection it became apparent that there were many interesting aspects, such as the differences in response and damage depending on whether the soil was a soft volcanic ash or hard volcanic rock. To add needed expertise, Messrs. Furumoto, Lum, and Morrill agreed to be a part of an investigating and reporting team.

N. Norby Nielsen

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R. B. Matthiesen and R. P. Maley of the Seismic Engineering Branch, U. S. Geological Survey (SEB, USGS), gave much assistance in reviewing the portion on strong motion data. V. Perez produced the spectra. D. W. Peterson and several others at the Hawaii Volcano Observatory provided information on aftershocks and local seismicity. The assistance of property owners on whose property our temporary stations were located is appreciated. W. M. Adams of the University of Hawaii made timely installation of pre-earthquake strong-motion instrumentation. The help of E. D. Sembera of SEB while in the field is much appreciated. We are thankful for the cooperation and help received from the Civil Defense offices in Honolulu and Hilo. The Special Projects Party, USGS (K. W. King, Chief), of Las Vegas provided analysis of the aftershock moniter records. The following members of the Hawaii Volcano Observatory, USGS, provided data on preliminary magnitudes: John D. Unger, Robert Y. Koyanagi, and A. T. Okamura. The Appendix discussing the intensity distribution was prepared by Patricia Principal and Karen Fujishima, both graduate assistants in Geology and Geophysics, University of Hawaii. The draft report was typed by Mrs. Mary Kamiya, Center for Engineering Research, College of Engineering, University of Hawaii.

ABSTRACT

The island of Hawaii is the most seismically active of the Hawaiian Islands. Since 1929 twelve earthquakes of magnitude 6 or larger have been recorded. There are two volcanoes on the island that are still active. However, for larger earthquakes there seems to be no connection with volcanic activity. At the time of the earthquake the Kilauea volcano was in active eruption, but the epicenter was far removed from the volcano. The earthquake occurred on a known fracture zone; the depth of focus was approximately 41 km; Hawaiian earthquakes usually occur at much shallower depths. The magnitude of the earthquake was 6.2. The epicenter was located at Honomu, which is 10 km north of Hilo and about 2 km inland.

About 2 months before the earthquake occurred two strong-motion accelerographs and four seismoscopes were installed in the islands. One of the strong motion accelerographs was installed at Kilauea on the island of Hawaii; its distance from the epicenter was 50 km. Another accelerograph was installed in Honolulu, about 300 km from the epicenter. Both instruments were triggered by the earthquake and the first strong-motion accelerograms were obtained in Hawaii. The maximum acceleration at Kilauea was 0.17 g and strong ground motion lasted about 7 seconds. The Honolulu record showed a maximum acceleration of 0.03 g. Three days after the earthquake additional instrumentation was flown in from Las Vegas to permit monitoring of aftershocks. The aftershock monitors recorded approximately 10 shocks of magnitudes between 2 and 3.

The Wailuku River, which runs into the ocean just north of downtown Hilo, is the dividing line between the Mauna Kea and the Mauna Loa lava flows. Mauna Kea is the older volcano and Mauna Loa is younger and still active. At the last stages of volcanic activity of Mauna Kea, ash deposits from the volcano covered the northeast portion of the island north of the Wailuku River. The result is that soil conditions are quite different on the two sides of the river. North of the river the ash cover is about 20 to 30 feet thick. The ground south of the river is lava rock. It was evident from the earthquake damage that behavior of the two soils was different; damage seemed to be much heavier on the volcanic ash north of the river. Aftershock equipment was installed on both sides of the river to explore the differences in response. From the records it is very clear that the velocity

response was much greater on the volcanic ash than it was on the lava rock. For most frequencies the velocity response of the volcanic ash was five to ten times as large as the response measured on the lava rock. There were no signs of liquefaction, even though the volcanic ash tends to liquefy under traffic of heavy construction equipment.

Damages were rather minor considering the 6.2 magnitude of the earthquake. This can be attributed to several facts: (a) the earthquake was very deep-seated (41 km); (b) the duration of the strong motion was short (7 sec); and (c) the island of Hawaii is sparsely populated (its total population is 70,000, of whom 30,000 live in Hilo). There are very few tall buildings in Hilo; most are one- or two-story residential units. The total amount of damage has been estimated at $6,000,000. A significant portion of this was damage to public roads and bridges. Numerous land and rock slides occurred in the northeastern portion of the island. Most of the damage to residential units occurred to buildings located on volcanic ash deposits within about a 20-km radius of the epicenter.

There was a good deal of "nonstructural" damage. Many students in school buildings were injured from falling light fixtures and false ceilings. Many residential units were shifted on their foundations; it was evident that an earthquake of longer duration would have caused considerably more damage. One 15-story shear wall building about 18 km from the epicenter had cracks in the shear walls at the first story level. It also suffered a good deal of "nonstructural" damage; in addition, its elevators jumped their tracks. The 8-story Mauna Kea Beach Hotel, about 75 km from the epicenter, suffered "nonstructural" damage; the damages were from minor design details. Footbridges connect the various wings of the hotel; the bridge seats were designed for sliding but apparently dowels were installed in the field, resulting in a good deal of spalling. Where additions were made to an elevator tower cracks showed up in the joints.

Damage to power lines, water supply, and telephone lines was severe. The northeastern portion was in a state of emergency for several days.

In Honolulu, about 300 km from the epicenter, damage was very minor; some pendulum clocks stopped and there were minor plaster cracks. Apparently, the long period waves' arriving coincided rather closely with the natural periods of some of the tall (20 to 30-story) buildings, resulting in sways of relatively large displacements. Near panic broke out in several buildings.

The earthquake was the first one for which strong motion accelerograms were obtained in Hawaii. Ground motion in the volcanic ash turned out to be quite different from the ground motion of the lava rock. This was evident not only from the damage picture but also from the recorded aftershocks. Volcanic ash remained stable during this earthquake; it is not necessarily true that the volcanic ash would not liquefy during an earthquake of longer duration. Damage was not as great as found in other earthquakes of this magnitude. Most of the lessons to be learned from a structural engineer's point of view are similar to those that already should have been learned from other earthquakes.

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Introduction

On the morning of April 26, 1973, at 10:27, Hawaiian Standard Time, residents throughout the Hawaiian Islands were disturbed by an earthquake. Damage amounting to 6 million dollars occurred on the island of Hawaii; people rushed out of buildings in Honolulu, 300 km from the epicenter; and tremors were felt on the island of Kauai, the farthest inhabited island from the epicenter.

This report will deal with data obtained from recordings on seismographs in Hawaii and in other parts of the world. Although the analysis and interpretations are only partially completed, a preliminary report is hereby made.

General Parameters of the Earthquake

The general parameters of the earthquake as published in the Preliminary Determination of Epicenters by the National Earthquake Information Center, National Oceanic and Atmospheric Administration, are:

Origin Time (UT)	1973 April 26 20h 26m 28.0 sec
Epicenter	Lat 19.933°N; Long 155.10°W
Depth of focus	50 km
Magnitude	MB 6.0, MS 6.1 (ERL)
	ML 6.2 (HVO)
	ML 6.3 (PAS)
	ML 6.1 (BRK)

The U.S. Geological Survey has provided the following parameters, based on calculations using known local crustal structure and travel time (HVO, 1973):

Origin Time	20h 26m 40.6 sec
Epicenter	Lat 19°51'N ±1.5'
	Long 155°08'W ±1.5'
Depth of focus	41 km ±4.5 km

The difference in distance between the two epicentral determinations is 9.5 km. In seismometric discussions, usually such a difference is not too relevant, but in this case the difference is significant. The PDE data put the epicenter at sea, whereas the Geological Survey epicenter is on land. In our discussion we shall choose the Geological Survey determination as the epicenter, as the calculations were based on local crustal structure and travel times.

Consideration of Past Large Earthquakes

Since 1929, when magnitudes of Hawaiian earthquakes began to be tabulated instrumentally, there have been 12 earthquakes with magnitudes equal to or larger than 6. The list of earthquakes with location of epicenters is given in Table 1.

An examination of the occurrence shows that large earthquakes have occurred in clusters at intervals of 11 years. Figure 1 shows the occurrence of the earthquakes with respect to time. Except for the two earthquakes in 1954, the earthquakes cluster around the years 1929, 1940, 1951, 1962, and 1973.

A map showing epicenters and volcanoes is given in Figure 2. An immediate conclusion is that epicenters are not obviously associated with centers of volcanism. Furthermore, a comparison with times of eruptive activity since 1929 shows that most of these large earthquakes did not occur at times of volcanic activity. Neither do large earthquakes occur preceding significant eruptions. The May 30, 1950, earthquake occurred just before a Mauna Loa eruption, but its epicenter was far removed from the Mauna Loa central vent or rift zone. Earthquakes associated with volcanic activity have been of smaller magnitude, being at most 4 or 5. The mechanism of large earthquakes seems to be quite independent of volcanic activity.

The April 26, 1973, earthquake was no exception to the rule. The epicenter was far removed from Kilauea Volcano, although Kilauea was then in active eruption.

Source Mechanism and Related Tectonics

Fault plane solution by first arrivals indicates strike-slip motion with alternate possibilities of (1) left lateral motion along a nodal plane striking N70°W and (2) a right lateral motion along a nodal plane striking N30°E (Koyanagi, Endo, and Ward, 1976). The fault plane solution of strike-slip motion agrees with strong-motion accelerograph data obtained at Namakani Paio, 50 km from the epicenter (Figure 6). There the maximum horizontal motion was 0.17 g while the maximum vertical motion was 0.07 g.

In Figure 3 are shown the faults that are known and the rift zones that radiate outward from volcanic centers. Geophysical data in recent years from geothermal exploration over the east rift of Kilauea Volcano support the theory that the rift zones are shallow structures and are surface expressions of subterranean conduits through which magma from the magma chamber under the central volcanic vent moves laterally to erupt along the flanks of the volcano. These conduits are thought to be lodged within the crust and not to extend to mantle depths. In Figure 3 it is shown that the earthquake occurred beneath the east rift of Mauna Kea, with one nodal plane deviating 25° from the trend of the rift zone. In spite of the geographical coincidence, we do not think that there is a tectonic relationship between the earthquake and the rift zone because the earthquake occurred at 41 km depth, whereas the rift zone may extend to a depth of only about 8 km.

The predominantly strike-slip motion of the Honomu earthquake favors the interpretation that the earthquake is of tectonic type, associated with a fault at depth. The N70°W nodal plane agrees with the general trend of the island chain, as the major islands from Maui to Kauai are aligned in the direction of N65°W. The volcanic centers on these islands also line up in that general direction. Although there is no known surface expression of a fault trending in that direction, it is very possible that a fault in that direction could have been buried by lava flows. On the other hand, the N30°E nodal plane, if extended southward, parallels the Honaupo-Kaoiki fault, which seems to separate Kilauea from Mauna Loa (Figure 3). In 1962, a shallow earthquake of 5 km depth and magnitude 6.1 occurred along that fault (Koyanagi, Krivoy, and Okamura, 1966). Fault plane solution of the 1962 Kaoiki earthquake agreed to within several degrees with the mechanism of the Honomu earthquake.

From the observation that earthquakes with magnitudes greater than 6 tended to occur at distances of tens of kilometers away from volcanic centers (Figure 2) and from the consideration that the focal mechanisms of the 1962 and 1972 earthquakes were predominantly strike-slip motions, the conclusion is drawn that there is an active tectonic process in Hawaii quite distinct from volcanic activity. Recent theories attribute Hawaiian volcanism to a hot spot (e.g., Dalrymple, Silver, and Jackson, 1973) beneath the lithosphere. Other types of tectonic theory have not been proposed. Although a major part of Hawaiian seismic data can be explained in terms of subterranean magmatic activity, nevertheless, there exists a hard core set of seismic data, especially data on large earthquakes, that cannot be accounted for by magma movements or by variants of the hot spot theory. At the present time, we can only say that midplate tectonics and seismicity of the Pacific are not clearly understood and that further study is warranted.

Strain Seismograms

A strain seismograph at Kipapa (KIP) on Oahu, installed by California Institute of Technology but operated by NOAA, recorded the earthquake as shown in Figure 4. The strain seismograph was oriented in the direction N61°W and is practically in line with the direction to the epicenter.

The recording shows a rarefaction just preceding the earthquake. Strain variations from meteorological origin are about that size and therefore we hesitate to attribute the rarefaction to stress buildup prior to the earthquake.

The earthquake itself turned out to be a large compression strain. This agrees with the source mechanism solutions.

A permanent strain of the order of 10^{-9} with a negative polarity was registered after the earthquake. The order of magnitude of strain agrees with the calculations by Press (1965), after fault length and source mechanism orientation have been considered.

Calculation of Source Parameters

Several long-period vertical component seismograms from World Wide Seismic Stations (WWSS) were obtained through the National Oceanic and Atmospheric

Administration. To obtain source parameters, analyses of these seismograms were attempted. The results presented here are preliminary, as parameters were sought to obtain their order of magnitude. A careful study using more seismograms is being planned.

Using the P-Wave and S-Wave recordings of BKS (Berkeley, California), GSC (Goldstone, California), PAS (Pasadena, California) and BAG (Baguio, California), the following parameters were obtained.

Average Seismic Moment, M_o, 0.37×10^{26} dyne-cm
Corner Frequency for P-wave, f_o, 0.11 hertz

The corner frequency was obtained by analyzing the record from GSC, which contained a good portion of high-frequency components. At the time of this report, short-period records from Hawaii were not available, as all seismographs, even those in Honolulu, were off the record. The P-wave part of the strong motion accelerograph at Namakani was not digitizable. In our further study, it is hoped that records from a hydrophone situated north of the island of Oahu will be made available.

If the Brune's method (1970, corrected version 1971) for determining source dimension by corner frequency is used,

$$r(P) = \frac{2.34\alpha}{2\pi f_o}$$

where $r(P)$: radius of a circular source area,
α: P-wave velocity, 8.2 km/sec, and
f_o: corner frequency of P-wave spectrum,

we obtain $r(P) = 28$ km and $A = \pi r^2 = 2460$ km^2.

Stress drop was calculated by following the discussion of Hanks and Wyss (1972) and Wyss and Hanks (1972)

$$\Delta\sigma = \frac{7}{16}\frac{M_o}{r^3}$$

where $\Delta\sigma$ is the stress drop. This gave $\Delta\sigma \approx 0.7$ bar.

From the strain data at Kipapa of 10^{-9}, the dislocation at the source parallel to the N70°W striking fault was calculated, using the equations provided by Press (1965). The dislocation was 2 cm. Then we applied Aki's (1966) formula,

$$M_o = \mu A \bar{u}$$

where μ: shear modulus,

A: area of fault surface, and

$\bar{u}$: average displacement across the fault surface.

Here, the velocity of the S-wave is 4.73 km/sec, density $\rho=3.3 g/cm^3$, and $\mu=\rho\beta^2=7.4\times10^{11}$ dyne/cm^2. The result of $M_o=0.36\times10^{26}$ is consistent with M_o from the spectral level data given above.

If we use Knopoff's (1958) formula,

$$\Delta\sigma = \frac{1}{2} \frac{U\ max}{h} \mu$$

where h = 24, 3/4 U max = $\bar{u}$, we obtain 0.2 bar. This is several factors smaller than the previous calculation.

It is proper to emphasize at this time that the foregoing calculations were based on available seismograms (October 1973) and that the aim was to obtain preliminary, order-of-magnitude estimates of source parameters. Even the meager results threw considerable light on regional tectonics. The stress drop of the earthquake was very low, a fraction of a bar, while the fault area was rather large, about 2500 km^2.

Absence of Field Data

One of the frustrating factors in investigating this particular earthquake was the absence of geological field data on ground movements, because of the depth of focus. No surface trace of fault movement, whether horizontal or vertical, was found. Elevation changes were not measured by precise surveying techniques as this was not felt necessary. A careful gravity survey was suggested but the available pre-earthquake data (Kinoshita, 1965) were not usable as tidal variations that may amount to 1 milligal were not taken out. The actual field notes of the gravity survey are being sought.

Summary and Discussion

The Honomu Earthquake of April 26, 1973, followed general patterns of large earthquakes, magnitude ≥ 6, in Hawaii. These earthquakes seem to come in clusters chronologically at 11-year intervals.

The earthquake was not associated with any center of volcanism, although Kilauea volcano, which is about 50 km from the epicenter, was in active eruption at that time. This dissociation is consistent with all other recorded large earthquakes, which were never near centers of volcanism. Although the epicenter coincided with the east rift zone of Mauna Kea, an inactive volcano, it is doubtful that there is any causal relationship with the rift zone, since rift zones do not extend downward to mantle depths and the earthquake was located at a depth of 41 km.

The fault plane solution was predominantly strike-slip motion, and its nodal planes agreed with those of the Kaoiki fault earthquake of 1962. At present only these two fault plane solutions for Hawaiian earthquakes have been published. Although it may seem unwise to jump to conclusion from only two fault plane solutions, nevertheless, the fact that strike-slip motions have been observed twice is significant. Combined with other observations that large earthquakes in the past occurred away from volcanic centers, the conclusion is drawn that a tectonic process quite apart from volcanism is in operation in the Hawaiian area. The examination of midplate tectonics and seismicity around Hawaii is a topic that warrants further support.

Calculations of source parameters indicated a low-stress earthquake. The low stress may be interpreted in terms of a regional thermal anomaly at depth, for which the volcanoes are surface expressions. Superimposed on this thermal anomaly are regional stresses, which can cause strike-slip earthquakes at depths of 40 km as well as at shallow places.

From the point of view of regional geology this earthquake contributes significantly to the understanding of tectonic processes around Hawaii. It provided another bit of evidence that a hot spot or spots beneath the lithosphere do not constitute adequate explanations for some of the observed geophysical phenomena. In addition to thermal processes at depth, whether they are hot spots or other anomalies, there is another mechanism at work causing strike-slip earthquakes in the magnitude 6 range.

PRELIMINARY STRONG-MOTION INSTRUMENTAL RESULTS AND AFTERSHOCKS

Early in 1973, the Seismological Field Survey, NOAA, shipped two strong-motion accelerographs and four seismoscopes to the University of Hawaii for installation in a Hawaiian Strong-Motion Network as proposed by Furumoto, et al. (1972). Fortunately, the University of Hawaii personnel were able to install all but one of the instruments prior to the April earthquake. The April 26 earthquake provided the first strong-motion recordings from the Hawaiian Islands. During the 40-year history of the operation of the Strong-Motion Network in California many records of ground motion have become available to engineers but as pointed out by Furumoto and Nielsen (1972) the characteristics of the strong ground motion could be different for the various islands as compared to typical records obtained in California.

Immediately following the April 26 earthquake Morrill was dispatched to the Islands to recover records, install instruments, and assist the University of Hawaii in the investigation of the effects of the earthquake. Within 24 hours following the earthquake, the earthquake investigation team met with U.S. Geological Survey personnel at the Hawaii Volcano Observatory at Kilauea, Hawaii, to determine the most efficient use of the personnel and materials available to the team and to determine whether additional temporary instrumentation would be of use. The following approach was adopted:

1. Morrill would immediately recover the strong-motion records and install the two additional accelographs at Hilo and Honomu (10 miles north of Hilo in the epicentral area).
2. Additional seismograph systems and technical assistance from the Special Projects Party, NOAA, would be requested. The developed area of Hilo is located on essentially two types of foundation materials, namely, volcanic flow in the south and east portions and volcanic ash in the north portion. With the opportunity at hand to record aftershocks it was apparent to all that siting of calibrated instruments capable of recording the small and medium sized aftershocks on these site materials could be of extreme importance to the engineers.
3. The remainder of the team would make a survey of damage and earthquake effects throughout the area.

4. The Geological Survey personnel would assist the team by providing aftershock and other data in the course of the investigation.

The following is a list of all equipment installed after the main shock:

Site No.	Equipment	Location	Date	Aftershocks recorded
	Accelerographs[1]			
TA-1	SMA-1, S/N 853	St. Joseph, Hilo	4-28-73	0
TA-2	SMA-1, S/N 852	Honomu	4-29-73	0
	Aftershock monitors[2]			
HO-1	L-7-B, S/N 110	Univ. Hawaii, Hilo	4-29-73	7
HO-2	L-7-B, S/N 114	Honomu	4-29-73	2
HO-3	L-7-B, S/N 109	Lyman residence, Hilo	4-30-73	?
HO-4	L-7-B, S/N 131	Bayshore Apt., Hilo	4-30-73	4

[1]See Halverson (1971).
[2]See Navarro and Wuollet (1972).

Table 2 lists aftershocks of magnitude 2 or greater which occurred in the area prior to removal of the aftershock monitoring equipment. The data in Table 2 are preliminary and subject to later correction by the Hawaii Volcano Observatory. Due to the low magnitude of the aftershocks none were recorded by the relatively insensitive accelerographs. Monitoring sites at which the aftershocks were recorded are given in the table. The aftershock monitors recorded approximately 10 shocks of magnitude 2 or greater. The monitors were removed to the mainland on May 4, 1973, for another project.

Table 3 provides site data on the equipment installed after the April 26 earthquake. With consideration of the limited amount and type of equipment available, the siting of the equipment was directed towards obtaining (1) relative response data on the various surficial geology representative of the building sites in Hilo, and (2) response of a multistory reinforced concrete building and the relation of such response to the free-field response of its foundation geology. In addition, backup instrumentation was installed in Hilo and the epicentral area to record any larger aftershocks that might overload the more sensitive aftershock monitoring equipment being operated by SEB and by the Hawaii Volcano Observatory, USGS. This instrumentation plan was agreed upon by the engineers and seismologists on the scene.

Figure 5 shows the locations of the strong-motion instruments and the aftershock monitoring equipment with respect to the epicenter of the April 26 earthquake. Each of the selected aftershock monitoring sites was instrumented with a three-component (orthogonally oriented) seismic system. The system has a flat velocity response from 0.1 Hz to 34 Hz and a velocity recording range from 10^{-4} cm/sec to 100 cm/sec. The high-frequency limit is imposed by the recording rate of 3/16 in/sec on magnetic tape.

As noted before and in Figure 5, two accelerographs and four seismoscopes were installed in Hawaii prior to the April 26 earthquake. Figure 6 shows reproductions of the two accelerograph records. The Honolulu instrument failed to record the longitudinal trace. Table 4 provides station and instrumental information along with maximum acceleration and distance information for the Honolulu and Kilauea accelerograph stations.

The type of strong-motion accelerograph installed in Hawaii, pictured in Figure 7, is the Kinemetrics Model SMA-1. It is described by Halverson (1971). Figure 8 shows the seismoscope described by Cloud and Hudson (1967). Essentially the seismoscope record represents the motion of a building whose natural period is 0.75 sec and whose damping is 10% if critical. Hence seismoscopes are normally installed in "free-field." Seismoscope data can be very useful when the instrument is used in conjunction with accelerographs, the seismoscope record providing a point on the response spectra.

The three seismoscopes installed in Hawaii are Wilmot-type; hence their sensitivities are about 5.5 cm/rad. For each record maximum displacement on the plate is measured from the initial zero point. From the sensitivity of the seismoscope in cm/rad, the maximum angular motion of the pendulum ϕ_{max} is determined. The maximum relative displacement response spectrum value S_d is then calculated from

$$S_d = \frac{gT^2}{4\pi^2} \phi_{max}\sqrt{\frac{n}{10}} \qquad \text{(Hudson and Cloud, 1967)}$$

where T: period (sec),

n: damping (percent critical), and

ϕ_{max}: trace amplitude/sensitivity.

In addition to the seismoscope magnetic damping, dry friction between the stylus and the glass record plate introduces some amplitude-dependent damping. The S_d values are thus corrected by the $\sqrt{n/10}$ term, where the percent critical damping, n, is taken corresponding to the maximum trace amplitude from the damping curve of Figure 9. This damping curve is an average curve obtained from some 450 observations on 12 glass record plates. It was shown from experience with a large number of records from the San Fernando earthquake (Morrill, 1971) that the use of the average damping curve introduces only negligible errors in the final corrected S_d values.

Table 5 gives the maximum relative displacement response spectrum value S_d for the seismoscopes installed on the Island of Hawaii along with epicentral distances. Values corresponding to the three or four largest peaks are given for each of the three major records. Vectors representing these S_d values are plotted on the map in Figure 5. Figure 10 shows the three seismoscope records.

The accelerograph record obtained at Kilauea was digitized and Figure 11 shows a plot of the resulting velocity response spectra. At Kilauea a seismoscope was located alongside the accelerograph and its S_d value is represented by the black dot near the 10% damping curve. Due to its low amplitude the Honolulu accelerograph record was not digitized. Figure 12 compares the maximum recorded acceleration from this earthquake to those obtained in past earthquakes (Cloud and Perez, 1971).

The seismic data from a selected aftershock, which was approximately 50 km from two of the aftershock monitoring stations, was analyzed by deriving a pseudo velocity response (PSRV) spectrum from the data. One station was located in Hilo near the University of Hawaii campus on a deep, weathered lava flow; the comparison station was located in the northern part of Hilo on a relatively extensive volcanic ash bed. The PSRV spectrum is derived from the seismic trace by digitally filtering the data and calculating the peak response of a series of single-degree-of-freedom systems to the ground motion. The systems were arbitrarily damped at 5%. Figure 13 shows the PSRV spectrum derived from the horizontal data. The spectrum for the lava station indicates a simple response peak in the period range of 0.3 to 0.1 sec, with attenuation (or reduced response) at the shorter and longer periods. The spectrum for the ash station is markedly different from that found on the lava. The response is complex with at least three bands of periods with high response. These bands are found in the 0.07-0.09, 0.3-0.5, and 3.3-5.0 sec ranges. The motion on the ash was at a higher amplitude than that on the lava.

It should be pointed out that the data on strong ground motion in Hawaii are meager. Hopefully, additional accelerographs can be provided in the near future for completion of the minimum array recommended by Furumoto et al. (1972). Furthermore, owners or builders of major structures in the more seismic zones of the Hawaiian Islands should be encouraged to provide instruments for their structures.

Hawaii, the largest and the youngest of the Hawaiian Islands, was formed by five volcanoes: Mauna Kea, Mauna Loa, Hualalai, Kilauea, and Kohala. Mauna Loa and Kilauea are still active. The bedrock under Hilo was formed by the lava flows from Mauna Kea and Mauna Loa. Mauna Kea is the older volcano and Mauna Loa is younger and still active. The Wailuku River, immediately north of downtown Hilo, is the dividing line between the Mauna Kea and Mauna Loa flows. Areas of volcanic ash deposits are shown in Figure 14.

Building foundations in downtown Hilo are mostly on lava rock and clinker from the flow lavas of Mauna Loa volcano. Except for Pier 1, where the 20-ft alluvial fill behind the retaining structure at the end of the pier settled several inches, the structural damages in downtown Hilo were minor, consisting mostly of broken glass windows, dishes, and jammed doors.

Most of the earthquake damage seemed to be concentrated around the lower slopes of the Mauna Kea lava flows just north of downtown Hilo and extended as far as Ookala, within a radius of 12 miles of the epicenter. Minor damage reports came from as far as Waimea and Puako near the Mauna Kea Beach Hotel about 33 and 47 miles, respectively, from the epicenter.

The Mauna Kea lavas are much older than the Mauna Loa lavas. This can easily be noted by the stream patterns on maps of the islands. Where lava flows are young, streams are unable to develop definite water courses because the lava is very porous. For example, there are very few channels in the Mauna Loa lavas which form the foundations for downtown Hilo. On the other hand, high rainfall (over 200 inches per year) and runoff have cut many "V"-shaped gulches into the ash and weathered rock slopes of the older Mauna Kea lava flows. The toe of the slope of the Mauna Kea flow has been cut away by waves to form the steep sea cliffs of the Hamakua Coast. The height of the cliffs varies from about 30 ft near Hilo to more than 100 ft toward the northwest near Laupahoehoe.

At the last stages of the volcanic activity of Mauna Kea, ash deposits from the volcano covered the northwest coastline (Hamakua) of the island. The ash cover over the sea cliff is about 20 to 30 ft thick near Hilo and thins out to about 6 ft or less toward the northwest. Some of the ash from Mauna Kea has blown over onto the Mauna Loa flow over parts of Hilo. The ash is relatively thin, probably less than 10 ft, above Hilo in the Kaumana area above (Mauka) downtown Hilo. Structural damage to residential foundations seemed to be greatest in the 25-ft thick ash deposits in the Pueo residential area which is immediately north of downtown Hilo and north of Wailuku River.

Even though the earthquake damage to structures was minor, the performance of the volcanic ash over the lava bedrock was unique. The natural water content of the material is about 200% except for surface layers which may be less than 100% in localized areas. The annual rainfall causes the liquid limit to approximate the natural water content of the soil. The degree of saturation is about 95 to 100%. The material plots below the "A" line on the Casagrande plasticity chart. On air drying, the liquid limit and plasticity index usually decrease and the material behaves much like a slightly cemented silt. Typical test data on the volcanic ash are shown in Figure 15.

Several failures of performance of foundations in the ash deposits will be described:

Sea Cliffs -- The toe of the slope along the Hamakua sea cliffs are constantly being eroded by wave action. The slopes are nearly vertical to about 1/4 to 1 slope, from 40 to over 100 ft high. The ash cover above the rock is actively falling back to about a 1/2 to 1 slope.

There may have been many soilfalls along the sea cliffs during the quake. Only two were noted because they involved structures.

The backyard of the Bayshore Tower in the Pueo area just north of Hilo fell and reduced a portion of the rear property about 5 ft. The height of the cliff is about 35 to 40 ft.

Another soilfall was reported from the Alae residential area which is about 2 miles north of Hilo. The soilfall extended halfway under the rear lanai slab of the Windham residence. The height of the sea cliff is about 70 ft.

Roadway Cuts -- Roadway cut slopes along the Hamakua Coast approximate the slopes of the sea cliffs. Cuts of 90 feet or more were made in the weathered lava at 1/4 to 1 and 1/2 to 1 slopes.

Twenty-foot high cuts have been made in ash deposits at 1/2 to 1 or steeper slopes.

Rock and soilfalls were greatest at Maulua Gulch Road on the state highway system and at Laupahoehoe Point Road and Kalopa Sand Gulch Road on the County road system. The rockfalls covered the roads and made them impassable. At these locations, the roads were notched into the sidewalls of gulches or seacliffs. The original cut slopes were almost vertical. The rockfalls tended to flatten the slopes to 1/4 to 1.

Most of the soilfalls along the highway cuts were minor and involved small quantities of debris. The soilfalls in ash slopes tended to flatten the slopes to 1/2 to 1.

Tension Cracks -- Sugar plantation camp roads were usually constructed by cutting into the sidewalls of the natural gulches along the tops of slopes. The road beds are usually placed in cut sections of the ash deposit.

During construction, the ash tends to liquefy after several passes of heavy equipment. Excavated materials are usually too wet for constructing embankments. They are usually wasted by casting over the side slopes of the gulches. The ash road bed is then usually covered with 24 inches of "aa" clinker and the pavement is capable of carrying heavy plantation truck traffic.

Following the earthquake, tension cracks and slumps of several inches were noted in the shoulders of the roadways, particularly in the northeastern part of the island. The toes of slopes in the above cases were usually being eroded by stream flows at the bottoms of the gulches.

Retaining Walls -- Retaining walls in ash may be better described as rock facings over cut slopes. The usual practice is to cut ash banks at 1/4 to 1 slopes and face them with either loose or mortared rock.

Many loose rock walls fell. The rock facings were between 10 to 15 ft in height. The natural slopes behind the rock facings that fell seem to stand up very well or approach a 1/2 to 1 slope.

Building Foundations on Ash -- Building foundations for concrete block bearing wall apartment buildings up to 3 stories in height have been constructed on ash with spread footing foundations. No bearing failures were reported or noted.

Observations and Comments

The performance of the volcanic ash deposit is of great interest and appears unique.

Even though the material has a high natural moisture content, over 200% (approximately equal to the liquid limit), and liquefies under the working of construction equipment, it did not liquefy under the shaking of the earthquake; strong shaking lasted less than 7 to 10 seconds. Steep road cuts (at 1/4 to 1 slopes) fell in localized areas and flattened to about 1/2 to 1 in localized areas. The volcanic ash behaved essentially as a slightly cemented granular material.

The relatively good performance of the ash may be partially explained: it probably is a wind or rain deposited material over very porous lava bedrock. The depth of the ash is relatively shallow, mostly less than 25 ft and the heights of cuts in ash were mostly less than 15 ft. The water table is tens of feet below the ash bed. Sufficient vertical drainage seems to prevail. The overall physical properties of the ash seem to improve toward a more siltlike material with air drying. Heavy rainfall, 200 inches per year, keeps the soil moist and sufficiently cohesive to maintain the steep roadside cuts at a 1/2 to 1 slope.

Whether or not the ash will perform as well under heavier shaking of longer duration is an open question.

SOIL DYNAMIC ANALYSES

Most of the reported damage centered within a 12-mile radius of Honomu, the epicenter. From a review of a soil map of the island (Figure 14), it appeared that most of the damages, particularly to residential structures, occurred in the ash deposits along the northeast coastline. The volcanic ash deposit is quite unique. It is light, 60 to 80 lb/ft^3, with a high water content over 200% that is close to the liquid limit. Typical soil test data are shown in Figure 15.

Construction equipment working directly on the ash tends to bog down after a few passes because the volcanic ash tends to liquefy under traffic. Road pavements over the ash are generally 24 to 30 inches thick and seem to carry heavy plantation truck traffic well. Soil dynamic analyses were made using standard formulas and charts available by Housner, Seed and others (Figures 16 through 22 and Tables 6 and 7) to estimate the natural periods and accelerations that may have contributed to the damages noted to structures constructed on ash.

Most formulas and design charts are based on the distance from the causative fault. On Hawaii, most of the faults have been covered by many thinly-bedded fairly recent lava flows. The faults are not visible at the surface. Furumoto, et al. (1972) have prepared a map (Figure 21) showing fault traces that cross the Hawaiian Islands. One of these traces just about crosses under Honomu, the epicenter.

Estimated values for natural periods and accelerations are given in Table 7. From the tabulations, it appears that the accelerations of 0.23 g may have acted on the structures near Hilo, 11 miles from the epicenter and 0.07 g at the Mauna Kea Hotel, 47 miles from the epicenter. Recalculating estimated values for natural periods and accelerations using distances from focus rather than from the causative fault, accelerations of 0.13 g were noted for areas around downtown Hilo and 0.07 g around Mauna Kea. These values seem to be more in line with the intensities of the damages noted in the field.

First impressions from visual field observations and a review of soil maps seemed to indicate that the damages were confined to structures built on the ash deposits. A closer check in the field showed that the largest land or rock slides occurred at Maulua Bay and Laupahoehoe Point, some 10 to

12 miles north of the epicenter where the ash is very thin and the foundation soil is mostly lava rock. The most serious damage to structural elements probably occurred at Papaaloa, 10 miles from the epicenter. The concrete rocker bearings cracked on the state's (Kaiwilahilahi) bridge.

Damages to structures of the same or larger degree as that found in structures on ash were noted as far away as Waimea and Mauna Kea Beach Hotel, 30 and 47 miles, respectively, northwesterly from the epicenter. The soils at Mauna Kea are mostly weathered lava with very little ash. The area is dry, with rainfall less than 20 inches per year.

From soil dynamic analyses for this earthquake, it appears that because of the thinness of the ash deposit, the influence of the ash on multistory buildings may not have been as much as one would suspect from casual observations. It appears that unreinforced masonry rock walls and small residential structures on volcanic ash soils suffered the greatest damage within about an 11- or 12-mile radius of the epicenter. From analyses and field checks, it appears that the 5- to 8-story shear wall buildings approached resonant frequencies with the ground motions and were most susceptible to damage from this quake.

How the ash would perform under a more intense earthquake of longer duration is a question that needs to be resolved to assist the foundation design engineer.

EARTHQUAKE DAMAGES

General

There were no fatalities and only 15 persons were injured in the earthquake. Damages were rather minor considering that the earthquake was of magnitude 6.2. There are several reasons for this. (1) The earthquake was very deep seated, 41 km. Usually earthquakes in Hawaii occur at much shallower depths. (2) The duration of the strong motion was very short, about 7 sec. (3) The island of Hawaii is sparsely populated--the total population of the island is 70,000; of this total 30,000 live in Hilo. There are very few tall buildings in Hilo, most are one- or two-story buildings. The damage to power lines, water supply systems, and telephone lines was severe. The northeastern portion of the island was in a state of emergency for several days. In most cases all lifelines were repaired within two days. The earthquake did not trigger a tsunami. This was rather fortunate since, due to a lack of funds, a system which gives immediate appraisal of a tsunami via tide gauges connected to radio-telemetry facilities, was not operational. If a tidal wave had been generated it would have reached densely populated Honolulu in 35 minutes.

In Honolulu, about 300 km from the epicenter, the damage was very minor; some pendulum clocks stopped and there were minor cracks in plaster. Apparently, the long period waves arriving coincided rather closely with the natural periods of some of the tall (20- to 30-story) buildings resulting in sways of relatively large displacements. Near panic broke out in several buildings.

Damage estimates as reported to the Civil Defense were:

Residences (738 reporting)	$2,000,000
Businesses (180 reporting)	1,500,000
Roads and Bridges	1,350,000
Schools	500,000
Pier 1	350,000
Water Works	300,000

Roads and Bridges

State and County roads were heavily damaged by numerous land and rock slides. Figure 14 shows the location of the damaged roads. Damage occurred along the coast highway from Hilo to the northeastern portion of the island. The heaviest damage occurred along the Laupahoehoe Gulch areas where the highway was closed at three points on the day of the 26th, and limited to one-way traffic on the 27th. Laupahoehoe is about 20 km north of the epicenter; the ash is very thin and the foundation soil is mostly lava rock. The heaviest damages occurred in the ash deposits from Hilo to Ookala. Typical pictures showing road damage, rock and soil slides are shown in Figures 22 through 26.

Several bridges suffered minor damages such as broken pipe railings and minor cracks in concrete columns. The most heavily damaged bridge was the Kaiwilahilahi Bridge, situated about 15 km from the epicenter. The concrete rockers and the bearing ends of the bridge beams were heavily damaged (Figures 26 and 27).

Buildings

By far the most severe damage to residences occurred in the northern portion of Hilo, north of the Wailuku River in the volcanic ash deposits. There were numerous failures of rock walls (Figures 28 and 29). There were many cases where "mixed" construction of rock walls and wood framing led to damage (Figure 30). In many cases houses were shifted on their foundations (Figures 31 and 32); carports fell down (Figure 33); concrete block buildings saw typical damage (Figure 34); cesspools in volcanic ash failed (Figure 35). A soil fall caused the collapse of the lanai (porch) of a house located about 3 km north of Hilo on a sea cliff with a height of 25 m (Figure 36).

There were minor structural damages in downtown Hilo. In the business district there was considerable damage to plate glass windows (Figure 37). One building, the typewriter center, collapsed. One of the parapets of the fire walls between the buildings apparently fell on the wood trusses of the typewriter center and collapsed the roof. One man trapped in the building was later freed with minor injuries. The building was old and termite-ridden (Figure 38). There was a good deal of damage to school buildings; the damage was in most cases nonstructural. Typically, false ceiling panels and lighting fixtures fell. Several school children were injured.

The Val-Hala Apartment Building is located about 18 km south of the epicenter. The building is a 5-story edifice constructed over 6 to 8 m of volcanic ash. The building is supported on piles, the site being on a gradual slope. The ground floor is a semibasement structure with fill on one side and open on the other. There was considerable damage to one of the end shear walls. Steps and the second-floor level serve as a bridge to the parking lot which is on fill. Differential motions between the building and the parking lot caused failure of the columns supporting the steps (Figures 39 and 40).

The Bayshore Tower is 18 km south of the epicenter. It is a 15-story building on 8 m of volcanic ash (Figure 41). The building is supported on pile foundations that extend through the ash. The earthquake resistant structural system consists of two heavy coupled shear walls running in both principal directions. Two canopy beams at the front of the building are rigidly attached to the shear walls (Figure 42). At the level where the beams were attached to the shear walls there were cracks in the shear walls. It is a possibility that the motions of the canopy beams during the earthquake could have thrown additional forces into the shear walls causing the cracks. There were many cases of concrete spalling (Figure 43). There was a good deal of nonstructural damage, especially in the upper stories. Typical damages were found where walls tied in to staircases and elevator shafts. The nonstructural damage was estimated to be approximately $10,000. Hairline cracks were noted at the top floor in the tie beams that coupled the shear walls together. The rear of the lot was reduced about 2 m by soil falls into the sea. A swimming pool in the rear of the lot showed no noticeable cracks. The parking lot in front of the building settled (Figure 44). The concrete block wall by the parking wall failed (Figure 45).

The Mauna Kea Beach Hotel is located 75 km from the epicenter. The hotel is an 8-story structure with foot bridges connecting the various wings (Figure 46). The hotel is well designed for earthquakes, with separate rectangular units. The bridge seats were designed for sliding, but did not slide, apparently because dowels were installed connecting the bridge decks to the seats. Spalling of concrete occurred (Figure 47). Minor cracks were noted at handrail connections. Cracks were noted where plaster walls and ceilings frame into the structural frame.

At Hilo Harbor, Pier 1, a 370 m-long concrete pier, was split from end to end by a 1 to 3 cm crack (Figure 48). At the end of the pier the concrete curb was broken (Figure 49). The damage for necessary repairs was estimated at $350,000. The dock at Pier 1 is constructed on pile foundations. The shed along the dock is partly on piles and partly on fill. A crack runs longitudinally along the floor of the building and the joint between the pile and fill supported floor. The crack was probably widened by the earthquake (Figure 50). The center row of columns in the shed is supported on piles. The floor probably settled before the quake below the concrete guards at the base of the column. The earthquake probably caused additional settlements (Figure 51).

Some Anomalies

As usually happens, tombstones toppled over in the earthquake (Figure 52). In quite a number of cases the tombstones did not topple over but were rotated. Curiously enough, in almost all cases, the tombstones were rotated in a counterclockwise direction (Figures 53 and 54).

An hour before the earthquake the Hawaiian station of the Navy's worldwide, long-range, very low frequency omega navigation system was not able to receive signals from the other stations in the network. At the same time a research team from the University of Hawaii which was bouncing waves off the ionosphere, transmitting from Kauai and receiving on Oahu, found a "hole" in the ionosphere. What apparently happened was that the ionosphere moved down to a level with higher absorption. It should be pointed out that a solar flare was sighted at the same time but it was only of a magnitude of 1^+. In the past, interference with the transmission has only occurred for solar flares of magnitude 3^+ or more. It is highly likely that these effects have nothing whatsoever to do with this earthquake.

However, since they happened such a short time before the earthquake, we have felt that they should be reported.

Interestingly enough, the same research team found that the Tokachi-Oki earthquake of May 1968 could be detected from their records. The long period Rayleigh waves were affecting the ionosphere and this showed up as Doppler effects in the data (Yuen, et al., 1969).

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TABLE 1

Major Earthquakes in Hawaii

Date			Location Lat.	Long.	Magnitude
1929	Oct. 5	7-51-99	19 3/4°N	156W	6 1/2
1938	Jan. 23	08-32-08	21.2°N	156.1W	6 3/4
1940	June 17	10-26-47	20 1/2	155 1/4	6
1941	Sept. 25	17-48-37	19	155	6
1950	May 30	01-16-16	19.5	156	6 1/4
1951	Apr. 23	00-52-21	19	155 1/2	6.5
1951	Aug. 21	10-56-57.5	19.4	156	6.75-7
1952	May 23	22-12-26	20	156	6
1954	Mar. 30	16-40-03	19.5	155.1	6
1954	Mar. 30	18-41-54	19.5	155.1	6
1962	June 28	4-27-14.3	19°24'	155°25'	6.1
1973	Apr. 26	20-26-40.6	19°51'	155°08'	6.2

TABLE 2

Some Aftershocks of the Honomu Earthquake of April 26, 1973

Date	Time (HST)	Magnitude	Recorded at Site No.
April 26	1053	3.8	
	1138	4.0	
	1221	3.5	
	1356	3.0	
	1558	3.6	
	1632	2.8	
	1726	3.4	
	2333	4.0	
April 27	1034	3.0	
	1048	2.8	
	1415	2.5	
	1427	2.6	
April 28	1208	3.5	
	1314	3.3	
	1444	2.4	
	2102	2.1	
	2252	3.0	
April 29	0400	2.2 (Kilauea)	
	0917	2.0 (Kilauea)	
	1549	2.0 (Kilauea)	
	1656	2.2	
April 30	0636	2.7 (Kilauea)	
	1927	3.1	HO-1, HO-2, HO-4
May 1	0058	2.1	
	0138	2.3 (Kilauea)	
	1614	3.1	HO-1, HO-2, HO-4
	2352	2.9	
May 2	0027	1.6	
	0415	1.8	

TABLE 2 (continued)

Some Aftershocks of the Honomu Earthquake of April 26, 1973

May 2 (continued)	0716	2.2	
	1607	2.0	
	1641	1.8	
	2201	2.0	
May 3	0212	2.0	
	0315	1.8	HO-1, HO-4
	0444	2.0 (?)	HO-1, HO-3
	0519	2.0	
	1330	2.7	HO-1, HO-4
	1514	2.5 (Kilauea)	HO-1
	1629 (?)		HO-1
	2140	1.5	HO-1
May 4	0913		HO-1
	1039		HO-1

TABLE 3

Site Characteristics of Temporary Stations

Site No.	Location	Coordinates	Instrument	Housing	Geology
1	St. Joseph High School Hilo, Hawaii	19°43.1'N 155°05.2'W	Accelerograph SMA-1, S/N 853	3x3m Metal concrete slab	Lava flow
2	Honomu, Hawaii	19°52.4'N 155°07.1'W	Accelerograph SMA-1, S/N 852	Residence concrete slab	Volcanic ash
3	Cloud Physics Lab. Univ. of Hawaii Hilo, Hawaii	19°42.3'N 155°04.9'N	3-component, 1 Hz seismometers L-7-B	Free-field	Lava flow
4	O. H. Lyman Res. Hilo, Hawaii	19°44.1'N 155°05.7'W	3-component, 1 Hz seismometers L-7-B	Free-field	Volcanic ash
5	Bayshore Tower Hilo, Hawaii	19°44.1'N 155°05.5'W	6-component, 1 Hz seismometers L-7-B	15-story, reinforced concrete	Volcanic ash
6	C. Tanimoto Res. Honomu, Hawaii	19°52.4'N 155°07.1'W	3-component, 1 Hz seismometers L-7-B	Residence Free-field	Volcanic ash

TABLE 4

Accelerograph Results and Site Characteristics for Honomu Earthquake of April 26, 1973

Location and Coordinates	Type and Serial Number	Component and Direction	Period (sec)	Damping	Sensitivity (cm/g)	Maximum Acceleration (g)	Period (sec)
Namakani Paio Kilauea, Hawaii 19°25.8'N 155°17.9'W	SMA-1 320	L S30°W	0.038	0.59	1.82	0.17	0.15
		V Down	0.038	0.59	1.86	0.07	0.10
		T S60°E	0.038	0.57	1.70	0.11	0.16
Location from epicenter:		Direction = 240°; distance = 50.3 km.					
Ala Wai Golf Course Honolulu, Oahu 21°16.8'N 157°49.3'W	SMA-1 318	L South	0.039	0.59	1.80	Instrument failure	
		V Down	0.039	0.57	1.86	0.01	0.2
		T East	0.040	0.59	1.84	0.03	0.15
Location from epicenter:		Direction = 300°; distance = 325 km.					

Housing and Geology:

Kilauea - Wood frame; one story; 5 x 7 m on-grade concrete slab. Shallow alluvium, mostly volcanic ash over lava flows. Less than 3.2 km to rim of active volcano. Elevation 1.23 km.

Honolulu - Wood frame; one story; 2.5 x 2.5 m on-grade concrete slab. 200 meters of sediment resting on basalt. Elevation sea level.

TABLE 5

Seismoscope Results, Honomu Earthquake of April 26, 1973

Location and Coordinates	Serial Number	Location from Epicenter Direction (deg)	Location from Epicenter Distance (km)	ϕmax (cm)	Damping (%)	Maximum Relative Displacement Direction (deg)	Maximum Relative Displacement S_d* (cm)
Univ. of Hawaii Hilo, Hawaii 19°42.3'N 155°04.9'W	682 (7435)	160	17.0	2.20	8.2	059	1.99
				1.45	9.3	230	1.40
				1.15	9.7	145	1.13
Namakani Paio Kilauea, Hawaii 19°25.8'N 155°17.9'W	697 (7436)	204	50.3	1.10	9.8	193	1.09
				0.84	10.3	036	0.85
				0.70	10.6	346	0.72
				0.50	11.0	104	0.52
Kailua Park Kailua, Hawaii 19°38.4'N 155°59.75'W	689 (7445)	256	93.0	0.20	15.0	180	0.25
				0.15	17.0	360	0.20
				0.09	20.0	090	0.13
Ala Wai Golf Course Honolulu, Oahu 21°16.8'N 157°49.3'W	703 (7431)	300	325.0	Negligible Amplitude			

*Based on standard constants: Period = 0.75 sec; sensitivity = 5.45 cm/rad and standard damping curve.

TABLE 6

Estimated Shear Modulus, Shear Wave Velocity, and Natural Period of the Soil Deposit

Strain (%)	Damping (%)	$\frac{G}{S_u}$	G (lb/ft^2)		$\rho = \frac{\gamma}{g}$	*V_s (ft/sec)		H (ft)	**T_s (sec)	
			@ S_u = 300 lb/ft^2	@ S_u = 600 lb/ft^2	Slugs/ft^3	@ S_u = 300 lb/ft^2	@ S_u = 600 lb/ft^2		@S_u = 300 lb/ft^2	@S_u = 600 lb/ft^2
10^{-3}	3	1800	5.4×10^5	10.8×10^5	2.485	467	660	20	0.17	0.12
10^{-2}	5	1000	3.0×10^5	6.0×10^5	2.485	347	490	20	0.23	0.16
10^{-1}	10	400	1.2×10^5	2.4×10^5	2.485	219	310	20	0.37	0.26

*$V_s = \sqrt{\frac{G}{\rho}}$

where V_s: shear wave velocity

G: shear modulus of the soil

ρ: mass density of the soil

**For the case of a single soil layer over bedrock:

$$T_s = \frac{4H}{V_s}$$

where T: period of the incoming wave

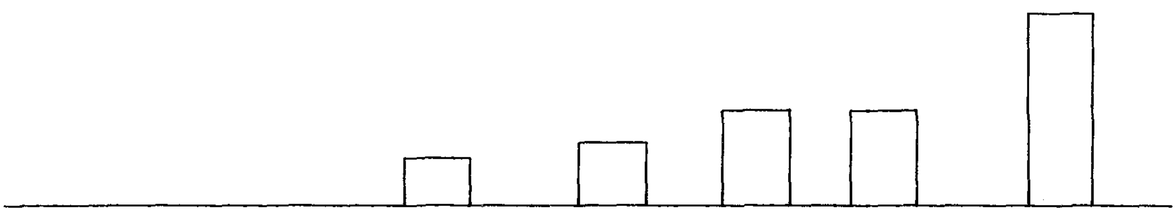
H: layer thickness

V_s: velocity of propagation of the shear wave in the soil

TABLE 7

Soil Dynamic Studies

Tabulation of Estimated Periods and Maximum Accelerations of Rock and Volcanic Ash

Building Description	3-Story Crescent (Hilo)	5-Story Val-Hala (Pueo)	8-Story Moanalua Shores (So. Hilo)	8-Story Mauna Kea (Puako)	15-Story Bayshore (Pueo)
					
Distance from Epicenter (miles)	12	11	11	47	11
Ash Thickness over Bedrock (ft)	20±	20-25±	0	0	25±
Natural Period of Building (T_b) (sec)					
$T_b = N/10$	0.3	0.5	0.8	0.8	1.5
$= N/20$	0.15	0.25	0.4	0.4	0.75
Natural Period of Ash Deposit (sec) $T_s = \frac{4H}{V_s}$	0.2-0.3±	0.2-0.3±	---	---	0.2-0.3±
Predominant Period of Rock Motion (T_p) (sec)	0.27±	0.27±	0.27±	0.33±	0.27±
Maximum Rock Acceleration (g)	0.26* 0.13**	0.26* 0.13**	0.26* 0.13**	0.07* ---	0.26* 0.13**
Maximum Ground Acceleration (g)	0.23* 0.13**	0.23* 0.13**	0.23* 0.13**	0.07* ---	0.23* 0.13**
Damage	5' Retaining Wall Collapsed	Stairway Bridge Concrete Spalls	Walkway Bet. Bldgs, Spalls @ Bearings	Foot Bridge Concrete Spalls @ Bearing	Hairline Cracks, Ground Floor Shear Wall

*Computation based on distance from epicenter.
**Computation based on distance from focus.

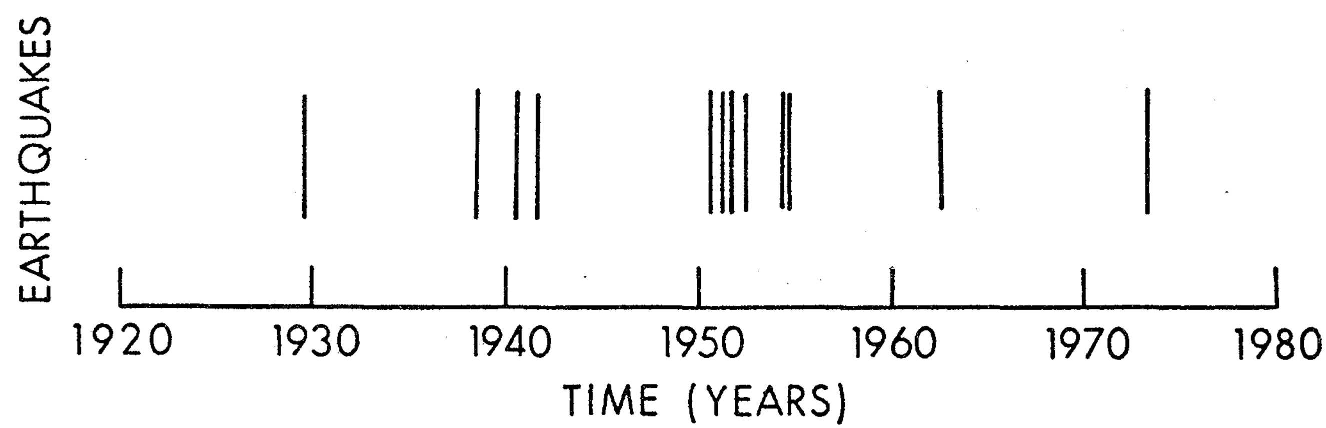


FIGURE 1 OCCURRENCES OF EARTHQUAKES WITH MAGNITUDES LARGER THAN OR EQUAL TO 6 SINCE 1929 IN HAWAII

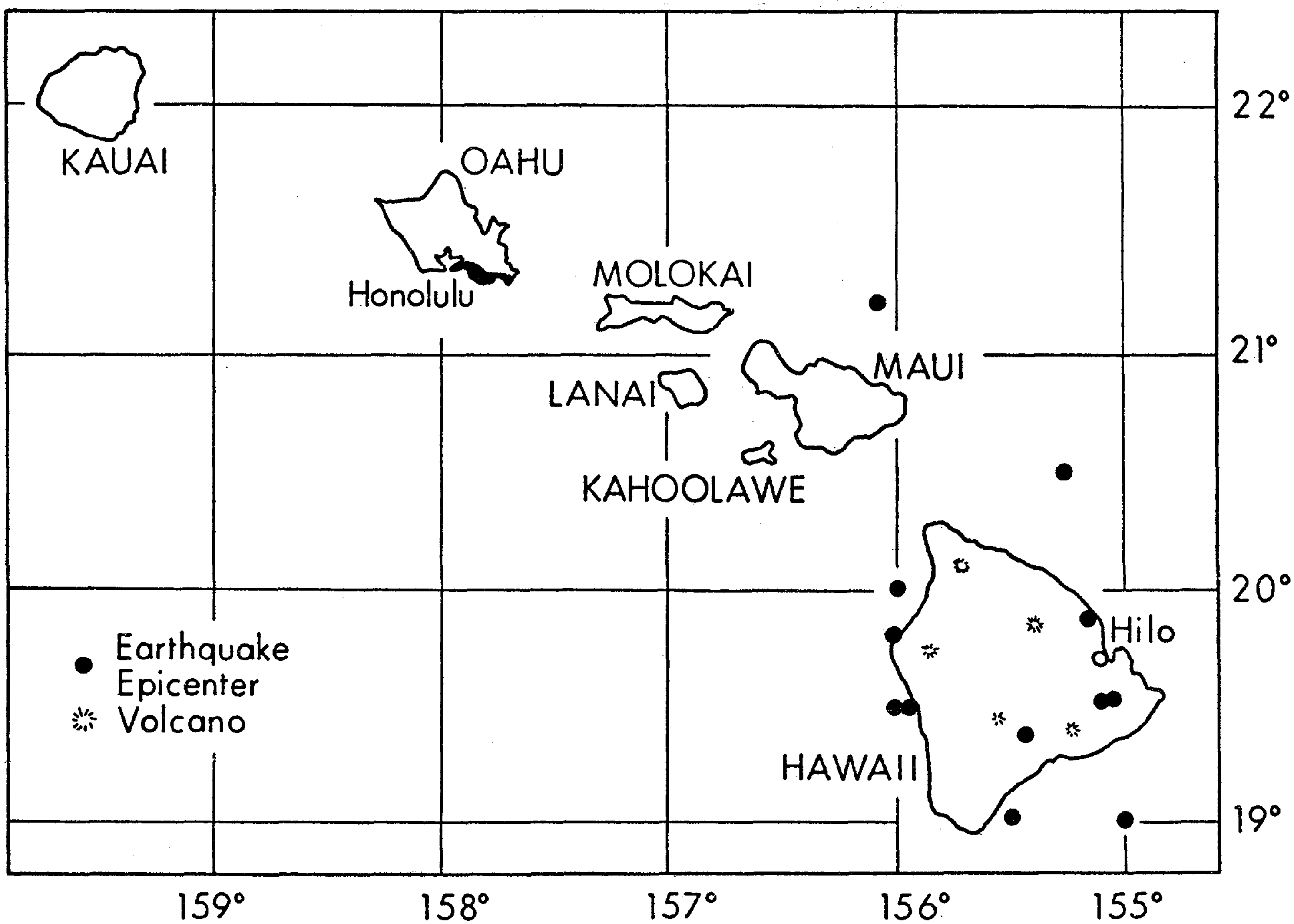


FIGURE 2 EPICENTER OF LARGE EARTHQUAKES ($M \geq 6$) IN HAWAII SINCE 1929

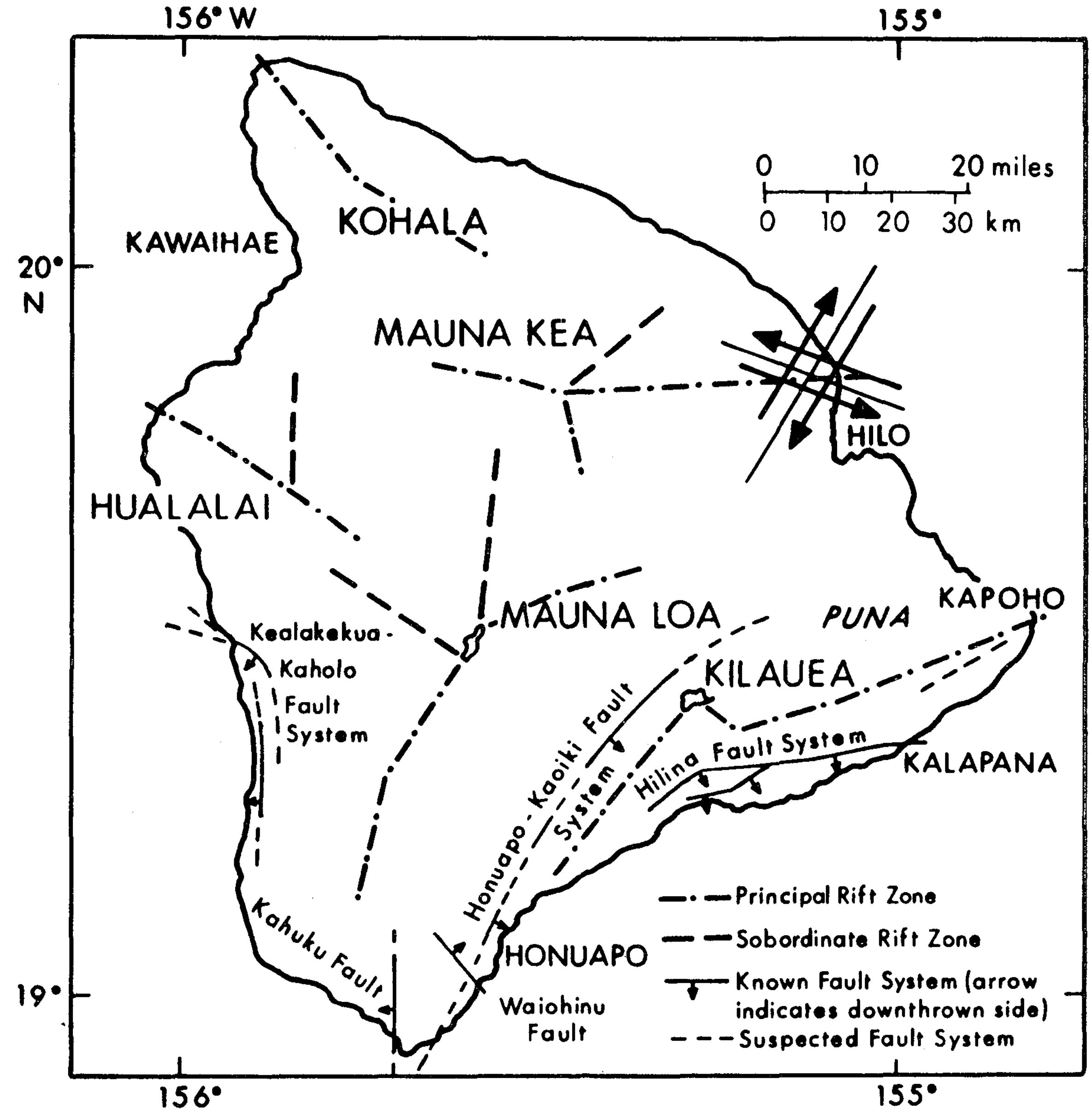


FIGURE 3 SOURCE MECHANISM OF THE APRIL 26, 1973, EARTHQUAKE AND THE LOCATION OF RIFT ZONES

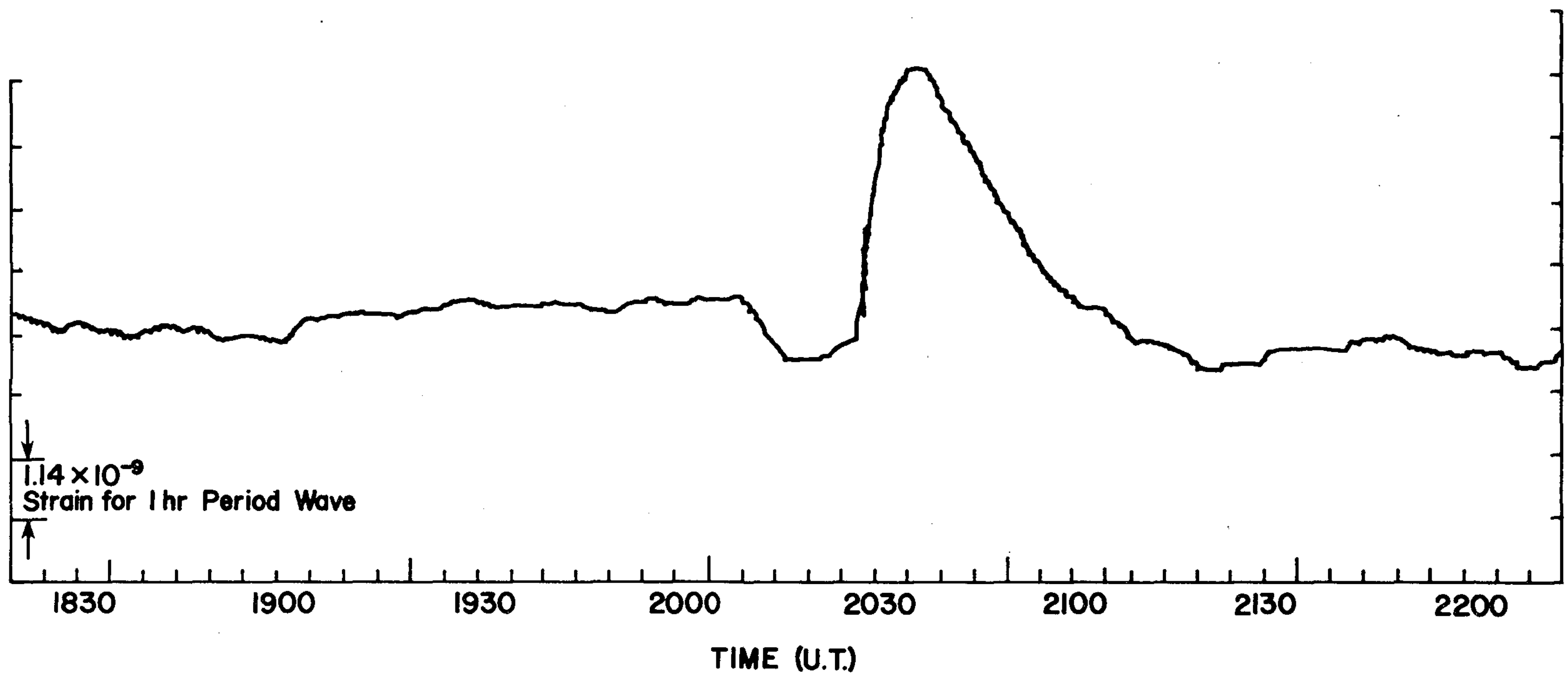


FIGURE 4 STRAIN SEISMOGRAM OF THE EARTHQUAKE FROM STATION KIPAPA (KIP) ON OAHU

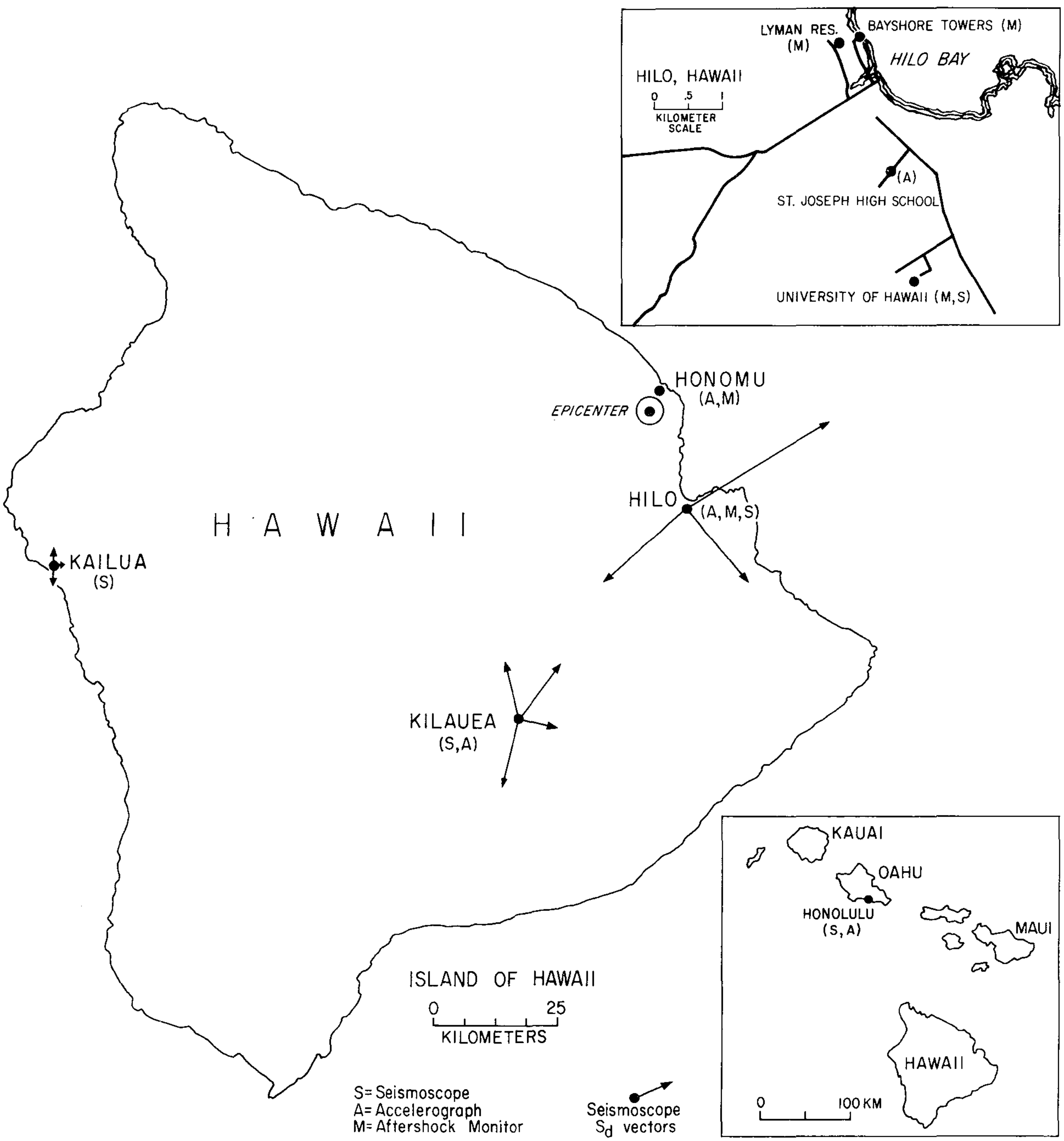


FIGURE 5 LOCATIONS OF STRONG-MOTION AND AFTERSHOCKS MONITORING EQUIPMENT INSTALLED IN HAWAII BEFORE AND AFTER THE EARTHQUAKE OF APRIL 26, 1973

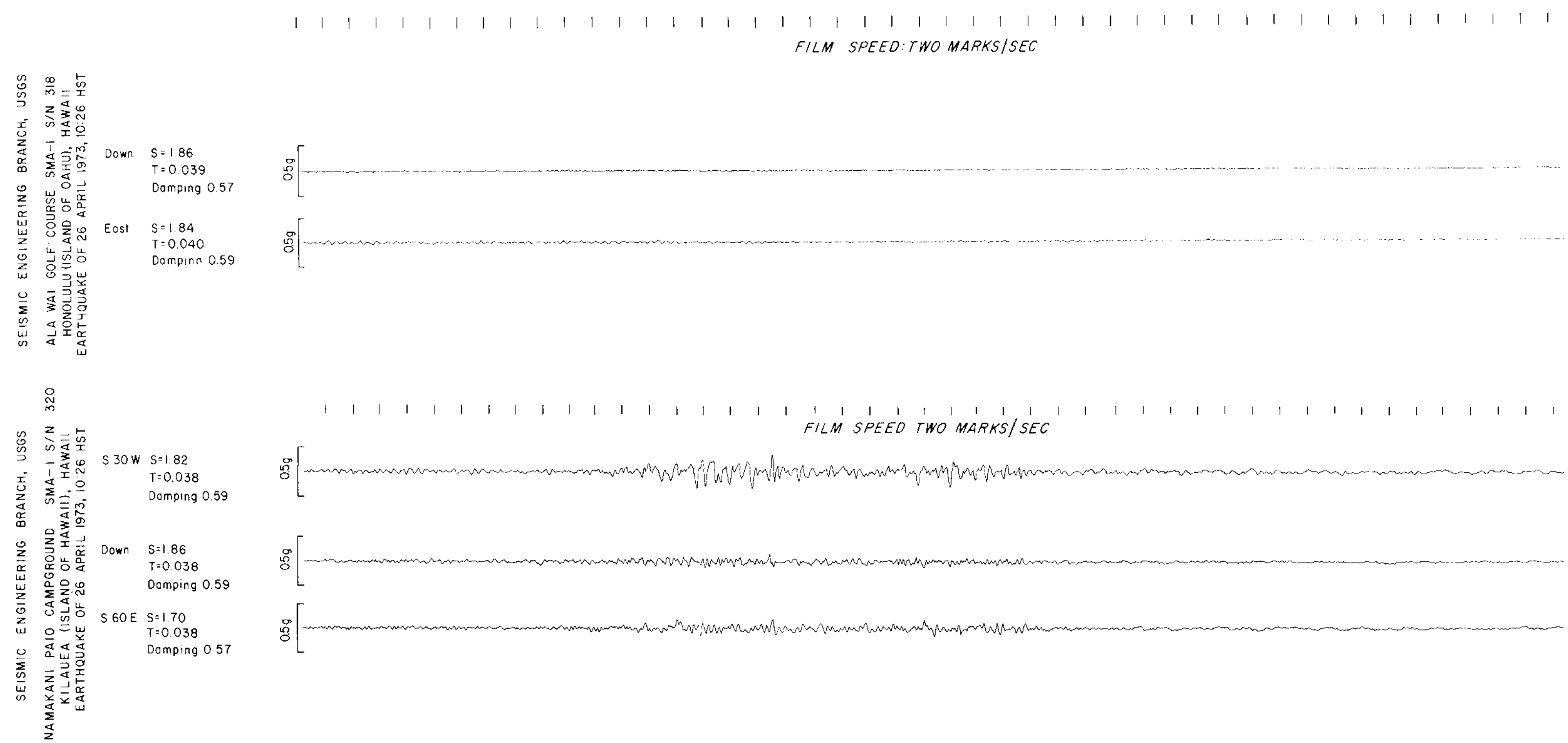


FIGURE 6 REPRODUCTION OF ACCELEROGRAMS RECORDED DURING THE APRIL 26, 1973, EARTHQUAKE

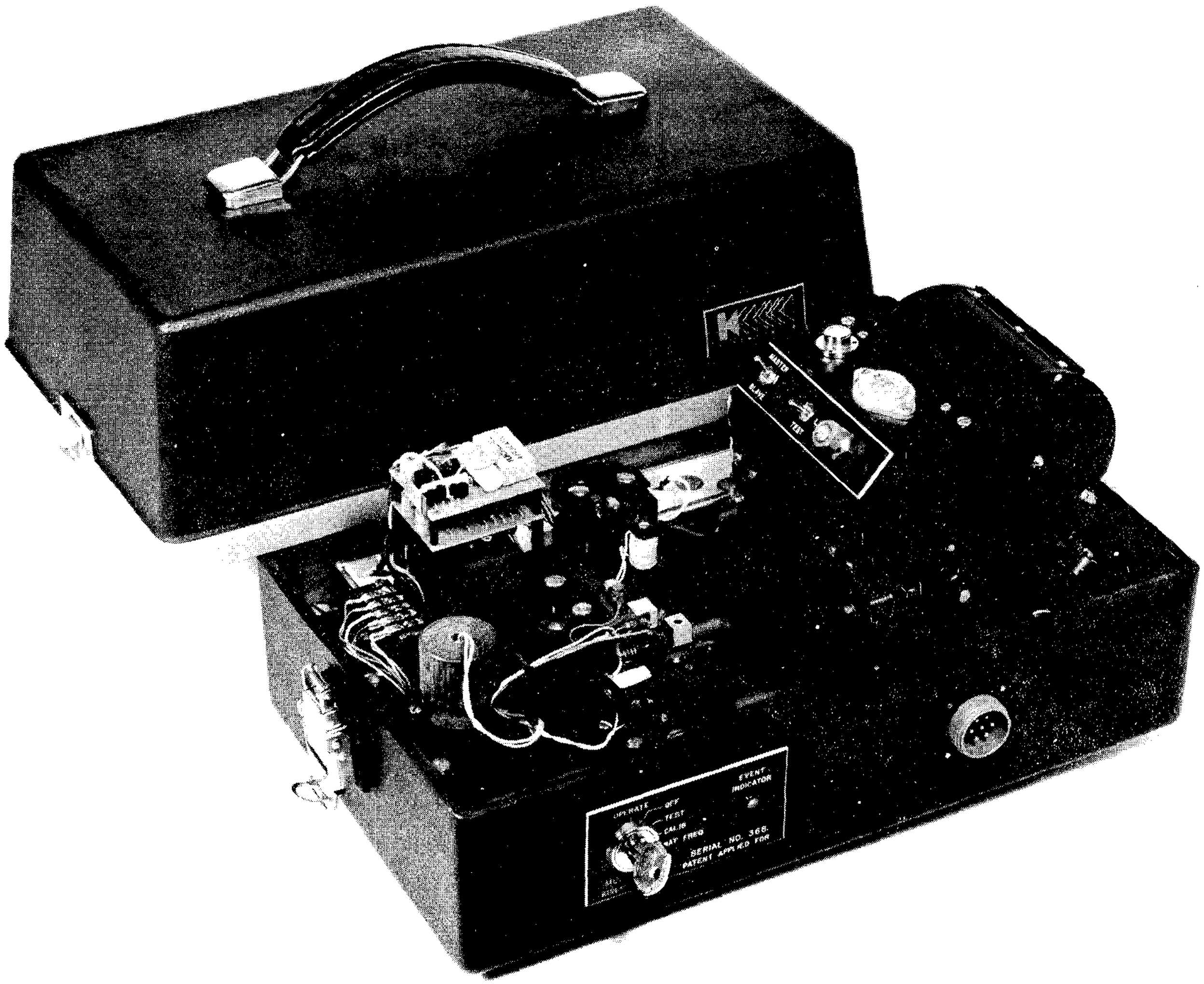


FIGURE 7   TYPE OF STRONG-MOTION ACCELEROGRAPH INSTALLED IN HAWAII

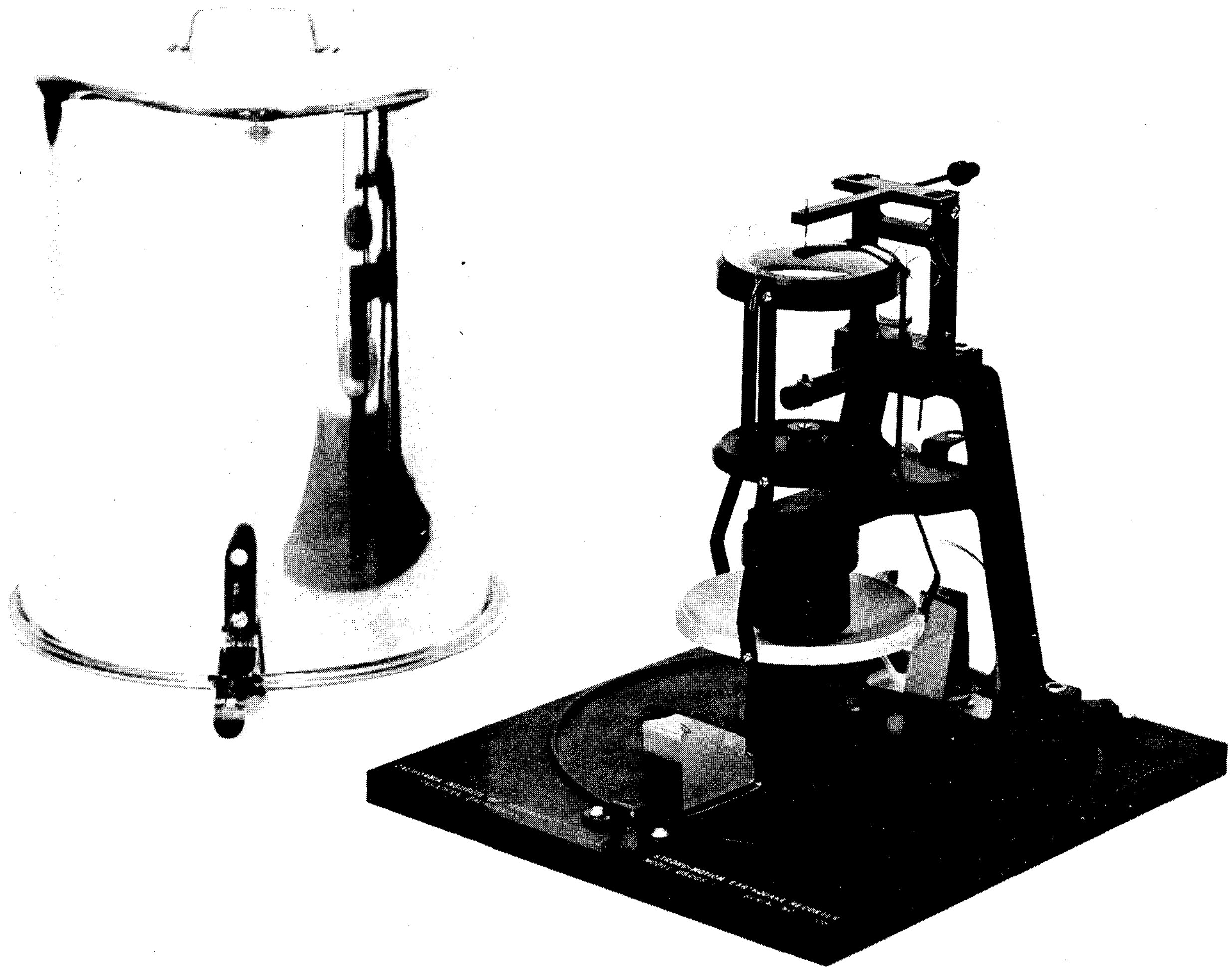


FIGURE 8 SEISMOSCOPE INSTALLED IN HAWAII

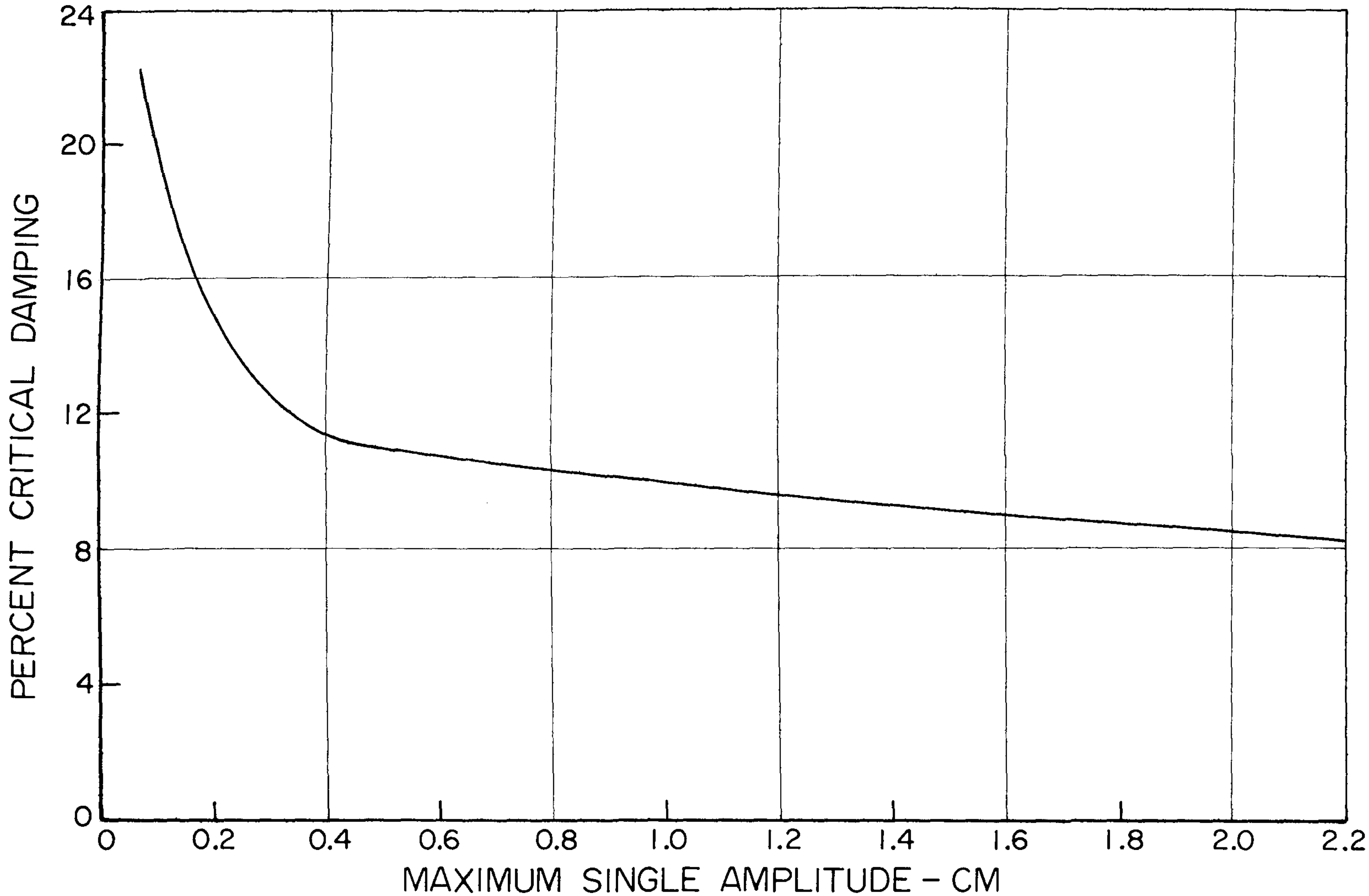
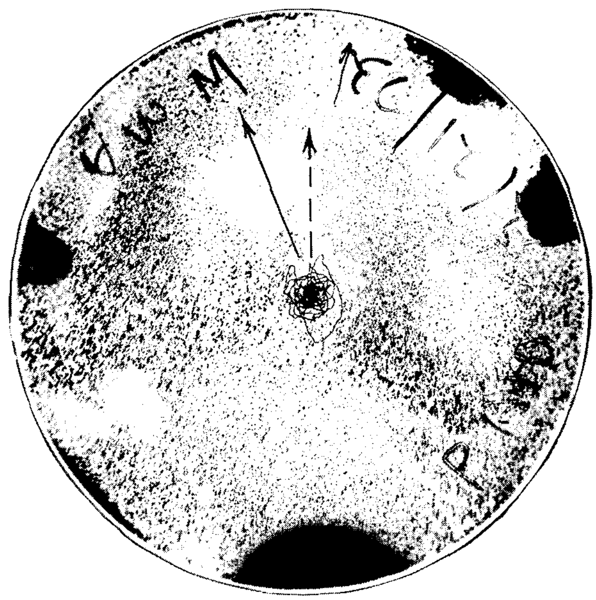
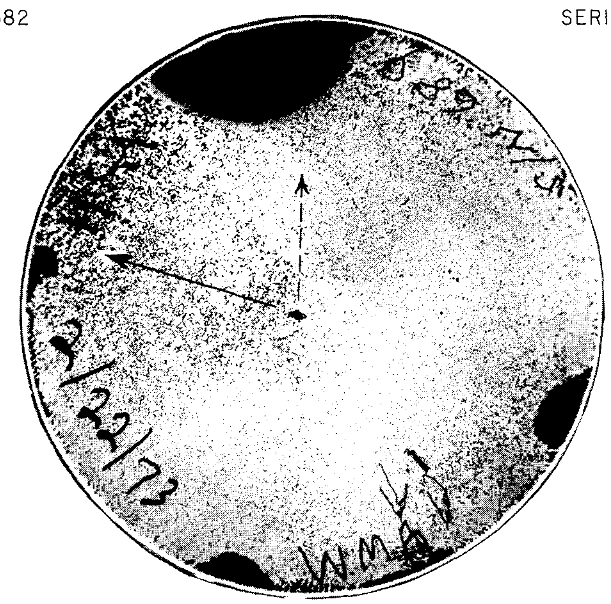


FIGURE 9 SEISMOSCOPE DAMPING CURVE

UNIVERSITY OF HAWAII
HILO, HAWAII
SERIAL 682

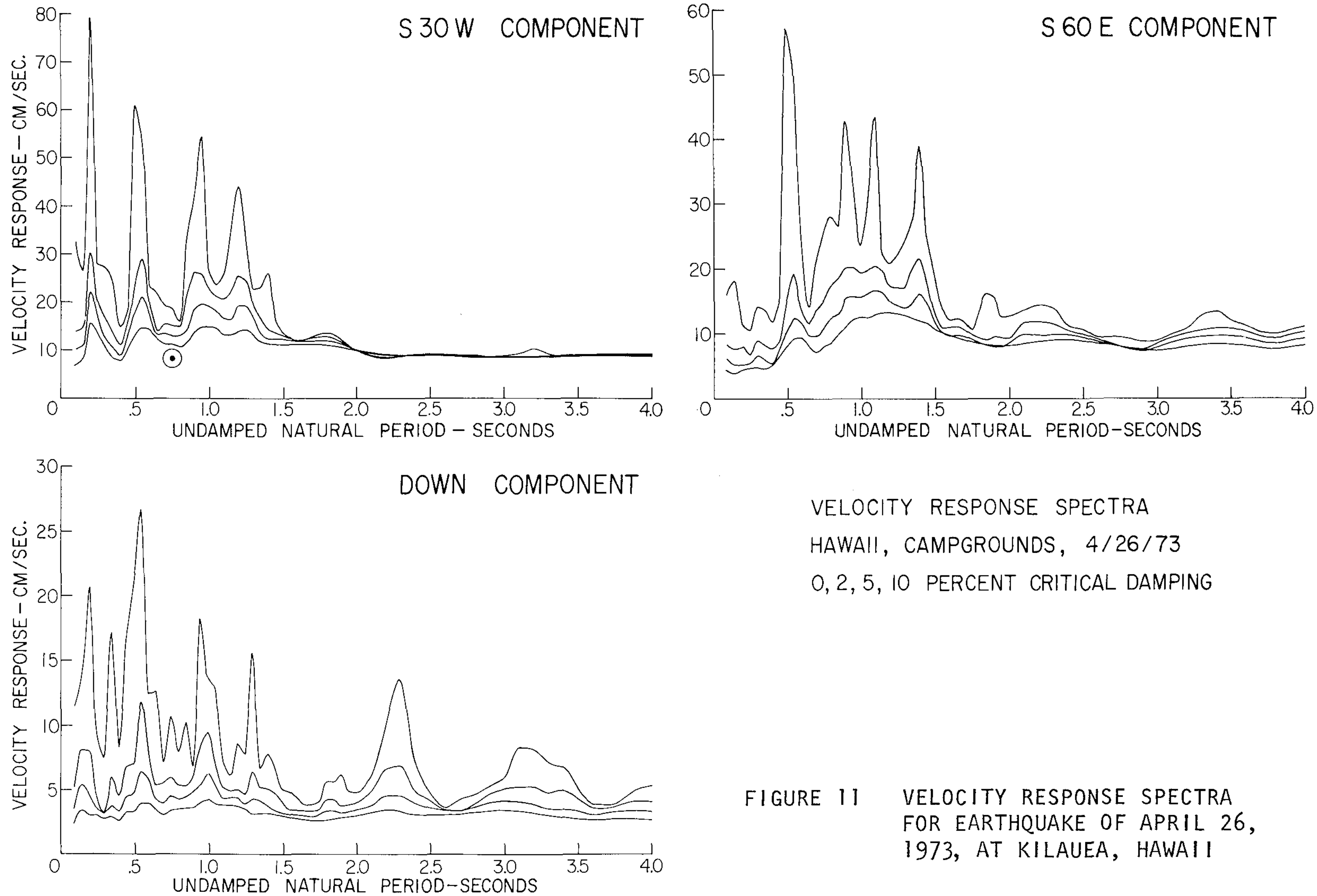


NAMAKANI PAIO
KILAUEA, HAWAII
SERIAL 697



KAILUA PARK
KAILUA, HAWAII
SERIAL 689

FIGURE 10 SEISMOSCOPE RECORDS FROM HONOMU EARTHQUAKE OF APRIL 26, 1973
(Dashed arrow points to epicenter)



VELOCITY RESPONSE SPECTRA
HAWAII, CAMPGROUNDS, 4/26/73
0, 2, 5, 10 PERCENT CRITICAL DAMPING

FIGURE 11 VELOCITY RESPONSE SPECTRA FOR EARTHQUAKE OF APRIL 26, 1973, AT KILAUEA, HAWAII

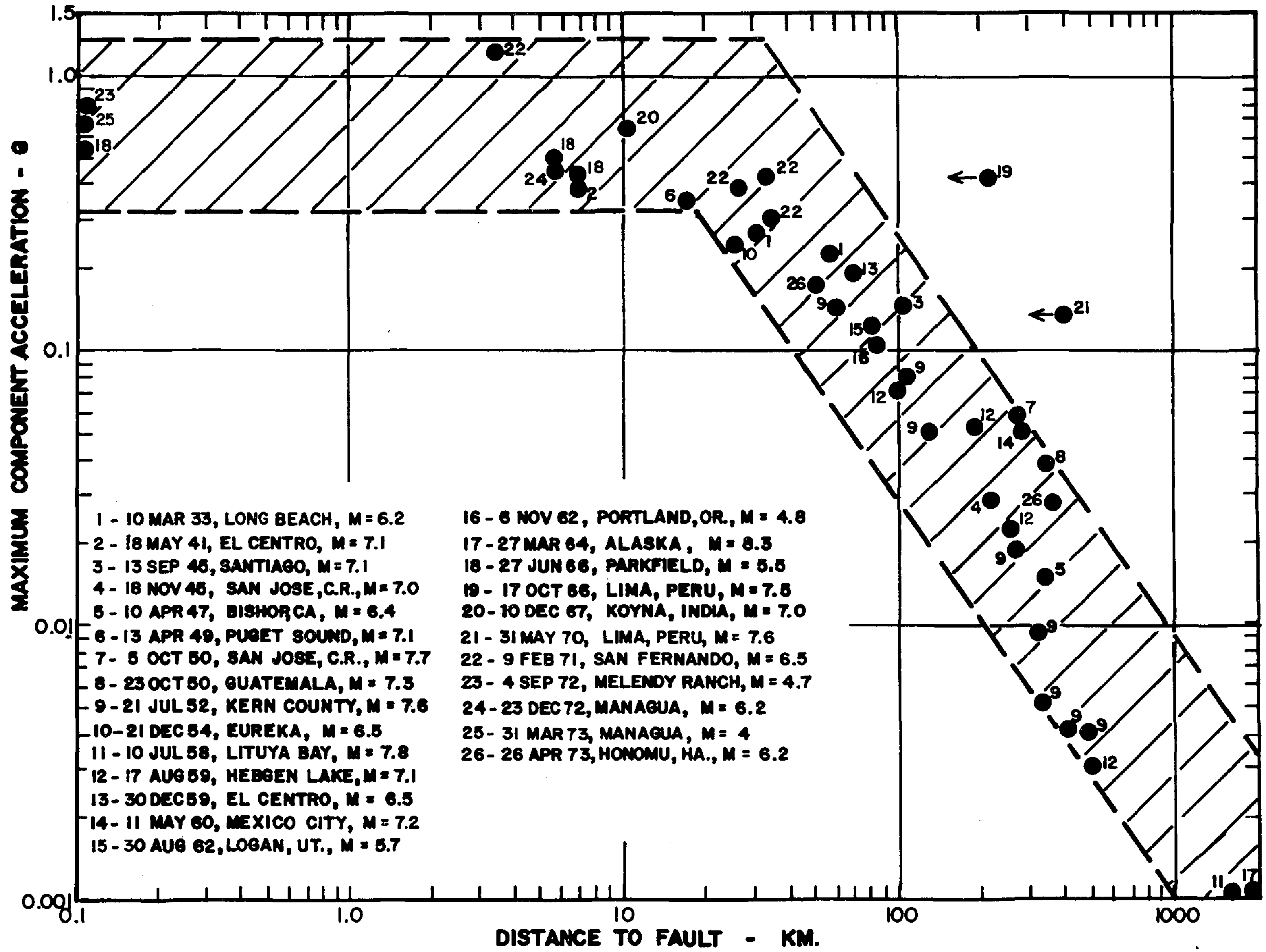


FIGURE 12 ATTENUATION OF MAXIMUM RECORDED ACCELERATION SHOWING THE NEW HAWAII DATA

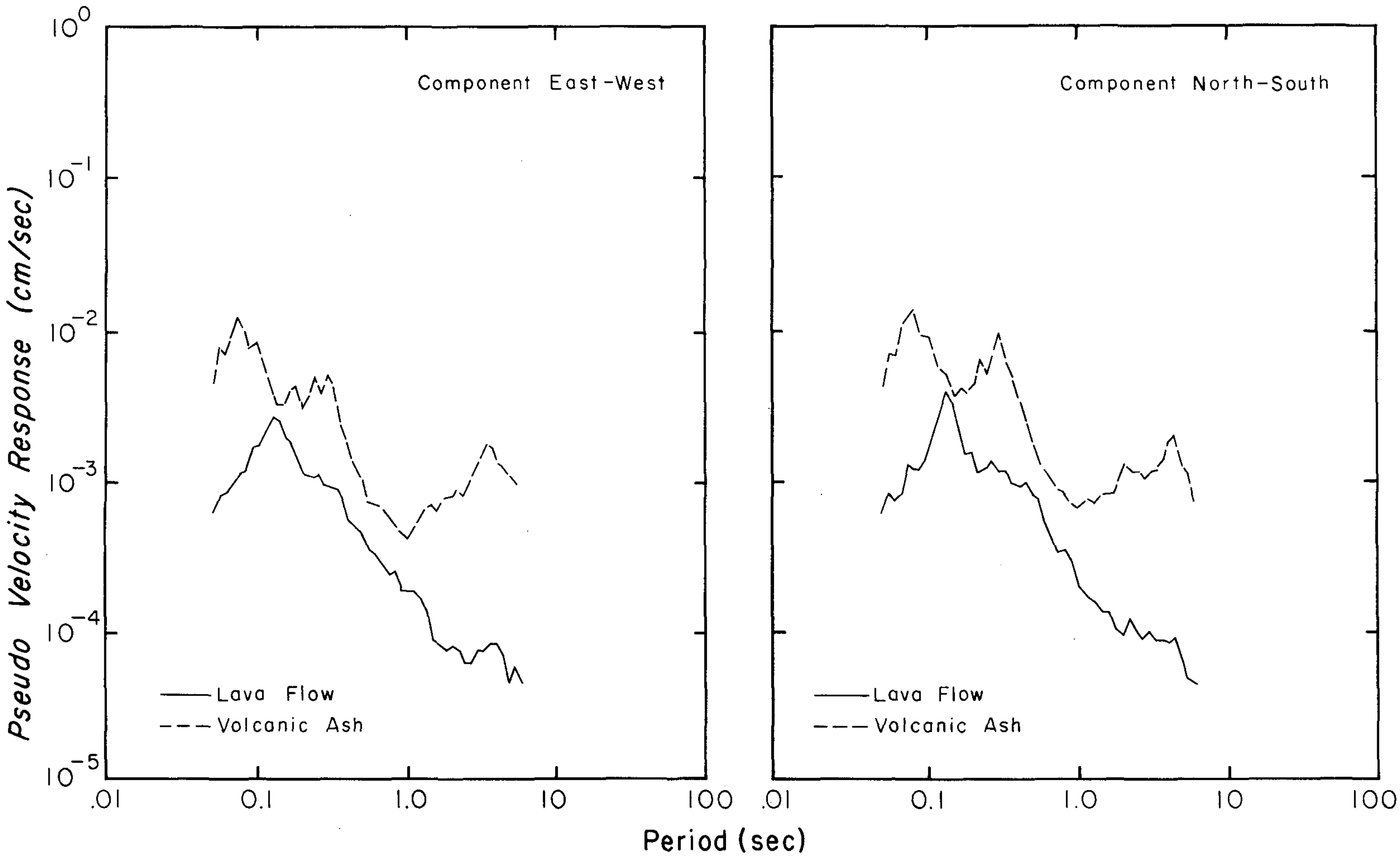


FIGURE 13 RELATIVE RESPONSE ON VOLCANIC ASH AND LAVA FLOW AT HILO, HAWAII (AFTERSHOCK RECORDED ON APRIL 30, 1973)

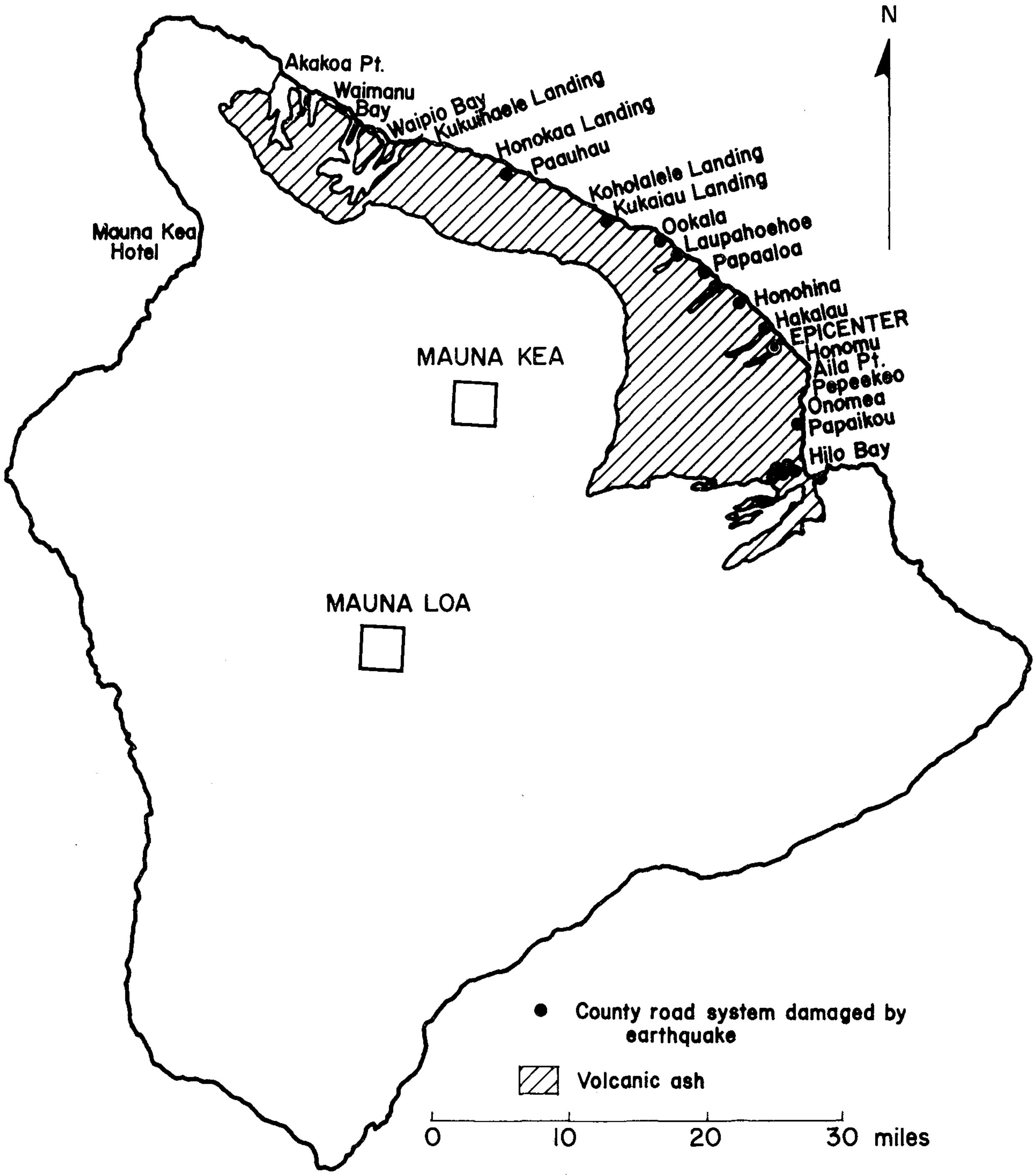


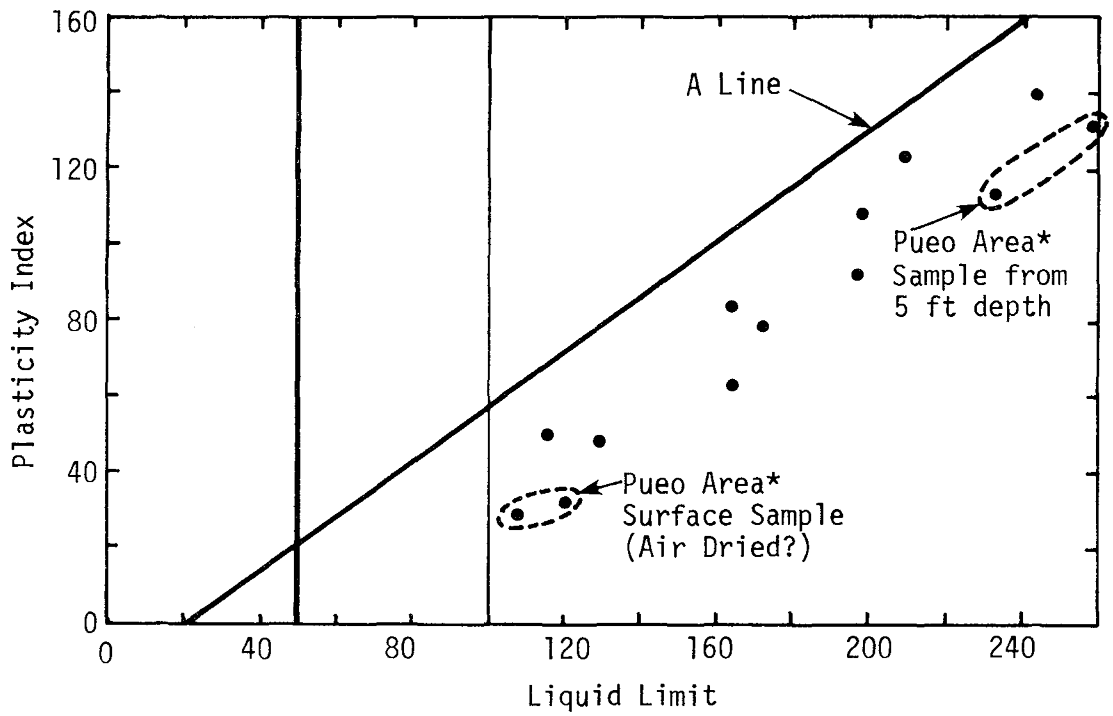
FIGURE 14 ROAD DAMAGE AND AREAS WITH VOLCANIC ASH

VOLCANIC ASH ALONG HAMAKUA COAST

Annual Rainfall . . . . About 200 inches

Typical Soil Test Data

Wet Density	60 to 80 lb/ft^3
Water Content	± 200%
Dry Density	25 to 30 lb/ft^3
Degree of Saturation	± 95 to 100%
Unconfined Compression	700 to 1200 lb/ft^2
Vane Shear	300 to 600 lb/ft^2
% Passing #200	Over 90%



PLASTICITY CHART

*Pueo Area, residential area immediately north of downtown Hilo, site of 15-story Bayshore and 5-story Val-Hala buildings.

FIGURE 15 VOLCANIC ASH, TYPICAL TEST DATA

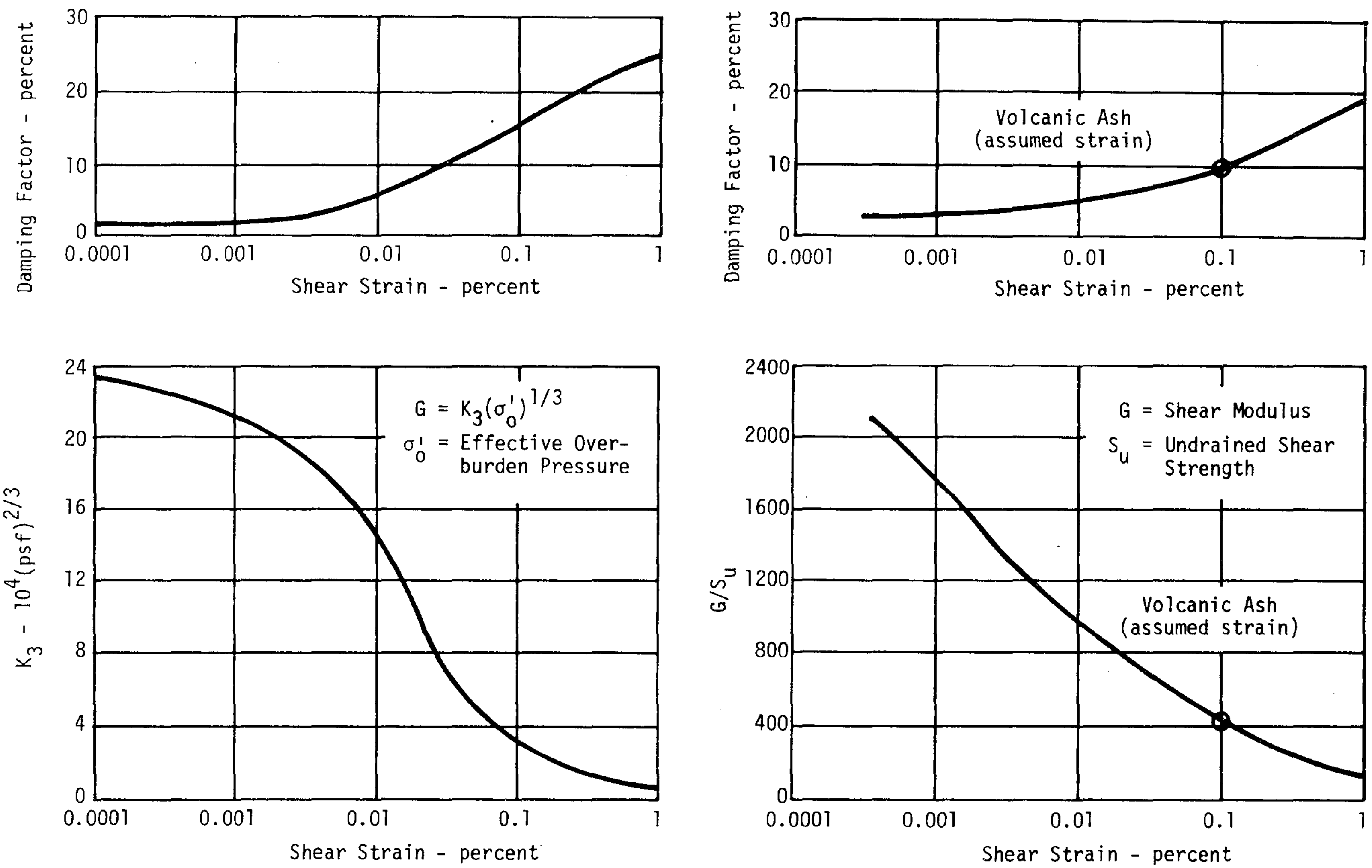


FIGURE 16 SOIL MODULI AND DAMPING FACTORS FOR DYNAMIC RESPONSE ANALYSES
(Seed and Idriss, 1970)

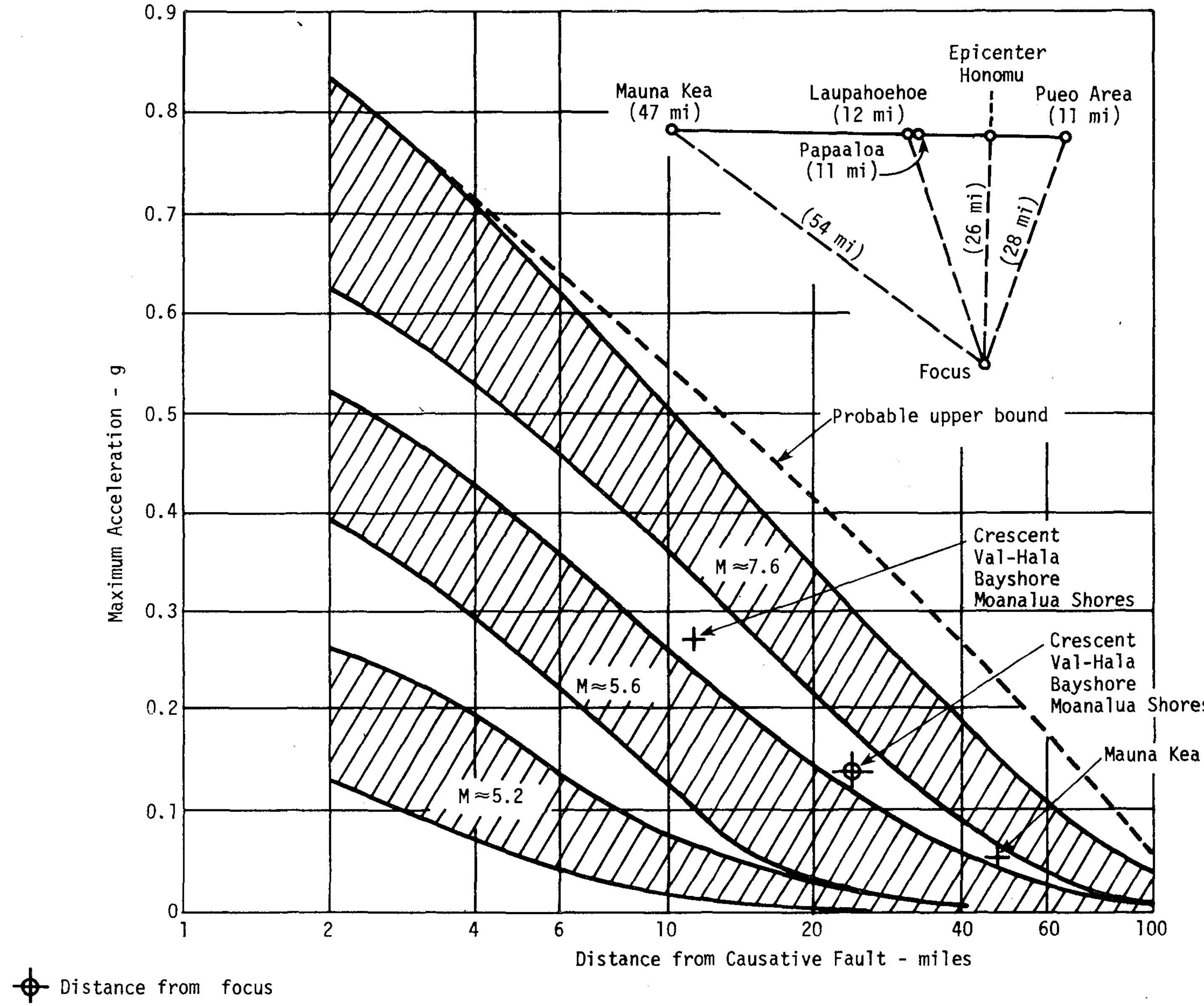


FIGURE 17 RANGES OF MAXIMUM ACCELERATION IN ROCK (After Schnabel, 1972)

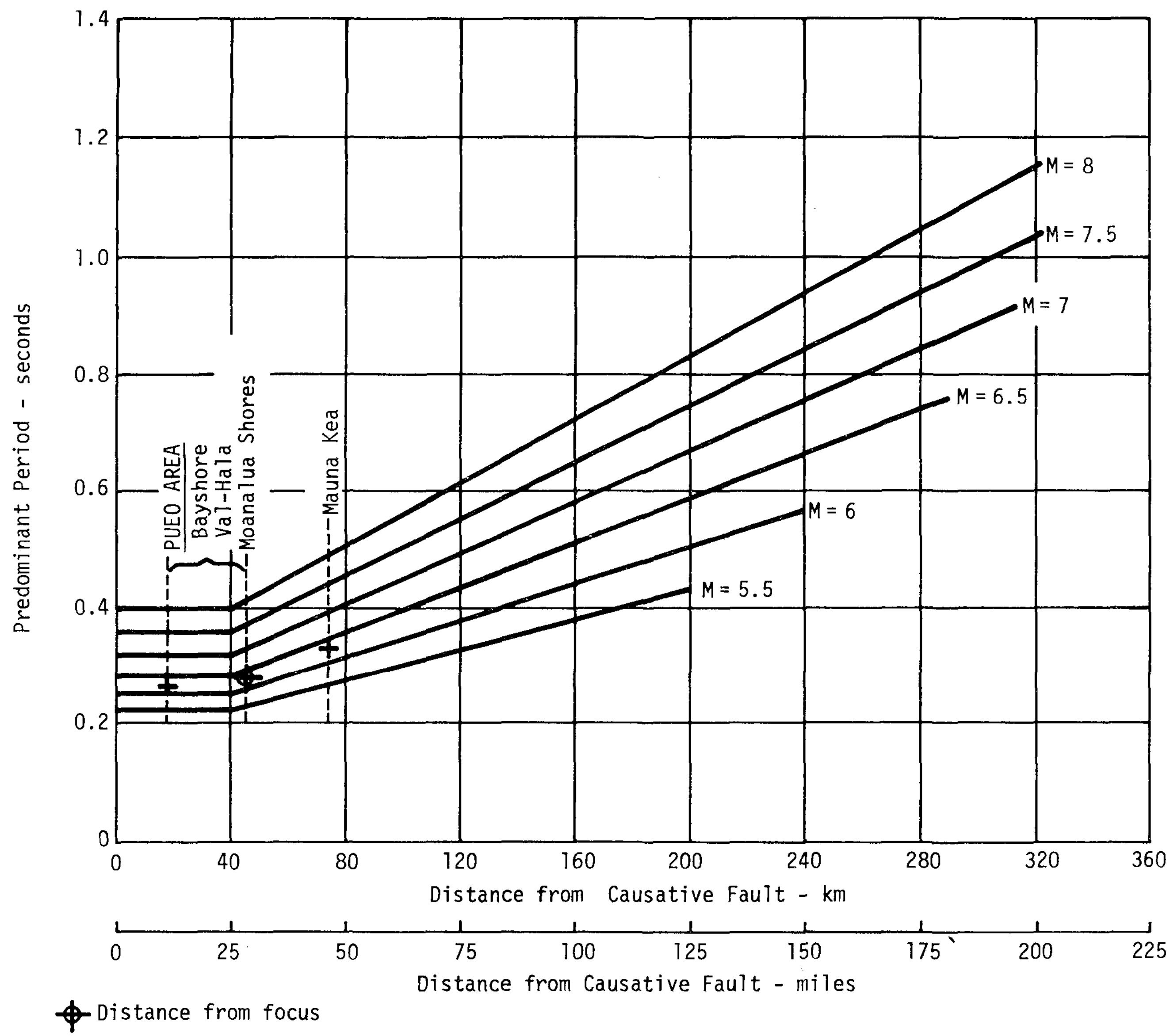


FIGURE 18 PREDOMINANT PERIODS FOR MAXIMUM ACCELERATION IN ROCK (After Seed, Idriss, and Kiefer, 1969)

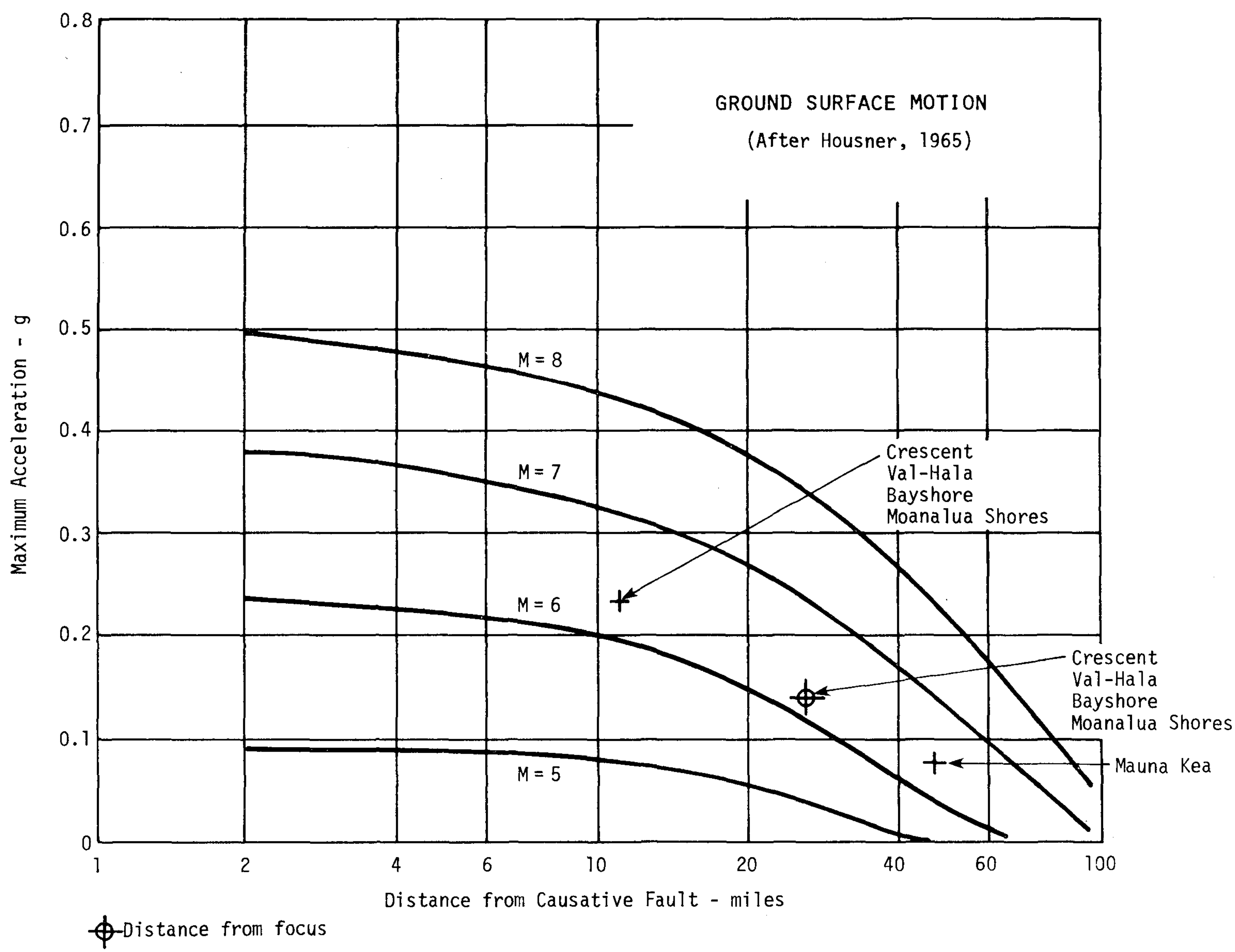
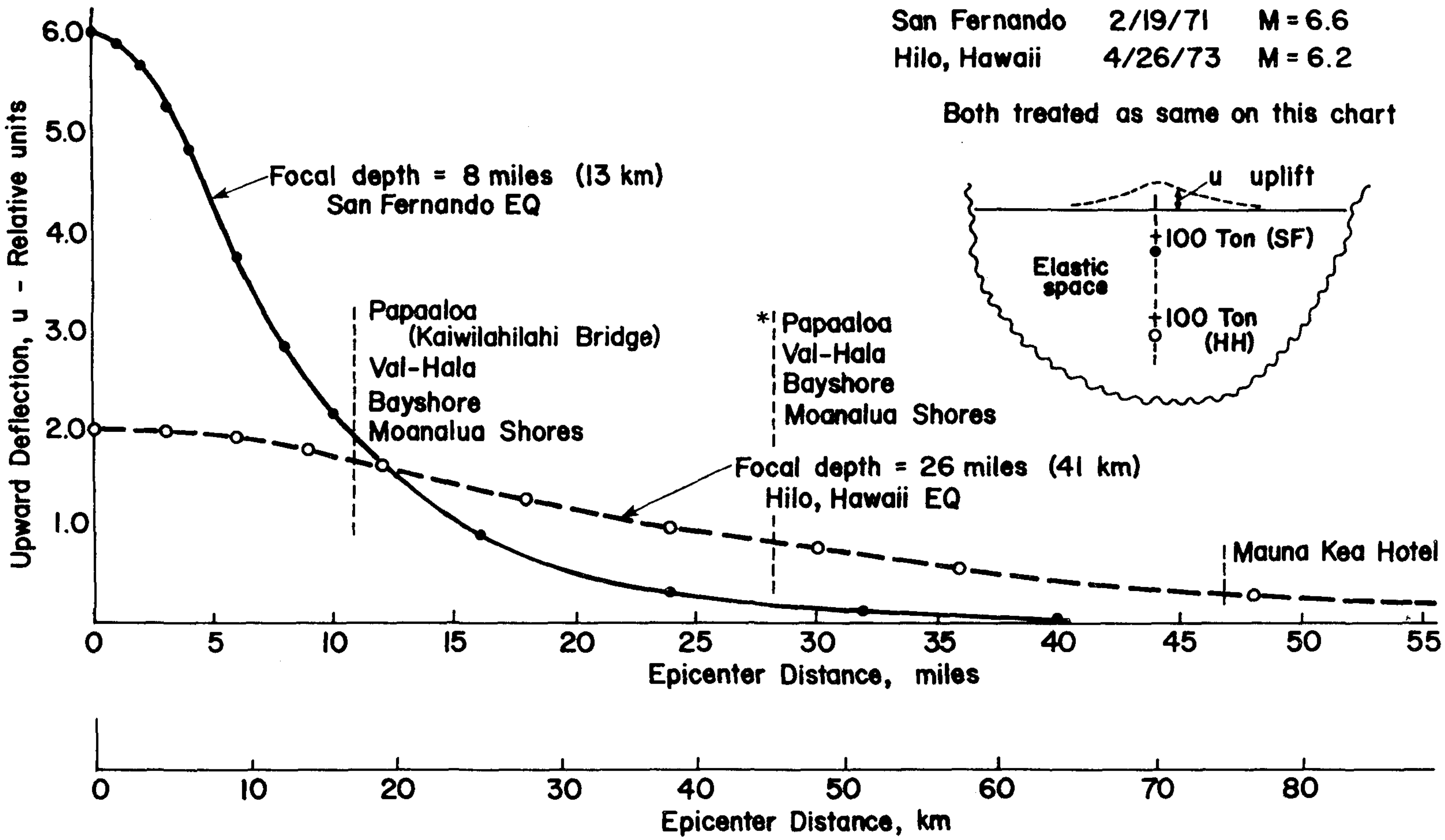


FIGURE 19 GROUND SURFACE MOTION (After Housner, 1965)



*Distance from focus

FIGURE 20 UPWARD DEFLECTION OF GROUND SURFACE DUE TO STATIC POINT LOAD AT DEPTH (After Lee, 1973)

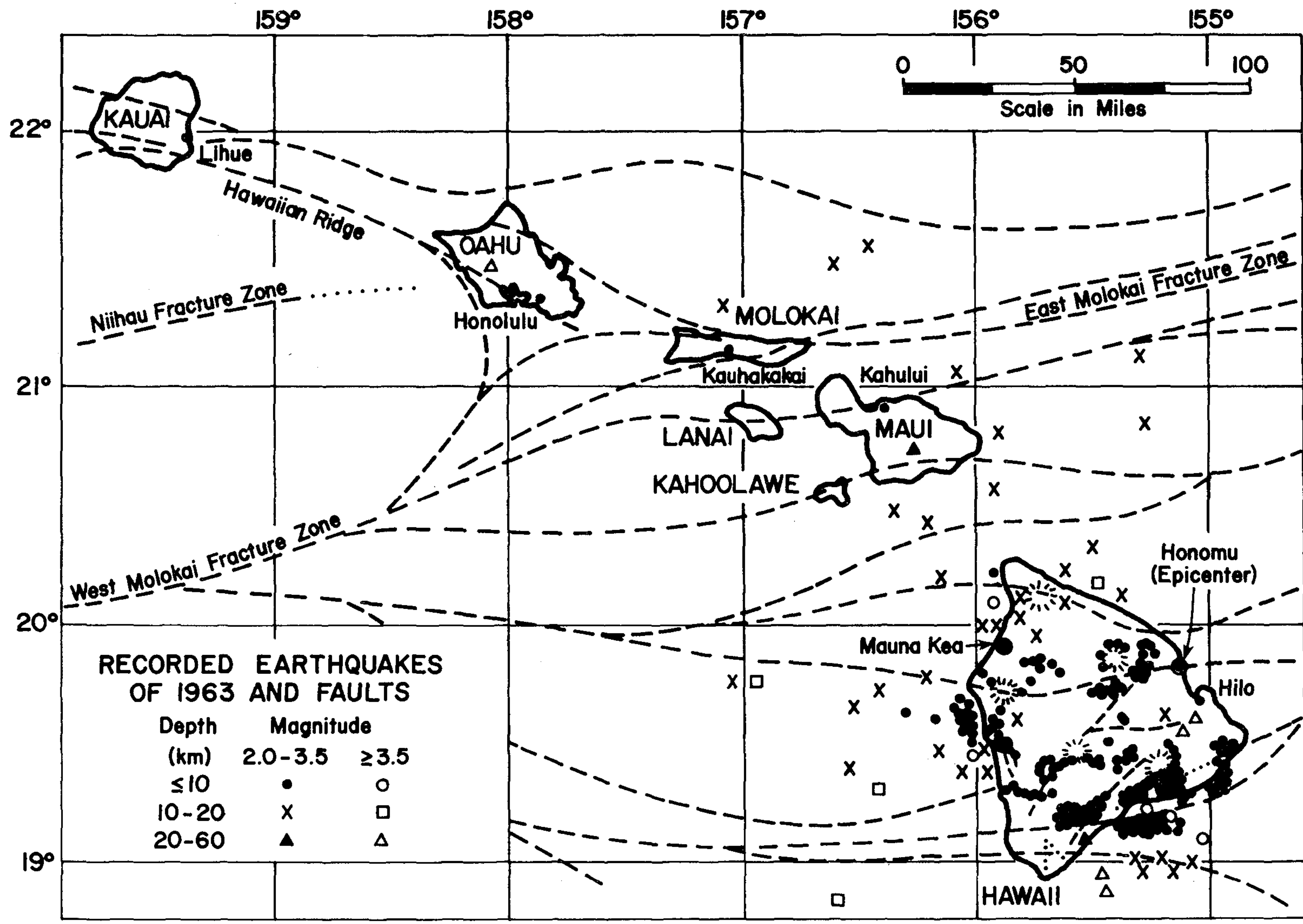


FIGURE 21 RECORDED EARTHQUAKES OF 1963 AND FAULTS (After Furumoto, Nielsen, and Phillips, 1972)

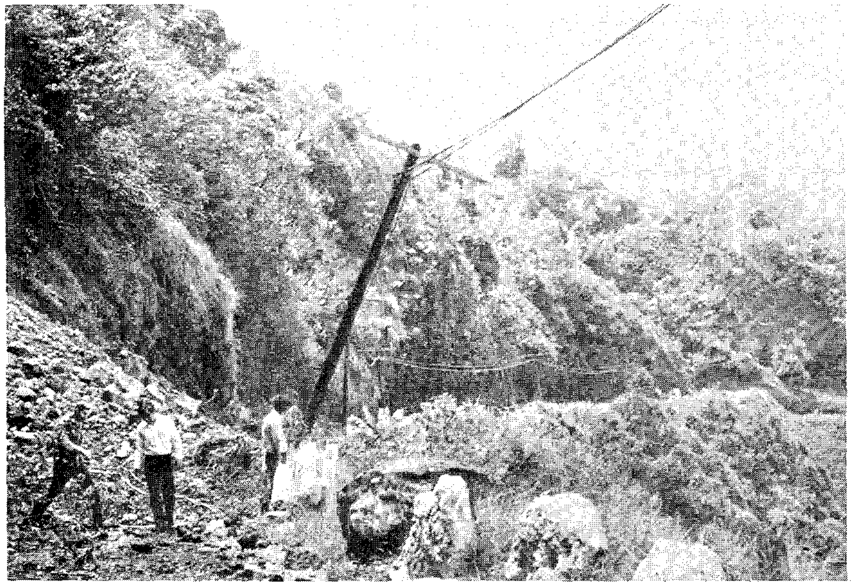


FIGURE 22 TYPICAL LANDSLIDE

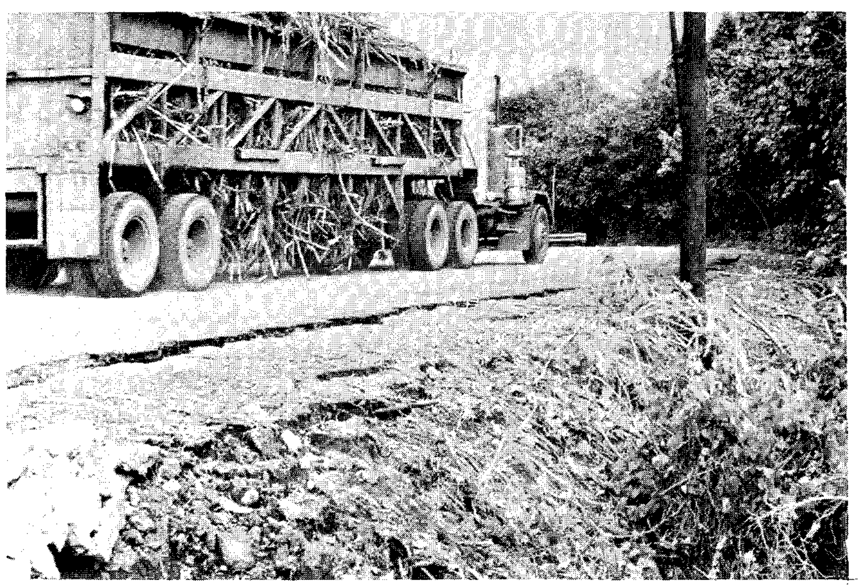


FIGURE 23 HEAVY CANE TRUCK; ROAD ON VOLCANIC ASH

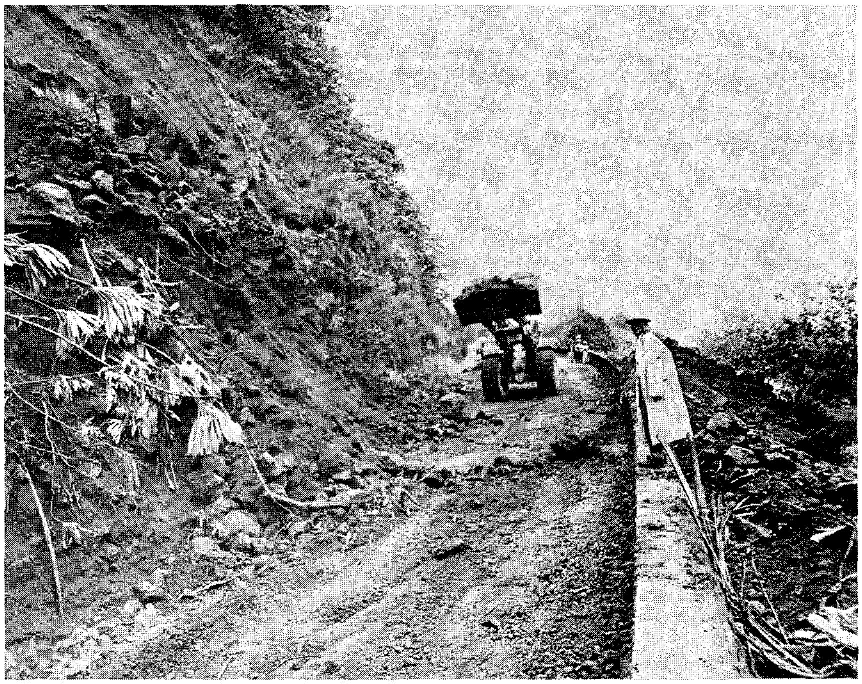


FIGURE 24 TYPICAL ROAD DAMAGE, NORTHEASTERN PORTION OF THE ISLAND

FIGURE 25 TENSION CRACKS, VOLCANIC ASH

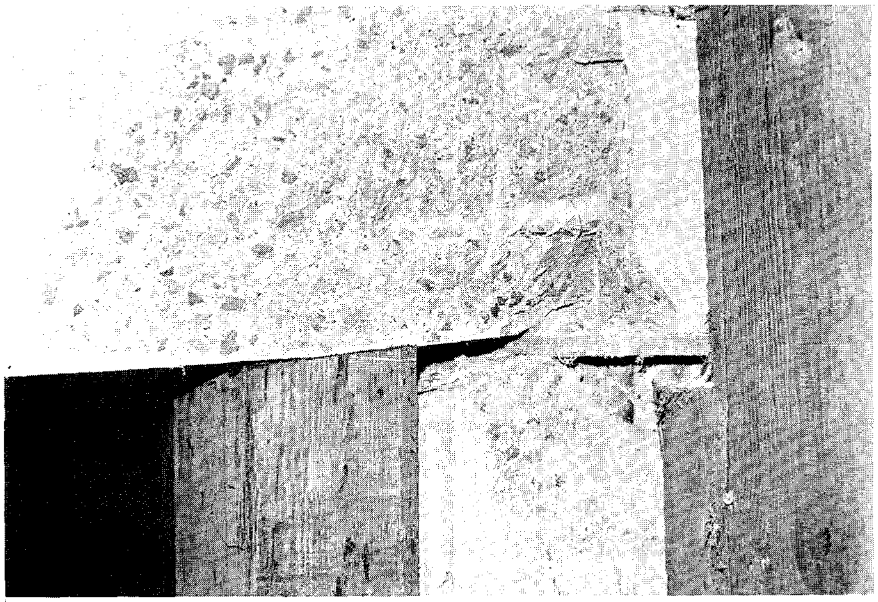


FIGURE 26 KAIWILAHILAHI BRIDGE, 15 km FROM EPICENTER

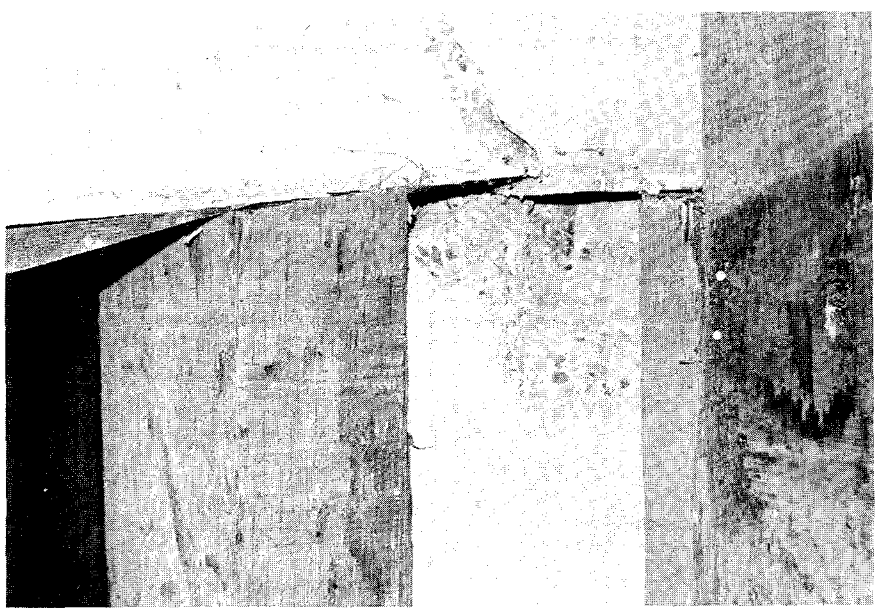


FIGURE 27 KAIWILAHILAHI BRIDGE, 15 km FROM EPICENTER

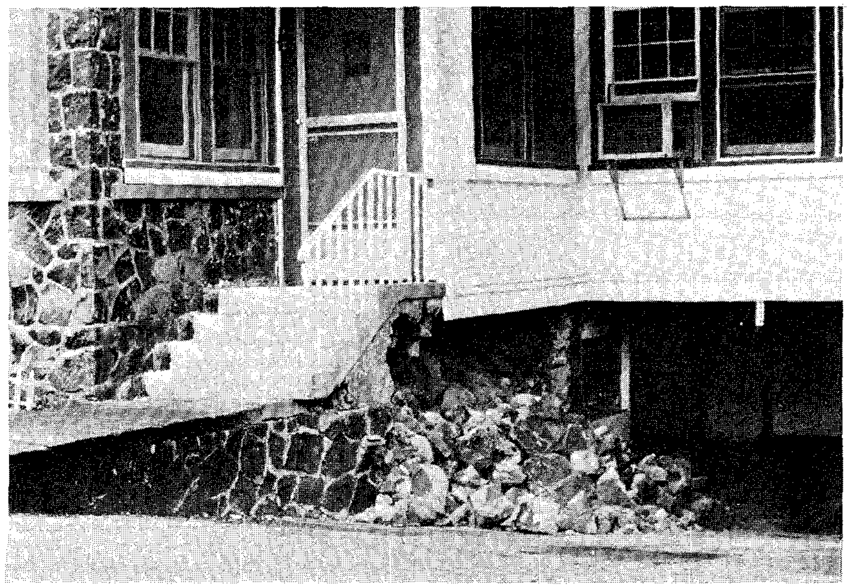


FIGURE 28 TYPICAL FAILURE OF ROCK WALL, NORTH HILO

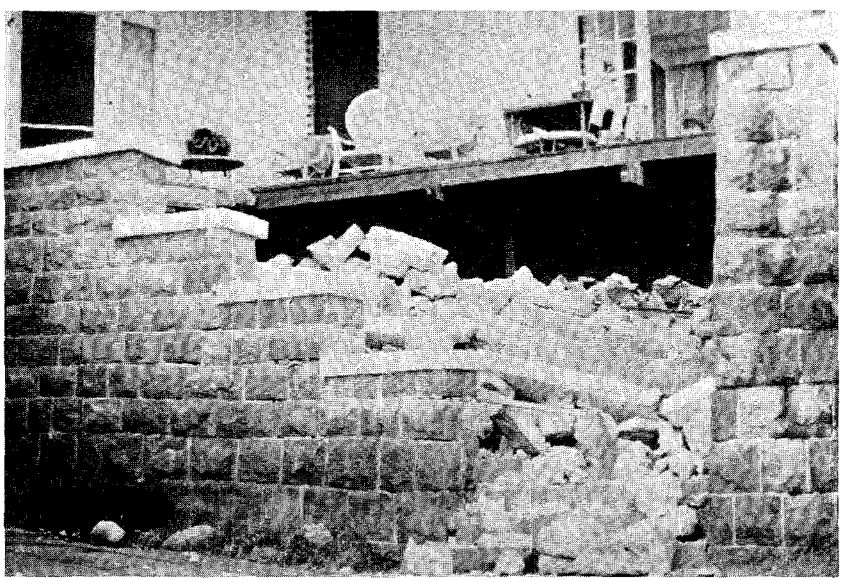


FIGURE 29 TYPICAL FAILURE OF ROCK WALL, NORTH HILO

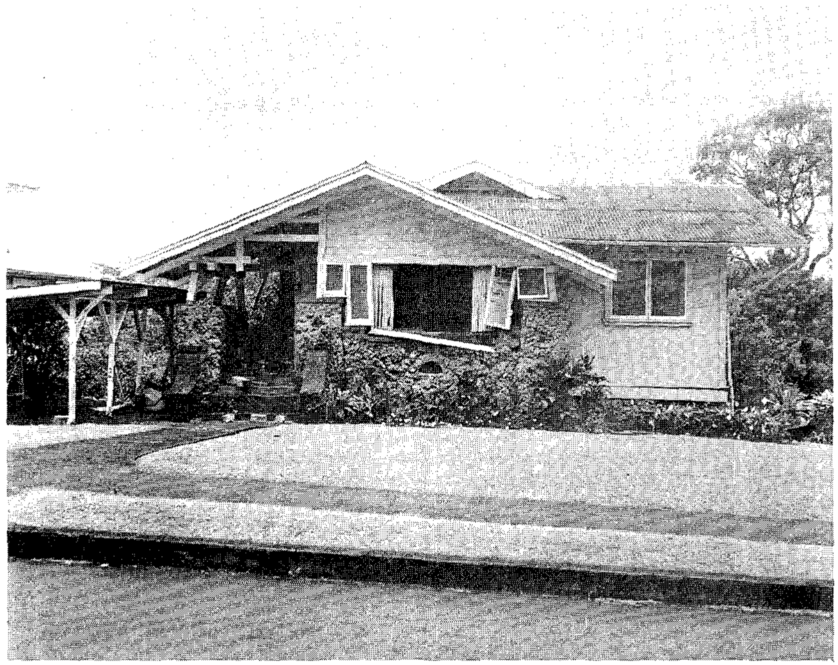


FIGURE 30 RESIDENCE, NORTH HILO

FIGURE 31 HOUSE SHIFTED ON FOUNDATION, NORTH HILO

FIGURE 32 HOUSE SHIFTED ON FOUNDATION, NORTH HILO

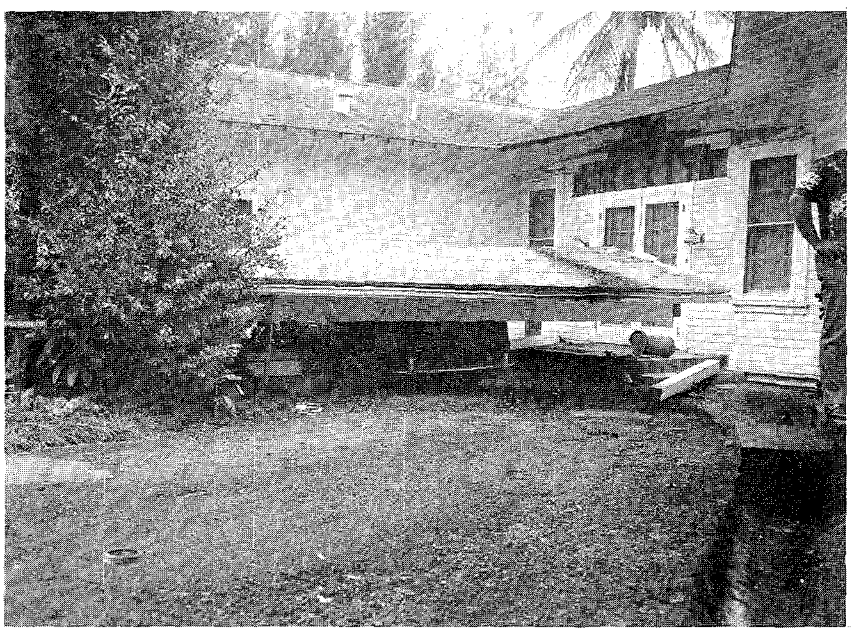


FIGURE 33 CARPORT COLLAPSE, NORTH HILO

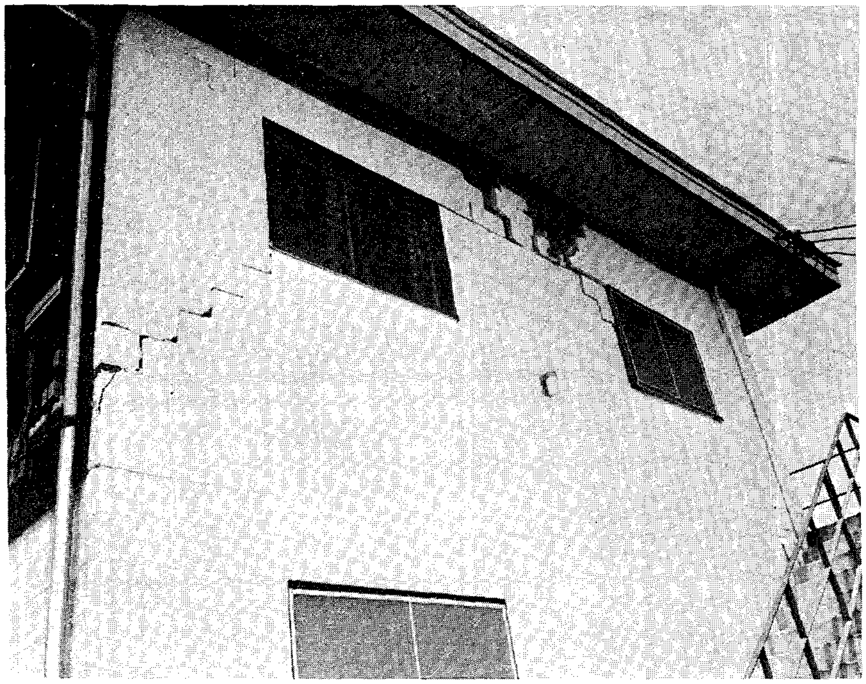


FIGURE 34 CONCRETE BLOCK BUILDING, NORTH HILO

FIGURE 35 CESSPOOL FAILURE, VOLCANIC ASH

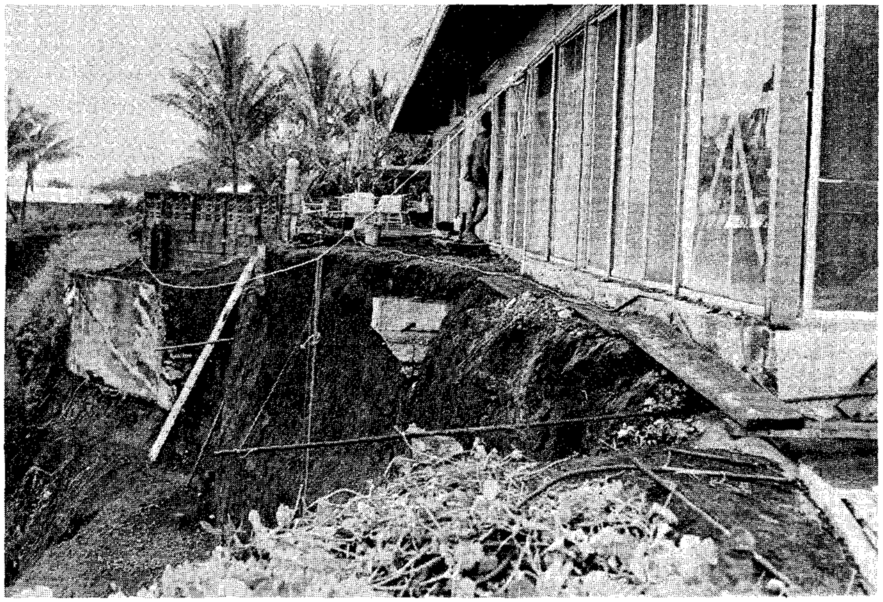


FIGURE 36 SOIL FALL, VOLCANIC ASH, 3 km NORTH OF HILO

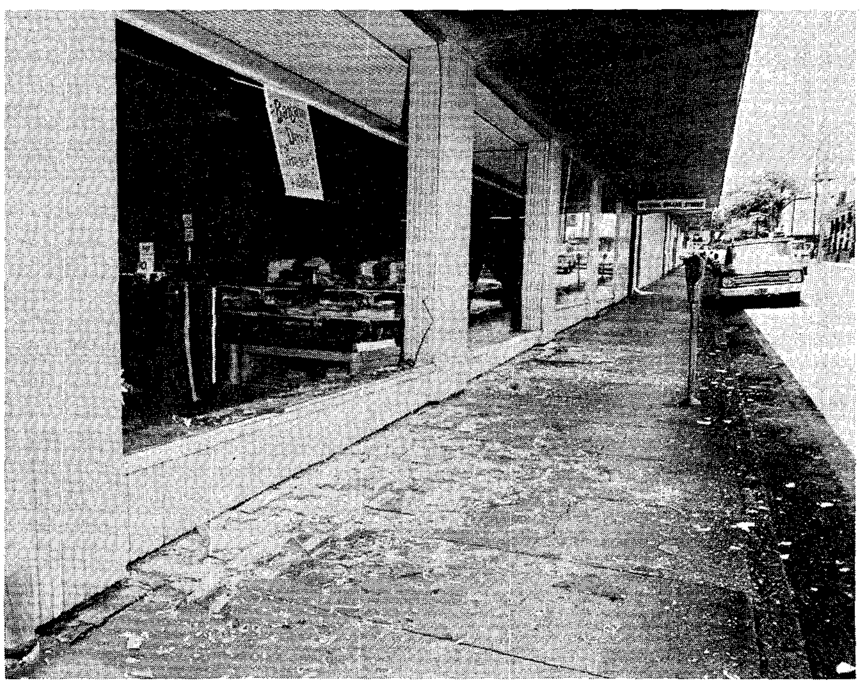


FIGURE 37 BUSINESS DISTRICT, DOWNTOWN HILO

FIGURE 38 TYPEWRITER CENTER, DOWNTOWN HILO

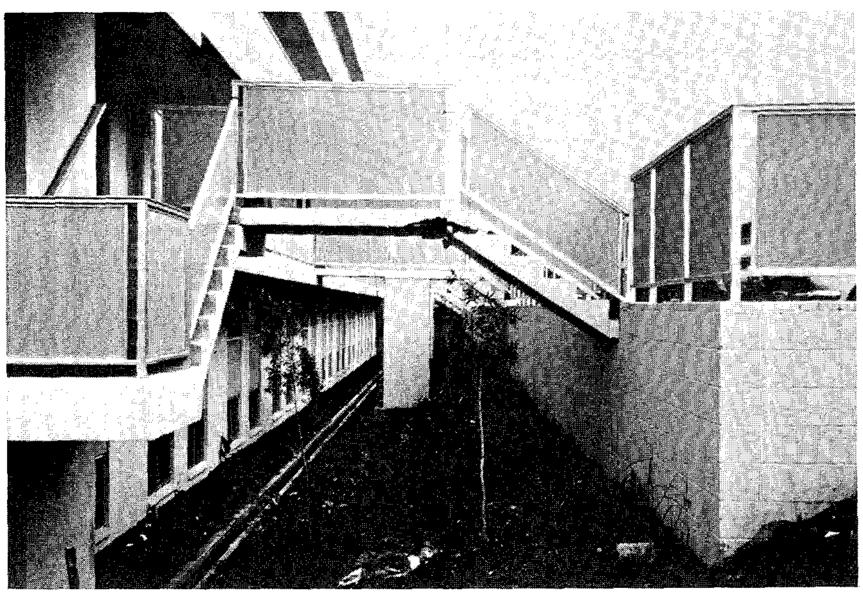


FIGURE 39 VAL-HALA APARTMENT BUILDING, 18 km SOUTH OF EPICENTER

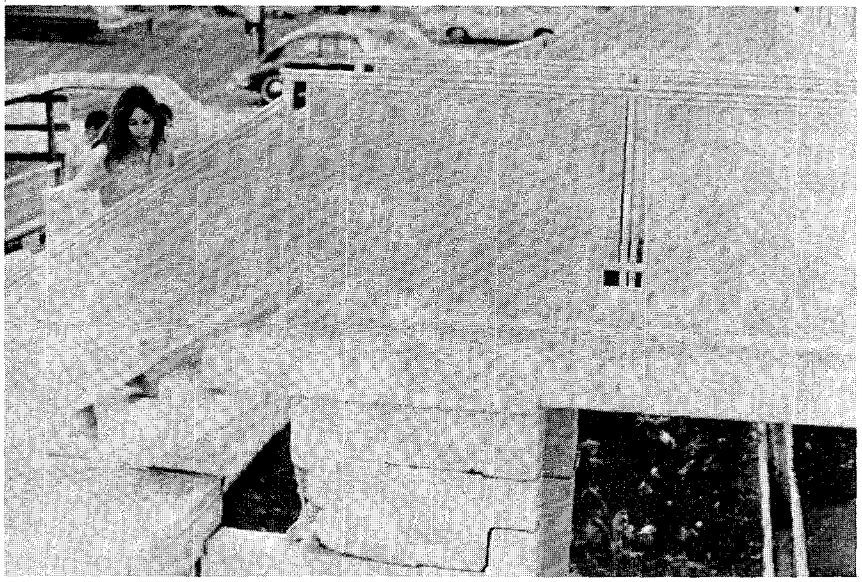


FIGURE 40 VAL-HALA APARTMENT BUILDING, 18 km SOUTH OF EPICENTER

FIGURE 41 BAYSHORE TOWER, 18 km SOUTH OF EPICENTER

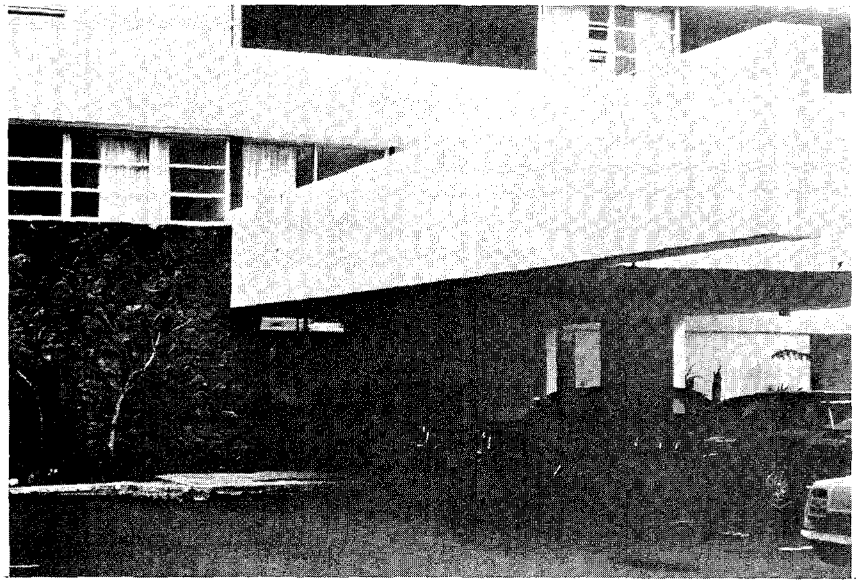


FIGURE 42 BAYSHORE TOWER, CANOPY BEAMS ATTACHED TO SHEAR WALLS

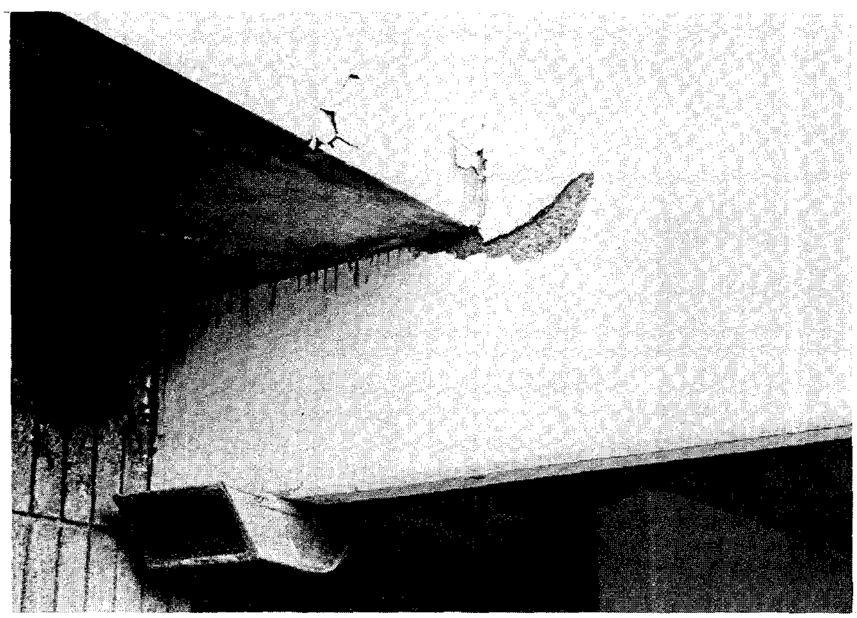


FIGURE 43 BAYSHORE TOWER, CONCRETE SPALLING

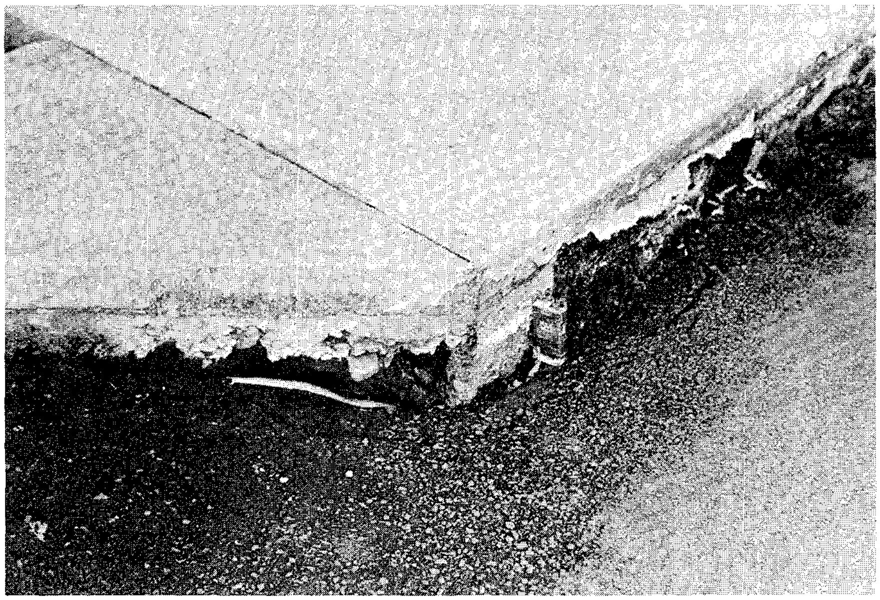


FIGURE 44   SETTLEMENT, FRONT OF BAYSHORE TOWER

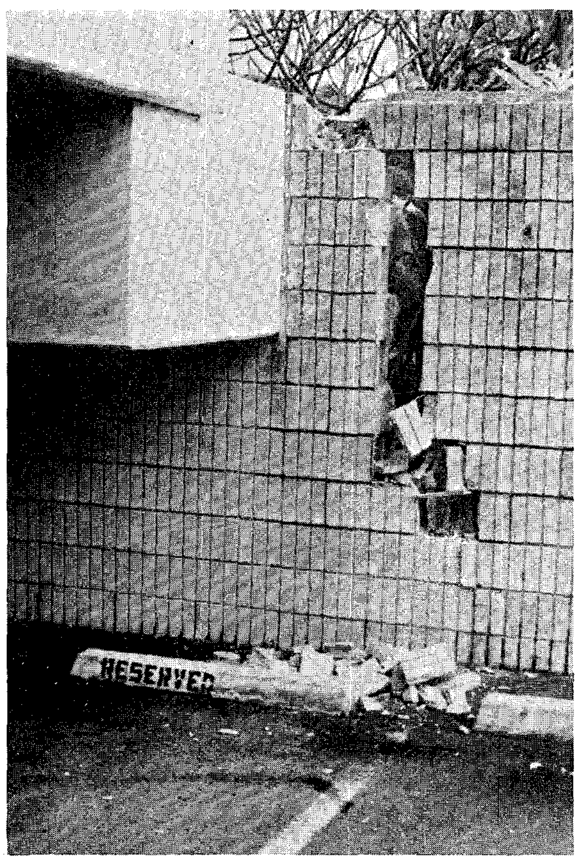


FIGURE 45   WALL AT PARKING LOT, BAYSHORE TOWER

FIGURE 46 MAUNA KEA BEACH HOTEL, 75 km FROM EPICENTER

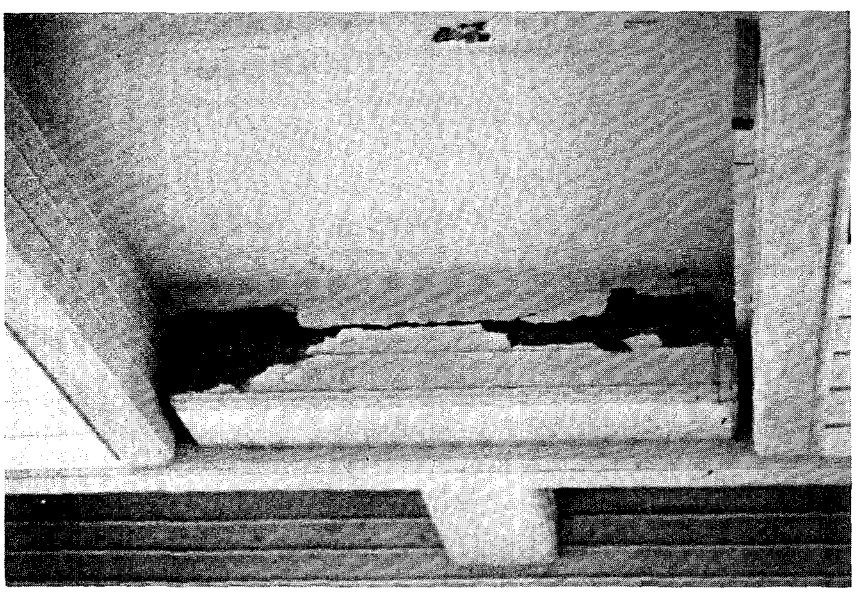


FIGURE 47 BRIDGE SEAT DETAIL, MAUNA KEA BEACH HOTEL

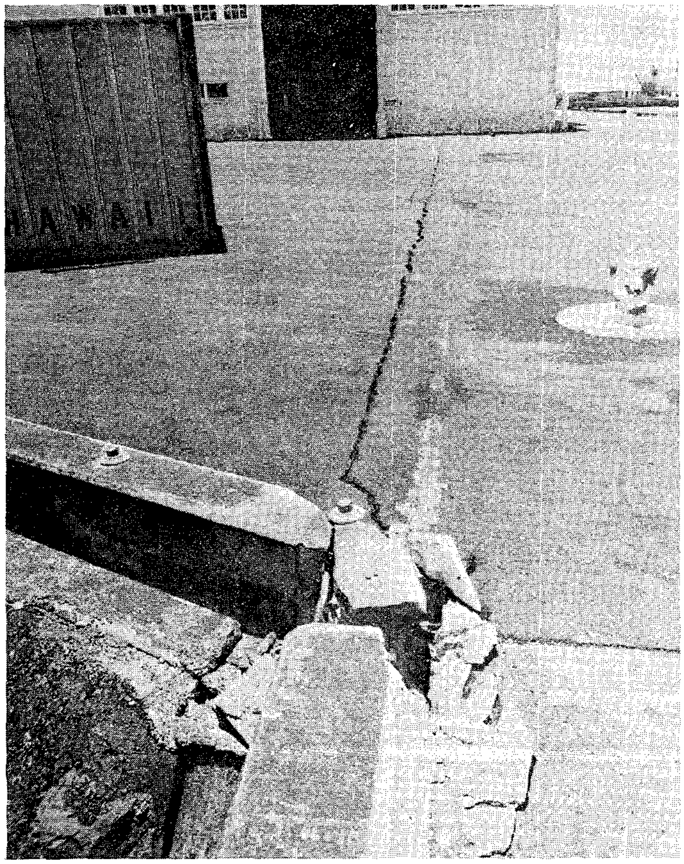


FIGURE 48 HILO HARBOR, PIER 1

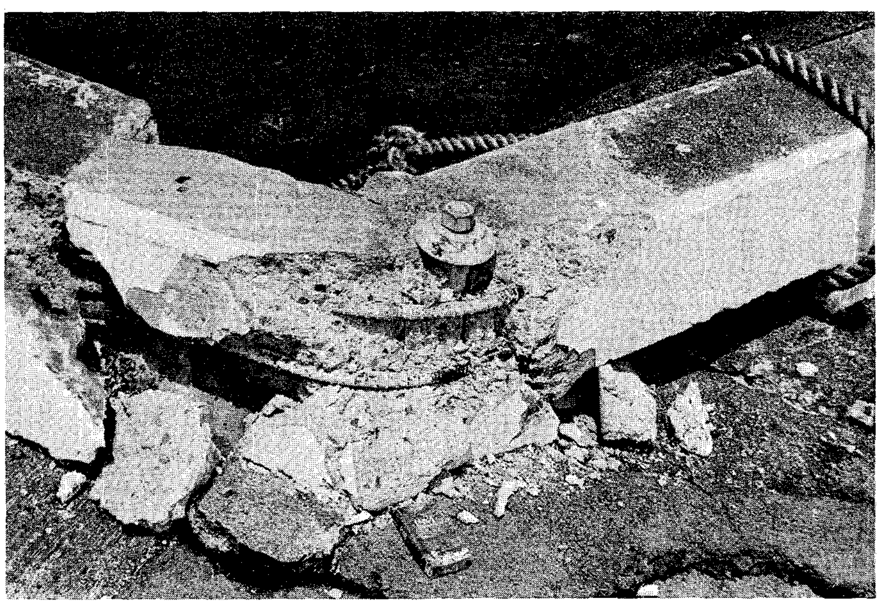


FIGURE 49 CONCRETE CURB, HILO HARBOR, PIER 1

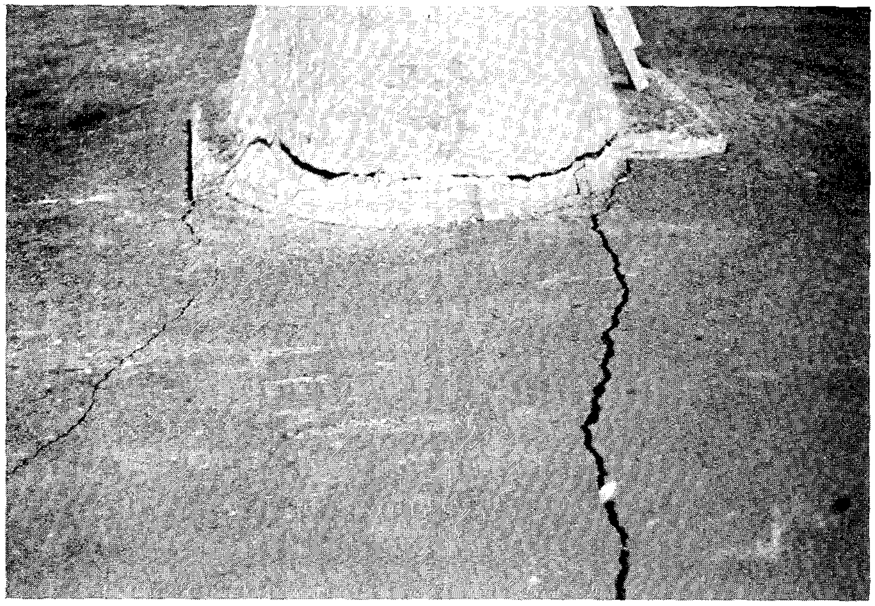


FIGURE 50 HILO HARBOR, PIER 1

FIGURE 51 HILO HARBOR, PIER 1

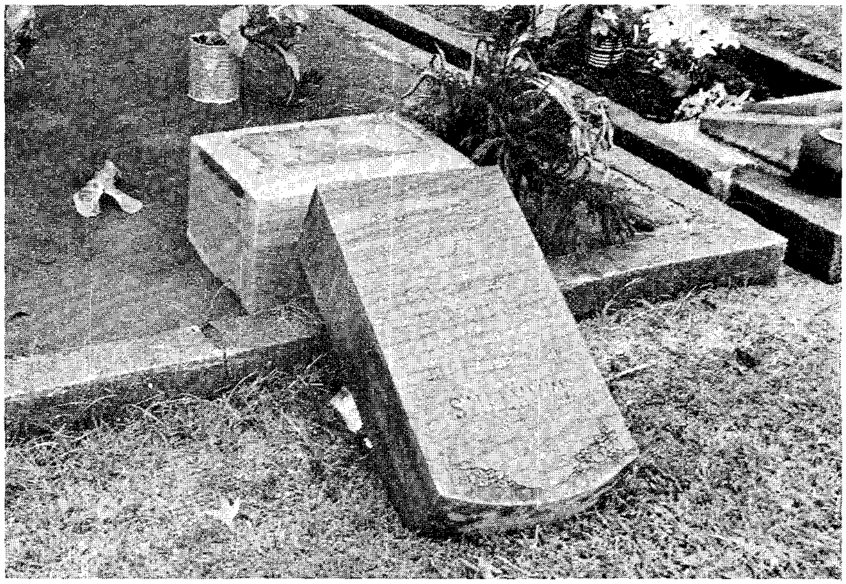


FIGURE 52 TOMBSTONE, TOPPLED OVER

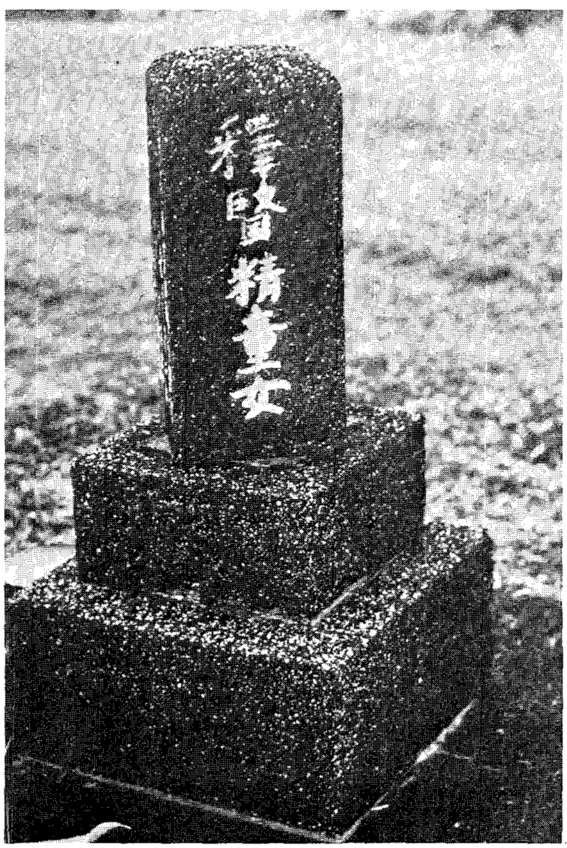


FIGURE 53 TOMBSTONE, ROTATED

FIGURE 54 TOMBSTONE, ROTATED

APPENDIX

Seismic Intensity Distribution

by

Patricia Principal* and Karen Fujishima*

Introduction

The island of Hawaii contains roughly 80,000 inhabitants. Although most of the population is concentrated in urban centers such as Hilo and Kailua-Kona, there are a number of villages and hamlets scattered throughout the island. The earthquake occurred in the midst of a well-populated rural area.

Almost immediately after the earthquake, the State of Hawaii set up a temporary civil defense headquarters in Hilo. As the number of injured people was very small and no one was really left homeless, the major task of the headquarters evolved into processing damage reports and claims. In about a week, damage claims amounted to four million dollars.

Data for Intensity Determination

The major source of data for determining the seismic intensity distribution was the 500 damage reports submitted to the State Civil Defense by the inhabitants of the island of Hawaii. The President of the United States had declared the island a disaster area, and since the island then qualified for Federal assistance, damage claims and reports were numerous. The State Civil Defense staff summarized these claims, divided them into business claims and private claims, and arranged them in alphabetical order of claimant's names. These summarized and classified reports were made available to the authors. The authors wish to thank the late Honorable John A. Burns, Governor of Hawaii, Robert E. Schank, and John Butchart of the State Civil Defense for providing these reports.

The second source of information was the standard U.S. Coast and Geodetic Survey questionnaires, which were sent to all the postmasters of the post office located in the state of Hawaii. The response was over 90%. The islands covered by the questionnaires were: Hawaii, Maui, Molokai, Lanai,

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Oahu and Kauai.

The third source of information was newspaper reports.

The fourth source of information was actual field observation by the investigating team. The field survey made obvious the difference in damage on the opposite side of the Wailuku River, which runs through Hilo. The north side had sufficient damage to warrant an intensity VIII on the Modified Mercalli Scale, while on the south side of the river, the intensity was on the low side of VII.

Determining Seismic Intensity

The information from damage claims submitted to the Civil Defense Headquarters was very detailed and therefore most useful. The intensities for the island of Hawaii were evaluated from them, supplemented by information from questionnaires answered by the postmasters. For the other islands, the questionnaires were the sole source of data.

Each individual damage report and each questionnaire were evaluated and assigned an intensity based on the Modified Mercalli Scale. It must be remembered that this is an observed intensity, not an instrumental measurement of parameters of motion. The number assigned to each report is derived from observed effects on people, ground and structures. Admittedly, there is a large amount of subjectivism.

Intensities were then collated according to city, village, or hamlet and mode intensity was determined for each particular area. It was hoped that this would average out subjectivism. Consideration was given to special circumstances and obviously divergent reports. "Special circumstances" constituted mainly overt overreaction by persons, peculiar structural weakness of buildings and scarcity of data in certain areas.

Intensities were plotted on a map of the Hawaiian Archipelago as far as Oahu. Isoseismals were then drawn as boundaries between regions of successive intensities, as opposed to connecting points of equal intensity. The isoseismal contours are for actual observed intensity with no correction for inferred local ground irregularities.

Figure A.1 shows the resulting distribution of seismic intensities for the Hawaiian Archipelago. The island of Hawaii experienced intensities ranging from VIII to V. The contour bounding intensity V has been omitted for lack of data. Intensity IV includes Lanai and all but the northeastern part of Maui. Within intensity III are Molokai and most of Oahu, the remainder ranging from II to I. Again the contour separating I and II is omitted for lack of data.

For the island of Hawaii the greatest intensity extending over the north section of Hilo is situated just south of the epicenter at Honomu. Structural damage as observed warrants a maximum intensity of VIII. The contours in general follow closely the major structural trends of the island. The southern boundary of VIII is along the Wailuku River which approximately delineates the structural border between Mauna Kea and Mauna Loa volcanoes. The VII isoseismal includes the major portion of the Mauna Kea and Mauna Loa shields, falling off to the north at Kohala and Hualalai volcanoes (Figure A.2). Isoseismal VI falls off to the south where there are the most recent Mauna Loa flows.

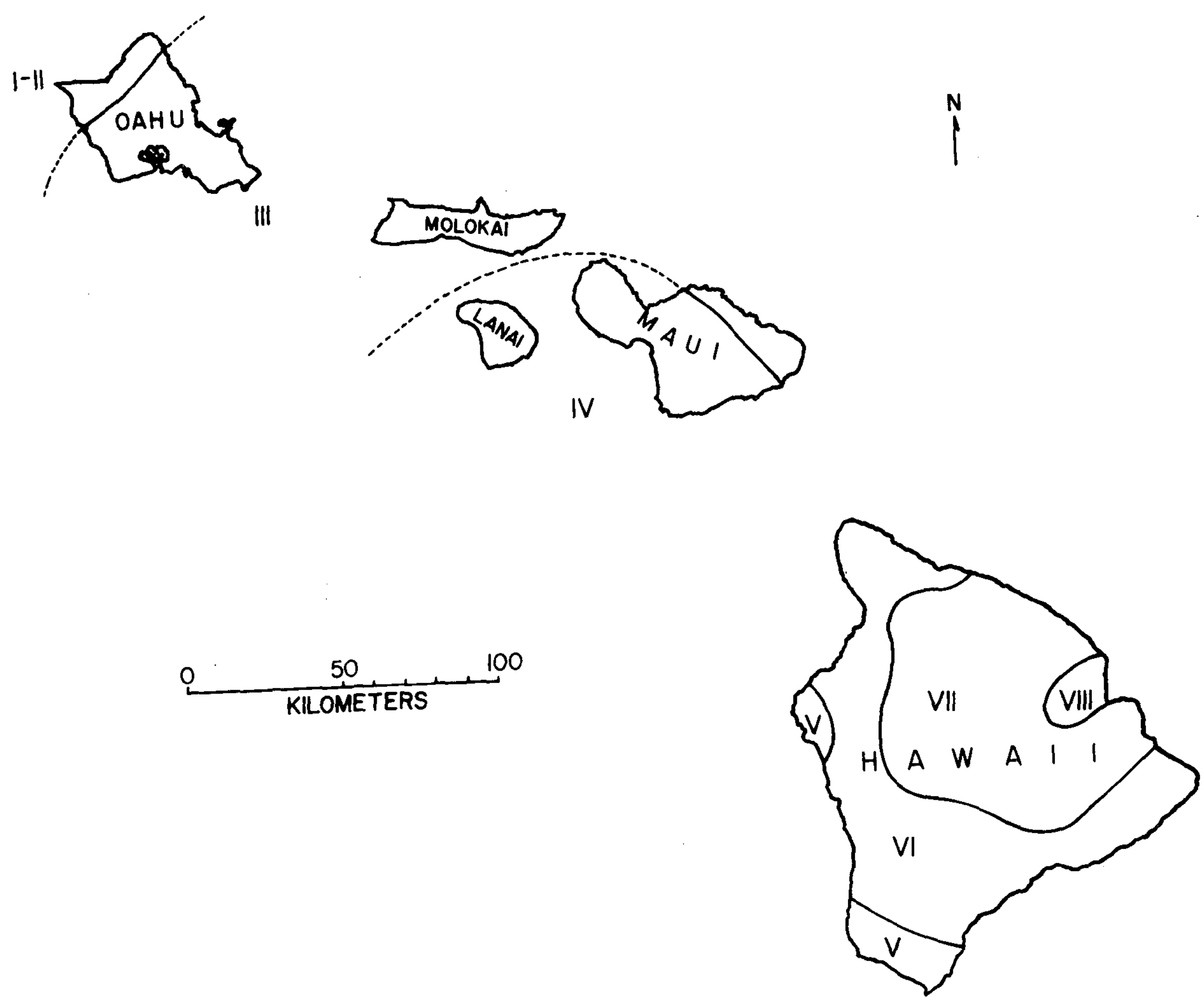
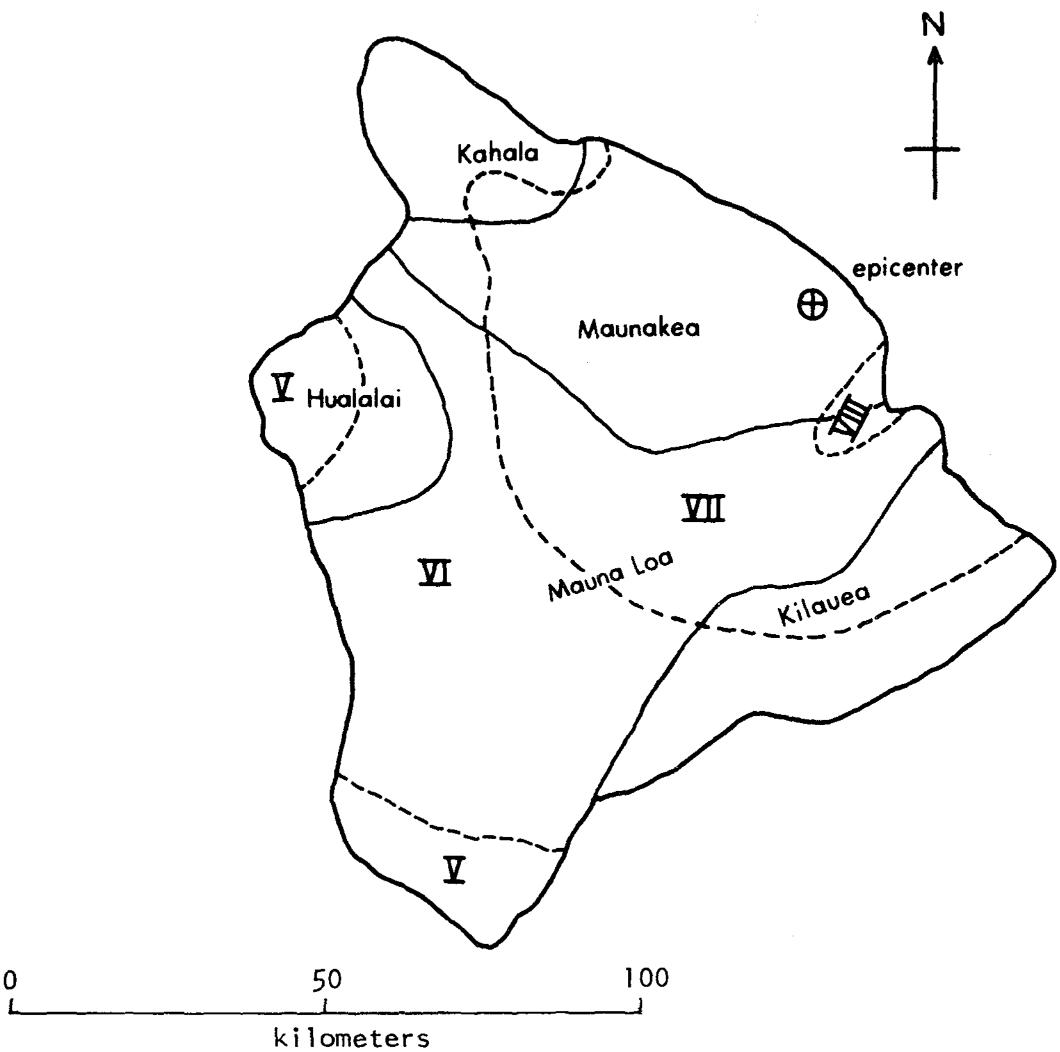


FIGURE A.1 SEISMIC INTENSITIES, HAWAIIAN ARCHIPELAGO



-------- intensities
———— separates different volcanic areas

FIGURE A.2 SEISMIC INTENSITIES, ISLAND OF HAWAII