Isoseismal Maps, Macroseismic Epicenters, and Estimated Magnitudes of Historical Earthquakes in the Hawaiian Islands

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Isoseismal Maps, Macroseismic Epicenters, and Estimated Magnitudes of Historical Earthquakes in the Hawaiian Islands

By MAX WYSS and ROBERT KOYANAGI

U.S. GEOLOGICAL SURVEY BULLETIN 2006

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1992

For sale by
Book and Open-File Report Sales
U.S. Geological Survey
Federal Center, Box 25286
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Wyss, Max, 1939–
Isoseismal maps, macroseismic epicenters, and estimated magnitudes of historical earthquakes in the Hawaiian Islands / by Max Wyss and Robert Koyanagi.
p. cm. — (U.S. Geological Survey bulletin ; 2006)
Includes bibliographical references (p.).
1. Earthquakes—Hawaii. 2. Earthquake intensity—Hawaii. 3. Seismology—Hawaii. 4. Earthquakes—Hawaii—Maps. 5. Earthquake intensity—Hawaii—Maps. 6. Seismology—Hawaii—Maps. I. Koyanagi, Robert Y., 1934– II. Title. III. Series.
[QE535.2.U6]
557.3 s—dc20 91–37448
[551.2'2'09969] CIP

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Isoseismal Maps, Macroseismic Epicenters, and Estimated Magnitudes of Historical Earthquakes in the Hawaiian Islands

By Max Wyss[1] *and* Robert Koyanagi[2]

Abstract

Macroseismic data were compiled for 56 moderate to large Hawaiian earthquakes that occurred between 1823 and 1989. The magnitudes (**M**) of the earthquakes range from 4.7 to 7.9, but most are 6±0.6. The maximum intensities (**I**) range from V to XII, and some of the radii of the felt areas are as much as 600 km, the extent of the chain of Hawaiian islands. For 43 earthquakes macroseismic maps were drawn. The two largest earthquakes (**M**>7) ruptured the south coast of Hawaii in April 1868 and November 1975. The two next largest events (**M**≤7) were located along its west coast (October 1929, August 1951), and major to large shocks (**M**≥6¾) also occurred off the island of Maui. The Kaoiki area, between the summits of the volcanoes Mauna Loa and Kilauea, produces the most frequent major earthquakes (**M**≥5.5) at the approximate rate of one every 10 years. A catalog for Hawaiian earthquakes for which the maximum intensity probably exceeded V contains 460 events for the period 1833 through 1955. Thus, the expected frequency of events having intensities greater than or equal to V in Hawaii is approximately 3.7 per year. The conditional probability for earthquakes having $\mathbf{I}_{max}$≥VII and ≥VIII and **M**≥6, ≥6.5, and≥7 for the next 10 years in the Hawaiian archipelago (and southern Hawaii) is 0.67 (0.63), 0.50 (0.39), and 0.84 (0.71), 0.50 (0.39) and 0.17 (0.17), respectively.

The fact that gradients of the isoseismals as a function of epicentral distance are steeper for earthquakes in Hawaii than for those in other areas of the United States indicates stronger attenuation of seismic waves in the crust. For earthquakes located along the southeast coast of the island of Hawaii, intensities are lower in the epicentral area than at 40 km to the north and west. This may suggest unusually strong attenuation below the southeast coast. The difference in isoseismal gradients between earthquakes of crustal depth and those deeper than about 15 km is noticeable in Hawaii. Peak accelerations for four recent earthquakes measured at 23 locations and having known intensities are greater than the values estimated using the average acceleration versus intensity relationship by a factor of four. This agrees with the observation that the relationships between magnitude and felt area derived from 15 earthquakes located on the island of Hawaii,

$$\mathbf{M}=1.0 \log (\mathbf{A}(\mathrm{VI}))+2.9 \text{ and}$$

$$\mathbf{M}=1.1 \log (\mathbf{A}(\mathrm{V}))+1.6,$$

yield magnitudes about 0.7 units greater than the same relationships for California earthquakes. Four subcrustal earthquakes and two earthquakes located offshore from Maui do not follow this relationship. Their magnitudes are approximately 0.7 units less for the same felt areas. The magnitudes of the well-documented historical earthquakes for which instrumental magnitudes are not available were estimated using these equations. For some of the earlier events the felt reports were not sufficient to estimate epicenter or magnitude and further compilation of data is needed.

INTRODUCTION

The County of Hawaii on the island of Hawaii (appendix 1) experiences frequently destructive earthquakes (table 1). During the last two decades more destructive earthquakes may have occurred there than in any county in the contiguous United States of America. It is therefore important to examine in detail the data available on widely felt historical earthquakes to improve our understanding of the earthquake process in Hawaii. Some of the recent destructive earthquakes in Hawaii have not attracted nationwide attention because the loss of property (table 1), although significant for the County and State of Hawaii, was comparatively low due to the sparse population in some of the epicentral areas. Earthquakes have occurred, however, in parts of Hawaii that are now undergoing rapid urbanization, such as Kona, and a

Manuscript approved for publication August 26, 1991.

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Table 1. Destructive earthquakes in Hawaii County since 1868 (I_{max}≥VIII)

[Intensity (I) is as defined by the Modified Mercalli Intensity Scale (appendix 2). Magnitude: M_S, surface-wave magnitude; M_L, local magnitude. Sources for magnitude values: GR, Gutenberg and Richter (1954); GS, U.S. Geological Survey; HVO, Hawaiian Volcano Observatory; PAS, California Institute of Technology]

Date	Epicenter location	Maximum intensity	Magnitude	Number of deaths	Damage
March 28, 1868	Southern Hawaii	IX	7	0	Extensive in Southern Hawaii.
April 2, 1868	Southern Hawaii	XII	7.9	81	More than 100 houses destroyed, tsunami.
October 5, 1929	Hualalai	VIII	6.5	0	Extensive in Kona.
August 21, 1951	Kona	VIII	6.9M_S (GR)	0	Extensive in Kona.
April 26, 1973	North of Hilo	VIII	6.1M_S, 6.2M_L (GS) (HVO)	0	Extensive in Hilo, $5.6 million.
November 29, 1975	Kalapana	VIII	7.1M_S, 7.2M_S (GS) (PAS)	2	Extensive in Hilo, $4.1 million.
November 16, 1983	Kaoiki fault	IX	6.7M_S, 6.6M_L (GS) (HVO)	0	Extensive damage in Southern Hawaii, more than $6 million.
June 25, 1989	Kalapana	VII	6.2M_S, 6.1M_L(GS) (HVO)	0	Southeast Hawaii almost $1 million.
1834–1983	14 earthquakes	≥VI			

mainshock in 1868 was one of the largest earthquakes in U.S. history. Therefore, we have reason to believe that earthquake disasters are possible in Hawaii.

In this report we document the occurrence of historical earthquakes, estimate magnitude, probable location, and relative focal depth for early Hawaiian earthquakes where data are sufficient, and calculate the probability for major to large earthquakes in the next 10 to 50 years. To estimate magnitudes and locations we compared macroseismic maps of early events with those of recent earthquakes for which instrumental source parameters are available. The data set of 56 earthquakes (table 2) is thus divided into a calibration set of recent events and a study set of earlier historical events. The division between these two sets is not sharply defined because of the gradual improvement in and increase of information with time. High-quality data for hypocenters and magnitude estimates exist only for nine events that occurred since 1962. The source parameters of shocks prior to 1935 are poorly known. For the 15 events in the period from 1935 to 1955, instrumental epicenters are variable in quality. Depth calculations based on instrumental records are available only for earthquakes after 1940 (table 3). For developing the magnitude versus felt-area relationship the calibration set consists of the 15 earthquakes that have occurred since 1938 and for which macroseismic data define the areas of intensity (I) of V or VI (appendix 2).

We first present the macroseismic data of the calibration set of earthquakes with instrumental magnitudes. Next we establish a relationship between magnitude and felt area for Hawaii. Then we investigate the gradient of intensity as a function of epicentral distance in an attempt to estimate focal depths to the extent of differentiating subcrustal sources from crustal sources. And, finally, from our comparison of instrumental and macroseismic data, we estimate magnitudes (M) and epicenters for the earlier earthquakes that had maximum intensities of greater than V for which sufficient data for defining isoseismal lines are available. For some early earthquakes, felt reports suggest that the event may have been fairly large, but isoseismals cannot be drawn. Nevertheless, the data for these events are given in appendix 3 along with the other macroseismic observations because they significantly contribute to the understanding of seismicity in Hawaii.

A list of earthquakes having recorded or inferred maximum intensity I_{max}≥V was also compiled (table 4) as a supplement to the list of larger earthquakes (mostly M≥6) given in table 2. Although the locations of most of these additional 404 earthquakes cannot be pinpointed, the catalog is a more complete record of Hawaiian seismicity than any catalog available to date.

Based on the earthquake catalogs compiled for the area for the last 160 years, we can estimate the conditional probability for the occurrence of major and large earthquakes in the future in Hawaii, and we can estimate location and magnitude for most of the larger ones. However, the accuracy of the results should not be overestimated, and it is difficult to make high-quality determinations of epicenters and magnitudes. Some of the epicentral areas lie offshore, and others are in sparsely populated areas; in addition, attenuation in the crust probably is heterogeneous. The maximum intensity is commonly biased toward regions of relatively dense population, and the population of Hawaii has changed in time and locality.

The first recorded population survey, made by Captain James Cook in 1778–1779, estimated 120,000–150,000 Hawaiians on the island of Hawaii (County of Hawaii Data Book, 1980). The population decreased markedly in the subsequent 100 years, mainly attributed to wars and disease, to the lowest population of 16,000 in 1872. From 1878 to about 1940, a rapid influx of people developed Hilo into the cultural center of the island (appendix 4). This increase, which coincided with high population growths for other districts of the island, is attributed to the immigration of people from Portugal, China, Japan, Puerto Rico, Spain, Korea, and the

Philippine Islands to supply the labor force for the developing sugar industry on Hawaii. Current population growth and distribution trends and the number of building permits, all of which reflect changes in cultural density, are described in appendix 4.

A problem common to all studies of historical earthquakes is the lack of uniform reporting over time. As instrumentation, funds, personnel, and missions change at observatories the quality of reports changes. The Hawaiian Volcano Observatory (HVO), located at the summit of Kilauea, was started in January 1912 by Thomas A. Jaggar to conduct systematic research of Hawaiian volcanoes. In mid-1912 an Omori horizontal-pendulum tronomometer was installed in the original Whitney vault on the north rim of Kilauea caldera. In 1922, two Hawaiian-type mechanical seismographs, with smoked drum recording, were built and installed in Hilo and Kona. In 1952, direct-writing time signals from WWVH radio time were introduced to improve relative timing between stations. From 1955, mechanical instruments were replaced by electromagnetic seismographs more sensitive to local earthquakes. These instruments were initially designed at HVO and had magnification of 25,000–40,000 peaked at about 5 Hz. In 1957, a station at Haleakala Volcano on the island of Maui and one at the Honolulu Magnetic Observatory at Ewa Beach on the island of Oahu were added to expand the network for covering the Hawaiian archipelago (Klein and others, 1987; Koyanagi and others, 1988). From 1970 onward, the introduction of radiotelemetry for remote sensing linked the increasing number of stations on the island of Hawaii to the observatory (Klein and Koyanagi, 1980). HVO currently operates a 52-station islandwide network of short-period seismographs with signals continuously telemetered to the observatory. The instrumentally detected and processed events are reviewed on a daily basis. The data compiled over at least the past three decades include instrumentally determined focal parameters of earthquakes of $M>2$ beneath the island of Hawaii and of $M>4$ beneath the entire Hawaiian archipelago (Klein and others, 1987; Koyanagi and others, 1988).

The small staff of volcano scientists that started with Jaggar in 1912 has increased to dozens of geoscientists and technicians who conduct studies of volcanism and seismicity in Hawaii using modern instrumentation. Over the years of operation HVO has been sponsored by various organizations: Massachusetts Institute of Technology 1911–1917, Hawaiian Volcano Research Association 1912–1940's, University of Hawaii 1912–1942, U.S. Weather Bureau 1919–1924, U.S. Geological Survey 1924–1935, National Park Service 1935–1947, and U.S. Geological Survey 1947–present. Over the past 40 years, the U.S. Geological Survey has typically supported HVO with about a half-dozen geologists, geophysicists, and geochemists, including one scientist-in-charge, assigned to the observatory for 2–5 years. This rotating staff of scientists complements a permanent staff of about 20 scientists, technicians, a photographer, a librarian, and administrative personnel.

The history of seismometric operation before 1979 was detailed by Klein and Koyanagi (1980). The pioneering research done in the early years, when instruments and equipment used were frequently designed and constructed at the observatory, was described by Appleman (1987). A listing of names, times of service, and technical and scientific specialties of the workers at the observatory contributing to the almost eight decades of gradual increase in staffing and advancing technology in volcanologic and seismologic research was compiled by Takahashi and Wright (1987).

In addition to changes in staffing and equipment at HVO the reporting in newspapers has also varied greatly. Concurrent newsworthy events may deemphasize the importance of an earthquake. For example, little attention was paid to the earthquake that occurred on the day France surrendered to Germany during the Second World War, whereas a comparatively minor event was described in great detail by a reporter who tried to write a funny story about reactions of frightened people. Nevertheless, systematic sorting and compilation of such documentation provided a considerable amount of information useful for the determination of the occurrence time, approximate location, and magnitude of early events.

The farther back in time we attempt to extend the record, the less complete are reports. For some earthquakes of the 19th century felt reports from more than one island indicate that an earthquake may have been a major event; however, the data are too sparse to draw an isoseismal map. We included these events in our list and report the intensity observations in appendix 3 if two independent sources of felt reports exist. We do this in order to document the occurrence and what is currently known about it. In the future more felt reports may become available for some of these events and isoseismal maps may be completed. It is likely that most of the earthquakes listed in table 2 had magnitudes greater than 5.5. Most of the earthquakes in table 4 probably had magnitudes greater than $4\frac{3}{4}$.

The attenuation of seismic waves is higher in Hawaii than elsewhere in the United States (as we shall show later). Numerous earthquakes in the 4.0–4.5 magnitude range are commonly not felt at epicentral distances beyond 20 km. For this reason and because of the uneven geographic distribution of the earthquake reporting population, it is rarely possible to construct a macroseismic map for $M<5.5$ earthquakes.

We examine magnitude scales used for Hawaii in order to get an idea how they compare to magnitudes used elsewhere. The intensities and accelerations observed are plotted against one another and as a function of distance and magnitude, and the resulting relationships are compared to those in other parts of the United States.

Table 2. Moderate to large earthquakes in Hawaii with felt reports

[Date is month and day. Time is local Hawaiian Standard Time. Latitude in degrees north; longitude in degrees west; where blank not known. Intensity refers to Modified Mercalli Intensity Scale (appendix 2)]

Year	Date	Time	Location	Latitude	Longitude	Maximum intensity
1823	06 ??	2200	Kaimu			IX
1834	02 19	1800	Hawaii			VI
1838	12 12	1300	Hawaii			VI
1841	04 07	2345	Hawaii			VII
1868	03 28	1328	Kau	19.1	155.65	IX
1868	04 02	1540	Kau	19.2	155.5	XII
1868	04 04	0029	Hawaii			VII
1868	04 30	0615	Hawaii			VI
1870	08 07	0413	Near Molokai			VI
1871	02 19	2205	Off Maui	21.0	156.2	VIII
1872	04 22	1630	Eastern or southern Hawaii			VI
1874	12 29	0430	Offshore north of Hawaii			V
1877	05 31	0420	Offshore north of Hawaii			VI
1881	09 30	0453	Maui			VI
1885	01 13	0630	Offshore north of Hawaii			IV
1887	01 13	0500	Oahu			V
1887	01 17	Several	Mauna Loa			VI
1887	01 23	2330	Kau			VIII
1888	08 20	0735	Eastern or southern Hawaii			V
1890	08 06	2310	Hawaii (possibly Kona)			VI
1896	09 13	0559	Hawaii deep or off Maui			VI
1900	06 27	0530	Kau			V
1905	05 03	1520	Southern or eastern Hawaii			V
1908	09 20	2015	Kilauea			VI
1918	11 02	2333	Kaoiki	19.4	155.45	VII
1919	09 14	1720	Hilea	19.2	155.55	VII
1924	08 20	0620	Hilea	19.25	155.55	V
1926	03 19	2230	Northwest off Hawaii			V
1927	03 20	0452	Northeast off Hawaii, deep			V
1929	09 25	1820	Hualalai	19.7	155.9	VIII
1929	10 05	2122	Hualalai	19.7	155.9	VIII
1930	05 25	2017	Kaoiki or Kilauea	19.4	155.4	V
1935	01 02	0647	Kilauea	19.43	155.28	VI
1935	06 28	0900	Mtn. View	19.6	155.2	VI
1935	11 21	0141	Mauna Loa	19.5	155.5	VI
1938	01 22	2203	North of Maui	21.2	156.1	VIII
1939	05 23	1414	Mauna Loa	19.46	155.37	VI
1939	07 14	0351	Kalapana	19.32	155.11	V
1940	06 16	2357	Off northern Hawaii, off eastern Maui	21.0	155.3	VI
1941	09 25	0718	Kaoiki	19.35	155.45	VII
1948	06 28	0141	Oahu	21.2	157.9	VI
1950	05 29	1516	Kona	19.5	156	VII
1951	04 22	1452	Glenwood	19.4	155.25	VII
1951	08 21	0057	Kona	19.50	155.95	VIII
1952	05 23	1213	Kona	19.48	155.98	VI

Table 2. Moderate to large earthquakes in Hawaii with felt reports—Continued
[Date is month and day. Time is local Hawaiian Standard Time. Latitude in degrees north; longitude in degrees west; where blank not known. Intensity refers to Modified Mercalli Intensity Scale (appendix 2)]

Year	Date	Time	Location	Latitude	Longitude	Maximum intensity
1954	03 30	0841	Kalapana	19.35	155	VII
1955	08 14	0228	Kilauea	19.31	155.29	VI
1957	08 18	0042	East of Maui	23.8	155.47	V
1962	06 27	1827	Kaoiki	19.40	155.45	VI
1963	01 08	0939	Kilauea	19.39	155.22	V
1973	04 26	1026	Honomu	19.87	155.15	VIII
1974	11 30	0354	Kaoiki	19.44	155.42	IV
1975	11 29	0447	Kalapana	19.34	155.04	VIII
1979	09 21	2159	Kalapana	19.35	155.07	VII
1982	01 21	1152	Hilea	19.23	155.59	VI
1983	11 16	0613	Kaoiki	19.43	155.45	IX
1989	06 25	1727	Kalapana	19.36	155.03	VII

The data presented in this report and the conclusions reached should not be considered the final word. Instead, we view this effort as a first attempt to gather what is known about Hawaiian seismicity and to make a preliminary interpretation of these observations. We hope that more data on historical seismicity in Hawaii may come to light in the future. Certainly more data on acceleration, magnitude scales, attenuation, and intensity will become available. The data contained in this report may serve as a starting point for future, more sophisticated investigations that may reveal the reasons for the rather anomalous relationships between some of these parameters and thus lead to a better understanding of the earthquake hazard in Hawaii.

DATA

Reports in "United States Earthquakes" and "The Volcano Letter" (Fiske and others, 1987) were our chief sources for earthquake origin times and approximate locations for the years prior to 1956, except for the earliest period for which the list compiled by the Lymans (Wyss, Koyanagi, and Cox, 1992) was the main source. The felt reports were in part obtained from these publications but mostly were derived from newspapers. Felt reports from earthquakes on the island of Hawaii were best documented in the "Hawaii Tribune-Herald" of Hilo. The "Pacific Commercial Advertiser" and the "Honolulu Star Bulletin," both of Honolulu, also published many detailed stories on earthquakes, especially for those felt on the island of Oahu. Some additional information came from the "Maui News" published on the island of Maui.

The "Hawaii Tribune-Herald" was first called the "Hilo Tribune-Herald" when it started in 1924. The first newspaper in Hawaii started publication in 1856 in Honolulu. It was then called the "Pacific Commercial Advertiser" and later changed its name to the "Honolulu Advertiser." The "Honolulu Star-Bulletin" has been published since 1912 and the "Maui News" since 1900. Except for the earliest years all of these papers were published daily.

Between 1930 and 1989 important detailed information came from formalized earthquake report cards distributed to local citizens by HVO staff. Our recent discovery of the private earthquake diary by the Lymans of Hilo (Wyss, Koyanagi, and Cox, 1992) suggests that other personal records of felt earthquakes in Hawaii may exist. If these could be found they would furnish further detail for macroseismic mapping and possibly expand our data base of historical earthquakes.

The epicenters of the earthquakes studied are listed in table 2, and those of earthquakes located on Hawaii are plotted in figure 1. We assigned a subjective quality rating to the macroseismic data using the letters A through D (table 3) as follows: A, good; B, fair; C, poor; and D, incomplete. The D rating was given to earthquakes located offshore for which no data are available in the vicinity of the epicenter and to early events for which data are sparse. For some of these events the data are so poor that we did not attempt to estimate epicenters or magnitudes. A-quality data are for strong earthquakes for which intensity data are sufficient to constrain well contours and distance-attenuation rates. For these events comprehensive intensity information is available for distances of from less than 10 km from the epicenter (with

Table 3. Radii of felt area for Hawaiian earthquakes

[Date is given in year, month, and day. Asterisk (*) indicates magnitude based on average felt-area equations; plus (+) indicates estimate based on comparison with two other Maui earthquakes; double asterisk (**) indicates estimate based on tidal-wave amplitude; triple asterisk (***) indicates estimate based on comparison with subcrustal earthquakes; n indicates normal depth less than 15 km; parentheses around radius value indicate that value is poorly defined. Quality is quality of macroseismic data (see text): A, good; B, fair; C, poor; D, incomplete]

Date	Magnitude	Depth (kilometers)	Radius (kilometers)							Quality
			I≥II	I≥III	I≥IV	I≥V	I≥VI	I≥VII	I≥VIII	
1868 03 28	7*	n					100	70	45	C
1868 04 02	7.9*	n				350	200	150	90	B
1870 08 07	≥6*					~180	~70			D
1871 02 19	6.8+	n				250		160	50	C
1877 05 31	~6¼*					~80				D
1881 09 30	≥6*					~150				D
1885 01 13	≥6**									D
1887 01 23	~6*					~70	~40			D
1896 09 13	≥6*					~150				D
1918 11 02	6.2*	n				60	30	15		B
1919 09 14	6.1*	n	380		130	60				C
1924 08 20	5.0*	n		70	50	(20)				C
1926 03 19	≥6				180	120				D
1927 03 20	~6				300					D
1929 09 25	6.1***	Deep			300	100	55	20	(5)	B
1929 10 05	6.5	n				220	90	60	25	A
1930 05 25	4.7*			90	40	(15)				C
1935 01 02	5.9*	n	(130)	90	70	50				B
1935 06 28	5.7*	n		95	75	40				B
1935 11 21	5.6*	n	330		100	35	(15)			B
1938 01 22	6¾	n				220	170	80		A
1939 05 23	4.8***	Deep	(300)	(170)	40		(7)			C
1939 07 14	5.5*				90	35				B
1940 06 16	6.0	n		(500)	270	150				C
1941 09 25	6.0	11	(350)	270	120	50	20			A
1950 05 29	6.4*	8				75	(35)	10		B
1951 04 22	6.3	35		400	(200)	120	50	10		A
1951 08 21	6.9	10			350	130	70	35	7	A
1952 05 23	6.0	10		200	100		20			A
1954 03 30	6.5	10		120	90	65	50			B
1955 08 14	6.0	29	550	420	280	110	40			C
1962 06 27	6.1	8	380	220	110	50	25			A
1963 01 08	4.6	31	380		150	55				A
1973 04 26	6.2	40			500	350	100	40	15	A
1974 11 30	5.5	8		60	35					B
1975 11 29	7.2	9	580		400	200	55	40	25	A
1979 09 21	5.5	9			65	35	12			B
1982 01 21	5.5	10			180	65	30			B
1983 11 16	6.6	11	520	350	160	80	55	35	15	A
1989 06 25	6.1	9	400		110	70	20	10		A

one exception) to distances of low intensities. Intensity contours beneath the populated islands are constrained to approximately 10 km within about 100 km of the epicenter. B-quality events generally have intensity contours with uncertainties of approximately 20 km at distances within 100 km of the epicenter, and, for some, the intensities at large distances are not reported. C-quality events have fewer than average data points, but reasonably reliable estimates of the earthquake epicenters are possible. For some of the C-quality events the extent of the areas of intensity V and VI are poorly defined; for others the meizoseismal area is not covered well. Summaries of the macroseismic observations on which our intensity estimates are based are given in appendix 3.

Table 4. Earthquakes in Hawaii 1833–1955 having maximum intensity ≥V

[Time is Hawaiian Standard Time (H.s.t.) or that given by the original source, which can differ by 30 min from H.s.t. Where numbers are given for location, they are latitude (degrees north) and longitude (degrees west). See text for explanation of word modifiers describing intensity. Sources: 1, United States Earthquakes; 2, HVO Bulletin (Bevins and others, 1988a, b); 3, The Volcano Letter (Fiske and others, 1987); 4, Hilo Tribune Herald; 5, Wood (1914); 6, Pacific Commercial Advertiser; 7, Hilo Daily Tribune; 8, Unpublished felt reports (HVO); 9, Wyss, Koyanagi, and Cox (1992); 10, Bulletin of the Seismological Society of America; 11, Cox (1986a); 12, Furumoto and others (1972); 13, Wood (1915); T, Text and other tables of this report. The horizontal lines in 1885 and 1915 separate the records compiled by Mrs. Lyman, Sr., Mrs. Lyman, Jr., and those in "United States Earthquakes"]

Year	Month	Day	Time	Location	Intensity (magnitude)	Source
1833	10	03	Night		Heavy	9
1833	10	13	1500		Heavy	9
1834	02	19	1800		V	1, 9
1834	05	14	1430		Heavy	9
1834	08	03	0400		V	9
1834	08	31	0004		V	9
1834	09	19	1800	Hawaii	VI	T
1837	06	20	1858		Smart	9
1838	01	20	0015		Smart	9
1838	01	29	2200		Heavy	9
1838	11	07	1145		Smart	9
1838	12	12	1300	Hawaii	VI	T
1839	04	07	1200		Smart	9
1840	02	01	1330		Severe	9
1840	12	18	0500		V	9
1841	04	05	1330		Smart	9
1841	04	07	2145	Hawaii	VII	T
1842	11	09			V	9
1844	02	18	1830		Severe	9
1844	09	01	0800		Heavy	9
1847	10	14	1500		Heavy	9
1848	02		1700		Heavy	9
1848	07	09	0415		Heavy	9
1851	01	12	1900		Smart	9
1852	03	31	1615		Very severe	9
1852	10	19	0445		Smart	9
1853	03	02	0500		Smart	9
1853	03	08			Smart	9
1853	03	11	0430		Smart	9
1854	08	26	1600		Smart	9
1854	10	29	2000		Smart	9
1855	03	18	2030		Smart	9
1855	05	24	0900		Smart	9
1855	06		1630		Smart	9
1855	08	03	2030		Smart	9
1855	09	17	0800		Smart	9
1855	11	02	0700		Smart	9
1856	01	08	0400		Smart	9
1857	07	30	0100		Severe	9
1857	09	09	0900		Smart	9
1858	04				Heavy	9
1858	07	05	a.m.		Smart	9
1859	07	16	2100		Smart	9
1859	11	21	0300		Smart	9
1860	07	18	1600		Severe	9
1861	03	12	1000		Smart	9
1861	06	01	2030		Severe	9
1861	12	05	1149		V	11
1861	12	15	1921		V	11
1863	05	06	1530		Heavy	9
1863	11	26	0330		Heavy	9

Table 4. Earthquakes in Hawaii 1833–1955 having maximum intensity ≥V—Continued

Year	Month	Day	Time	Location	Intensity (magnitude)	Source
1865	03	03	0700		Heavy	9
1865	12	11	0130		Smart	9
1867	10	30	1730		Heavy	9
1867	11	07	0200		Smart	9
1868	03	28	1322		Severe	5, 9
1868	03	28	1328	Kau	IX (7)	T
1868	03	28	1615			5, 9
1868	03	29	0110		V	5, 9
1868	03	29	1310		Smart	5, 9
1868	03	30	0100		V	5, 9
1868	04	01	2108			5, 9
1868	04	02	1540	19.2°, 155.5°	XII (7.9)	T
1868	04	03	0145		VI	5, 9
1868	04	04	0007			5
1868	04	04	0012			5, 9
1868	04	04	0029	Hawaii	IX	T
1868	04	08	1100		Smart	9
1868	04	08	1212		Smart	5, 9
1868	04	10	a.m.		V	9
1868	04	19	2000		Smart	9
1868	04	29	2400		V	9
1868	04	30	0615	Northern Hawaii	VI	T
1868	05	10	2100		Smart	9
1868	05	15	0545		Smart	9
1868	05	17	2020		Smart	9
1868	05	24	2400		Severe	9
1868	05	26	0740		Hard	9
1868	05	29	0000		Protracted	9
1868	06	10	0715		Smart	9
1868	07	12	0800		Smart	9
1868	07	24	2240		V	9
1868	08	08			Smart	9
1868	08	10	1040		Smart	9
1868	08	20	0800		Smart	9
1868	09	07	1430		Hard	9
1868	09	11	1000		Decided	9
1868	09	12	2000		Decided	9
1868	09	22	0600		Decided	9
1868	10	20	0500		Smart	9
1868	11	02	1300		Hard	9
1868	11	10	2200		Quite a shock	9
1868	11	16	2200		V	9
1868	11	22	0500		Smart	9
1868	11	28	0830		Hard	9
1868	12	11	0200		Smart	9
1868	12	25	0500		Smart	9
1869	01	31	0500		Smart	9
1869	02	04	0030		Decided	9
1869	02	11	Night		V	9
1869	02	18	1200		VI	9
1869	02	18	1215		Smart	9
1869	02	21	0140		V	9
1869	02	22	0445		Hard	9
1869	04	14	1100		IV	9
1869	04	19	0000		Smart	9
1869	04	12(21?)	1940		VI	9
1869	04	24	0050		V	9
1869	04	24	0055		VI	9

Table 4. Earthquakes in Hawaii 1833–1955 having maximum intensity ≥V—Continued

Year	Month	Day	Time	Location	Intensity (magnitude)	Source
1869	05	20	0645		IV	9
1869	05	30	a.m.		Smart	9
1869	06	22	1500		Smart	9
1869	08	01	0000		V	9
1869	08	15	0400		(Large?)	9
1869	08	17	1100		Smart	9
1869	08	19	1700		Smart	9
1869	10	22	2300		Smart	9
1869	12	28	0640		Decided	9
1870	01	07	1930		Decided	9
1870	02	26	1940		Smart	9
1870	03	21	2030		Severe	9
1870	05	02	0415		Smart	9
1870	06	13	0300		Protracted	9
1870	07	21	0230		Protracted	9
1870	08	07	0413	Near Molokai	VI (≥6)	T
1870	11	20	0400		Heavy	9
1870	11	24	2100		Heavy	9
1870	12	11	0045		Hard	9
1871	02	08	2230		Smart	9
1871	02	15	2140		Protracted	9
1871	02	19	2205	Off Maui	VIII (6.8)	T
1871	03	19	2211	Oahu	VI	1, 11
1871	06	19	0545		Smart	9
1871	06	22			V	9
1871	07	17	0400		Protracted	9
1871	09	11	1100		Hard	9
1871	09	13	1215		VI	9
1871	09	25	0300		Smart	9
1871	11	02	1920		Protracted	9
1872	01	06	1530		Smart	9
1872	02	05	1745		Smart	9
1872	03	06	0400		Smart	9
1872	04	22	1630	Hawaii	VI	T
1872	08	18	0100		Smart	9
1872	10	13	1800		Decided	9
1873	01	23	0945		Smart	9
1873	06	05	0730		Smart	9
1873	07	10	1100		Smart	9
1873	08	30	1530		Decided	9
1873	09	03	0300		Smart	9
1873	09	05	1630		Smart	9
1873	11	13	0600		Decided	9
1874	02	12	2015		Smart	9
1874	03	28	2100		Smart	9
1874	04	10	0430		Smart	9
1874	04	27	1920		Protracted	9
1874	04	30	0515		Smart	9
1874	05	15	1145		Severe	9
1874	06	29	1600		Hard	9
1874	10	02	2100		Smart	9
1874	12	29	0430	Off northern Hawaii	V	T
1875	01	29	1215		V	9
1875	06	06	0140		V	9
1875	08	17	2000		Protracted	9
1875	11	23	1130		V	9
1876	03	30	0400		Hard	9
1876	05	03	2100		Smart	9

Table 4. Earthquakes in Hawaii 1833–1955 having maximum intensity ≥V—Continued

Year	Month	Day	Time	Location	Intensity (magnitude)	Source
1876	11	01	0430		Smart	9
1877	02	23	1800		Decided	9
1877	05	06	0530		Protracted	9
1877	05	31	0420	Off northern Hawaii	VI (6¼)	T
1877	08	02	2000		Decided	9
1878	01	20		Maui		1
1878	01	28	0650		Protracted	9
1878	04	30	1530		Decided	9
1879	03	11	0200		Smart	9
1879	05	15	2130		V	9
1879	11	04	0855		V	9
1879	11	27	0840		Smart	9
1880	04	21	0100		V	9
1880	08	18	0345		V	9
1880	09	23	1515		Severe	9
1880	09	25	0400		V	9
1881	09	30	0453	Maui	VI (≥6)	T
1882	07	26	0200		Decided	9
1882	10	18	1200		Decided	9
1883	05	15	0600		Decided	9
1883	07	12	1900		Decided	9
1883	07	26	0100		Protracted	9
1883	12	02	2100		Smart	9
1884	04	19	1200		Protracted	9
1884	08	21	0300			9
1884	11	18	1300		Decided	9
1884	11	21	0100		Decided	9
1884	12	10	0900		Smart	9
1885	01	13	0630	Off northern Hawaii	IV (≥6)	T
1885	02	23	2100		Smart	9
1885	12	19	0045		Smart	9
1886	01	20	0500		Decided	9
1886	03	06	Night		43 felt	9
1886	04	29	0330			9
1886	10	18	1840		Hard	9
1886	10	19	0000		Long	9
1887	01	11	0120		Sharp	9
1887	01	13	0500	Oahu	V	T
1887	01	17	Several	Mauna Loa	VI	T
1887	01	18	1330		Long	9
1887	01	23	2330	Kau	VIII (6)	T
1887	01	23	2340		Hard	9
1887	02	16	0120		Long	9
1887	07	23	1200		Decided	9
1887	08	07	0130		V	9
1887	09	13	0110		V	9
1887	10	01	2305		V	9
1888	05	08	0030		V	9
1888	08	20	0735	Hawaii	V	T
1888	11	08	1800		Long	9
1888	11	09	0330		Long	9
1889	02	21	0500		Decided	9
1889	05	07	1100		Protracted	9
1890	03	24	2025		Long	9
1890	05	11	1000		Long	9
1890	06	05	1510		Noise	9
1890	06	15	0600		Protracted	9

Table 4. Earthquakes in Hawaii 1833–1955 having maximum intensity ≥V—Continued

Year	Month	Day	Time	Location	Intensity (magnitude)	Source
1890	07	01	1630		Sharp	9
1890	07	10	1420		Sharp	9
1890	07	28	1600		V	9
1890	08	06	2310	Hawaii	VI	T
1890	08	21	0350		V	9
1891	03	06	2100		Long	9
1891	03	08	0200		V	9
1891	03	13			Decided	9
1891	07	05	1400		Long	9
1891	10	15	1730		Hard	9
1892	12	23	0030		V	9
1892	12	24	0145		Long	9
1893	04	08	2300		Long	9
1893	11	03	1730		Smart	9
1894	05	28	0015		V	9
1894	06	16	0220		Long	9
1894	12	03	0330		V	9
1894	12	03	1110		Long	9
1894	12	03	2210		Long	9
1895	01	11	0410		IV	9
1895	03	31	1425		Long	9
1895	10	25	1430		V	9
1895	11	05	1145	Oahu and Hawaii		9
1895	12	08	2304	Oahu	V	9, 11
1896	01	29	0515		Sharp	9
1896	09	13	0559		VI (≥6)	T
1896	11	17	1330		Noise	9
1896	11	25	0420		Long	9
1897	02	04	0530	Waimea		9
1897	03	08		Puna		9
1897	03	10	0500		Decided	9
1897	04	01	1600		Decided	9
1897	05	06	2100		Long	9
1897	06	11	a.m.		Long	9
1897	08	16		Oahu		9
1897	10	24	1700		Hard	9
1897	12	18	1820		Long	9
1898	02	04	0300		IV	9
1898	03		1100		IV	9
1898	05	01	1855		IV	9
1898	05	17	1655		Long	9
1898	08	05	0600		IV	9
1898	08	06	0600	Kau		9
1898	09	11	0535		Sharp	9
1898	09	15	1145		Hard	9
1898	12	29	2100		Long	9
1898	12	30	0200		Long	9
1899	01	04	0210		V	9
1899	07	11	1040		Decided	9
1899	10	29	2210		Long	9
1899	10	31	0710		IV	9
1899	11	06	0100	Kau		9
1900	06	27	0530	Kau	V	T
1900	07	10	2040		Hard	9
1900	10	11	0005		IV	
1900	10	12	0355		IV	9
1901	01	24	1500		Long	9
1902	09	25			Long	^

Table 4. Earthquakes in Hawaii 1833–1955 having maximum intensity ≥V—Continued

Year	Month	Day	Time	Location	Intensity (magnitude)	Source
1902	09	28	0625		Smart	9
1902	11	11			Long	9
1904	03	19	2100		Smart	9
1904	06	04	1225		Long	9
1904	06	28	2200		Long	9
1904	07	12	1010		Smart	9
1904	07	17			Hard	9
1904	11	13	2015		IV	9
1905	05	03	1520	Hawaii	V	T
1905	05	03	1615		Long	9
1905	05	03	1840		Long	9
1905	05	28	0922		Smart	9
1905	11	14	0830		IV	9
1906	04	25	0200		Smart	9
1906	09	06	0315		Smart	9
1907	01	10	2100		Smart	9
1907	07	05	0010		Long	9
1907	09	05	1852		Smart	9
1908	09	20	2015	Kilauea	VI	T
1908	09	22	1915		IV	9
1908	09	26	2005		Smart	9
1909	03	12	0330	Hawaii	V	1, 9
1909	06	30	1500		Smart	9
1909	10	09	2200		Smart	9
1909	12	24	0747		Decided	9
1910	02	13	0130		IV	9
1910	02	21	0630		IV	9
1910	04	19	0345		Smart	9
1910	10	21	1305		Quite a shock	9
1911	02	09	1040		Long	9
1911	07	01	1525		Smart	9
1911	07	14	1130		Long	9
1912	04	10	1000		IV	9
1912	04	17	1710		IV	9
1912	05	15			Quite a shock	9
1912	09	02			IV	9
1912	10	13	0645	Hawaii	V	1, 6, 9
1913	05	18	1940		Sharp	9
1913	09	08	1208	Kilauea	IV	1, 2, 9
1913	09	20	0815		IV	9
1913	10	25	0128	Kilauea	V	1, 2, 9
1914	04	29	1450		Long	9
1914	06				Smart	9
1914	07	20	0415		Sharp	9
1914	09	27	1015	Mauna Loa	Long	9, 13
1915	01	13	1945		Long	9
1917	09	15	0315		Sharp	9
1918	11	02	2333	Kaoiki	VII (6.2)	T
1919	01	28	1753	Hawaii	V	2, 1
1919	08	26	0234	Hawaii	V	2, 1
1919	09	14	1750	Hilea	VII (6.1)	T
1923	01	14	0258	Hawaii		2, 1
1923	02	09	2111	Hawaii		1, 2, 4
1923	12	14	0604	Hawaii		2, 1
1923	12	25	1916	Hawaii	IV	1, 2, 11
1924	08	20	0620	Hilea	V (5.0)	T
1924	09	10	1910	Kilauea	V	12

Table 4. Earthquakes in Hawaii 1833–1955 having maximum intensity ≥V—Continued

Year	Month	Day	Time	Location	Intensity (magnitude)	Source
1925	07	08	0615	Hawaii		2, 1
1926	02	07	1128	Oahu, Maui		2, 1, 3
1926	02	28	0711	Hawaii	V	1, 2, 4, 3
1926	03	19	2230	Northwest off Hawaii	V (≥6)	T
1926	04	22	0502	Mauna Loa	V	1, 2, 4, 3
1926	06	09	1005	Hawaii	V	1, 2, 4, 3
1927	03	20	0452	Hawaii	V (6)	T
1927	08	03	1012	Hawaii	VI	1, 2, 3
1929	02	05	0225	Hawaii	V	3, 12
1929	06	18	1001	Hawaii	VI	3, 4
1929	09	19	Night	Hualalai	V	12
1929	09	23	Night	Hualalai	V	12
1929	09	24		Hualalai	V	12
1929	09	25	1820	19.7°, 155.9°	VIII (6.1)	T
1929	09	27	1120	Hualalai	VI	3, 4
1929	09	28	0738	Hualalai	VII	1, 3, 4
1929	09	28	1548	Hualalai	VI	3, 4
1929	09	30	1225	Hualalai	VI	3, 4
1929	10	03		Kona		12
1929	10	05	2122	19.7°, 155.9°	VIII (6.5)	T
1929	10	10	0630	Hawaii		12
1929	10	21	1200	Hualalai		12
1930	05	20	1922	Hualalai	V	1, 3, 4
1930	05	25	2017	Kaoiki	V (4.7)	T
1930	10	20	0825	Kilauea	V	3,12
1931	01	30	0008	Waiohinu	V	3, 1
1931	06	11	1851	Kona	V	3, 12
1932	06	14	0521	19.47°, 155.37°	V	3
1932	07	07	1101	Kau Desert		3, 6, 10
1933	10	13	0301	19.2°, 154.4°	IV	3, 12
1933	10	21	0910	19.35°, 155.53°		3, 12
1933	10	21	0911			3, 12
1933	12	02	0630	Mauna Loa	VI	3, 4, 1
1934	04	09	0236	20.15°, 155.88°		3
1934	05	10	1039	19.6°, 155.4°	VI	1, 3, 4
1934	06	26	0737	19.20°, 155.08°		3
1934	10	13	0744	19.47°, 155.50°	V	3, 6, 10
1935	01	02	0647	19.4°, 155.3°	VI (5.9)	T
1935	06	25	0045	19.44°, 155.28°	V	3
1935	06	28	0900	19.6°, 155.2°	VI (5.7)	T
1935	09	30	2306	19.4°, 155.7°	V	1, 3, 4, 8
1935	10	01	0028	19.6°, 155.4°	V	1, 3, 4, 8
1935	11	21	0141	19.5°, 155.5°	VI (5.6)	T
1936	04	15	0857	19.4°, 155.2°	V	3, 8, 1
1937	01	10	2250	19.3°, 155.15°		3, 12
1937	10	25	0543	19.3°, 155.25°	IV	3, 12
1938	01	22	2203	21.2°, 156.1°	VIII (6¾)	T
1938	02	17	0248	19.6°, 155.4°	V	3, 1
1938	03	07	0626	19.70°, 155.53°	V	3, 10
1938	05	28	0632	19.4°, 155.25°	V	3, 12
1939	05	08	0703	Hilina	IV	3, 12
1939	05	15	1058	19.4° ,155.1°	VI	1, 3, 4, 8
1939	05	23	1414	19.46°, 155.37°	VI (4.8)	T
1939	05	24	1329	19.4° ,155.2°	VI	1, 3, 4, 8
1939	05	29	1945	19.5°, 156.8°	V	1, 4
1939	05	31	2121	19.6°, 155.2°	V	1, 3, 4, 8
1939	06	12	0141	Kau Desert	V	1, 3, 4, 8
1939	07	01	0020	19.38°, 155.19°	V	3

Table 4. Earthquakes in Hawaii 1833–1955 having maximum intensity ≥V—Continued

Year	Month	Day	Time	Location	Intensity (magnitude)	Source
1939	07	14	0351	19.32°, 155.11°	V (5.5)	T
1940	06	16	2357	21.0°, 155.3°	VI (6)	T
1940	07	15	1718	20.9°, 155.1°	(5.5)	1, 3
1940	09	01	2245	21.0°, 155.3°	V (5.5)	1, 3
1941	09	25	0718	19.35°, 155.45°	VII (6)	T
1941	11	16	1011	Waimea	VI	1, 3, 4
1941	11	18	0326	Waimea	VI	1, 3, 4
1941	11	22	2153	Waimea	V	1, 3, 4
1942	02	18	1139	Kilauea	V	3
1942	02	21	0841	Mauna Loa	V	3, 4
1942	03	20	2335	Mauna Loa	V	3
1943	11	10	1652	Southern Hawaii	V	3, 1
1944	11	12	0526	Kilauea	V	3, 1
1944	12	27	0412	19.5°, 155.5°	VI (5.5)	3, 4, 1
1945	03	04	0000	Mauna Loa	V	3, 1
1945	05	19	0148	Mauna Loa	V	3, 1
1945	07	13	0215	Kalapana		3
1945	09	19	0533	Saddle Area	V	3, 1
1947	03	19	2306	Mauna Loa	V	3, 4, 1
1947	09	21	0550	Humuula		3
1947	09	30	0404	Kilauea	V	3, 4, 1
1947	10	31	0213	Mauna Loa	V	3
1947	12	14	1010	Kilauea	IV	3, 4
1948	06	28	0141	Oahu	VI	T
1949	02	26	1354	Mauna Loa	V	3, 4, 1
1949	05	02	0502	Kona	V	3, 4, 1
1949	05	07	2326	Kona	IV	3
1949	05	23	1024	Kaoiki	V	3
1949	09	01	1253	Kaoiki	V	3
1949	11	25	0758	Mauna Loa		3
1950	03	25	0543	Mauna Loa	V	1, 3
1950	05	29	1516	19.5°, 156°	VII (6.4)	T
1950	12	10	2125	19.5°, 155.5°		3, 7, 10
1950	12	26	0255	Kau Desert		3
1951	04	22	1452	19.4° ,155.25°	VII (6.3)	T
1951	08	21	0057	19.50°, 155.95°	VIII (6.9)	T
1951	08	21	0957	19.50°, 155.95°		3
1951	08	21	2248	19.50°, 155.95°		3
1951	08	22	1715	19.50°, 155.95°		3
1951	09	16	0143	19.2°, 155.5°	V	1, 3
1951	11	08	0934	Southwest Mauna Loa	VI	1, 3
1952	02	02	0116	Kaumana	V	1, 3
1952	03	14	1821	19.05°, 155.08°		3
1952	03	17	1758	19.1°, 155.0°	V	1, 3
1952	03	18	1418	19.08°, 155.41°		3, 6, 10
1952	04	06	2110	21°, 157°	V	1, 3
1952	05	23	1213	19.48°,155.98°	VI (6)	1, 7
1952	07	12	1353	Kona	V	1, 3
1953	01	09	2110	19.4°, 155.55°	V	1, 3
1953	01	15	0205	19.3°, 155.4°	V	1, 3
1953	08	21	1947	Hualalai	V	1, 3
1953	08	23	0053	Hualalai		3, 7
1954	03	30	0841	19.35°, 155°	VII (6.5)	T
1954	07	03	1153	20.5°, 155.5°	VI	1, 7, 3
1954	10	07	2056	Naalehu	V	3, 7
1954	10	11	0626	Hookena	V	3, 7
1955	03	07	2221	Pahoa	V	3, 10
1955	03	07	2257	Pahoa		3, 10

Table 4. Earthquakes in Hawaii 1833–1955 having maximum intensity ≥V—Continued

Year	Month	Day	Time	Location	Intensity (magnitude)	Source
1955	03	27	1602	Kilauea	VII	1, 7
1955	04	01	0424	19.5°, 155.0°	V	1, 3
1955	08	07	0718	20.5°, 155.5°	V	1, 8, 7, 3
1955	08	14	0228	19.31°, 155.29°	VI (6)	T
1955	10	26	1656	19.5°, 155.5°	V	1, 3

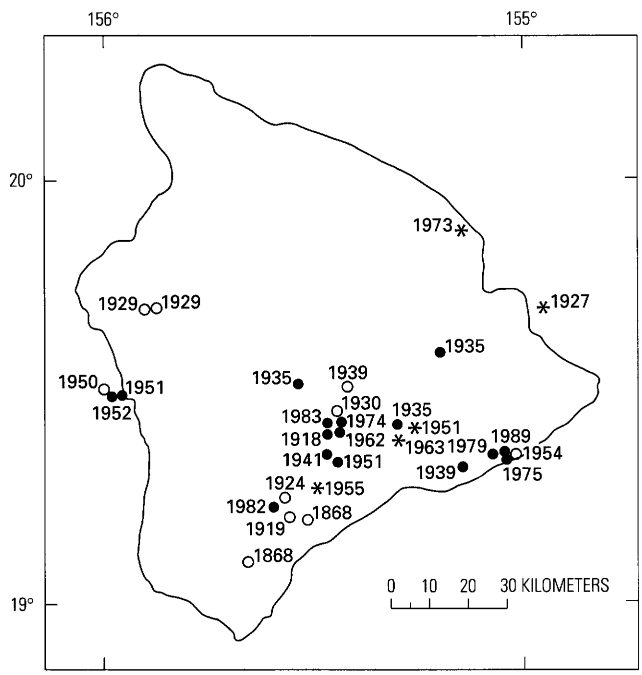


Figure 1. Epicenter map of earthquakes (and their years of occurrence) located on the island of Hawaii and for which isoseismal maps were compiled. Solid dots are instrumentally determined epicenters, and open circles are epicenters estimated using macroseismic data. Asterisks mark epicenters of subcrustal earthquakes.

CALIBRATION DATA SET

The macroseismic data for earthquakes for which instrumental locations and magnitudes are known were selected as the calibration data set. An earthquake-magnitude versus felt-area relationship for the island of Hawaii was then developed using these data. This relationship we then used to estimate the magnitudes of historical earthquakes for which felt reports but no instrumental records are available. The two earliest events for which instrumental magnitudes are available were not included in this calibration set because their magnitude estimates may not be accurate. The calibration data and other data were used to estimate epicenters of historical events by comparison of the isoseismal maps using the assumption that similar macroseismic patterns result from events of similar epicenters. The accuracy of epicenter locations on the island of Hawaii since 1962 is approximately 2 km. For the earthquakes before 1962 errors in epicenter coordinates of 5–10 km are likely. A brief description of macroseismic data for each earthquake is given starting with the most recent earthquake. Detailed accounts of the damage caused and pertinent references are given in appendix 3. Most of the locations mentioned are shown in figures A1–A4 of appendix 1. The time of the event (in Hawaiian standard time) and its latitude, longitude, and depth are given in parentheses following the date of the event. Abbreviations used are M_S, surface-wave magnitude; M_L, local magnitude; and m_b, body-wave magnitude.

1989 June 25 (1727, 19.36° N., 155.03° W., 9 km deep): This was the largest earthquake in Hawaii for the past six years (M_L=6.1). It was located near the epicenter of the M_S=7.2 Kalapana earthquake of November 1975, and a model for its source meachanism was constructed by Arnadottir and others (1991). Its isoseismals are well defined (fig. 2) and comparatively simple, unlike those from the larger event in the same area (fig. 6). This earthquake and its aftershocks were discussed by Koyanagi and others (1989).

1983 November 16 (0613, 19.43° N., 155.45° W., 11 km deep): This M=6.6 earthquake is the most comprehensively reported Kaoiki event (fig. 3). The Kaoiki area is located between the summits of the volcanoes Mauna Loa and Kilauea. Parameters for this event, its precursor, and its recurrence time were described by Koyanagi and others (1984) and Wyss (1986a, b). Some ground rupture and structural damage were described by Buchanan-Banks (1987). Surface faulting of several kilometers was mapped by Jackson and Endo (1989). The fault-plane solution was determined by Endo (1985), and the strain and stress tensors derived from fault-plane solutions were studied by Wyss, Liang, and others (1992). The attenuation in the source volume of this earthquake was studied using the coda (Huang and Wyss, 1988) as well as P-wave spectra (Scherbaum and Wyss, 1990).

1982 January 21 (1152, 19.23° N., 155.59° W., 10 km deep): The isoseismals of this M=5.5 earthquake are concentric around its epicenter at Hilea (fig. 4). The gradient of the isoseismals is not unusual, but the extent of the felt areas is larger than for the typical Hawaiian crustal earthquake. This event better fits Toppozada's (1975) magnitude versus felt-area relationship for California than any other of the

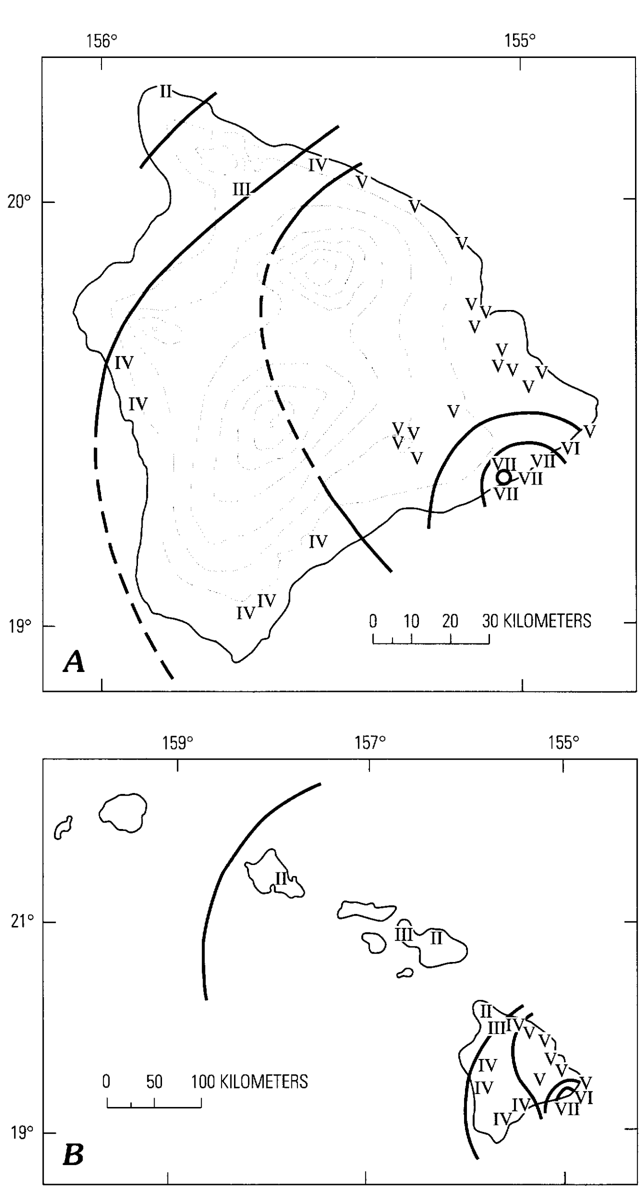


Figure 2. Isoseismal maps for the earthquake of June 25, 1989. The Modified Mercalli Intensity Scale (appendix 2) was used; each Roman numeral represents one intensity report or the average of several. The manually drawn isoseismals are shown by heavy solid and dashed lines where they are well and poorly defined, respectively. *A*, Island of Hawaii. The open circle indicates the instrumental epicenter. Light lines are contours of topography; interval 2,000 ft. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*.

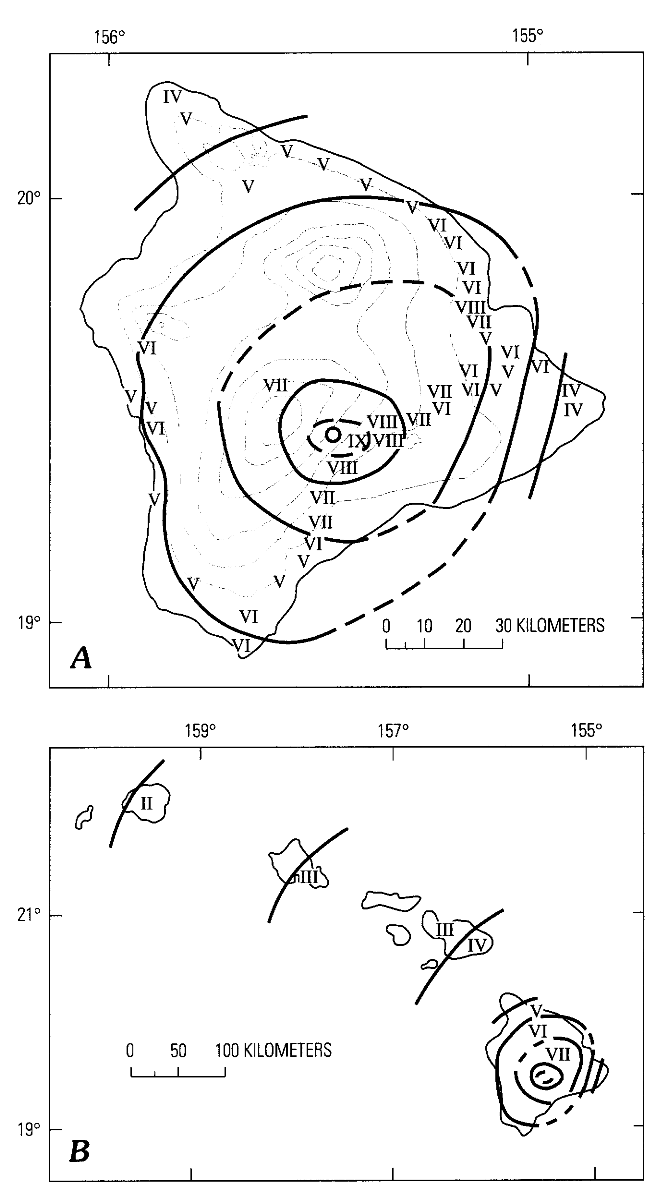


Figure 3. Isoseismal maps for the earthquake of November 16, 1983. *A*, Island of Hawaii. The open circle indicates the instrumental epicenter. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

Hawaiian earthquake data (fig. 19). Numerous aftershocks define its source volume, and a weak precursory quiescence before this event was discussed by Wyss and Fu (1989). Focal mechanisms and strain and stress tensors in this area and for this earthquake as well as its aftershocks were studied by Liang and Wyss (1991) and Endo (1985).

1979 September 21 (2159, 19.35° N., 155.07° W., 9 km deep): Felt reports for this M=5.5 earthquake are abundant except in the epicentral area (fig. 5). Macroseismic evidence suggests that the epicenter was located near Hilo; however, the instrumental epicenter lies in Kilauea's south flank 50 km south of Hilo. This is perhaps the best example of events having extremely low intensities in Puna, especially along the adjacent south coast, and high intensities at Hilo. Other similar events are the November 29, 1975, and March 30, 1954, earthquakes (figs. 6, 12).

1975 November 29 (0447, 19.34° N., 155.04° W., 9 km deep): This is the largest event for which detailed instrumental data are available. Although this earthquake ruptured along 45 km of the south coast of Hawaii and had a

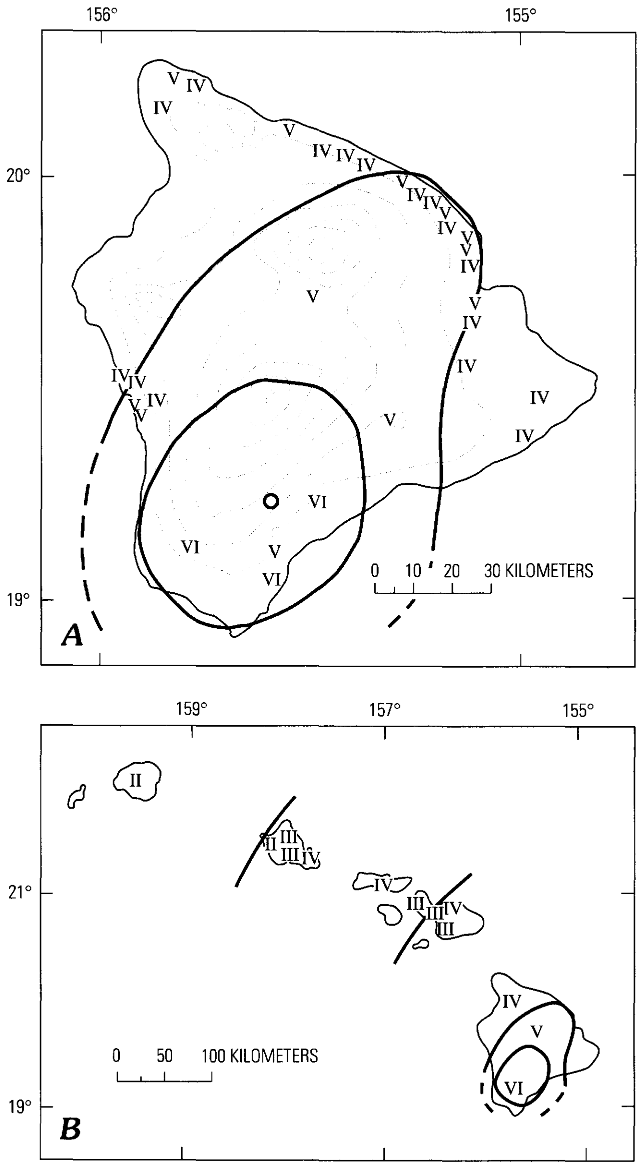


Figure 4. Isoseismal maps for the earthquake of January 21, 1982. *A*, Island of Hawaii. The open circle indicates the instrumental epicenter. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

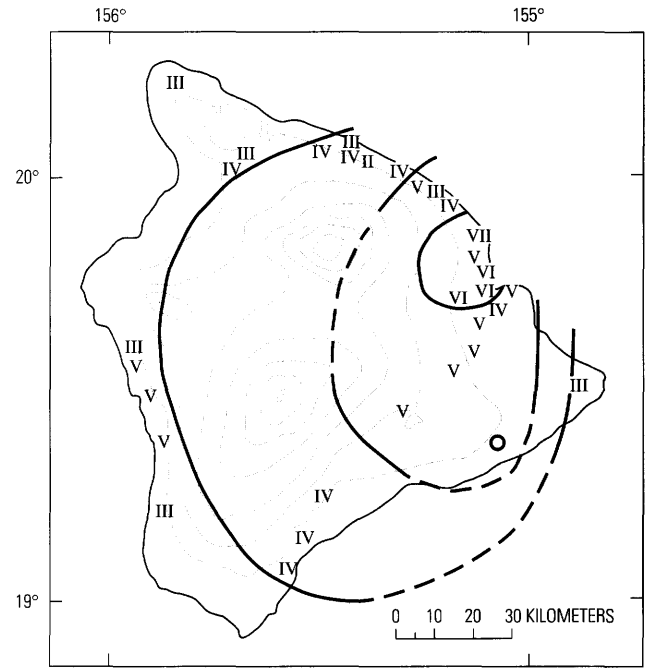


Figure 5. Isoseismal map for the earthquake of September 21, 1979, island of Hawaii. Note: the epicenter (open circle) does not coincide with the area of highest intensities. (For additional explanation see figure 2.)

magnitude of 7.2, intensities in the epicentral area near Kalapana were relatively low (fig. 6). This high magnitude and low epicentral intensity is typical for earthquakes in this area and in part may be attributed to low population density in the epicentral area and to the earthquake focal mechanism. It is also likely, however, that the attenuation of seismic waves is stronger along the southeast coast than elsewhere on Hawaii. At greater distances the intensity gradients are normal (figs. 6*A*, *B*, 48*B*). Along the south coast, where surface faulting and permanent subsidence were observed, it might be appropriate to assign larger intensities.

This earthquake was anticipated on the basis of large accumulations of crustal strain (Swanson and others, 1976). Instrumental data, ground rupture, damage, volcanic effects, and tsunami generation are described in numerous publications (Tilling and others, 1976; Cox and Morgan, 1977; Ando, 1979; Furumoto and Kovach, 1979; Wyss and others, 1981a, b; Johnston and others, 1982; Cox, 1986a; Harvey and Wyss, 1986; Eissler and Kanamori, 1987, 1988; Zuñiga and others, 1987; Wyss and Kovach, 1988). Focal mechanisms and faulting processes in the epicentral area were studied by Crosson and Endo (1982) and Thurber and Gripp (1988). Geodetic surveys of ground deformation were examined in detail to evaluate the structure of the south flank of Kilauea and the mechanism of the earthquake (Lipman and others, 1985), and a model was designed by Dieterich (1988) to explain the stress accumulations and release.

1974 November 30 (0354, 19.44° N., 155.42° W., 8 km deep): This earthquake was associated with a surface rupture in the Kaoiki region (Endo, 1985) and shows that even in recent times it is difficult to identify an $\mathbf{M}_L$=5.5 event as a Kaoiki source using isoseismal data alone (fig. 7). The intensity distribution of this earthquake is similar to that of the May 1930 event, which includes an unusually high value from the vicinity of Pahoa. In a detailed study of the 1974 mainshock and its aftershocks Endo (1985) relocated the hypocenter and determined its focal mechanism as near-vertical strike slip along a northeast-trending fault plane. A change of orientation of the strain tensor may have preceded this mainshock (Wyss, Liang, and others, 1992).

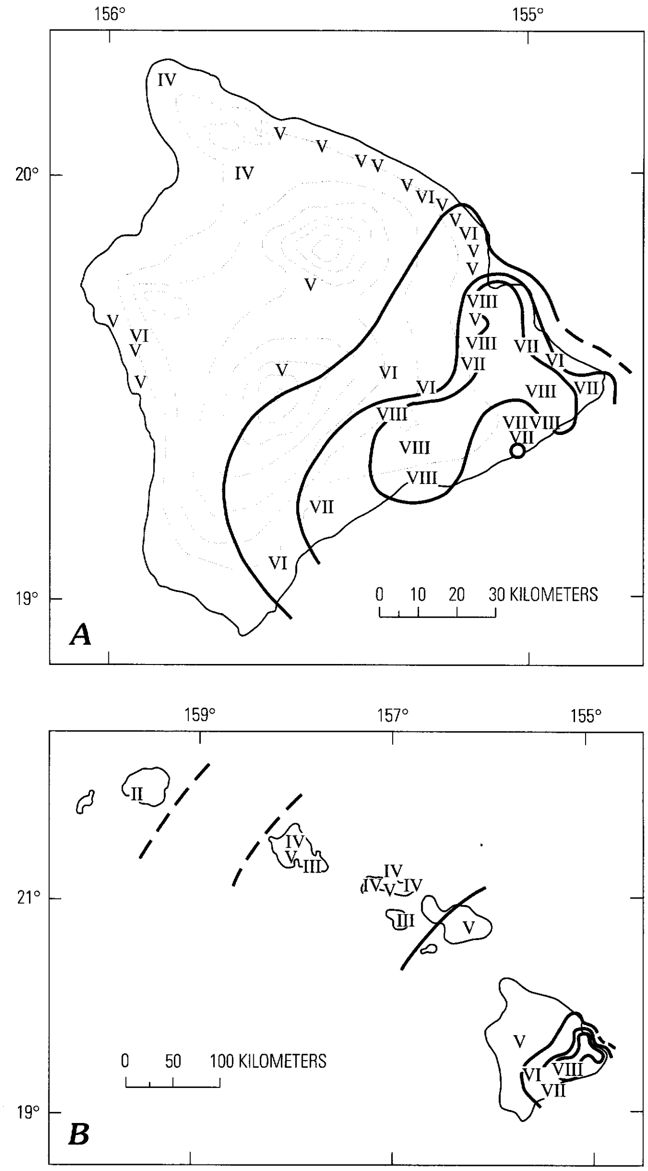


Figure 6. Isoseismal maps for the earthquake of November 29, 1975. *A*, Island of Hawaii. The epicenter (open circle) does not coincide with the area of highest intensities. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

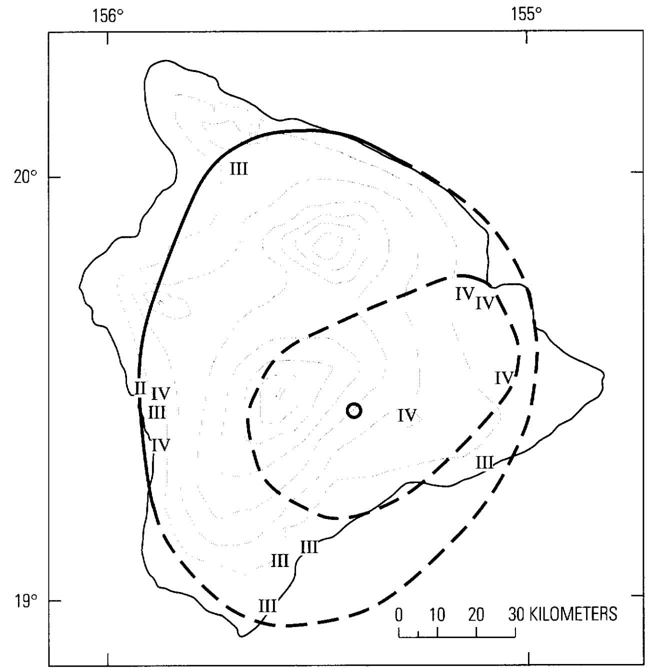


Figure 7. Isoseismal map for the earthquake of November 30, 1974, island of Hawaii. The open circle indicates the instrumental epicenter. (For additional explanation see figure 2.)

1973 April 26 (1026, 19.87° N., 155.15° W., 40 km deep): Macroseismic data for this largest (M=6.2) and deepest recent subcrustal earthquake are shown in figure 8. Its focal mechanism and location were studied in detail by Unger and Ward (1979).

1963 January 8 (0939, 19.39° N., 155.22° W., 31 km deep): This relatively small M=4.6 earthquake provides one of the best examples of isoseismals resulting from subcrustal sources (figs. 9, 48*B*). Its macroseismic pattern is similar to that of an event in April 1951. Both earthquakes were subcrustal and had almost identical epicenters.

1962 June 27 (1827, 19.40° N., 155.45° W., 10 km deep): This M=6.1 Kaoiki earthquake is one of the most typical examples for a crustal earthquake in south-central Hawaii. Its isoseismal maps (fig. 10) serve as a model to identify earlier Kaoiki epicenters. This event has been studied in detail by Koyanagi and others (1966), and the hypocenter was relocated by Endo (1985). The epicenters of this shock and the recent earthquakes discussed above have errors that probably do not exceed 2 km.

1955 August 14 (0228, 19.31° N., 155.29° W., 29 km deep): This earthquake was felt as far away as Oahu and Molokai islands (fig. 11), in spite of its moderate size (M=6.0). The felt areas are large because of its subcrustal depth. The earthquake is one of the events used to define isoseismal gradients for subcrustal earthquakes in Hawaii (fig. 48*A*). The epicentral error of this earthquake and the ones in the calibration set that occurred earlier may be in the 5–10 km range. Arrival times at Hawaiian seismographs were examined in detail to determine seismic velocities beneath Hawaii and to refine the epicenter estimate for this event (Eaton, 1962).

1954 March 30 (0330, 19.35° N., 155° W., 10 km deep): Felt reports of this earthquake (fig. 12) would have suggested the epicentral area to be near Hilo if the instrumental epicenter at 50 km south of Hilo was not available. This is one of three examples (see also figs. 5 and 6) that show relatively low intensities in Puna for earthquakes located near Kalapana as compared to higher intensities reported in Hilo.

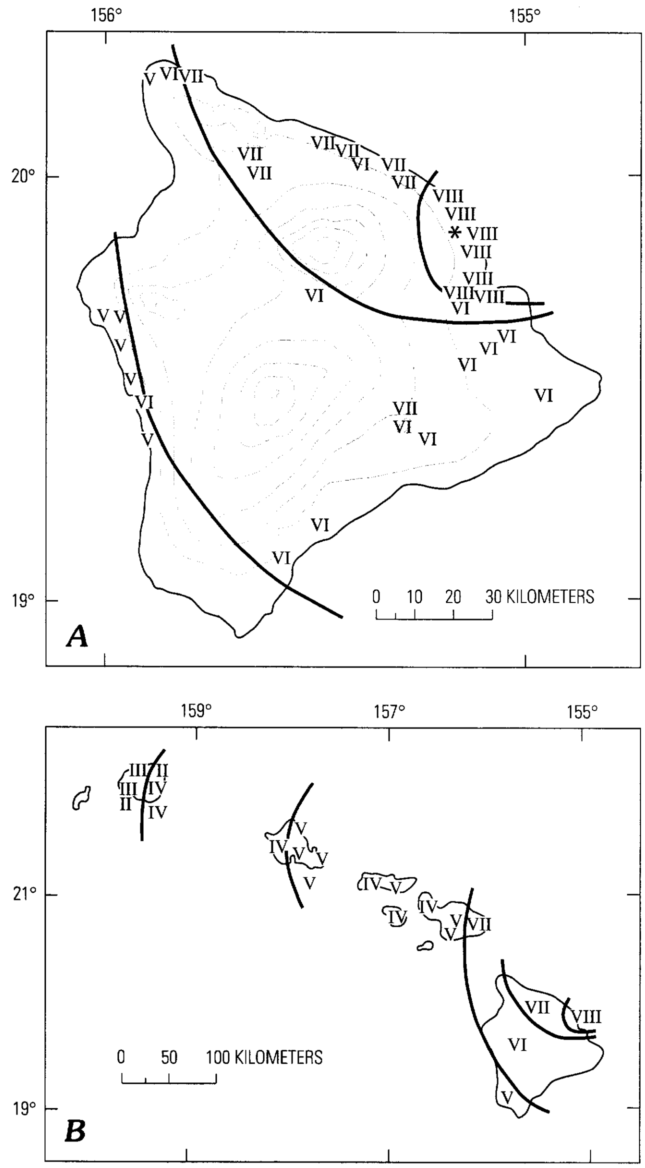


Figure 8. Isoseismal maps for the earthquake of April 26, 1973. The focal depth was 40 km. *A*, Island of Hawaii. The asterisk indicates the instrumental epicenter. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

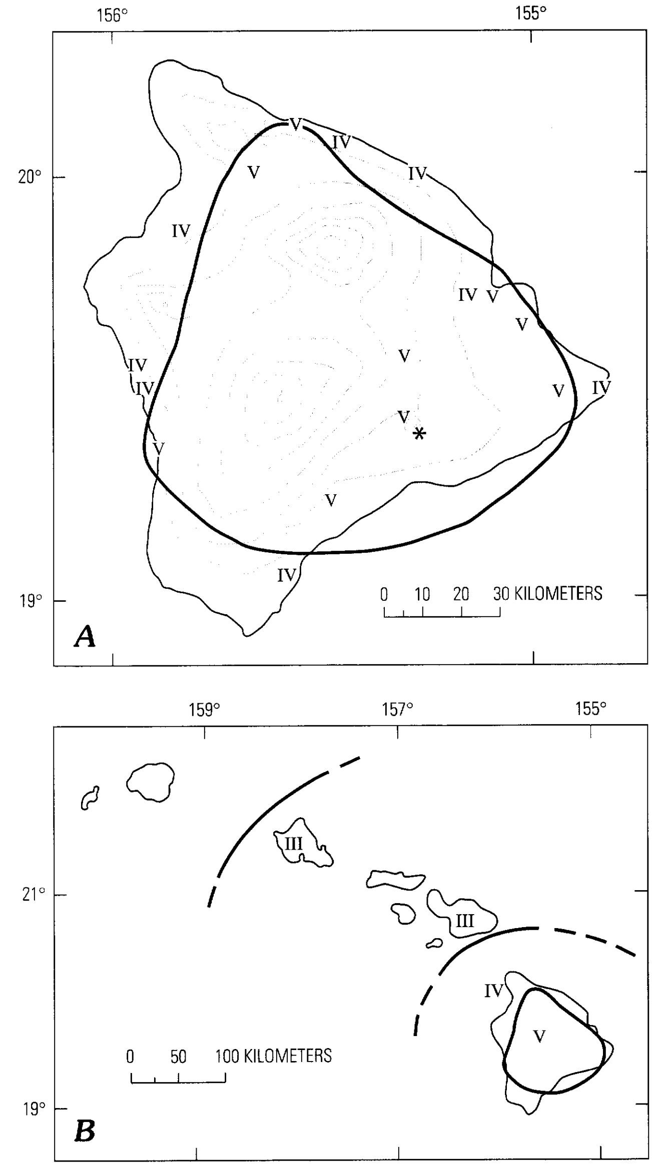


Figure 9. Isoseismal maps for the earthquake of January 8, 1963. The focal depth was 31 km. *A*, Island of Hawaii. The asterisk indicates the instrumental epicenter. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

1952 May 23 (1213, 19.48° N., 155.98° W., 10 km deep): Although this earthquake occurred 9 months after the large event of August 1951 (fig. 14), it could be considered an aftershock. P-arrivals (HVO) and isoseismals (fig. 13) indicate that the two events had almost the same epicenters.

1951 August 21 (0057, 19.50° N., 155.95° W., 10 km deep): This second largest earthquake of the calibration data set (M=6.9) was well reported (fig. 14) and helped establish that isoseismal gradients of earthquakes on western Hawaii are similar to those of central to southern Hawaii (fig. 48). Macroseismic data for this event and its aftershocks were discussed in detail in "The Volcano Letter" (Fiske and others, 1987). Fault-plane solutions and the orientation of the stress tensor in the epicentral area of this earthquake were studied by Gillard and others (1992), and the fault-plane solution of the main shock was derived from synthesis of teleseismic signals by Gillard and others (1992).

1951 April 22 (1452, 19.4° N., 155.25° W., 35 km deep): Isoseismal gradients of this event (figs. 15, 48*A*)

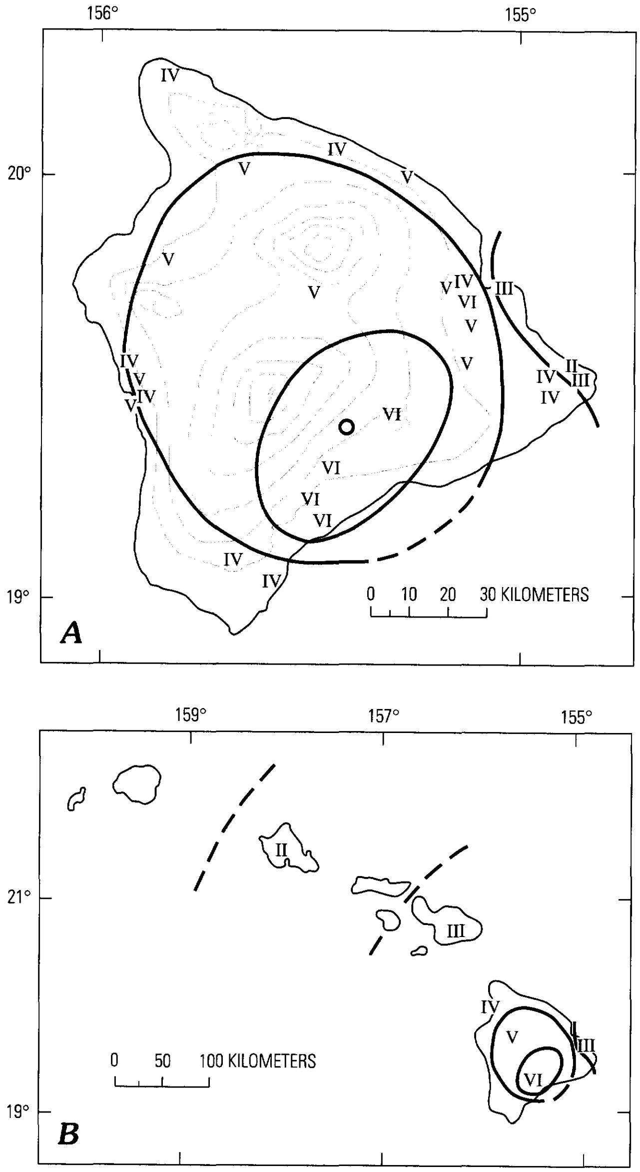


Figure 10. Isoseismal maps for the earthquake of June 27, 1962. *A*, Island of Hawaii. The open circle indicates the instrumental epicenter. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

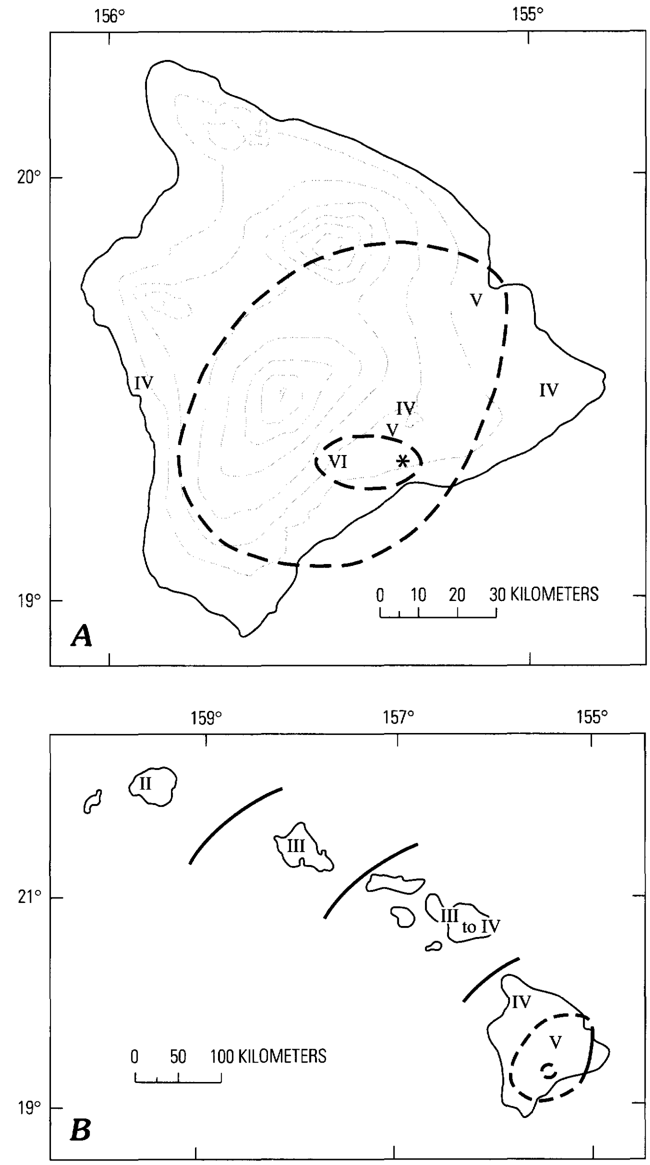


Figure 11. Isoseismal maps for the earthquake of August 14, 1955. Eaton (1962) determined a depth of 29 km for this shock. *A*, Island of Hawaii. The asterisk indicates the instrumental epicenter. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

agree with P-arrival time solution (HVO) and surface-wave excitation evidence (Eissler and Kanamori, 1986) that place the source at subcrustal depth.

1941 September 25 (0718, 19.35° N., 155.45° W., 11 km deep): Isoseismals of this earthquake (fig. 16) are similar to those of the June 1962 event (fig. 10) in location, areal extent, and gradient. This earthquake was attributed to the Kaoiki area (Endo, 1985). The isoseismal data support this interpretation and do not support the proposal of Eissler and Kanamori (1986) that the depth of the event was subcrustal.

1940 June 16 (2357, 21.0° N., 155.3° W., <15 km deep): This earthquake was given an instrumental magnitude of M=6.0 (Gutenberg and Richter, 1954), which is small relative to its large felt area (fig. 17). On the magnitude versus felt-area plot (fig. 19) the event plots near the curve for California events, as does the other event located offshore near Maui; the event might be interpreted as having

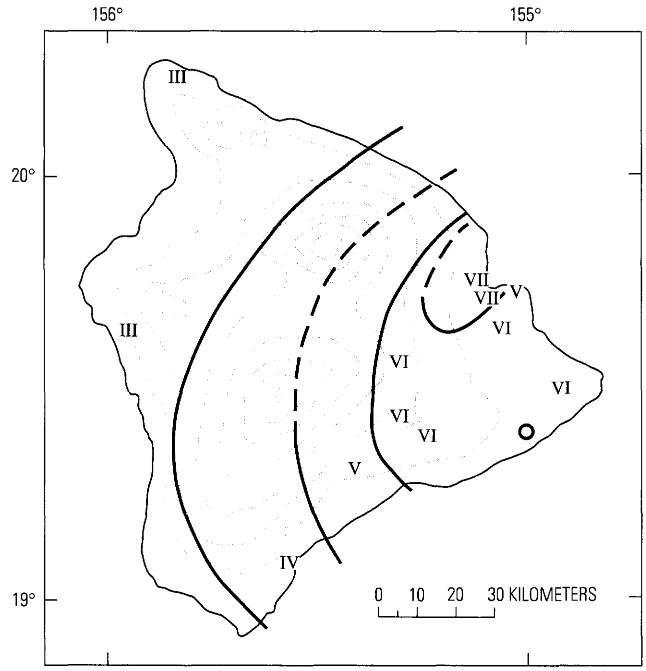


Figure 12. Isoseismal map for the earthquake of March 30, 1954, island of Hawaii. The instrumental epicenter (open circle) does not coincide with the area of strongest intensities. (For additional explanation see figure 2.)

subcrustal depth, or it may be that attenuation in this part of the island chain is similar to that in California. Effects on Oahu were summarized by Cox (1986a).

MAGNITUDE SCALES IN HAWAII

For moderate earthquakes after 1962, surface-wave magnitudes $\mathbf{M}_S$, body-wave magnitudes $\mathbf{m}_b$, and local magnitudes $\mathbf{M}_L$ are generally available; however, for large events $\mathbf{M}_L$ cannot be measured because recordings are clipped and $\mathbf{m}_b$ may be saturated. For some events where amplitudes from local seismograms are clipped, magnitude was extrapolated from the signal durations. For some of the smaller moderate earthquakes $\mathbf{M}_S$ may not be available or it may be unreliable. For moderate earthquakes before 1962 only $\mathbf{M}_S$ is available. For a limited number of earthquakes the seismic moment has been measured in addition to magnitude (Zuñiga and others, 1988).

In order to assess the differences between these scales we plotted the different magnitudes (fig. 18) against each other for events that were assigned more than one magnitude (table 5). The bulk of the information available is for the relationship of $\mathbf{M}_L$ versus $\mathbf{m}_b$, and for **M**<5.5 (fig. 18); however, we are mostly interested in historical and calibration events for which **M**>5.5.

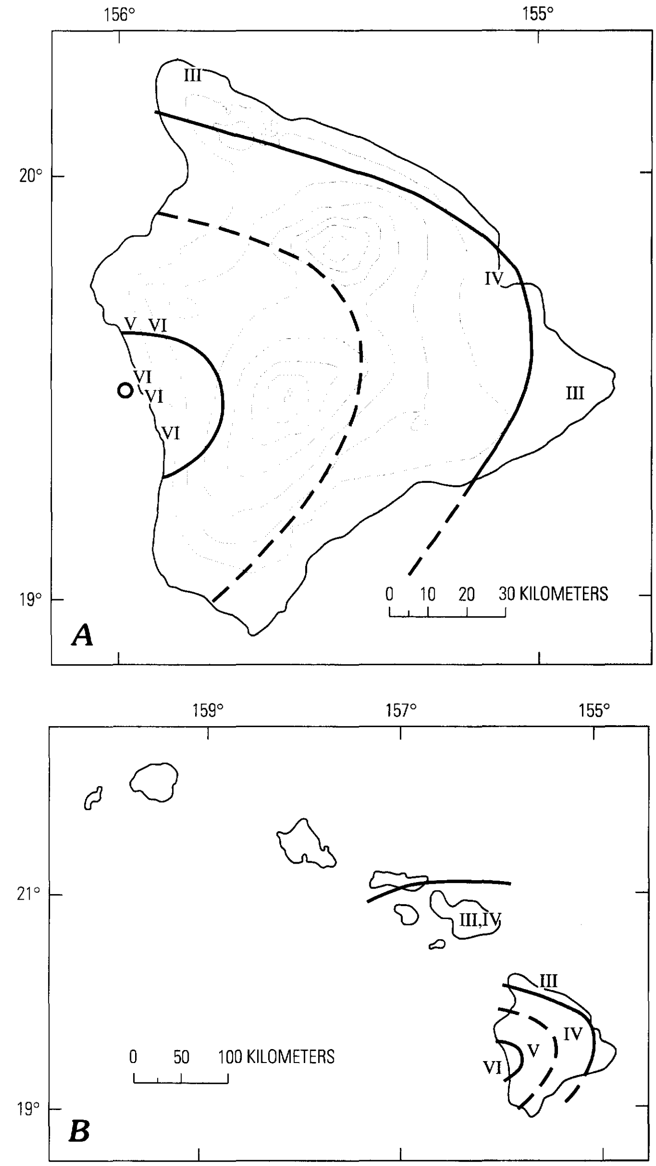


Figure 13. Isoseismal maps for the earthquake of May 23, 1952. *A*, Island of Hawaii. The open circle indicates the instrumental epicenter. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

For establishing a relationship between two magnitude scales, the simplest approach is to fit a linear least-squares line through the data, as was done in figure 18. The underlying assumption that the same linear relationship should hold for the entire magnitude range may not be correct, however, and a break of relationships may exist in the range of 5<**M**<6 (Wyss and Brune, 1968). For this reason and because there

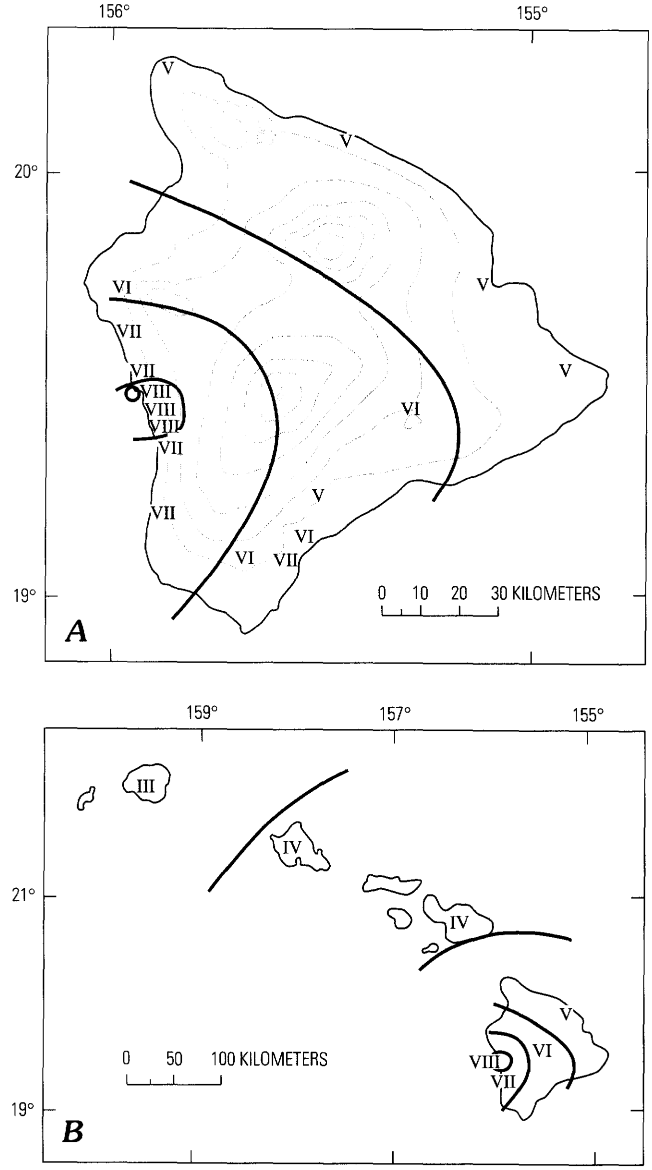


Figure 14. Isoseismal maps for the earthquake of August 21, 1951. *A*, Island of Hawaii. The open circle indicates the instrumental epicenter. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

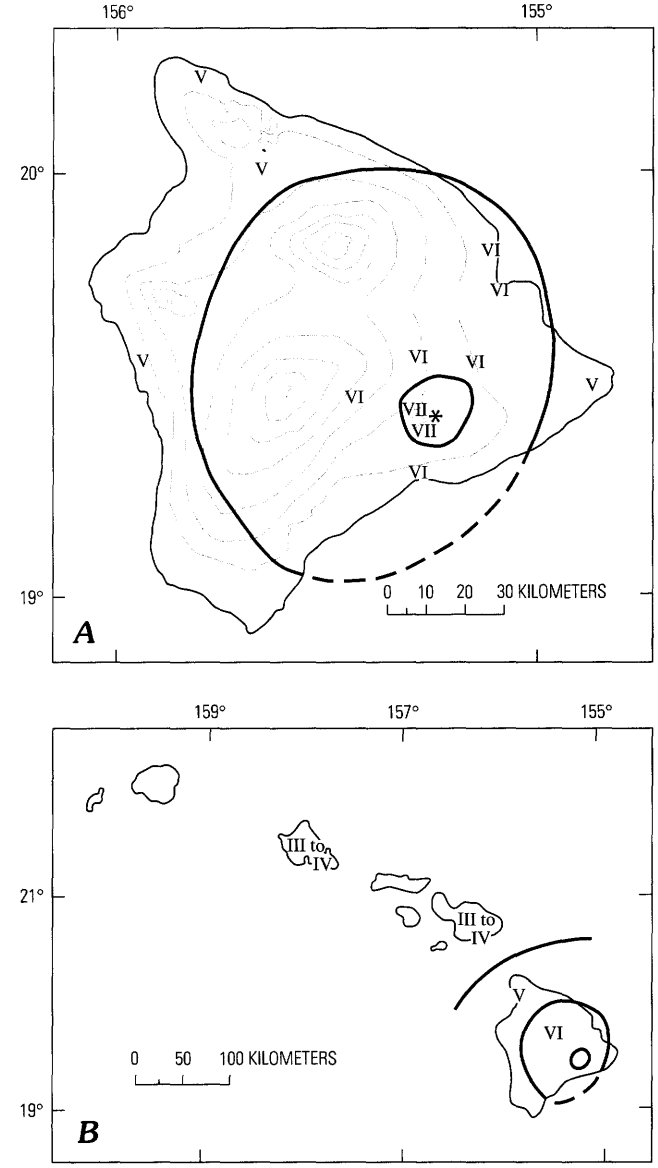


Figure 15. Isoseismal maps for the earthquake of April 22, 1951. *A*, Island of Hawaii. The asterisk designates the instrumental epicenter of the subcrustal focus. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

are only 15 data points for $\mathbf{M}_S$, we believe that the relationship between $\mathbf{M}_S$ and the other magnitudes is not well established. The least-square fits shown in figures 18*B* and *C* were obtained by minimizing the error in the ordinate and assuming $\mathbf{M}_S$ as error free,

$$\mathbf{M}_L = 0.58\mathbf{M}_S + 2.51 \text{ and} \tag{1}$$

$$\mathbf{m}_b = 0.48\mathbf{M}_S + 2.96. \tag{2}$$

Although these linear fits are reasonable and could be valid for the entire magnitude range for which we have data, one could also argue that the magnitudes are approximately equivalent for M>5, whereas $\mathbf{M}_S$ is definitely smaller than either of the other magnitudes for M≤5. We will accept this latter interpretation because of the current paucity of data and the likely existence of a break in the linear relationship as mentioned above.

The data for $\mathbf{M}_L$ versus $\mathbf{m}_b$ (fig. 18*A*) scatter around the dashed line for which the magnitudes are equivalent. The

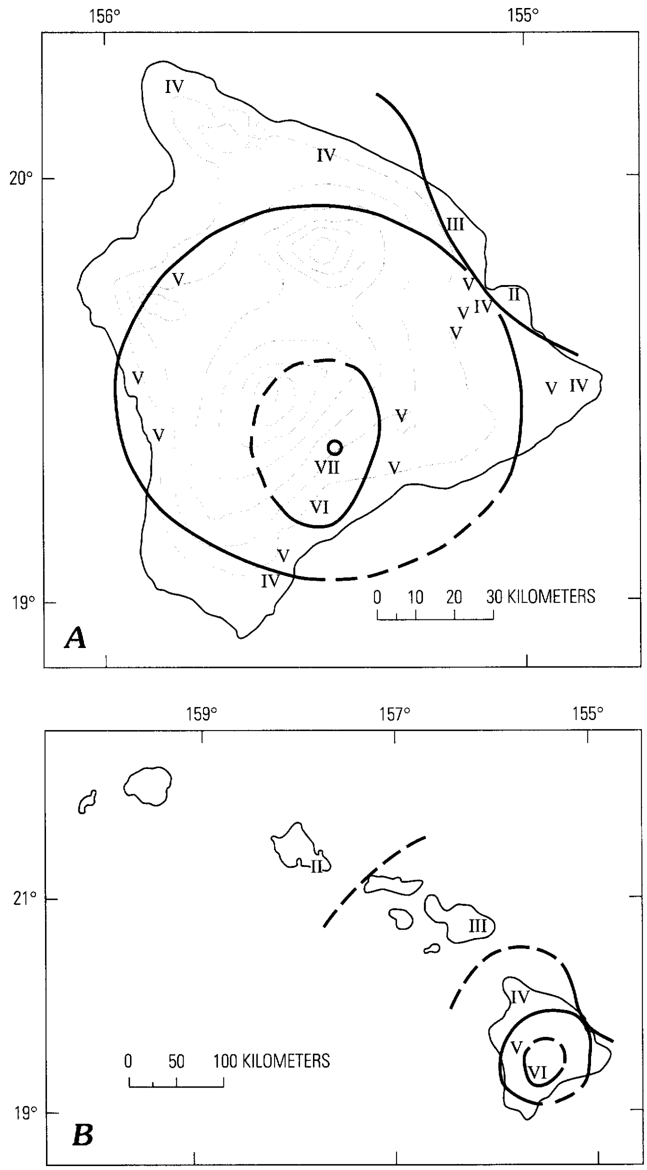


Figure 16. Isoseismal maps for the earthquake of September 25, 1941. *A*, Island of Hawaii. The open circle indicates the instrumental epicenter estimated by Endo (1985). *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

least-square fits minimizing the values of the ordinate and abscissa, respectively, are symmetrical with respect to the line of equivalence. Hence it is best to assume that

$$\mathbf{M}_L=\mathbf{m}_b. \qquad (3)$$

Thus we conclude that there is no compelling evidence indicating that the three magnitude scales are not equivalent for M>5. We will use $\mathbf{M}_L$ when it is available because this magnitude is tabulated for most earthquakes; if $\mathbf{M}_L$ is not available, we will substitute without change $\mathbf{m}_b$ first and $\mathbf{M}_S$ second.

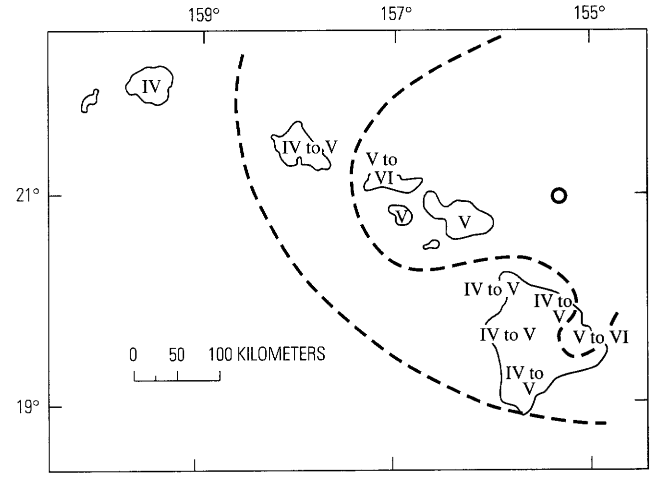


Figure 17. Isoseismal map for the earthquake of June 16, 1940, Hawaiian Islands. The open circle indicates the instrumental epicenter. (For additional explanation see figure 2.)

MAGNITUDE AS A FUNCTION OF THE FELT AREA

Many authors have proposed relationships between magnitude and areas of a given range of intensities in order to estimate magnitudes of early historical earthquakes (for example, Toppozada, 1975; Cox, 1985a). The difference between isoseismal gradients for relatively inactive tectonic areas as the Eastern United States and active areas as the Western United States is attributed to stronger attenuation in the Western United States (Howell and Schultz, 1975; Nuttli and others, 1979). The limited data available on seismic attenuation in the Hawaiian crust suggest that attenuation is relatively large; **Q** values of 100–200 have been reported (Chouet, 1976; Huang and Wyss, 1988; Scherbaum and Wyss, 1990). Because attenuation is stronger in Hawaii than in the Eastern United States or California, an independent magnitude versus felt-area relationship must be established for Hawaii.

In the Hawaiian archipelago the areal extent of a given intensity cannot be uniformly established as it can in continental regions because the linear island chain offers the only areas of observation. For most earthquakes that originate on the island of Hawaii, at the southeastern end of the archipelago, the information along the island chain furnishes only the radii of the isoseismals in one direction. For this reason the basic observation in most of our cases is the distance to the lower intensity threshold along one azimuth only. This measure was used to define radius in table 3. For smaller earthquakes, for which some of the intensity areas could be defined on the island of Hawaii, we tabulated the average radii for consistency with the data defined by the intensities along the archipelago.

For the purpose of estimating the magnitudes of the earlier events we converted the radii from table 3 into area (table 6) assuming circular areas ($A=\pi r^2$). In this way the Hawaii results can be compared with those obtained for other regions. The relationship between the logarithm of the felt area and magnitude is shown in figure 19 for events having known instrumental magnitudes. Earthquakes having subcrustal hypocenters and epicenters northeast of Maui are marked by open circles and crosses, respectively, in figure 19 because they form a separate group from the rest of the Hawaiian earthquakes.

The least-squares fit, minimizing the error in magnitude and assuming the area estimate to be error free, gives the following average relationships for crustal earthquakes located on or near the island of Hawaii,

$$M=1.0 \log(A(\mathrm{VI}))+2.9 \text{ and} \quad (4)$$

$$M=1.1 \log(A(\mathrm{V}))+1.6, \quad (5)$$

where M is the local or surface-wave magnitude and $A(\mathrm{I})$ in km^2 is the area corresponding to intensity ≥I. The solid lines for the relationships (4) and (5) in figure 19 are on the average about 0.7 magnitude units above the corresponding relationships that apply to California (dashed lines in fig. 19) (Toppozada, 1975). The earthquakes located off Maui and those having subcrustal depths agree better with the relationship for California than with that for Hawaii, suggesting that attenuation along the archipelago is similar to that in California, whereas attenuation below the island of Hawaii is stronger.

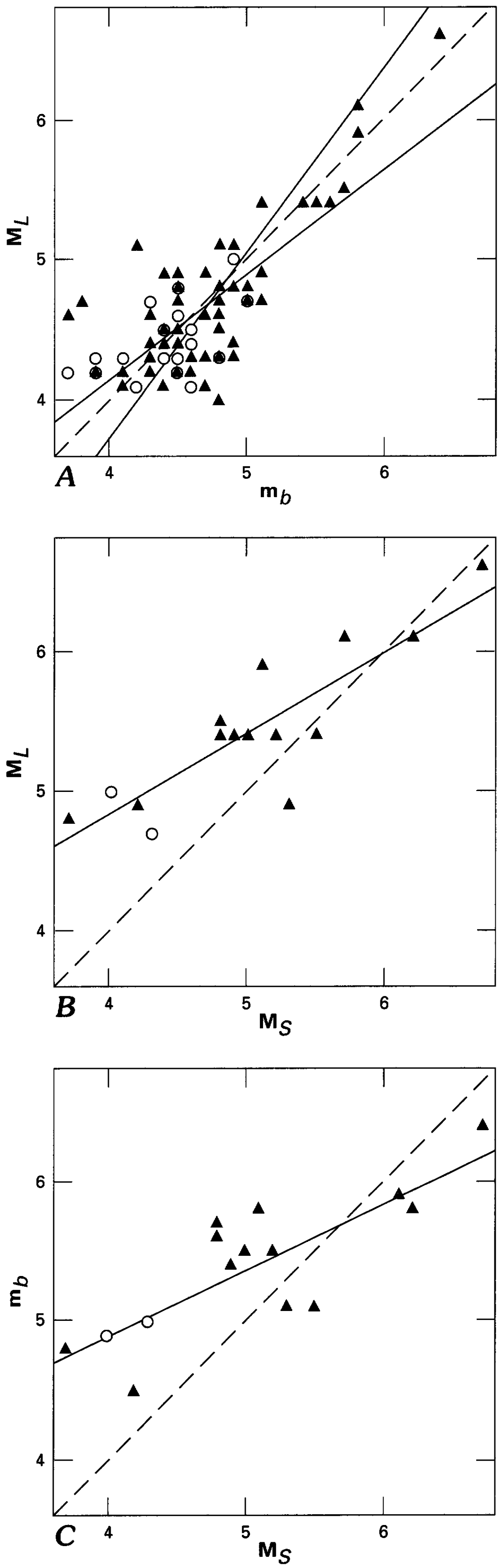


Figure 18 (facing column). Comparison of magnitude scales for Hawaiian earthquakes. Triangles and circles mark earthquakes having crustal and subcrustal hypocenters, respectively. The dashed line shows the relationship between the magnitudes assuming they are equivalent, the solid lines are the linear regressions through the data. *A*, Local magnitude (M_L) derived from Wood-Anderson records versus teleseismic m_b as listed in the "Preliminary Determination of Epicenters, Monthly Listing (PDE)," published by the U.S. Geological Survey. *B*, M_L versus surface-wave magnitude M_S. *C*, m_b versus M_S.

Table 5. Comparison of magnitude scales for Hawaiian earthquakes

[Date in year, month, and day. M_L, local magnitude (recalculated hypoinverse); m_b, body-wave magnitude; M_S, surface-wave magnitude. Depth: C, crustal (≤15 km); S, subcrustal (>15 km)]

Date	M_L	m_b	M_S	Depth	Date	M_L	m_b	M_S	Depth
1962 06 27	6.1		5.7	C	1975 11 29	4.8	4.9		C
1968 09 23	4.2	3.7		S	1976 01 01	4.2	4.5		S
1969 02 09	4.2	4.5		C	1976 01 15	4.5	4.8		S
1969 02 22	4.2	3.9		C	1976 01 29	4.7	4.5		C
1969 09 03	4.4	4.6		S	1976 02 20	5.0	4.9	4.0	S
1969 11 09	4.6	3.7		C	1976 04 02	4.5	4.5		C
1969 11 24	4.7	3.8		C	1976 12 18	4.8	5.0		C
1970 11 25	4.8	4.5		C	1977 01 22	5.1	4.2		C
1971 08 01	4.6	4.8		C	1977 01 23	4.0	4.8		C
1972 09 05	4.5	4.4		C	1977 02 03	4.5	4.5		C
1972 12 23	5.1	4.9		C	1977 06 05	5.1	4.8		C
1973 04 26	6.2	5.9	6.1	C	1978 06 23	4.4	4.9		C
1973 10 09	4.6	4.8		S	1978 08 31	4.3	4.5		S
1973 10 09	4.3	4.8		S	1978 12 27	4.3	4.6		C
1973 10 13	4.3	4.3		C	1979 03 06	4.7	5.0	4.3	S
1974 01 12	4.7	4.8		C	1979 03 10	4.5	4.8		C
1974 02 04	4.1	4.1		C	1979 03 21	4.5	4.6		S
1974 05 05	4.3	4.4		S	1979 03 27	4.9	4.4		C
1974 06 19	4.7	5.1		C	1979 09 21	5.5	5.7	4.8	C
1974 06 20	4.2	4.3		C	1979 09 21	4.3	4.8		C
1974 08 08	4.1	4.2		S	1979 09 27	4.3	4.7		C
1974 08 27	4.5	4.8		C	1979 10 30	4.2	4.1		C
1974 11 21	4.3	3.9		S	1981 01 12	4.5	4.4		S
1974 11 30	5.4	5.1	5.5	C	1981 01 12	4.3	4.1		S
1974 12 15	4.6	4.3		C	1981 01 13	4.3	4.5		S
1974 12 15	4.7	5.0		C	1981 08 22	4.4	4.3		C
1974 12 25	4.6	4.5		S	1982 01 21	5.4	5.4	4.9	C
1974 12 31	5.4	5.5	5.2	C	1982 01 21	5.4	5.6	4.8	C
1975 01 01	4.1	4.7		C	1982 04 11	4.2	4.6		C
1975 01 01	4.6	4.7		C	1982 05 14	4.8	4.5		S
1975 01 01	4.3	4.9		C	1982 05 18	4.8	4.8	3.7	C
1975 01 01	4.4	4.5		C	1982 11 12	4.1	4.4		C
1975 01 01	4.1	4.7		C	1983 02 07	4.1	4.6		S
1975 01 02	4.9	4.5	4.2	C	1983 03 20	4.8	4.9		C
1975 01 03	4.9	4.7		C	1983 09 09	5.4	5.5	5.0	C
1975 01 03	4.4	4.3		C	1983 11 16	6.6	6.4	6.7	C
1975 01 04	4.9	5.1	5.3	C	1985 02 21	4.8	5.0		C
1975 01 06	4.4	4.4		C	1985 06 30	4.2	3.9		S
1975 05 28	4.1	4.6		S	1985 12 12	4.7	4.3		S
1975 11 06	4.5	4.4		S	1989 06 25	6.1	5.8	6.2	C
1975 11 29	5.9	5.8	5.1	C					

MAXIMUM INTENSITY VERSUS MAGNITUDE

Magnitude is plotted as a function of maximum intensity in figure 20. Earthquakes located offshore were not included in this plot. The least-squares regression line through the data for crustal sources yields the relation

$$M=3.7+0.4(I_{max}). \quad (6)$$

Comparing this relationship with that for California (Toppozada, 1975), we find that Hawaiian earthquakes have to register at least a unit in magnitude greater than those in California to produce the same maximum intensity. Or, alternatively, for a given magnitude, the maximum intensity in Hawaii is, on average, two units smaller than in California.

It is possible that for some Hawaiian earthquakes the maximum intensity in the epicentral area was underrated because of the low population density, however, this does not apply to all Hawaiian earthquakes, and even if we added

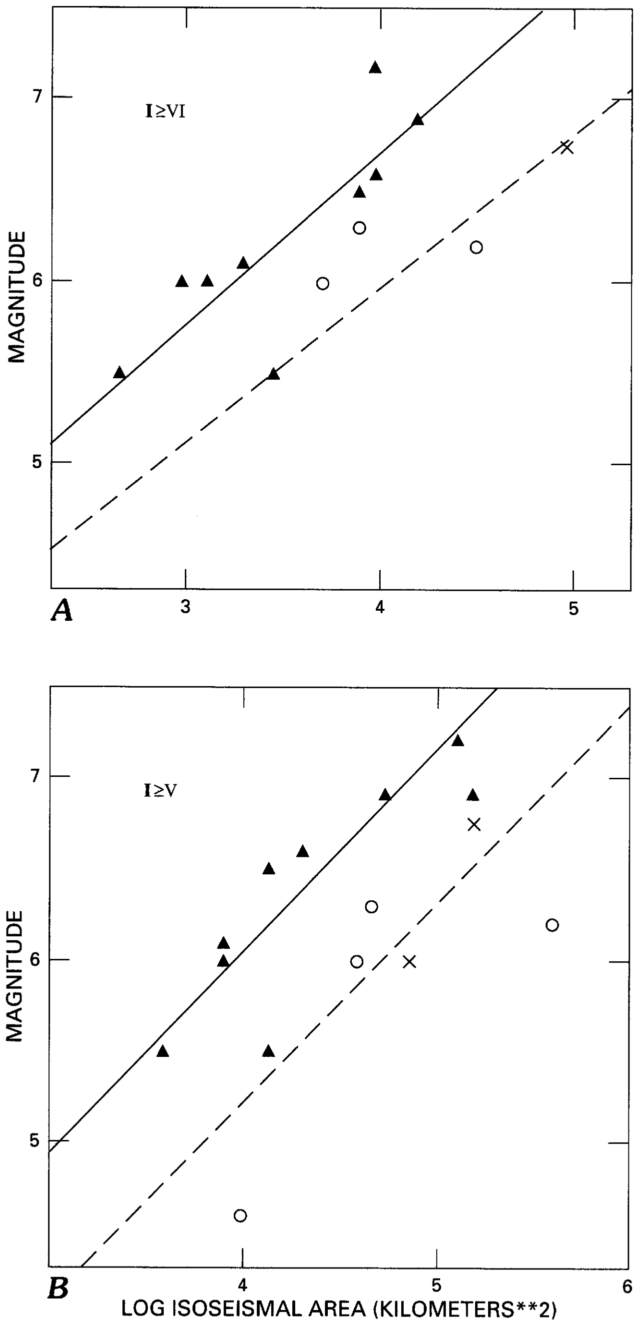


Figure 19. Instrumentally determined magnitude as a function of felt area for Hawaiian earthquakes for intensities (*A*) I≥VI and (*B*) I≥V. Crosses, circles, and triangles mark earthquakes located near Maui, at subcrustal depths, and at shallow depths on the island of Hawaii, respectively. The solid lines are least-squares fits for the crustal Hawaiian earthquake data that minimize magnitude variations assuming the area estimate to be error free. The dashed lines are the corresponding relationships for California earthquakes (Toppozada, 1975).

Table 6. Areas within intensity V and VI isoseismals of Hawaiian earthquakes for which there are instrumentally determined magnitudes

[Date in year, month, and day. M_S, surface-wave magnitude; M_L, local magnitude]

Date	M_S	M_L	Logarithm of area (km^2) V	VI
1929 10 05	6.5		5.18	4.41
1938 01 22	6.75		5.18	4.96
1940 06 16	6.0		4.85	
1941 09 25	6.0		3.89	3.11
1951 04 22	6.25		4.66	3.90
1951 08 21	6.9		4.73	4.19
1952 05 23	6.0			2.98
1954 03 30	6.5		4.12	3.90
1955 08 14	6.0 (?)		4.58	3.70
1962 06 27	5.7	6.1	3.90	3.29
1963 01 08		4.6	3.98	
1973 04 26	6.1		5.59	4.50
1974 11 30	5.5	5.4		
1975 11 29	7.2		5.10	3.98
1979 09 21	4.8	5.5	3.59	2.66
1982 01 21	4.9	5.4	4.12	3.45
1983 11 16	6.7	6.6	4.30	3.98
1989 06 25	6.2	6.1	4.19	3.10

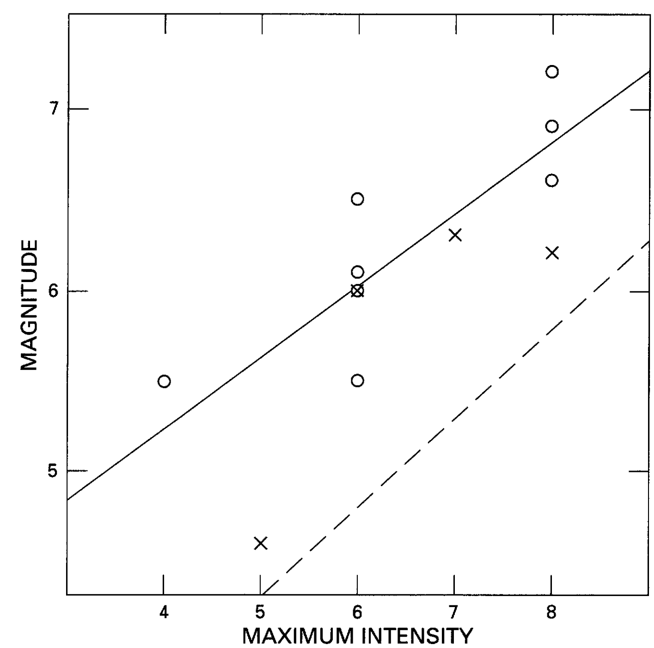


Figure 20. Instrumentally determined magnitude as a function of maximum intensity for Hawaiian earthquakes. Circles mark crustal earthquakes and crosses mark subcrustal earthquakes. The solid line is a least-squares fit that minimizes **M**, assuming $\mathbf{I}_{max}$ as error free and using earthquakes beneath the island of Hawaii having crustal depths only. The dashed line is the average relationship for California earthquakes (Toppozada, 1975). Earthquakes having epicenters offshore are not included.

one unit to all I_{max} values the curves for Hawaii and California in figure 20 would still be separated by more than a unit of intensity. Therefore we conclude that in the Hawaiian crust attenuation for seismic waves in the frequency band that causes damage is much larger than in California or elsewhere in the United States.

HISTORIC EARTHQUAKES WITH REPORTS OF STRONG SHAKING

We next discuss the macroseismic data of historical Hawaiian earthquakes. The reports of damage and sensations that form the basis for the isoseismal maps are given in appendix 3. For earthquakes without epicenter estimates from instrumental records, the epicenters were estimated (table 2) by assuming that they coincided with the centers of the strong shaking, as defined by the isoseismal maps. The magnitudes (table 3) were estimated as the average of those derived from equations (4) and (5). The events are discussed in reverse chronological order.

1950 May 29: Felt reports for this earthquake are few relative to the fairly high intensities reported (fig. 21), and it is likely that interest in earthquake reporting in Hawaii was low at this time. M_L was not computed. The depth cannot be defined using the sparse intensity data. We assume a crustal depth because of the relatively high number of instrumentally determined crustal earthquakes in the meizoseismal area of central Kona and estimate the magnitude as 6.4. Finch (Fiske and others, 1987, p. 508–12) believed that the earthquake was centered at Mauna Loa's upper southwest rift, where many microearthquakes had been occurring and where a major eruption followed in June. However, the macroseismic data are very similar in distribution to those of the 1951 and 1952 central Kona earthquakes (figs. 14 and 13, respectively), suggesting that this event might have been located in central Kona.

1948 June 28: This earthquake was located near the south coast of Oahu. Its effects were described in detail by Cox (1986b), who also plotted an isoseismal map (his fig. 3) from which the epicenter given in table 2 was estimated. The maximum intensity was VI and the earthquake was felt at Hilo.

1939 July 14: This is one of the smaller events estimated at M=5.5 (table 3), and it has fairly well defined isoseismals, except in the sparsely populated epicentral area (fig. 22).

1939 May 23: For this event the intensity IV isoseismal is small and the intensity V isoseismal is not defined (fig. 23); thus the magnitude estimate is less reliable than for other cases. The isoseismal gradient for this event is somewhat less than the average (fig. 23*A*), and the event was felt as far away as Honolulu (fig. 23*B*). The similarity between this intensity gradient and those of subcrustal earthquakes suggests that the hypocenter may have been subcrustal.

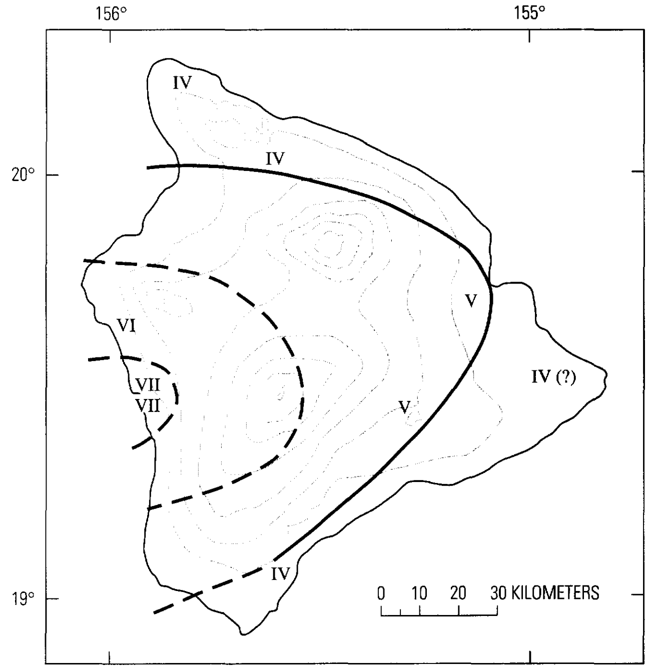


Figure 21. Isoseismal map for the earthquake of May 29, 1950, island of Hawaii. (For additional explanation see figure 2.)

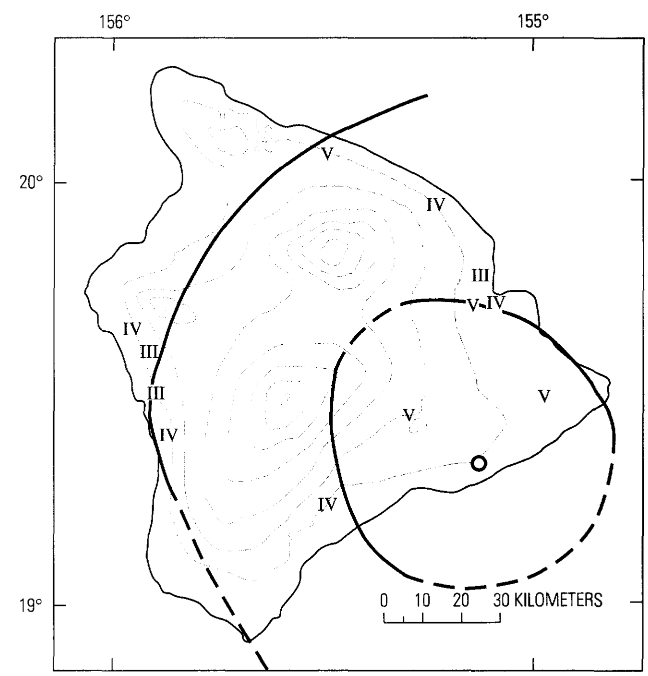


Figure 22. Isoseismal map for the earthquake of July 14, 1939, island of Hawaii. The open circle indicates the instrumental epicenter. (For additional explanation see figure 2.)

Assuming a slightly subcrustal depth for this event we estimate a magnitude of 4.8. Although the isoseismal pattern of this earthquake is similar to that of May 25, 1930, the event

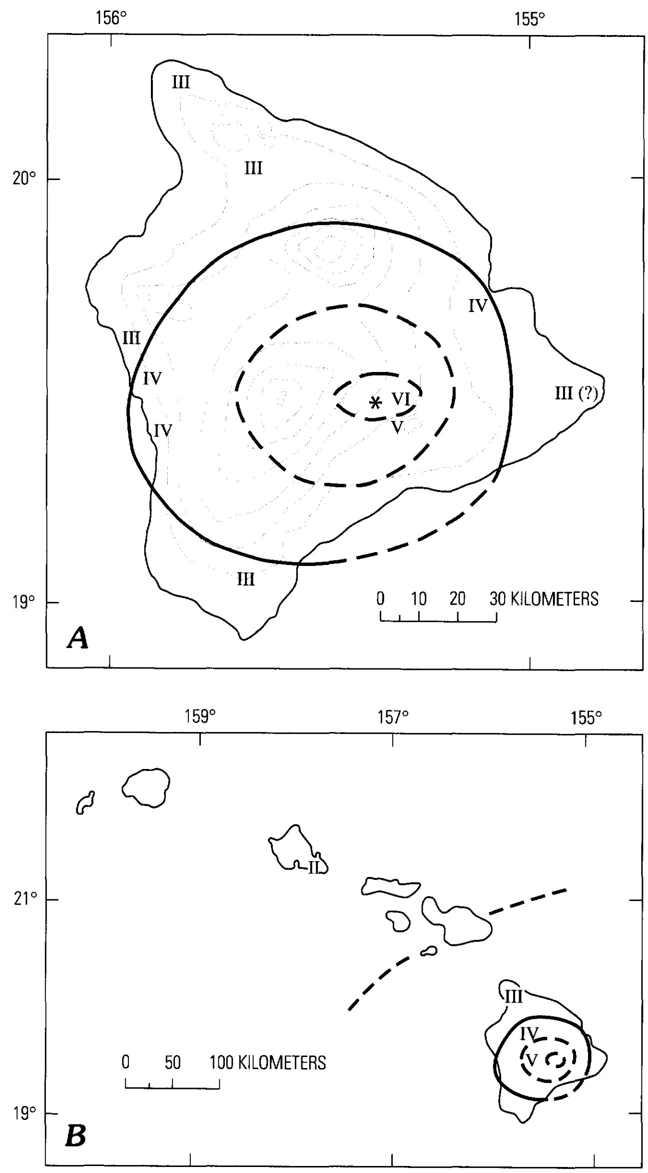


Figure 23. Isoseismal maps for the earthquake of May 23, 1939. *A*, Island of Hawaii. The asterisk marks the instrumental epicenter. The macroseismic data suggest a subcrustal focus. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

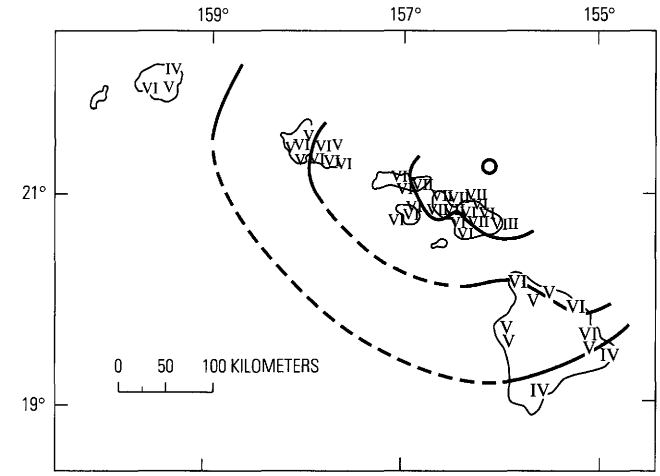


Figure 24. Isoseismal map for the earthquake of January 22, 1938, Hawaiian Islands. The open circle indicates the instrumental epicenter. (For additional explanation see figure 2.)

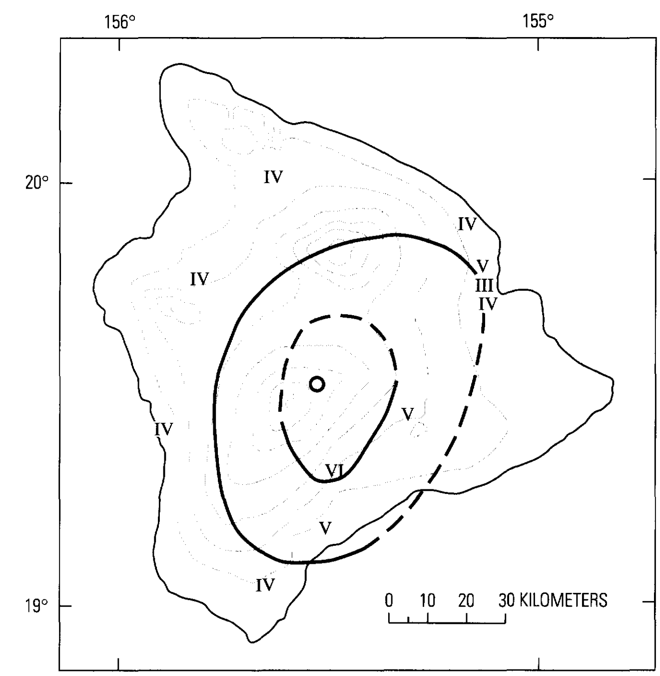


Figure 25. Isoseismal map for the earthquake of November 21, 1935, island of Hawaii. The open circle indicates the instrumental epicenter. (For additional explanation see figure

was not located in the Kaoiki area according to the instrumental epicenter. The highest intensity was reported north of Kilauea.

1938 January 22: This earthquake was assigned an instrumental magnitude of 6 by Gutenberg and Richter (1954) and its intensities were compiled by Cox (1986a). It was located offshore north of the island of Maui (Holman, 1982). Its well-defined isoseismals (fig. 24) show fairly high intensities throughout the Hawaiian Islands. Although the isoseismal gradient fits the pattern for earthquakes of crustal depth (fig. 48*D*), the felt area is large compared to that for earthquakes of similar magnitude located on the island of Hawaii. The relations of felt area versus magnitude and normalized intensity versus radius are similar to those for California events rather than to those for events from the island of Hawaii (figs. 19 and 48, respectively). Data from this earthquake were not used to define the felt-area magnitude relation for Hawaii because the felt areas of earthquakes near Maui seem to be appreciably larger than those of earthquakes located on the island of Hawaii.

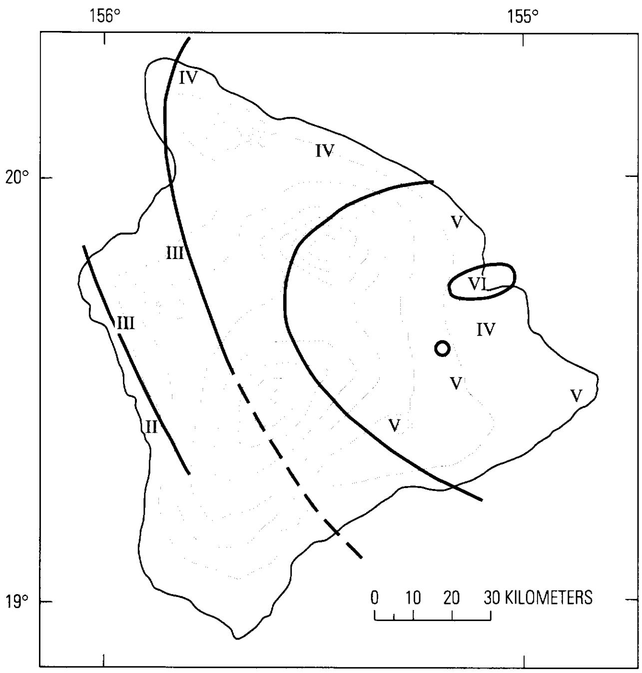


Figure 26. Isoseismal map for the earthquake of June 28, 1935, island of Hawaii. The open circle indicates the instrumental epicenter. (For additional explanation see figure 2.)

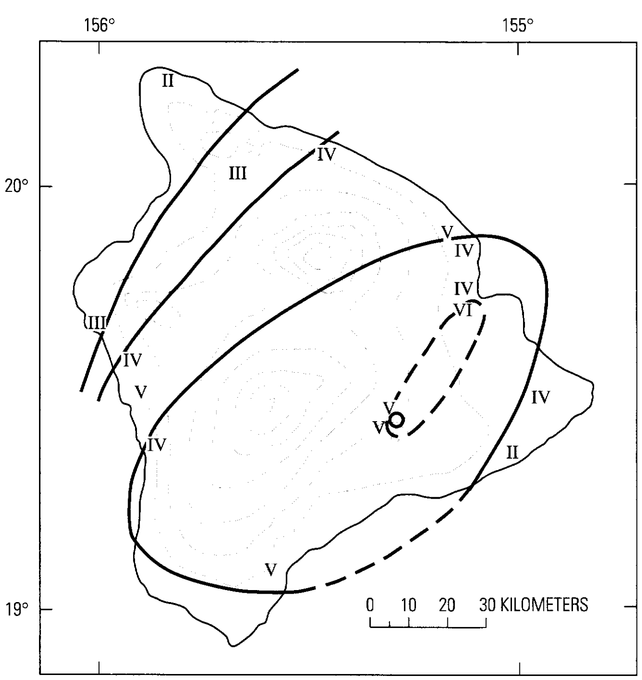


Figure 27. Isoseismal map for the earthquake of January 2, 1935, island of Hawaii. The open circle indicates the instrumental epicenter. (For additional explanation see figure 2.)

1935 November 21: This earthquake was located beneath Mauna Loa's northeast rift zone (fig. 25), and the magnitude estimate is 5.6.

1935 June 28: The epicenter of this earthquake was located midway between Hilo and Kilauea, but the

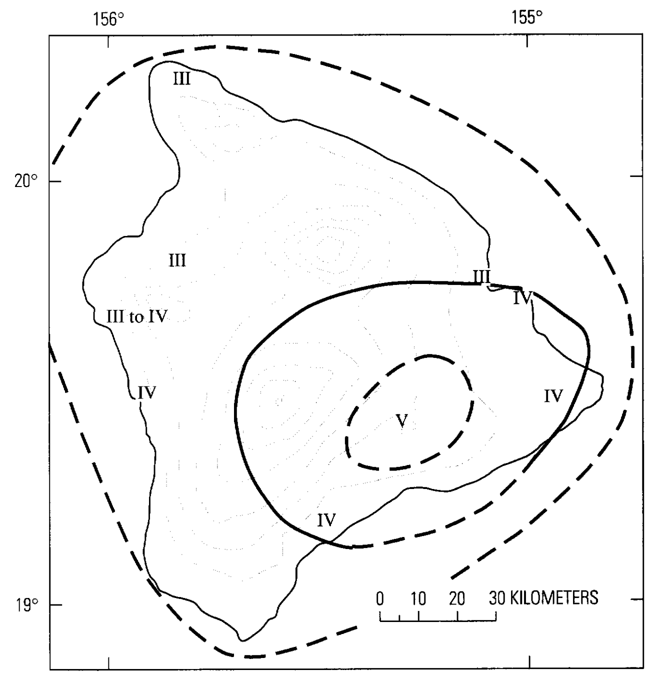


Figure 28. Isoseismal map for the earthquake of May 25, 1930, island of Hawaii. (For additional explanation see figure 2.)

maximum intensity was reported in Hilo (fig. 26). Lower isoseismal curves were approximately concentric around the epicenter. This and the next example show that accurate determination of epicenters based on isoseismals is often not possible for earthquakes in Hawaii if M<6. The data indicate crustal depth and a magnitude of 5.7.

1935 January 2: The fairly large intensity V area of this event (fig. 27) might suggest a subcrustal origin; however, the earthquake was not felt on the other islands. If the intensity II reports from the northeastern part of Hawaii are included, the intensity gradient is almost normal (fig. 48*B*). The area of maximum intensity is uncertain because reports from some parts of Hilo are higher than average for many earthquakes. The estimated magnitude is 5.9. The epicenter location shown on figure 27 would have been difficult to estimate reliably without instrumental data because the high intensity in Hilo would have biased the estimate.

1930 May 25: Data for this event are marginal (fig. 28), but they were included in the data set because the event was described as "deep movement somewhere under Kilauea and Mauna Loa" (Fiske and others, 1987, p. 282–4) by Jagger, placing it into the highly seismic Kaoiki region. This region is of special interest because of its regularity of mainshocks (Wyss, 1986a). Although the intensity pattern of this event and that of the subcrustal earthquake of April 1951 are somewhat similar, the gradient of this event is similar to those of shallow earthquakes (fig. 48*B*), and thus we interpret it as a crustal Kaoiki earthquake.

1929 October 5: This earthquake originated approximately from the same location as that of September 25, 1929,

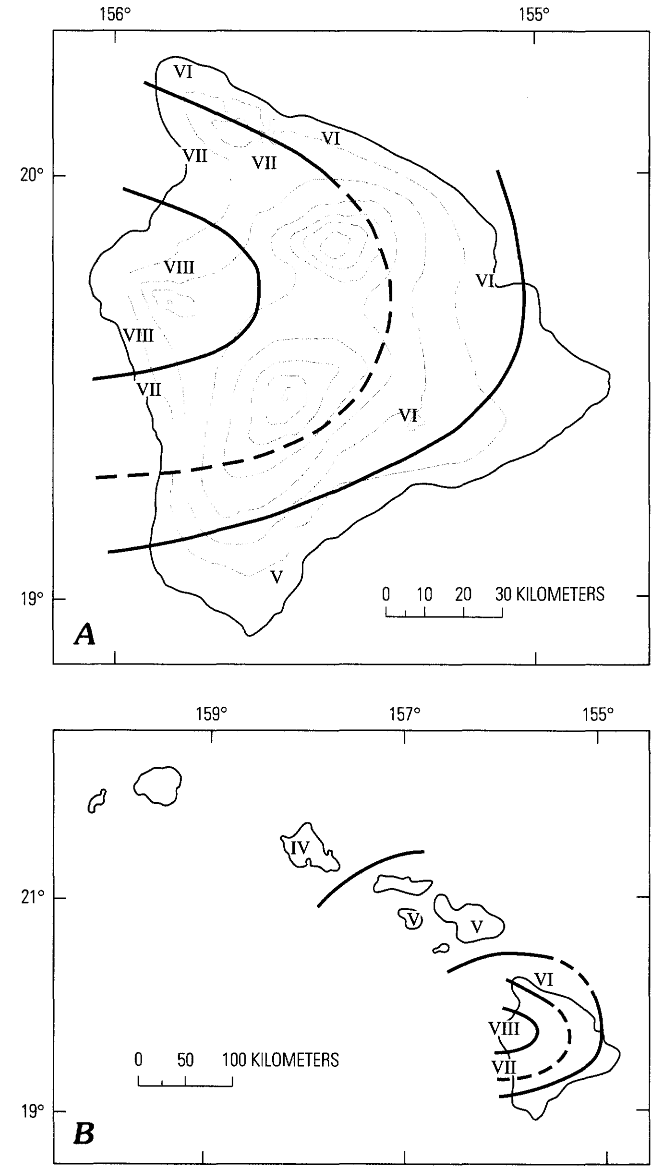


Figure 29. Isoseismal maps for the earthquake of October 5, 1929. *A*, Island of Hawaii. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

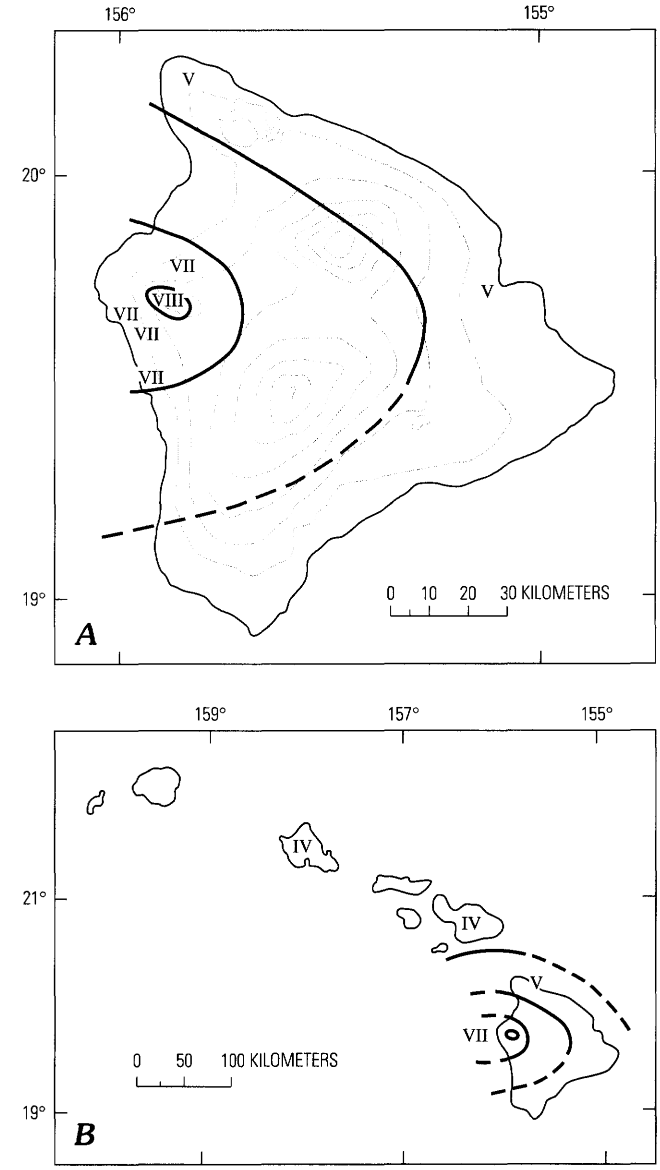


Figure 30. Isoseismal maps for the earthquake of September 25, 1929. *A*, Island of Hawaii. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

but its maximum-intensity area was larger (fig. 29). The isoseismal gradient conforms to those of the other shallow earthquakes located in Kona (figs. 48*C*). This event was assigned an instrumental magnitude of 6.5 (Gutenberg and Richter, 1954), but the extent of the felt area suggests a greater magnitude. For a subcrustal depth origin, the magnitude estimate based on isoseismal data would be reduced by about 0.5. The uncertainties in magnitude estimate based on early seismograms may be substantial. Because this instrumental magnitude predates all others by about one decade, we did not include it in the calibration data for the magnitude-intensity relationship.

1929 September 25: This shock was fairly well reported (fig. 30), but it was uncertain whether an intensity VIII should be assigned to the epicentral area. If the intensity gradient as a function of distance is compared to those of earthquakes in southern Hawaii, one might argue that the gradient of this event was shallower than average. Because all Kona earthquakes have lower gradients (fig. 48), we will assume a crustal depth, and using this assumption the magnitude would be estimated as 6.7. Yet the intensities for this event were clearly less than those for the event of October 5, 1929, for which Gutenberg and Richter (1954) gave **M**=6.5; however, Gutenberg and Richter assigned magnitudes at inter-

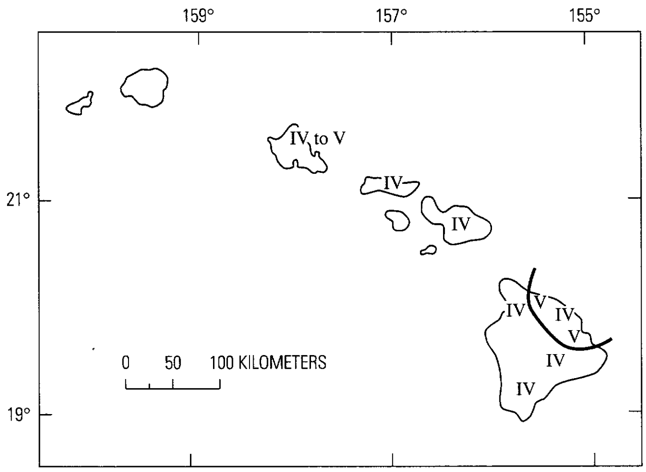


Figure 31. Isoseismal map for the earthquake of March 20, 1927, Hawaiian Islands. (For additional explanation see figure 2.)

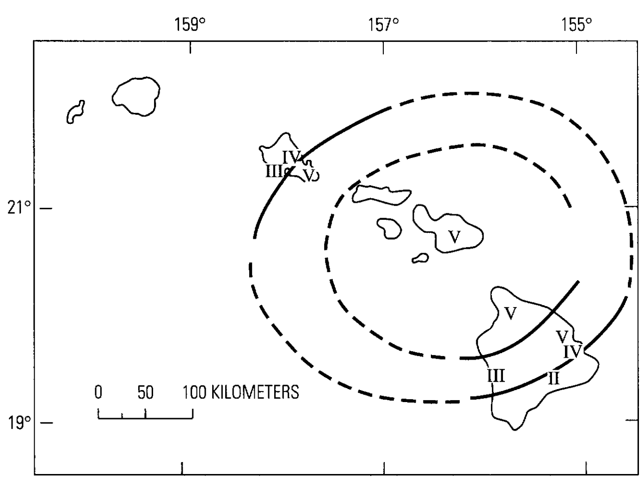


Figure 32. Isoseismal map for the earthquake of March 19, 1926, Hawaiian Islands. (For additional explanation see figure 2.)

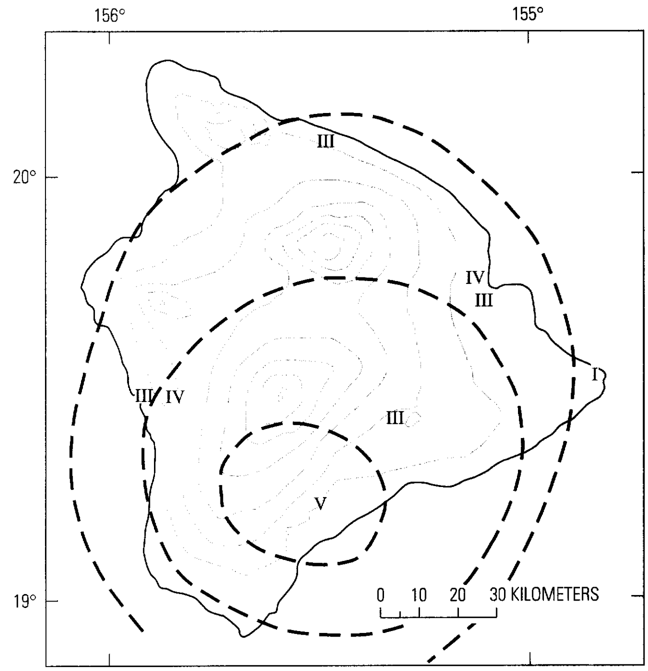


Figure 33. Isoseismal map for the earthquake of August 20, 1924, island of Hawaii. (For additional explanation see figure 2.)

vals of 0.5 only. Our magnitude estimate is also approximate, and the felt-area versus magnitude relationship for the Kona earthquakes is different from our average equations (1) and (2) because their gradients are lower (fig. 48). To be consistent with the instrumentally assigned magnitude for the earlier October 5 event, we assign this event a provisional magnitude of M=6.4. The isoseismal maps show that this earthquake was located in north Kona beneath Hualalai Volcano.

1927 March 20: This is an offshore event of uncertain location and magnitude (fig. 31). Although the data for this and the earthquake of March 19, 1926, are poor, the events were included because of their relatively significant size. Smaller events for which data are similarly sparse were excluded from this report. Felt reports for this earthquake show a pattern similar to reports for the April 1973 event but indicate somewhat smaller maximum intensity. Based on this comparison a magnitude of about M=6 and possibly subcrustal depth are estimated.

1926 March 19: This earthquake was probably located offshore (fig. 32), and determination of its epicenter is too uncertain to list an estimate. Because the event was felt widely, its magnitude may have been approximately 6. Cox (1986a) discussed this event.

1924 August 20: This relatively small event rated at 5.0 in magnitude and provided poorly defined isoseismals (fig. 33). The approximate epicenter was in the Hilea area.

1919 September 14: The magnitude of this shock is estimated at 6.1. Although data are less detailed (fig. 34) than those for of the November 1918 earthquake, we gave it a B- instead of C-quality rating because some of the crucial isoseismals are adequately defined, and felt reports were also received from Maui and Oahu (fig. 34*B*). At HVO the intensity was lower for this earthquake than for the event of 1918, although the rest of the pattern was similar; this suggests an epicenter in the Hilea rather than Kaoiki area.

1918 November 2: Data of this earthquake received a quality factor of B because the event was well reported except in the epicentral area (fig. 35). Based on fairly well defined intensity V and VI isoseismals, its magnitude was computed as 6.2. The pattern of the isoseismals of this event is very similar to those of the Kaoiki mainshocks of June 27, 1962 (fig. 10), and November 16, 1983 (fig. 3). Based on these comparisons we propose that the 1918 shock occurred in the same area as these two earthquakes.

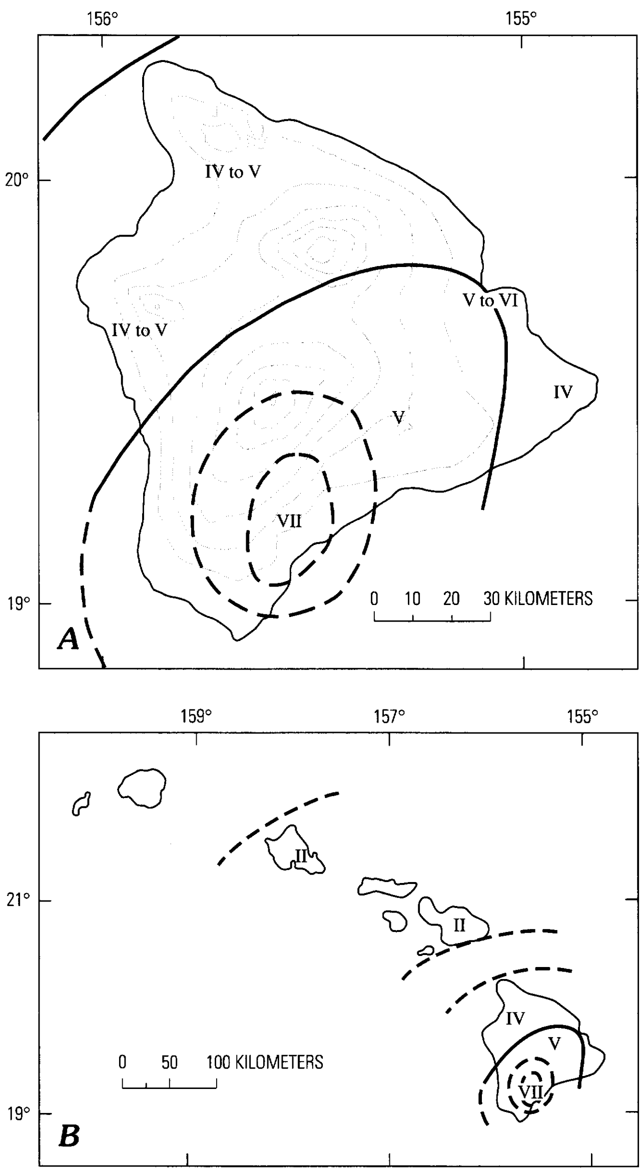


Figure 34. Isoseismal maps for the earthquake of September 14, 1919. *A*, Island of Hawaii. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

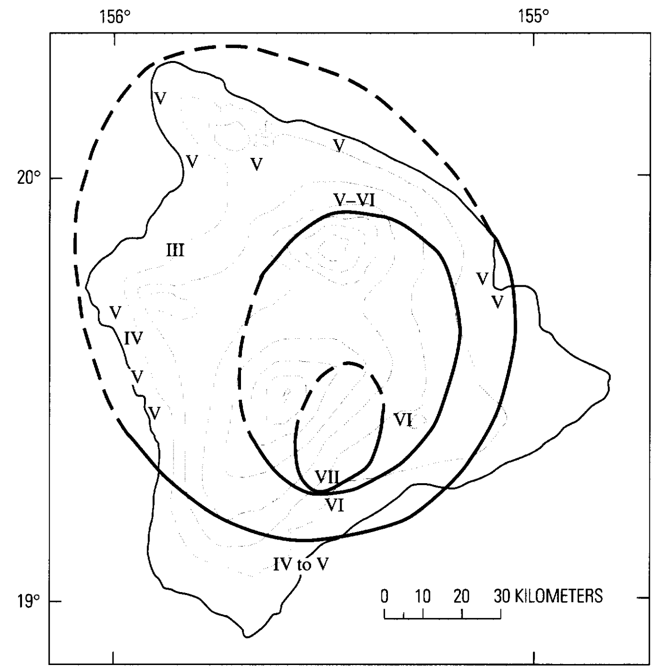


Figure 35. Isoseismal map for the earthquake of November 2, 1918, island of Hawaii. (For additional explanation see figure 2.)

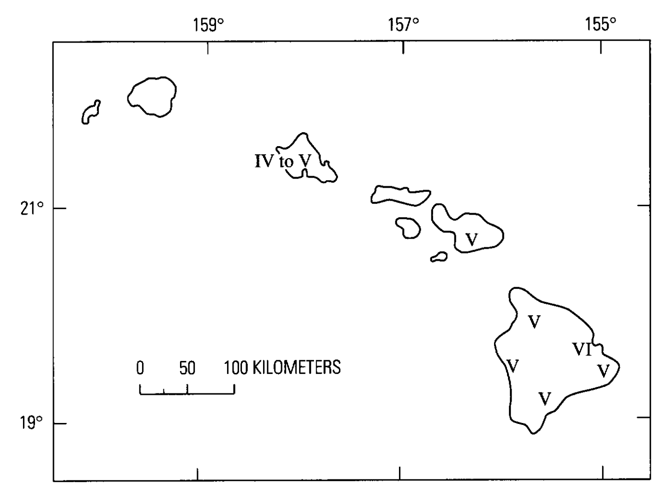


Figure 36. Intensity map for the earthquake of September 13, 1896, Hawaiian Islands. (For additional explanation see figure 2.)

1908 September 20: Macroseismic data for this event are too sparse to draw an isoseismal map. The high intensities produced in Hilo and Puna (appendix 3), combined with the substantial effect on the level of the active lava lake at the summit of Kilauea, suggest that this event was a Kilauea south flank earthquake in the Puna area.

1905 May 3: A local earthquake in eastern or southern Hawaii. No macroseismic map was drawn (appendix 3).

1900 June 27: A local earthquake in Kau (appendix 3).

1896 September 13: The intensities reported from Hawaii, Maui, and Oahu are very similar (fig. 36); those in Hilo are strongest and those in Oahu weakest. Because Hilo often experiences higher intensities than surrounding areas on the island, we cannot estimate an epicenter in this case. The focus may have been subcrustal or located offshore.

1890 August 6: This local earthquake probably originated in southwestern Hawaii (appendix 3) and might have been fairly strong considering the intensities at Hilo, which is on the opposite side of the island. Nevertheless, there are not enough data points to define isoseismals.

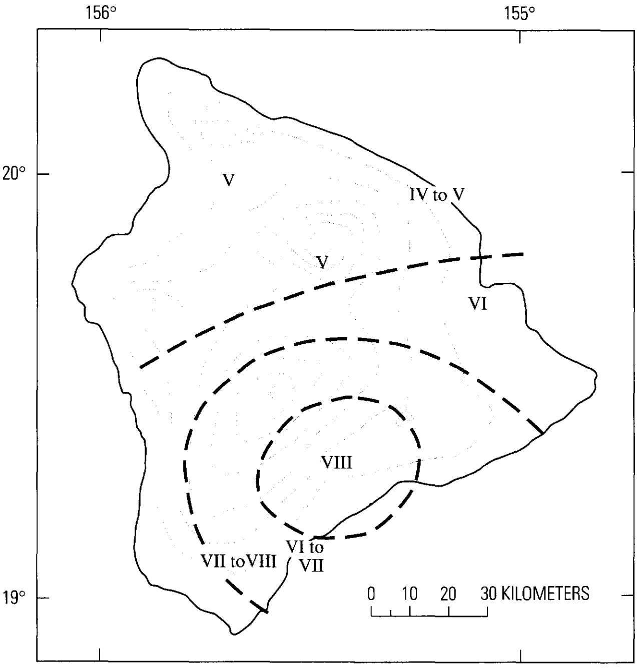


Figure 37. Intensity map for the earthquake of January 23, 1887, island of Hawaii. (For additional explanation see figure 2.)

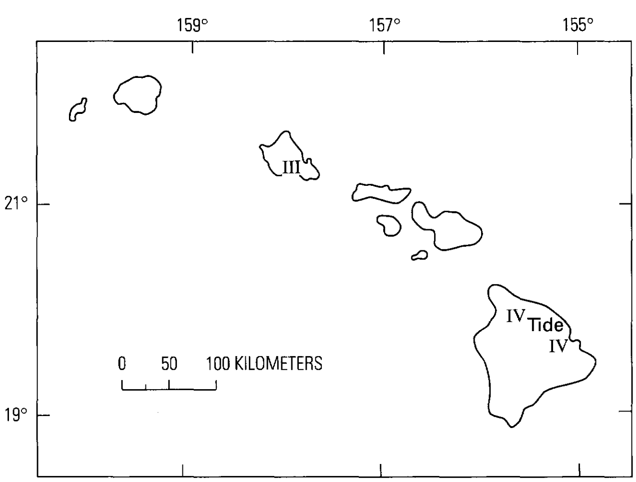


Figure 38. Intensity map for the earthquake of January 13, 1885, Hawaiian Islands. "Tide" indicates the location of the reported tidal wave (tsunami). (For additional explanation see figure 2.)

1888 August 20: Local earthquake, probably in eastern Hawaii (appendix 3).

1887 January 23: The epicenter of this earthquake was located in the Kaoiki or Hilea areas and the event had fairly high maximum intensities. The extent of the intensity V and VI areas can be estimated approximately (fig. 37). The magnitude of 6.5 derived from these (table 3) is very approximate. The similarity between this event and other Kaoiki and Hilea mainshocks (figs. 3, 4, and 10) clearly indicates, however, that the magnitude of this event was greater than 6. The event may have been one of the regular Kaoiki sequence. Its date fits that sequence, but its epicenter is not constrained well enough to conclusively attribute it to the Kaoiki source. Because a volcanic crisis of Mauna Loa was under way, this earthquake might also have been directly associated with the eruption; however, such an origin is less likely than a Kaoiki origin because there were no reports of damage in Kona.

1887 January 17–22: Although numerous earthquakes were felt during the apparent swarm associated with the eruption of Mauna Loa at this time, no detailed reports are available (appendix 3).

1887 January 13: A local earthquake reported as felt in Honolulu only (appendix 3).

1885 January 13: Without intensity data from Maui the epicenter of this event cannot be estimated (fig. 38); however, the report of a tsunami on the northeast coast of Hawaii suggests a shallow epicenter off northeastern Hawaii and a magnitude greater than or equal to 6.

1881 September 30: The intensity pattern reported for this earthquake (fig. 39) is somewhat similar to those for events located offshore near Maui (figs. 17, 24, 31, and 32), but no data from Maui are available. The data suggest that the size of this earthquake was larger than the event of 1926, smaller than that of 1938, and approximately the same as those of 1940 and 1927; however, the fact that the strongest damage was reported from Kona shows that this earthquake must have been in a different location than others near Maui mentioned above and may be similar to Kona earthquakes (fig. 14, August 1951). Without reports from Maui the location of the epicenter can be only estimated as offshore west or northwest of Hawaii. The large extent of the intensity V area requires a magnitude of approximately 6 or greater.

1877 May 31: This earthquake may have been located offshore north of Hawaii. The extent of the intensity V area (fig. 40) suggests a magnitude of approximately 6¼.

1874 December 29: Although reported from only two locations (fig. 41), this earthquake may have been fairly large. A location offshore about midway between Hawaii and Oahu is consistent with the pattern observed.

1872 April 22: A local earthquake in eastern or southern Hawaii (appendix 3).

1871 February 19: This earthquake probably was centered near the island of Lanai (Furumoto and others, 1972, 1990; Holman, 1982; Cox, 1985b), but its exact location is uncertain. Comparing its felt area (fig. 42) with the pattern of intensities associated with the January 1938 earthquake (fig. 24) suggests that the events had similar location and magnitude.

1870 August 7: This earthquake was located near the middle of the archipelago, possibly near Molokai. The intensity distribution (fig. 43) is similar to that of earthquakes originating offshore from Maui (figs. 17, 24). In comparison to these offshore Maui earthquakes a magnitude of greater than or equal to 6 is estimated.

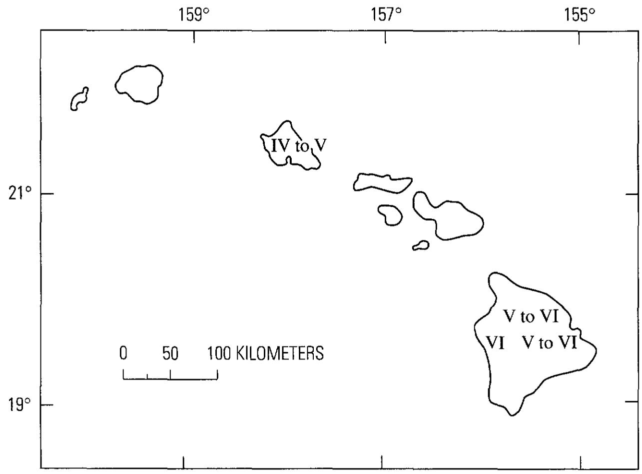


Figure 39. Intensity map for the earthquake of September 30, 1881, Hawaiian Islands. (For additional explanation see figure 2.)

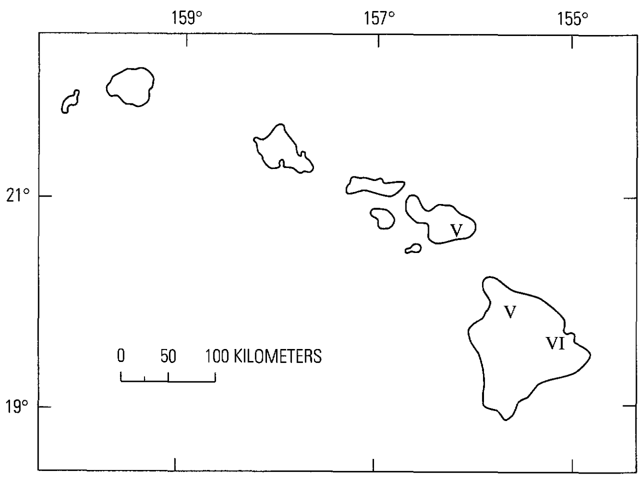


Figure 40. Intensity map for the earthquake of May 31, 1877, Hawaiian Islands. (For additional explanation see figure 2.)

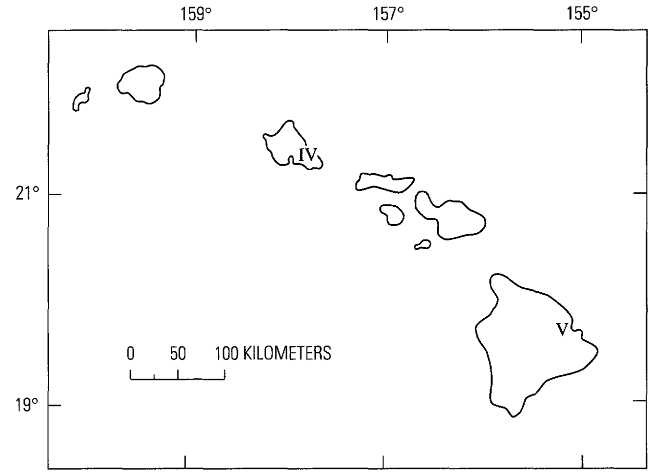


Figure 41. Intensity map for the earthquake of December 29, 1874, Hawaiian Islands. (For additional explanation see faigure 2.)

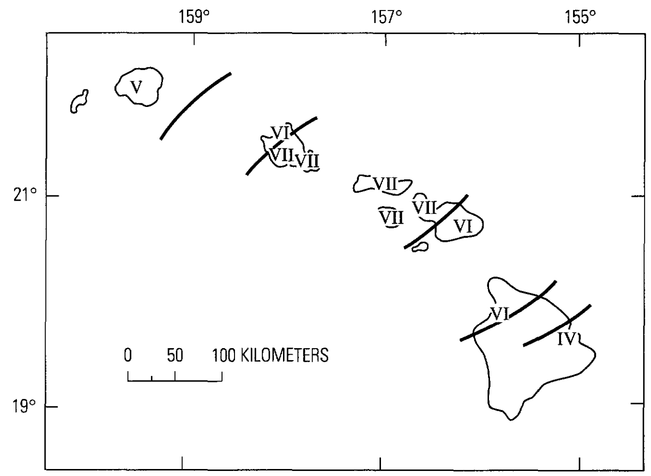


Figure 42. Isoseismal map for the earthquake of February 19, 1871, Hawaiian Islands. (For additional explanation see figure 2.)

1868 April 30: This event was reported felt from Honolulu to Hilo and most severely in Kohala (fig. 44). Although the reports are limited, the event was included because such widespread felt reports (Wood, 1914) suggest that it may have been in the M≅6 class.

1868 April 4: Some of the largest aftershocks of the great earthquake of April 2 took place on April 4, but it is not clear whether all reports address the same events. Two seismic disturbances of similar strength were reported at 0030 and 0045 from several islands (fig. 45). At Kealakekua the event was judged comparable to that of March 28, and at Maui it was judged stronger than the mainshock. Thus, Wood (1914) concluded that these events were located farther north than the April 2 mainshock. The reported intensities suggest that the magnitude may have been greater than or equal to 6.5.

1868 April 2: This earthquake was preceded during several days by numerous foreshocks, of which at least one was a major earthquake (March 28, 1868), and it was followed by thousands of aftershocks, including some strong ones (Wood, 1914). A compilation of the intensity data was made by Wood (1914), from which he concluded that the epicenter was located in southern Hawaii. He also believed that this event was of tectonic not volcanic origin. Based on Wood's intensity data and magnitude-intensity relationships for earthquakes in Japan, Furumoto (1966) estimated M= 7¼–7¾. Subsequently in 1975, a 7.2-magnitude earthquake struck the southeast coast of Hawaii and provided an excellent set of data for comparison. The greater extent of the felt areas in 1868 at each intensity level, as well as the maximum intensity of VIII in 1975 compared to maximum intensity of XII in 1868 and the generally higher wave heights from the

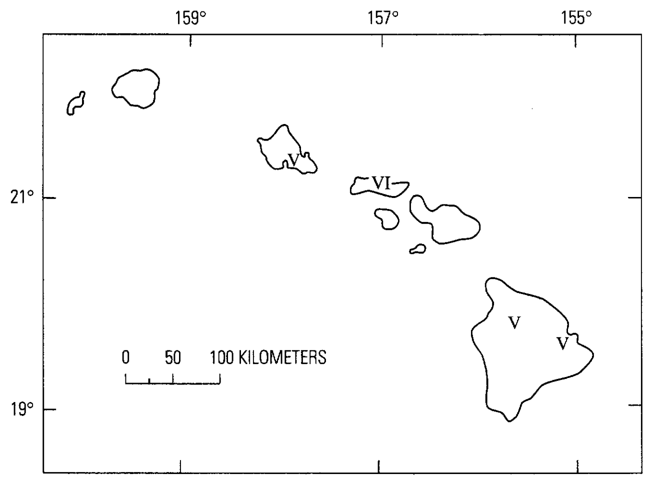


Figure 43. Intensity map for the earthquake of August 7, 1870, Hawaiian Islands. (For additional explanation see figure 2.)

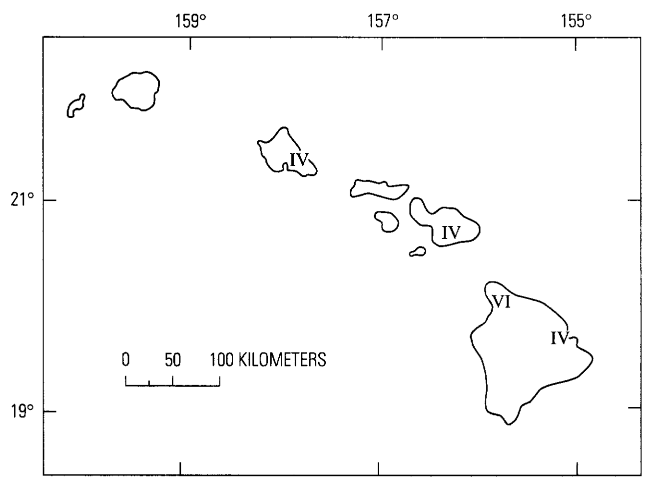


Figure 44. Intensity map for the earthquake of April 30, 1868, Hawaiian Islands. (For additional explanation see figure 2.)

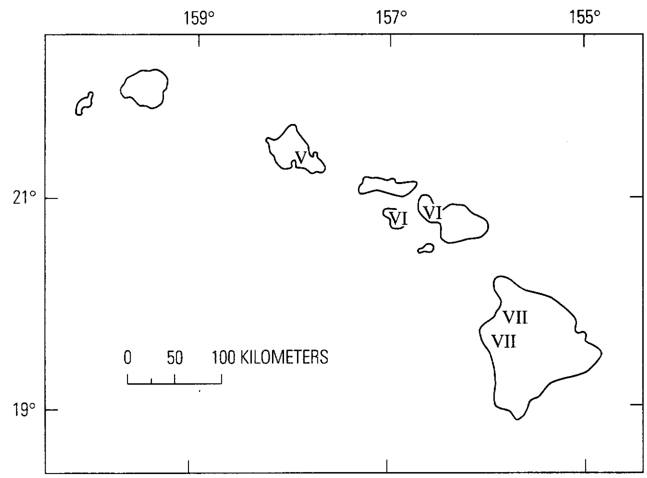


Figure 45. Intensity map for the earthquakes of April 4, 1868, Hawaiian Islands. (For additional explanation see figure 2.)

local tsunami generated for the 1868 event, suggests that Furumoto's magnitude estimate is too low. Hitchcock (1912) also discussed this earthquake. We estimate a magnitude of 7.9 (table 3) using equations 1 and 2. The center of the maximum intensity area is assumed to have been the epicenter (fig. 46, table 3). Wyss (1988) proposed a source mechanism for this earthquake in which Mauna Loa's expanding rift zones provided the strain energy for the rupture. The isoseismal maps shown in figure 46 were redrawn using the Modified Mercalli (MM) Intensity Scale and with more detailed information than was available to Wood (1914).

Reports from Keaiwa and Kiolakaa (Kau) suggest that vertical accelerations were greater than 1 *g*. One of these reports was convincing enough to warrant assignment of intensity XII. From many points along the south and southeast coast evidence of permanent subsidence was reported. Although the intensity of shaking cannot be estimated from this evidence, we conclude that these coastal areas were part of the meizoseismal area or the source area and assigned intensity X to these locations.

1868 March 28: This event is considered a foreshock of the earthquake of April 2, 1868. The magnitude is at approximately 7 based on the extent of the intensity VII and VIII areas (fig. 47), which are similar to those of the M=6.9 Kona earthquake in 1951 (fig. 14*A*). The magnitude versus felt-area relationship of figure 19 results in an estimate of M=7.4; however, this value may be too large because the isoseismal lines for intensities VI and V are poorly defined and unknown, respectively.

1841 April 7: This was "the most severe shock ever felt" (Wyss, Koyanagi, and Cox, 1992) in Hilo until the great earthquake sequence of 1868, but we do not know where it originated (appendix 3).

1838 December 12: This may have been a moderate to major earthquake because intensity VI was reported in Hilo (appendix 3). The origin is unknown.

1834 February 19: The first strong earthquake reported from Hilo (Wyss, Koyanagi, and Cox, 1992) is one of three before 1868 that stands out as clearly more severe than the other 115 reported during this period (appendix 3).

1823 June, date unknown: The fissures at Kaimu created by the first known strong earthquake in Hawaii were examined by Ellis (1827) two months after the event. The effects described are similar to those due to the M=7.2 Kalapana earthquake of November 1975.

GRADIENT OF ISOSEISMALS AS A FUNCTION OF EPICENTRAL DISTANCE

Many investigators have pointed out that the gradient of the isoseismals cannot be expected to show a simple and predictable function of distance because intensity is an arbitrarily defined quantity. Nevertheless, the gradient can

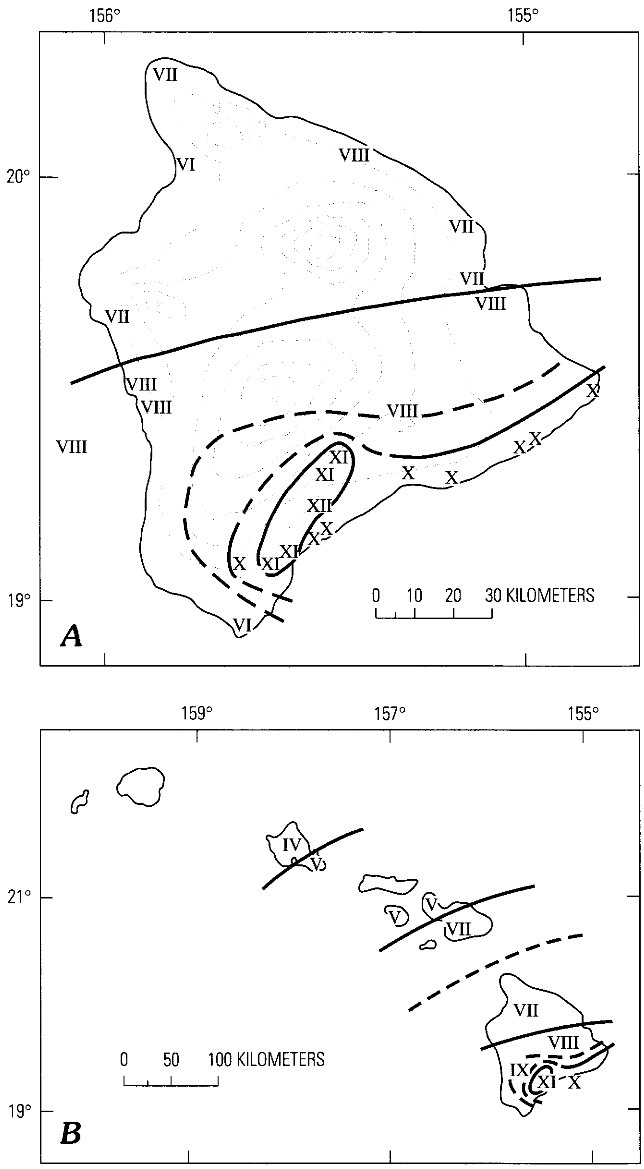


Figure 46. Isoseismal maps for the earthquake of April 2, 1868. *A*, Island of Hawaii. *B*, Hawaiian Islands. The isoseismals for the island of Hawaii shown in *B* are defined by the data in *A*. (For additional explanation see figure 2.)

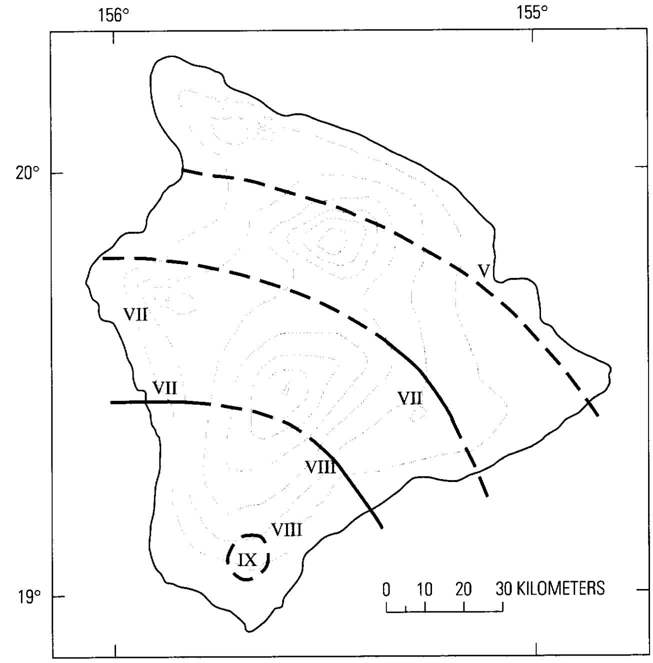


Figure 47. Isoseismal map for the earthquake of March 28, 1868, island of Hawaii. (For additional explanation see figure 2.)

be useful for identifying sources located deeper than normal and for making regional comparisons. For example, subcrustal earthquakes (deeper than 15 km) beneath Kilauea that had magnitudes of 4.0–4.5 were reported felt in Oahu, whereas crustal events in this magnitude range were typically felt within parts of the island of Hawaii only. The intensity gradient as a function of distance is compared for different Hawaiian earthquakes in figure 48. Earthquakes having subcrustal hypocenters show lower isoseismal gradients than do those located in the crust, but this difference is well defined for relatively short distances only (fig. 48*A*). The similar isoseismal gradients of crustal and subcrustal earthquakes at greater distances for most of the examples (figs. 48*A*, *B*) suggest that attenuation in the upper mantle is similar in California and along the Hawaiian archipelago, but that attenuation in the crust on the island of Hawaii, especially in its southeastern part, is stronger than in California and the rest of the United States. For the deepest earthquake (April 26, 1973) the gradient is lower than those for shallow earthquakes to a distance of 350 km (fig. 48*A*). Subcrustal depths might be identified in cases that plot below the average magnitude versus felt-area relationship (fig. 19); however, for earthquakes without instrumental data this method cannot be applied to help identify subcrustal sources. Thus, isoseismal gradients are the only means to distinguish between crustal and subcrustal foci for historical earthquakes. This may not be a very reliable means of identifying subcrustal sources, particularly if the isoseismal gradient in the first 50 km is not well defined and especially if events have a very small, or poorly defined, maximum intensity area. Nevertheless, we commented about gradients that may be unusual for some of the older events in our discussions of individual earthquakes. The entries "n" for normal depth (probably within the top 15 km) and "deep" (subcrustal) in table 3 are based on comparison of the isoseismal gradients for the older earthquakes with those for the more recent events having known depths.

Isoseismal gradients for earthquakes located in the south-central area of Hawaii (fig. 48*B*) are surprisingly uniform. Gradients for the events of 1918, 1919, 1924, 1935, and 1941 conform to those of the known recent crustal earthquakes having average depths of about 10 km. Therefore, we con-

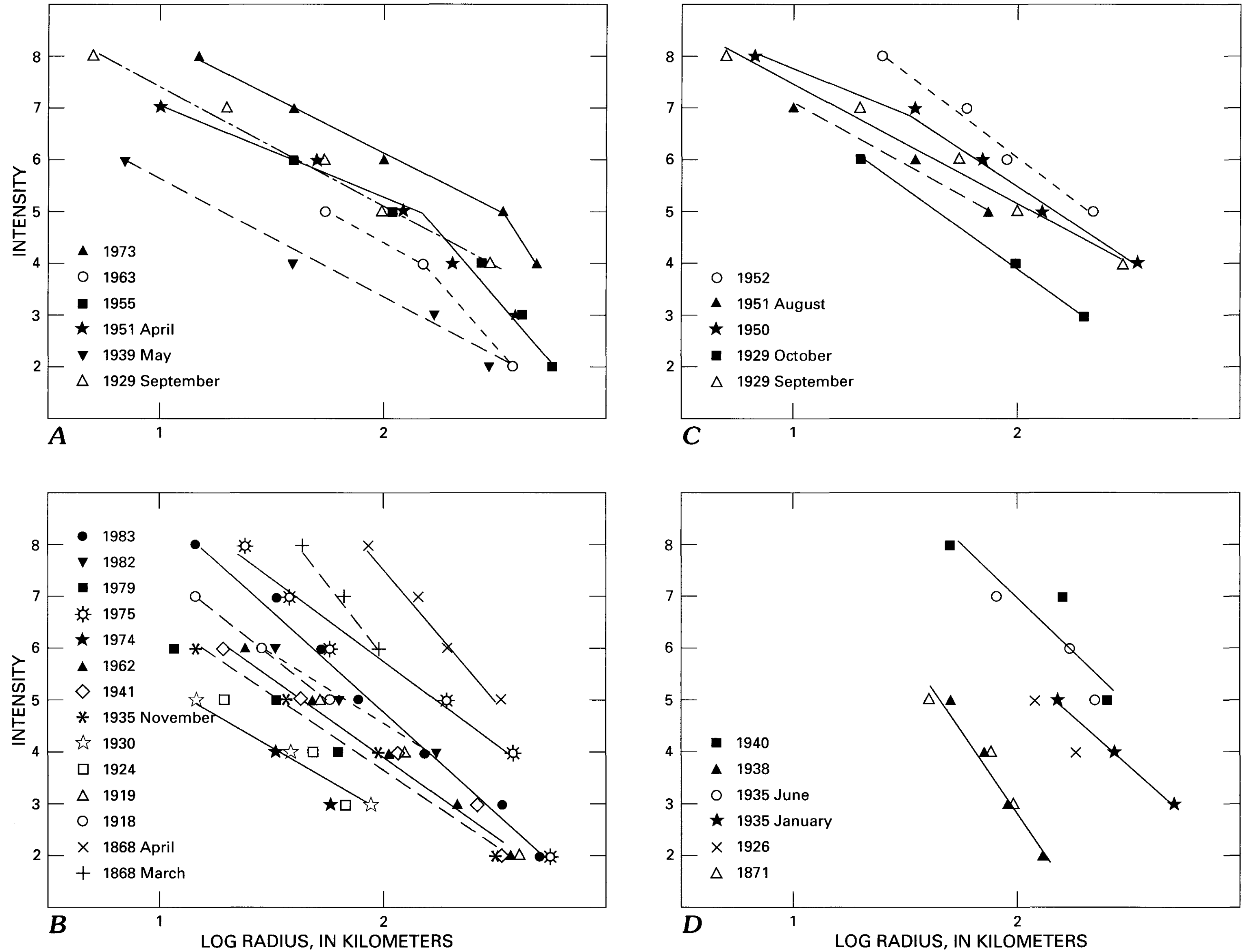


Figure 48. Intensity as a function of epicentral distance for Hawaiian earthquakes having foci (*A*) at subcrustal depths beneath the island of Hawaii, (*B*) at crustal depths beneath southern and central parts of the island of Hawaii, (*C*) in the western part of the island of Hawaii, and (*D*) off the coast of Maui and the eastern coast of the island of Hawaii.

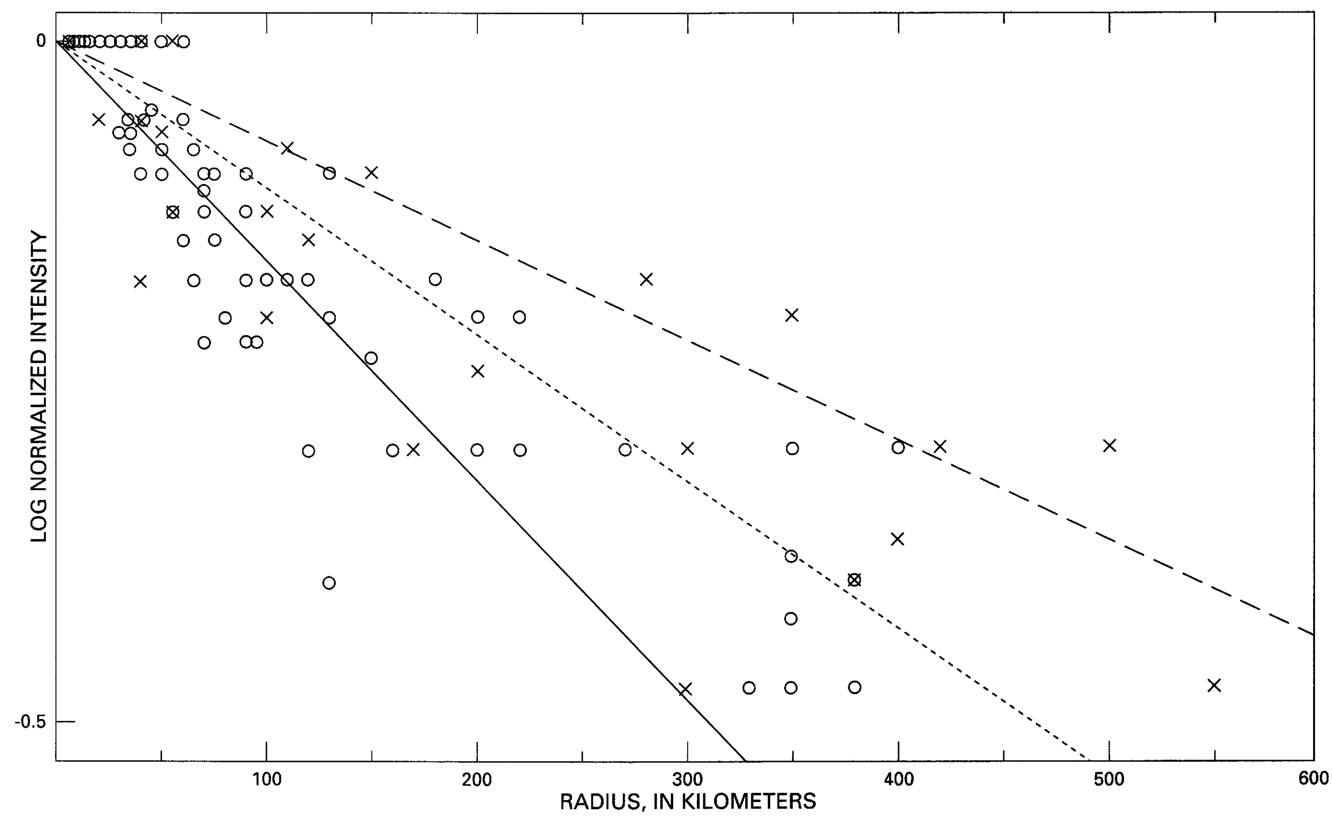


Figure 49. Normalized intensity as a function of distance for all earthquakes of Hawaii. Open circles and x's mark data from crustal and subcrustal earthquakes, respectively. The long-dashed, short-dashed, and solid lines show the corresponding relationship for earthquakes from the eastern United States, Cordilleran, and San Andreas fault regions, respectively (Howell and Schultz, 1975).

clude that these older events had sources within the crust (table 3). The gradients for the events of 1926 and 1930 are slightly lower than the average but are too poorly defined to support a claim of subcrustal hypocenter depths.

The only event from southern Hawaii for which the gradient is probably lower than average is that of May 1939, but this gradient (fig. 48*A*) is not low enough to clearly indicate a subcrustal focus. The slightly lower gradient suggests that the hypocenter might have been somewhat deeper than 15 km but probably not as deep as 30 km.

Isoseismal gradients of the earthquakes along the west coast of Hawaii are shown separately in figure 48*C*. Gradients of the Kona events of October 1929, August 1951, and May 1952 are similar to those of earthquakes in central Hawaii (fig. 48*B*). The data for the 1950 shock are poor. Although the 1950 data could be interpreted as indicating subcrustal depth, we hesitate to accept this interpretation because it solely relies on the extent of the maximum intensity area. The gradient for the September 1929 shock is similar to that for the 1973 subcrustal earthquake (fig. 48*A*) and lower than most of the others in the same area (fig. 48*C*). Because the gradient is well defined, we propose that the September 1929 Hualalai earthquake may have had a subcrustal hypocenter.

The isoseismal gradients of earthquakes located near Hilo and off the coast of Maui are similar (fig. 48*D*) and on average steeper than those from other areas (figs. 48*A–C*). The high gradients suggest that these hypocenters were crustal; however, the instrumentally compiled locations of earthquakes of M>4 in recent decades suggest that subcrustal events were dominant in the Hilo area.

The normalized intensities, I/I_{max}, as a function of distance (fig. 49) are compared with average curves for other U.S. provinces studied by Howell and Schultz (1975). At distances of less than 70 km the normalized intensities from Hawaii agree approximately with the average for California. For distances between 70 and 160 km the Hawaiian data plot below the average for California, and beyond 160 km they plot consistently above it. We interpret these results as follows. In Hawaii, unusually strong attenuation near the epicenter results in a comparatively low value for the maximum intensity I_{max} (fig. 20). The same is true for intensities observed within distances of as much as about 70 km, hence the ratio $I(r<70)/I_{max}$ is approximately the same as in California. If transmission of seismic waves to distances of more than 160 km is approximately the same as in California, then the ratio $\mathbf{I}(r>160)/\mathbf{I}_{max}$ in this distance range will be larger for Hawaii because we observed that $\mathbf{I}_{max}$ (Hawaii) is less than $\mathbf{I}_{max}$ (California) (fig. 20). For the middle range ($70<r<160$), data are sparse but suggest that transmission of seismic energy is even poorer to this distance range than in the epicentral area (fig. 49).

MAGNITUDE ESTIMATES BASED ON FELT AREAS

The magnitude estimates based on felt areas are approximate. First, for some of the older events in the calibration set the magnitudes are not well constrained instrumentally and they are derived from a variety of sources. Relatively large magnitudes are commonly $\mathbf{M}_S$, and others are $\mathbf{M}_L$. Second, the magnitude estimates depend on the source depth. Most events were crustal, but some historical events may have been subcrustal or their depths may be uncertain. Nevertheless, it is important to obtain approximate magnitudes for the older events in order to expand the seismic history of Hawaii. Further refinements in estimation of magnitude for some historical earthquakes may be possible by reevaluating available seismograms from early mechanical instruments, such as the Bosch-Omori seismograph operated at HVO since 1913.

The magnitudes given in table 3 are the average of the two values derived from equations (4) and (5), with two exceptions. The magnitudes of the September 1929 and May 1939 earthquakes were derived from comparison with the deeper events, choosing the most appropriate value from figure 19.

RELATIONSHIP BETWEEN PEAK ACCELERATION AND INTENSITY

The relationship between peak ground acceleration and intensity may be useful for estimating accelerations due to early historical earthquakes. Investigators who have studied this relationship found a great deal of scatter (Trifunac and Brady, 1975), and it is likely that the local geological setting can explain some of this scatter (Krinitzsky and Chang, 1988). In view of the differences in intensity patterns within Hawaii, as well as in comparison with other areas, we thought it of interest to compare the relationship between peak acceleration and intensity observed in Hawaii with that for other areas.

Data for peak accelerations and intensity are available for 4 Hawaiian earthquakes and a total of 23 locations (table 7). In all cases the largest peak acceleration was recorded by one of the horizontal instruments ($\mathbf{a}_H$). For most of these observations the nearest report of intensity ($\mathbf{I}_{MM}$) was from a location within about 10 km of the recording site. One accelerogram record was not included because the nearest intensity estimate was made more than 20 km from the recording site (Mauna Kea).

The logarithm of the vectorially combined peak accelerations on the two horizontal instruments is plotted as a function of intensity in figure 50; this assumes that the peak accelerations were recorded at the same time on the two instruments. Out of 23 observations only 1 plots slightly below the average curve for horizontal peak acceleration of Trifunac and Brady (1975). The rest of the observations plot above that curve, and most values are substantially greater than expected. Trifunac and Brady reported a scatter of an order of magnitude, and the Hawaiian data do not fall outside this scatter but are systematically high. A least-squares fit minimizing acceleration and assuming intensity as error free gives the following average relationship for Hawaii:

$$\log \mathbf{a}_H = 1.10 + 0.20\mathbf{I}_{MM}.$$

The relationship that Krinitzsky and Chang (1988) found for hard-rock near-field sites ($\log \mathbf{a}_H = 1.05 + 0.198\mathbf{I}_{MM}$) is very close to the relationship for Hawaii (fig. 50); however, more than half of our data points come from the far field, for which the relationship of Krinitzsky and Chang (1988) is much lower than that derived from our data (fig. 50). Thus, we observe that accelerations in Hawaii are substantially higher than average for a given intensity (fig. 50). These higher accelerations agree with the fact that magnitudes are greater than average by about 0.7 units for a given extent of the area with an intensity V or VI (fig. 19). A possible explanation is that attenuation in the frequency band of waves causing damage is stronger in Hawaii than elsewhere, in contrast to attenuation in the frequency band where peak accelerations occur and where magnitudes are defined.

EARTHQUAKES HAVING MAXIMUM INTENSITY ≥V

Earthquakes for which enough macroseismic data exist to indicate that they were major to large events are listed in tables 2 and 3. Some moderate events are also listed in these tables, but other moderate to fairly large events may have occurred for which the macroseismic data are not sufficient to estimate the magnitude or location. Some such

Table 7. Accelerations and intensities for Hawaiian earthquakes

Date	Location	Component	Acceleration (*g*)	Intensity
April 26, 1973	Kilauea	210°	0.17	VI
		Down	0.07	
		120°	0.11	
November 29, 1975	Honokaa	345°	0.09	V
		Down	0.04	
		255°	0.11	
	Hilo	74°	0.11	VIII
		Down	0.10	
		144°	0.22	
	Punaluu	126°	0.12	VII
		Down	0.05	
		36°	0.10	
November 16, 1983	Hawaii National Park, Wahaula Maintenance Center	145°	0.12	V
		Up	0.05	
		055°	0.07	
	Hawaii National Park, Volcano Observatory	360°	0.87	VIII
		Up	0.21	
		270°	0.39	
	Hilo, Sewage Plant	333°	0.10	VI to VII
		Up	0.02	
		243°	0.07	
	Hilo, University of Hawaii	085°	0.07	VI to VII
		Up	0.04	
		355°	0.11	
	Kailua-Kona, Fire Station	312°	0.04	V
		Up	0.01	
		222°	0.03	
	Kealakekua	346°	0.10	VI
		Up	0.07	
		256°	0.10	
	Kapa'au, Kohala Police Station	102°	0.07	V
		Up	0.05	
		012°	0.09	
	Pahoa, Fire Station	087°	0.18	VI
		Up	0.07	
		357°	0.11	
	Waimea, Fire Station	155°	0.13	V
		Up	0.07	
		065°	0.08	
	Hilo, U.S. Fish and Wildlife	360°	0.40	VII
		Up	0.15	
		270°	0.50	
	Honokaa, Fire Station	021°	0.25	V to VI
		Up	0.10	
		291°	0.37	
	Mauna Loa, Observatory	030°	0.34	VII
		Up	0.46	
		300°	0.58	
	Pahala, Kau Hospital	188°	0.59	VI
		Up	0.16	
		098°	0.31	
	Waiohinu, Ka'u Baseyard	065°	0.19	VI
		Up	0.09	
		335°	0.17	

earthquakes were reported by the Lymans (Wyss, Koyanagi, and Cox, 1992). Based on this diary and other sources, we compiled a list of Hawaiian earthquakes for the years 1833 to 1955 for which the maximum intensity was most likely V or greater (table 4). We have used I_{max}≥V because "sleepers awakened" is intensity V and the expressions used by the Lymans to describe the strength of the earthquake shaking can be calibrated as either greater than or equal to V or less

Table 7. Accelerations and intensities for Hawaiian earthquakes—Continued

Date	Location	Component	Acceleration (*g*)	Intensity
June 26, 1989	Pahoa	085°	0.19	V
		Up	0.07	
		355°	0.21	
	Pahala	360°	0.05	IV
		Up	<0.05	
		270°	0.05	
	Hilo, University of Hawaii	360°	0.11	V
		Up	<0.05	
		270°	<0.05	
	Hilo, Sewage Plant	360°	0.07	V
		Up	<0.05	
		270°	0.05	
	Hilo, Hospital	352°	0.12	V
		Up	0.05	
		262°	0.07	

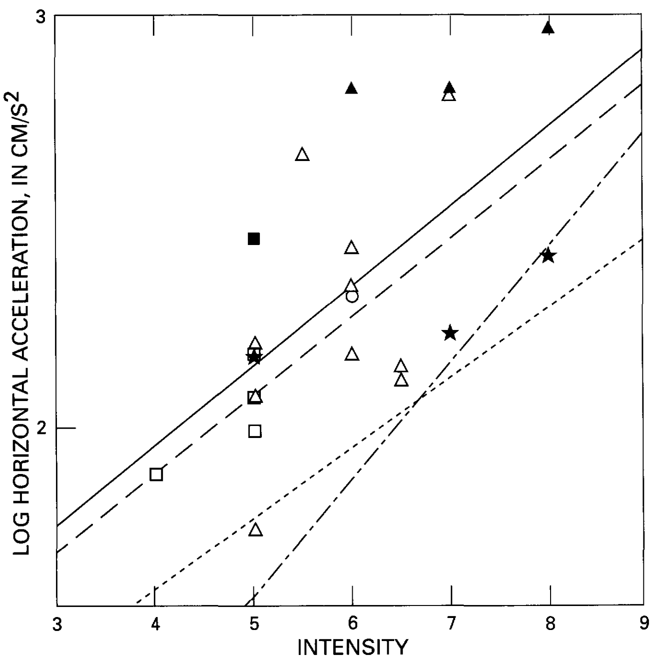


Figure 50. Horizontal acceleration as a function of intensity for four Hawaiian earthquakes. Circles, stars, triangles, and squares mark the data of April 1973, November 1975, November 1983, and June 1989, respectively. Open and solid symbols are for the far and near fields, respectively, as defined by Krinitzsky and Chang (1988). The solid line is a linear fit assuming intensity as error free and minimizing the squares of the errors in acceleration. The dashed, dotted, and dot-dashed lines are the fits obtained by Krinitzsky and Chang for near-field hard sites and far-field sites and the average relationship of Trifunac and Brady (1975), respectively.

than V because many earthquakes occurred during nighttime when in most cases the recorder must have been asleep.

The beginning of the catalog of I_{max}≥V events is set by the beginning of the earthquake diary of Mrs. Sarah Lyman, who arrived in Hawaii in 1832 and made her first note of an earthquake in 1833 (Wyss, Koyanagi, and Cox, 1992). The end is 1955 when "The Volcano Letter" ends and modern seismographs were installed. At approximately this time the earthquake catalog of the HVO begins with improved reporting including accurate magnitudes. Therefore, a catalog based on intensities for the years after 1955 is not necessary.

Our major sources were the Lyman diaries (Wyss, Koyanagi, and Cox, 1992) for the years before 1915 and "The Volcano Letter" (Fiske and others, 1987), "United States Earthquakes," and the "HVO Bulletin" (Bevins and others, 1988a, b) for the following years. In the Lyman diaries only a few entries contain information that can be used to estimate the intensity value; however, the authors continued to use the same words to describe the degree of shaking experienced, and they seemed to use these words consistently. We accepted all events reported when they were described with the following attributes: severe, heavy, hard, smart, decided, and protracted. We did not include in table 4 events described as moderate, distinct, or slight or for which no attribute was used. In our estimate the Lyman scale from strongest to weakest was severe, heavy, hard, smart, decided, moderate, no attribute, distinct, and slight and corresponds approximately to intensity as shown in table 8.

Our reasons for accepting or excluding events as we did are the following. The attributes severe, heavy, and hard obviously were used to describe the effects due to some of the largest events, and thus these events had to be included in table 4. Moderate and slight were used to describe sensations that would fall in the intensity III range. Earthquakes for which no attributes were used could not be included because of lack of information, but probably the intensities were low for these events because they did not stimulate comments. Also, it was felt that the information that the disturbance was protracted warranted inclusion in the list

Table 8. The Lyman scale for earthquake strength in Hawaii

[Intensity is given using the Modified Mercalli Intensity Scale (appendix 2)]

Attribute used to describe shaking	Approximate intensity
Severe	VII
Heavy	V–VI
Hard	V–VI
Smart	V
Decided	IV–V
Moderate	III–IV
Distinct	III–IV
Slight	II–III
Protracted	II–V

because several of the earthquakes located at the center of the archipelago and several events associated with eruptions were described using this attribute. These types of events would have been located at distances of more than 40 km and had $I_{max} \geq V$.

Expressions for events near the border line were smart, decided, and distinct. The word smart was used to describe disturbances that (1) "awakened many," (2) "lasted several seconds," (3) "caused all at the table to suddenly spring forward," and (4) occurred at night and early morning hours, when the reporters were most likely asleep. The attribute decided was also used for events of category (4) above and for one event that "drove us from our beds." We therefore concluded that these two attributes were used to describe disturbances typically in the intensity V range (table 8). The expression distinct was not used for disturbances during usual sleeping hours, but it was used as "distinct but slight" and "distinct but not hard." Thus we estimate that distinct was in the III to IV category and we excluded these events.

Events for which clear evidence for intensity IV was available were included because most of these would not be located straight below the recording site, and the maximum intensity would most likely be V or greater when recorded as IV at Hilo. For many fairly strong events, descriptions in "The Volcano Letter" and other sources that we used did not furnish information that could be used for estimating Mercalli intensities. In these cases we included in table 4 those events that were "widely felt over the entire island [of Hawaii]" or at least throughout the southern half.

The earthquake diary (Wyss, Koyanagi, and Cox, 1992) spoke of two disturbances following each other on several occasions without specifying the time that separated them. These were entered in table 4 as one earthquake only because it is possible that different phases seconds apart could have been taken to suggest two earthquakes. The effort by the Lymans was a very conscientious one as evidenced by the fact that the average annual number of earthquakes that they reported remained constant over many decades (Wyss, 1988). Thus we believe that table 4 represents the best list we can assemble of earthquakes having maximum intensities greater than or equal to V as recorded at Hilo during a period of 123 years.

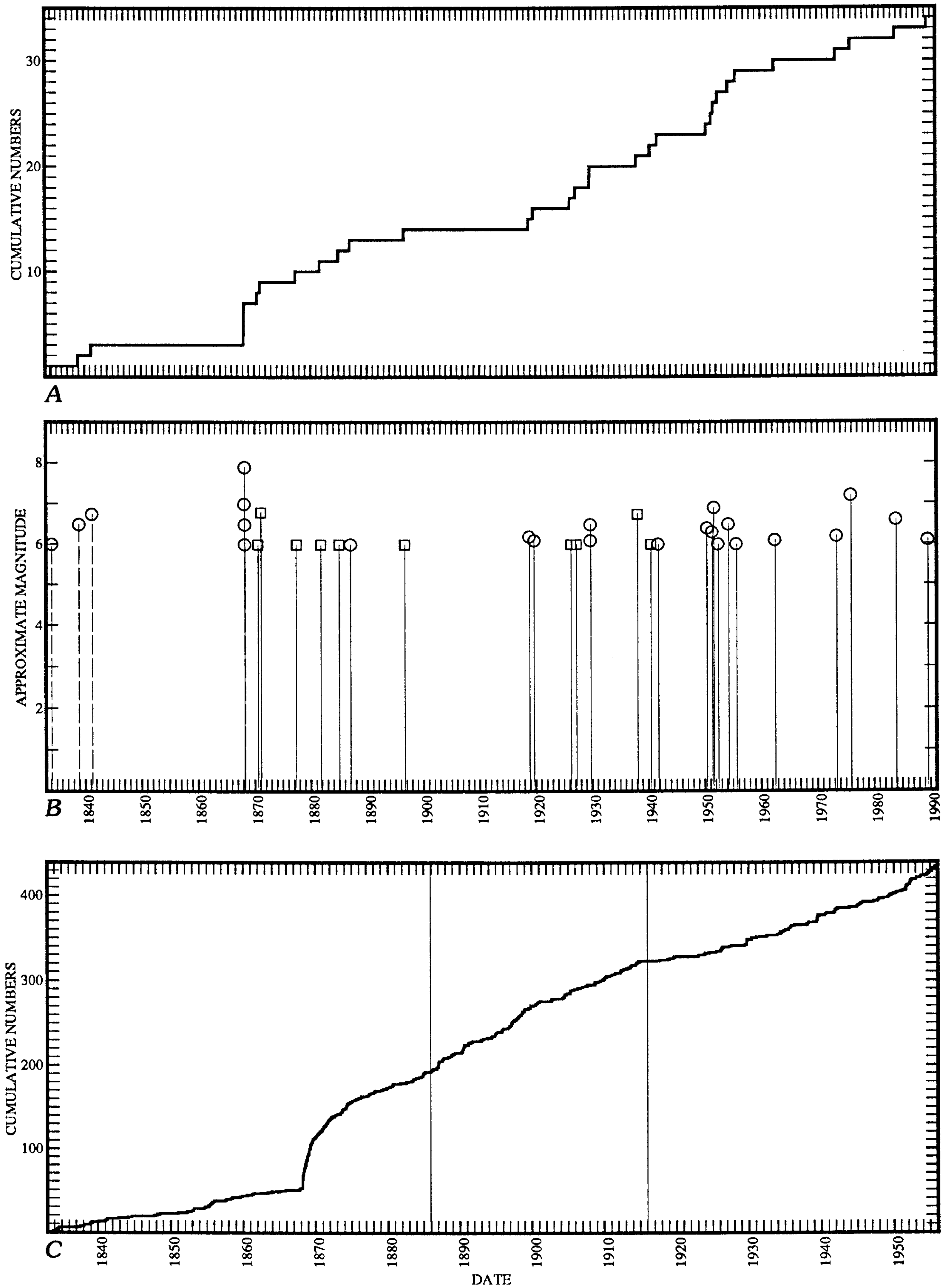
The list of earthquakes for which $I_{max} \geq V$ (table 4) includes 460 events for the 123-year period. This means that on average 3.7 events in this category may be expected per year in Hawaii. The cumulative number of these earthquakes (fig. 51*C*) shows some variations in slope; that is, occurrence rate. The most outstanding feature is the aftershock sequence of the great 1868 earthquake that lasted many years, perhaps a decade. Mrs. Lyman, Jr., reported earthquakes of all magnitudes at a higher rate than Mrs. Lyman, Sr. (Wyss, 1988). This is also seen in the steeper slope after 1885 (fig. 51*A*). We do not know whether this change was due to a difference in personality of the observers or because they lived in parts of Hilo that had different sensitivities to earthquakes.

The rate of earthquakes for which $I_{max} \geq V$ after 1915 (based on reports in "United States Earthquakes" and "The Volcano Letter") is intermediate between the rates inferred from the reports of the Lymans (fig. 51*C*). Thus we conclude that on average the record we assembled in table 4 and figure 51*C* reasonably approximates the true record for Hawaiian earthquakes of $I_{max} \geq V$, although the record is undoubtedly incomplete.

CONDITIONAL PROBABILITY FOR EARTHQUAKES IN HAWAII

The seismic hazard in the Hawaiian Islands is obviously high. Table 1 summarizes the largest earthquakes and their damage, and tables 2-4 give magnitudes and maximum intensities. The seismic hazard can be expressed in terms of the conditional probability, P_c, which is the probability that an earthquake having $M \geq M_{min}$ (alternatively maximum intensity $I_{max} \geq I_{min}$) will occur in the interval $T_{tot}+\Delta t$, condi-

Figure 51 (facing page). Number of earthquakes as a function of time for the Hawaiian archipelago. *A*, Cumulative number of earthquakes having $M \geq 6$ (approximately). *B*, Occurrence time for earthquakes having $M \geq 6$ (approximately) as a function of time. Open circles and squares denote epicenters located on the island of Hawaii and elsewhere in the archipelago, respectively. *C*, Cumulative number of earthquakes having $I_{max} \geq V$. Fine vertical lines divide the records due to Mrs. Lyman, Sr., Mrs. Lyman, Jr., and "The Volcano Letter" (Fiske and others, 1987) and "United States Earthquakes," from left to right, respectively.


CUMULATIVE NUMBERS
A
APPROXIMATE MAGNITUDE
B
CUMULATIVE NUMBERS
C
DATE

tional on the event not having occurred before time t. Here we follow the logic of Nishenko and Bollinger (1990), who estimated P_c for the Central and Eastern United States. Because the history is too short to establish recurrence times for large earthquakes in individual source volumes, we cannot calculate the probability of the returns of individual earthquakes, except for the Kaoiki source ($5.5 \leq M \leq 6.6$, Wyss, 1986a). Therefore we estimate the probability of an earthquake occurring anywhere in the Hawaiian Islands (and alternatively in the southern part of the island of Hawaii), assuming a Poisson distribution of these events.

The assumption of a Poisson distribution in time is a viable approach because several source volumes having unknown and different strain accumulation rates are contributing to the overall seismicity of the archipelago and Hawaii. Therefore, the probability of the occurrence of a destructive earthquake may be assumed to be the same per time interval at all times. The return time, T, is defined as the average interval between earthquakes of $M \geq M_{min}$, calculated by

$$T = T_{tot}/N(M \geq M_{min}),$$

where T_{tot} equals the duration of the earthquake history (1830 through 1990; that is, T_{tot}=160 years), and N is the number of earthquakes for which $M \geq M_{min}$.

The conditional probability, as calculated by

$$P_c = 1 - \exp(-\Delta t/T)$$

(Nishenko and Bollinger, 1990), is given in table 9 for the entire archipelago and for the southern part of the island of Hawaii (in parentheses). This division was made because the southern part of the island of Hawaii contributes most of the damaging earthquakes. The probabilities for the central part of the archipelago and for Oahu were not calculated separately because others have evaluated the hazard in these areas (Furumoto and others, 1972; Cox, 1986c).

For the calculation of the return time T we assumed that our records for earthquakes of $M \geq 6$, $M \geq 6.5$, $M \geq 7$, $I_{max} \geq$VII, and $I_{max} \geq$VIII are complete. The proposal that the record of earthquakes may be complete at the M=6 level for 1830 through 1990 is supported by the facts that the earthquake diary by the Lymans (Wyss, Koyanagi, and Cox, 1992) was kept very conscientiously and that the rate of events throughout time is relatively constant, as shown by the cumulative seismicity curve (fig. 51*A*).

For the case of $M \geq 6.5$ we believe that the record is most likely complete, but a second assumption was necessary. The magnitudes of several of the 19th century earthquakes are only given as $M \geq 6$ (table 3), but it is not known which of these were greater than 6.5. Because these sources were located offshore it may well be that several of them were in the M=6.5 range. For calculating $T(M \geq 6.5)$ we assumed that two of the five offshore earthquakes with $M \geq 6$ in table 3 had magnitudes greater than or equal to 6.5.

Table 9. Conditional probability estimates for earthquakes in the Hawaiian archipelago and in the southern parts of the island of Hawaii

[M, magnitude; I, intensity. Parentheses enclose estimates for southern parts of the island of Hawaii]

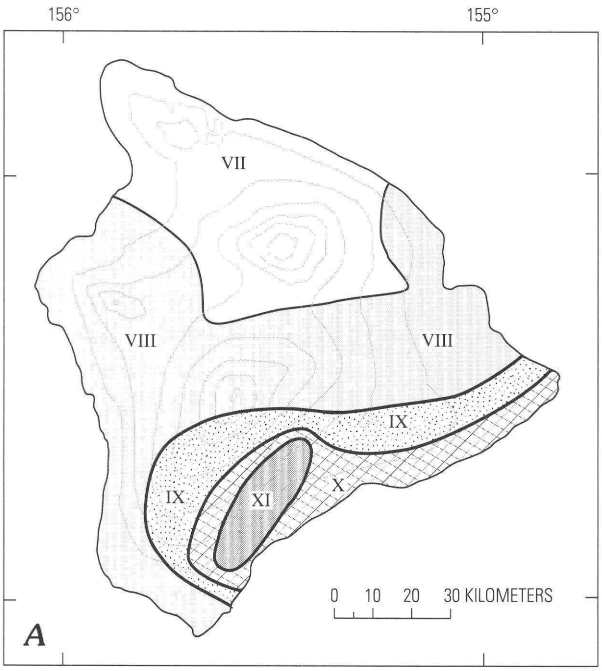
	1990–2000	1990–2010	1990–2040
$M \geq 6$	0.84 (0.71)	0.97 (0.92)	0.999 (0.998)
$M \geq 6.5$	0.50 (0.39)	0.75 (0.63)	0.97 (0.92)
$M \geq 7$	0.17 (0.17)	0.31 (0.31)	0.61 (0.61)
$I_{max} \geq$VII	0.67 (0.63)	0.89 (0.86)	0.997 (0.99)
$I_{max} \geq$VIII	0.50 (0.39)	0.75 (0.63)	0.97 (0.92)

For the category of $M \geq 7$ the estimate of P_c may be sensitive to the judgment of which earthquakes to include. The earthquakes of March 1868 and November 1975 (tables 1, 3) indisputably belong in this category. In addition, one foreshock and one aftershock of 1868 had magnitudes close to 7, and the August 1951 event was assigned a magnitude of 6.9. On the one hand, one may argue that foreshocks and aftershocks should not be included in estimating the characteristics of the Poisson distribution, and, on the other, one may want to include the August 1951 earthquake in the count. Thus we propose to use $N(M \geq 7)$=3 as a reasonable compromise.

We found that the conditional probabilities for destructive earthquakes in the next 10, 20, and 50 years for the Hawaiian Islands are high (table 9). In the next 10 years the probability for an $M \geq 6.5$ ($I_{max} \geq$VIII) event is 50 percent, in the next 20 years 75 percent, and in the next 50 years 97 percent. Even for an earthquake of $M \geq 7$, the probability in the next 20 years is 31 percent for the archipelago as well as for the southern part of Hawaii. These facts suggest that earthquake hazards should be considered in the cultural development of Hawaii.

DISCUSSION AND CONCLUSIONS

The chief purpose of this study was to gather as much information as possible from newspapers and other sources on historical Hawaiian seismicity for the period before the seismograph network was established. We compiled macroseismic data for 56 earthquakes during the period 1823 through 1989 (table 2). For 15 of these events macroseismic maps could not be drawn because the data were insufficient; for an additional 6 events the isoseismals could not be defined. For the remaining 35 earthquakes approximate magnitudes and locations (tables 2, 3) were estimated using the isoseismal maps. The highest intensities reported during historic time (fig. 52) show that most parts of the archipelago



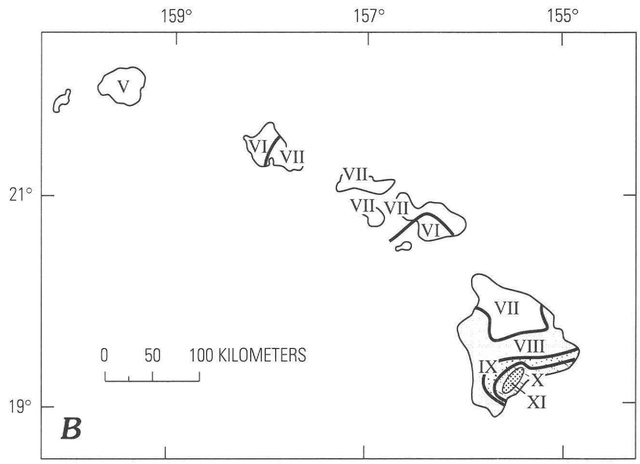


Figure 52 (above and facing column). Contours of highest intensities (as indicated by Roman numerals) from the earthquakes compiled in this report. *A*, Island of Hawaii, where the earthquakes of 1868, 1929, and 1973 dominate. *B*, Hawaiian Islands, where the largest values are due to the earthquakes of 1871 and 1938.

Figure 53. En echelon cracks from surface rupture of the Kaoiki earthquake of November 16, 1983 ($\mathbf{M}_L$ = 6.6). Photographed by C.H. Thurber.

experienced **I**=VII, with the largest values (X to XI) along Hawaii's southeast coast.

The magnitudes of 46 and 29 earthquakes probably exceed 5.5 and 6.0, respectively, during the past 122 years. If the record of **M**≥6.0 events is complete for that period, one **M**≥6.0 earthquake could be expected every 4.2 years in the Hawaiian Islands. If the record of **M**≥5.5 earthquakes is complete for the period since about 1915, then we count 36 (table 3) such events and on the average we expect one **M**≥5.5 earthquake approximately every 2 years. These frequencies are minimum estimates because it may be that the catalog we assembled is not complete at these levels. The records of **M**≥6.5 and **M**≥7.0 earthquakes are probably complete, but the history is not long enough for estimating recurrence times for the major individual sources. The return times of major to large earthquakes can be calculated, however, by assuming random occurrence, and then conditional probabilities for large earthquakes during the next decades can be estimated (table 9). We find that these probabilities are very high. For example, the probabilities of events of intensity VII or VIII and greater occurring during the next 50 years in the southern half of Hawaii are 0.99 and 0.92, respectively, and maximum accelerations of more than 1 *g* are possible.

An additional motivation for this study was the suggestion that Kaoiki mainshocks (fig. 53) of **M**=6 ±0.6 occur regularly and have a recurrence time of approximately 10 years (Wyss, 1986a). This hypothesis is based on post-1940 epicenters. To investigate the possibility that pre-1940 epicenters might provide a test of this hypothesis, macroseismic data were analyzed in an attempt to separate Kaoiki earthquakes from those located in Hilea and in the summit regions of Kilauea and Mauna Loa. In this we were partly successful. We found that between 1912 and 1940 no major Kaoiki earthquake took place at times other than those expected by the extrapolation of the regular sequence; that is, near 1930 and near 1920.

The mainshock of November 1918 (fig. 35) shows a macroseismic pattern that is very similar to that of the recent Kaoiki mainshocks of June 1962 (fig. 10) and November 1983 (fig. 3). Based on this comparison we derive a Kaoiki epicenter for this earthquake and a magnitude of 6.2, approximately the same as that of the 1962 shock.

The origin of the earthquake of May 1930 was placed at depth "somewhere under Kilauea and Mauna Loa" by Jagger (Fiske and others, 1987, p. 283–284). At the time of this statement the hypocentral depths of Hawaiian earthquakes were not known. Volcanologists used the expression "deep" for events other than those in the top few kilometers where earthquakes typically occur in swarms beneath the volcanoes. Based on this assessment, Wyss (1986a) initially included this event in the Kaoiki sequence; however, macroseismic data do not require a Kaoiki location for the event (fig. 28). Rather, based on these data one would place the epicenter at Kilauea. The macroseismic data are sparse and very similar to those of the Kaoiki mainshock in November 1974 (fig. 7). For both of these events relatively high intensities were reported from the Puna area, and, although this is the only macroseismic evidence suggesting a Kilauea epicenter, Jaggar, who had much experience with local earthquakes, never considered the 1930 earthquake to be located at Kilauea, where he resided at the time, but instead contemplated and rejected the possibility of a Kona epicenter for this shock (Fiske and others, 1987, p. 283–284). Our preference is to accept Jaggar's determination for a Kaoiki location.

The record before 1912 is less complete than afterward, and details of these earlier felt reports are less extensive. The earthquake of January 1887 might have originated in the Kaoiki area; its date fits the regular occurrence sequence, but its location is not certain.

The attenuation of seismic waves in the Hawaiian Islands has not been studied much to date. From the gradients of the isoseismal curves (fig. 48) and the magnitude versus felt-area relationship (fig. 19), it is clear that the average crustal attenuation is higher than in California. Differences in attenuation also may exist between the island of Hawaii and the rest of the island chain (fig. 48). The relatively low intensities of the southeast coast and Puna (figs. 5, 6, and 12) suggest that those areas have stronger than average attenuation than other parts of Hawaii.

The observation that maximum intensities for given magnitudes of earthquakes are lower in Hawaii than elsewhere (fig. 20) is especially significant for earthquakes for which recorded surface- and body-wave magnitudes are available, although we have shown that for **M**≥5.5 (most of our data) M_L values are approximately equivalent to $\mathbf{m}_b$ and $\mathbf{M}_S$. Thus we believe that the low intensity values furnish strong evidence for unusually high attenuation in the Hawaiian crust. The observation that for a given magnitude maximum intensities in Hawaii are lower by more than two units as compared to California leads to the conclusion that attenuation in the crust is greater beneath Hawaii. This conclusion is also supported by relatively high measured acceleration for a given intensity observation (fig. 50).

Transmission of seismic waves in the upper mantle beneath the island chain most likely is similar to transmission elsewhere. This conclusion is supported by the similarity of the magnitude versus felt-area relationships for Maui and California earthquakes and by the large values for the normalized intensities at epicentral distances of more than 160 km (fig. 49). We conclude that the unusually strong attenuation of seismic waves is a crustal phenomenon characteristic of southern Hawaii and that it is most pronounced along the southeast coasts within the volcanic pile.

Magnitude estimates are somewhat uncertain for early historical earthquakes. Sources of error include variations in the different types of magnitudes available for the limited number of calibration events, differences in near-source attenuation, and a paucity of felt reports. Nevertheless, the approximate magnitude values provide a rough measure of the energy release. Based on the historical seismicity data presented in this paper, it is clear that the seismic hazard in Hawaii is very serious. The implication is particularly of concern because of the accelerated cultural growth on Hawaii during the past decade, as inferred by the rapid population growth in North Kona, Hilo, and Puna. One of the largest U.S. earthquakes (M=7.9) occurred in southern Hawaii in 1868. The recurrence time of this earthquake is unknown, and the strain accumulation rate in its source area is also unknown. Ground deformation surveys could furnish information on the strain accumulation rate in the critical areas, but at present geodetic networks do not exist with which to monitor the expected strain accumulation in the source area of the largest Hawaiian earthquake documented in historical time. West Hawaii also has experienced earthquakes approaching magnitude 7, and we do not know either the recurrence time or the strain accumulation rate for that area. Our earthquake lists and analysis of historical Hawaiian earthquake data suggest that additional surveys and studies could significantly improve our understanding of the seismic hazard in Hawaii, one of the most active seismic regions of the United States.

Acknowledgments.—The contents of this paper were developed with support from grant number 14–080001–G1325 from the U.S. Geological Survey, Department of the Interior, and grant number EAR–8916252 from the National Science Foundation. We thank Carl Stover for carefully editing the manuscript including suggestions for adjustments of intensity estimates. We thank J. Dewey, D. Gordon, T. Wright, and C. Kisslinger for critical reading of the manuscript. We also thank our patient word processors Barbara Sloan, Nan Regnier, and Robin Wright, who corrected many inconsistencies. The authors appreciate the assistance provided by Jim Kauahikaua, Charlotte Forbes, and Sandra Zane in editing the many Hawaiian names used in this report.

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APPENDIXES 1–4

Appendix 1—Principal Reference Locations on the Hawaiian Islands Mentioned in the Text

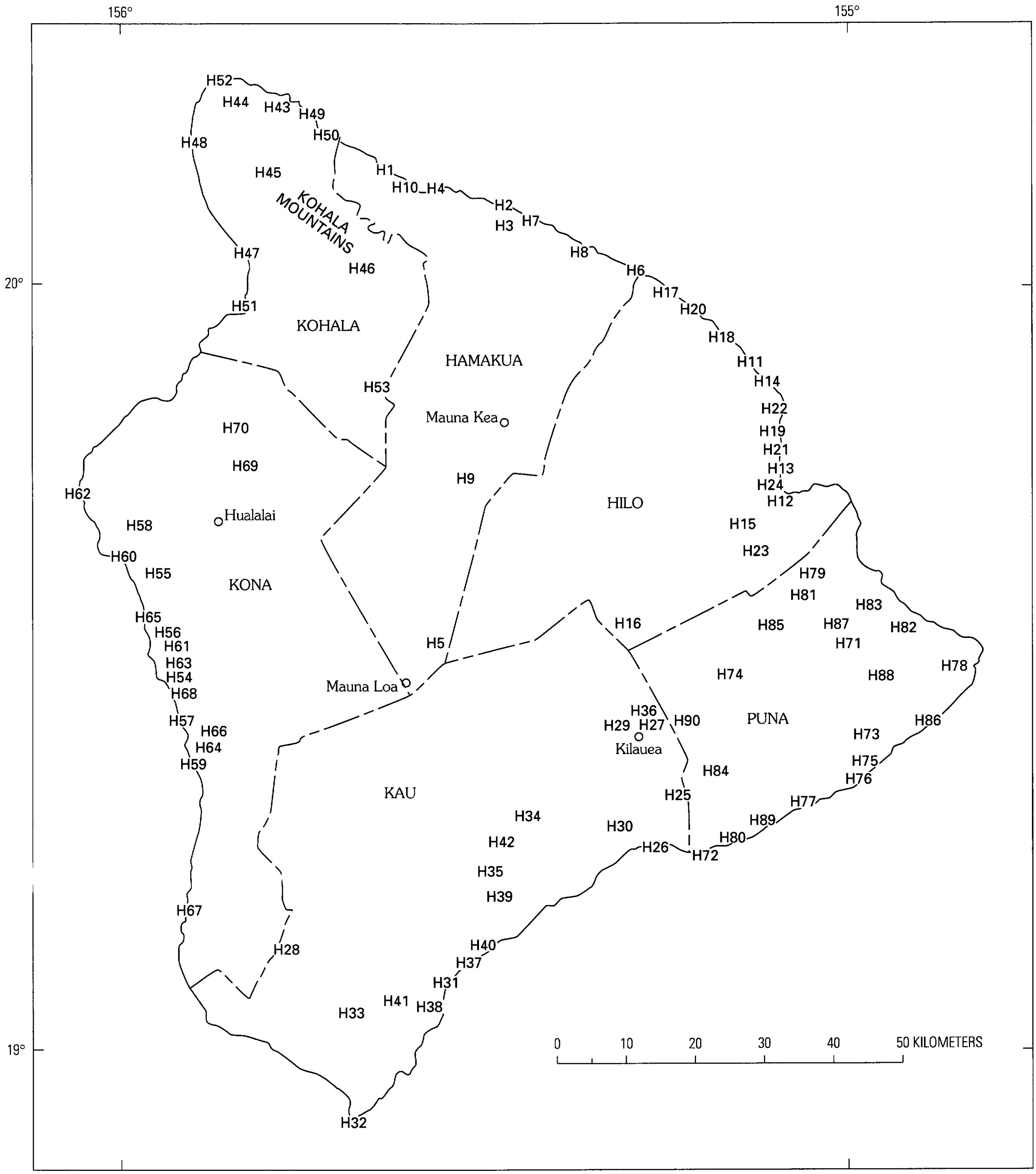

Figure A1. Map of the island of Hawaii showing districts (dashed lines) and volcano summits (dots). The numbers mark locations listed in table A1.

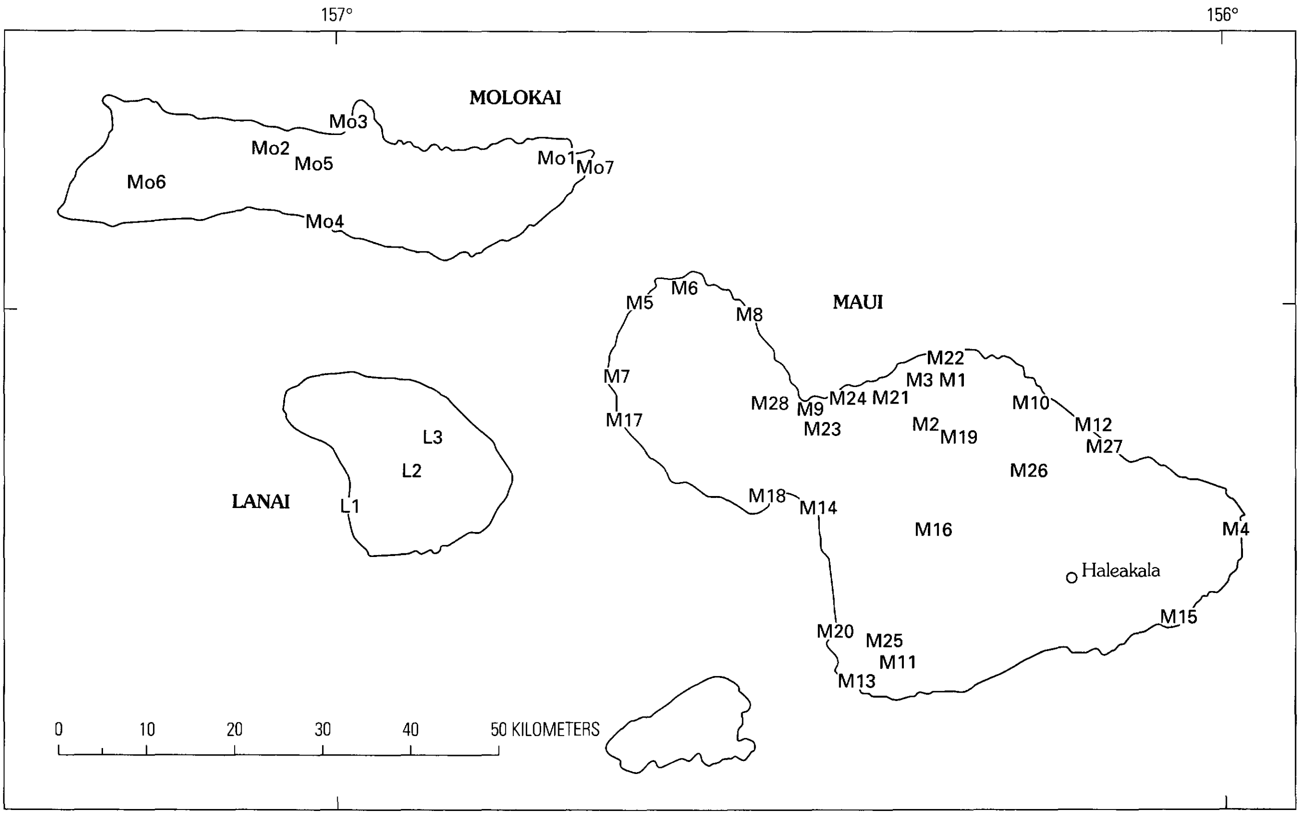

Figure A2. Map of Maui County with the islands of Maui, Molokai, and Lanai. The numbers mark locations listed in table A2.

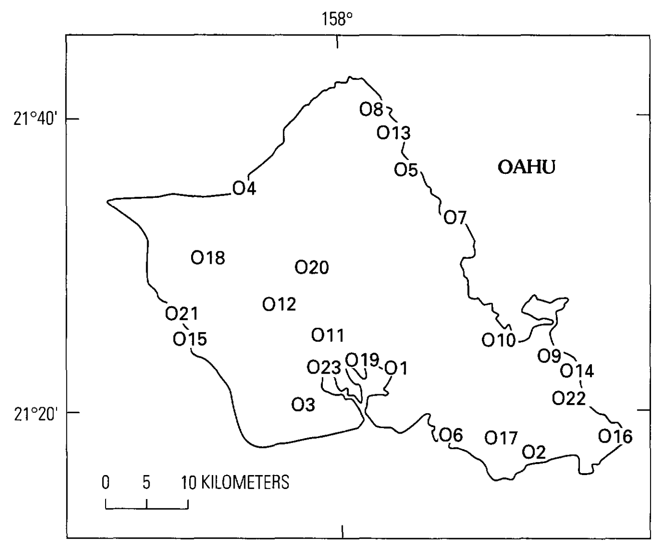

Figure A3. Map of Oahu. The numbers mark locations listed in table A3.

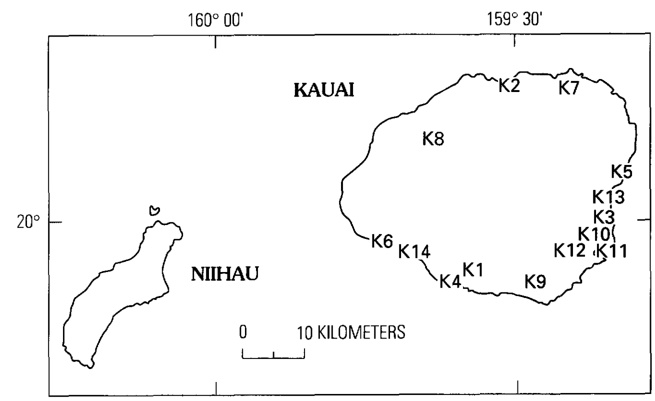

Figure A4. Map of Kauai. The numbers mark locations listed in table A4.

Table A1. Locations on Hawaii Island (County of Hawaii) by district
[Districts and locations shown in figure A1]

Hamakua		Hilo		Kau		Kohala		Kona		Puna	
H1	Apua	H11	Hakalau	H25	Ainahou Ranch	H43	Halaula	H54	Captain Cook	H71	Ainaloa
H2	Haina	H12	Hilo (city)	H26	Halape	H44	Hawi	H55	Holualoa	H72	Apua Point
H3	Honokaa	H13	Honolii	H27	Hawaii Volcanoes Nat. Park Hdqtrs.	H45	Kahua Ranch	H56	Honalo	H73	Black Sands
H4	Kukuihaele	H14	Honomu	H28	Hawaiian Ocean View Estates	H46	Kamuela (Waimea)	H57	Honaunau	H74	Glenwood
H5	Mauna Loa Obs.	H15	Kaumana	H29	Hawaiian Volcano Obs. (HVO)	H47	Kawaihae	H58	Honokohau	H75	Kaimu
H6	Ookala	H16	Kulani Project	H30	Hilina Pali	H48	Mahukona	H59	Hookena	H76	Kalapana
H7	Paauhau	H17	Laupahoehoe	H31	Honuapo	H49	Niulii	H60	Kailua	H77	Kamoamoa
H8	Paauilo	H18	Ninole	H32	Ka Lae (South Point)	H50	Pololu Valley	H61	Kainaliu	H78	Kapoho
H9	Pohakuloa	H19	Onomea	H33	Kahuku Ranch	H51	Puako	H62	Keahole Point	H79	Keaau (Olaa)
H10	Waipio Valley	H20	Papaaloa	H34	Kapapala Ranch	H52	Upolu Point	H63	Kealakekua	H80	Kealakomo
		H21	Papaikou	H35	Keaiwa	H53	Waikii	H64	Kealia	H81	Kurtistown
		H22	Pepeekeo	H36	Kilauea Military Camp			H65	Keauhou	H82	Hawaiian Beaches
		H23	Waiakea Uka	H37	Kohaahu Ninole			H66	Keokea	H83	Hawaiian Paradise Park
		H24	Wainaku	H38	Naalehu			H67	Milolii	H84	Makaopuhi Crater
				H39	Pahala			H68	Napoopoo	H85	Mountain View
				H40	Punaluu			H69	Puu Waawaa	H86	Opihikao
				H41	Waiohinu			H70	Puuanahulu	H87	Orchidland Estates
				H42	Wood Valley Camp					H88	Pahoa
										H89	Puuloa
										H90	Volcano

Table A2. Locations in the County of Maui by island
[Locations shown in figure A2]

Maui				Molokai		Lanai	
M1	Haiku	M15	Kipahulu	Mo1	Halawa	L1	Kaumalapau
M2	Haliimaile	M16	Kula	Mo2	Hoolehua	L2	Lanai City
M3	Hamakua Poko	M17	Lahaina	Mo3	Kalaupapa	L3	Maunalei Gulch
M4	Hana	M18	Maalaea	Mo4	Kaunakakai		
M5	Honokahua	M19	Makawao	Mo5	Kualapuu		
M6	Honokohau	M20	Makena	Mo6	Maunaloa		
M7	Kaenapali	M21	Paia	Mo7	Puu O Hoku		
M8	Kahakuloa	M22	Pauwela				
M9	Kahului	M23	Puunene				
M10	Kailua	M24	Spreckelsville				
M11	Kanaio	M25	Ulupalakua				
M12	Keanae	M26	Waikamoi Stream				
M13	Keoneoio	M27	Wailua				
M14	Kihei	M28	Wailuku				

Table A3. Locations on Oahu Island, County of Honolulu
[Locations shown in figure A3]

O1	Aiea	O13	Laie
O2	Aina Haina–Wailupe Gulch	O14	Lanikai
O3	Ewa	O15	Maili
O4	Haleiwa	O16	Makapuu Point
O5	Hauula	O17	Manoa
O6	Honolulu (city)	O18	Mount Kaala
O7	Kaaawa	O19	Pearl City
O8	Kahuku	O20	Wahiawa
O9	Kailua	O21	Waianae
O10	Kaneohe	O22	Waimanalo
O11	Kipapa Gulch	O23	Waipahu
O12	Kunia		

Table A4. Locations on Kauai Island
[Locations shown in figure A4]

K1	Eleele	K8	Kokee
K2	Hanalei	K9	Koloa
K3	Hanamaulu	K10	Lihue
K4	Hanapepe	K11	Nawiliwili
K5	Kapaa	K12	Puhi
K6	Kekaha	K13	Wailua
K7	Kilauea	K14	Waimea

Appendix 2—Modified Mercalli Intensity Scale

[From Richter, C.F., 1956, "Elementary seismology," San Francisco, W.H. Freeman, 768 p.]

I. Not felt. Marginal and long-period effects of large earthquakes.

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frame creak.

V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle—CFR).

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments—CFR). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations—CFR). Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Appendix 3—Macroseismic Data for Strong Hawaiian Earthquakes

Intensity (I) values are based on the Modified Mercalli Intensity Scale (MM) (Wood and Neumann, 1931; Richter, 1956) (appendix 2). The chronological listing also includes available instrumental parameters on hypocenters and magnitude (M). The macroseismic data are listed in order of decreasing intensity and alphabetically by names of places. Instrumental locations are reported as given in the original source. In the description of the damage the wording is kept close to that of the original sources (mostly newspaper accounts), except for some shortening. For locations on islands other than Hawaii the island is specified, generally in parentheses. The island is also specified if the intensities apply generally over the entire island. The code numbers in tables A1–A4 (appendix 1) refer to locations on the maps in figures A1–A4 (appendix 1). Times are Hawaiian standard time or times given by the original source.

1823 June (about 2200, date unknown)

Natives described the effects of the first known strong earthquake in Hawaii to Ellis (1827), who visited the Kaimu area 2 months after the event.

> We also examined the effects of an earthquake experienced in this place about two months before. We are informed that it took place about ten o'clock in the evening. The ground, after being agitated some minutes with a violent tremulous motion, suddenly burst open, for several miles in extent, in a direction from north by east, to south by west, and emitted, in various places at the same instant, a considerable quantity of smoke and luminous vapour, but none of the people were injured by it.
>
> A stone wall, four feet thick and six feet high, enclosing a garden at the north end of the village, was thrown down.
>
> A chasm about a foot wide marked distinctly its course; this was generally open, though in some places it seemed as if the earth had closed up again.
>
> We entered a house, sixteen feet by twelve in the inside, through which it had passed. Ten persons, viz. one man, six women, and three children, were asleep here at the time it occurred. They were living on both sides of the house, with their heads towards the centre; some of them very near the place where the ground was rent open. The trembling of the ground, they said, awoke them, but before they could think what it was that had disturbed them, the earth opened with a violent percussion; a quantity of sand and dust was thrown up with violence, and smoke and steam were at the same time emitted.
>
> After a short interval, a second percussion was felt, vapour again arose, and at the opposite end of the house to that in which they were lying, they saw a light blue flame, which almost instantly disappeared.
>
> We asked them if they were not alarmed? They said they were at first, but after remaining awake some time, and finding the shock was not repeated, they lay down and slept till morning, when they filled up the fissure with grass and earth!
>
> We examined the aperture, that still remained open at one end of the house, and found its sides perpendicular, and its breadth one foot and eleven inches. The north-west corner of the house was broken by the shock.
>
> We next traced its course through the fields of potatoes. In some places the ground seemed hardly disturbed, yet it sunk six or eight inches beneath our tread. At other places we saw apertures upwards of 2 feet wide. The potatoes that were growing immediately in the direction of the fissure, were all spoiled. Several roots of considerable size were thrown out of the ground, and, according to the representations of the natives, appeared as if they had been scorched.
>
> At the south end of the village, it had passed through a small well, in which originally there was seldom more than eighteen inches' depth of water, though since that period there has been upwards of three feet.
>
> The crack was about ten inches wide, running from north to south across the bottom of the well. The water has not only increased in quantity, but suffered a great deterioration in quality, being now very salt[y]; and its rising and falling with the ebbing and flowing of the tide, indicates its connection with the waters of the ocean, from which it is distant about 300 yards.

Kaimu IX: Ground fissures opened, native hut damaged, all people awakened, sand blows, potato roots thrown from the ground. Created permanent connection to the ocean for a previously fresh water well. A stone wall, 4 ft wide and 6 ft high, thrown down.

1834 February 19 (1800)

The first strong earthquake in Hawaii for which the effects were documented immediately in writing (Martin and others, 1979, p. 224).

> Whilst at the supper table tonight, we experienced a severe shock of earthquake. The first intimation we had of it, we heard a rustling among the thatch which was instantly followed by a heavy shaking, which lasted some seconds and abated seemingly to gather strength for a more powerful shaking. Everything seemed to be in commotion around us, and our little cottage shook so terribly that I, fearful it would be down on our heads, sprang from my chair and ran out of doors and husband followed. I looked instantly toward the houses of Mr. Dibble and Goodrich to see if they were standing, for it appeared to me that they could not stand the shock. Things standing on the bureau were upset but nothing was precipitated to the ground. The walls of Mr. Dibble's house were somewhat

injured. Mr. Goodrich's sustained no injury though it is a two story building with a cellar under the whole of it. All the cream was thrown out of the pans of milk standing in their cellar. The undulations were from north to south and lasted some seconds and were rather gentle at first. I could compare the shaking of our house to nothing but the shaking of a elephant in attempting to remove a man from his back. I was for a moment a good deal terrified, but feel that we have great occasion for gratitude of God's preserving care over us***.

Hilo V to VI: Stone walls thrown down, cream thrown off milk, small jars upset.

1838 December 12 (1300)

Hilo VI: Difficult to walk, stone walls thrown down, plaster cracked, doors and windows rattled.

1841 April 7 (2345)

Hilo VI to VII: Seams opened in the plastering of every room, whitewash thrown as much as 2 ft from the walls. Everyone awakened, house seemed to come down. Milk and water from half full pail thrown out.

1868 March 28 (1328)

Extensive damage in south Hawaii. This earthquake and the subsequent sequence of shocks for the next five days were considered foreshocks to the great earthquake on April 2. From March 28 to April 10 the aftershock activity (related to this event) was very strong. Near Kilauea and around Kapapala there were too many to count. In Kau more than 300 per day, and in Kona 50–60 per day were felt (Brigham, 1909).

Kahuku IX: A stone house and some cattle pens destroyed, stone walls flattened, chimney of mission parsonage thrown down.

Kau VIII: Stronger in Kau than in Kona. Walking was difficult.

Seemed stronger the more southward you went.

Keauhou VIII: Shocks appear to have been stronger here than at the Volcano.

Waiohinu VIII: Two houses moved from their foundations, walls of stone church cracked.

Kealakekua VII: Strongest experienced by the oldest inhabitant, portion of pali thrown down, stone walls overturned in certain places. Every 15 or 30 minutes an earthquake was felt.

Kona VII to VIII: Stone walls overthrown, masses of rock thrown off pali (cliff), buildings strained, some stone buildings rendered unsafe, people alarmed, cisterns cracked.

Kilauea VII: Volcano House. Observer swayed to and fro losing footing as on vessel's deck rolling in rough sea. Portions of Kilauea crater rim thrown down.

Hilo V: A hard shock which waked us all from sleep.

1868 April 2 (1540)

Strongest historical earthquake in Hawaii. Severe damage along the south coast of Hawaii Island from the earthquake and local tsunami. This earthquake was discussed in detail by Wood (1914) and Wyss (1988).

Description of damage is summarized in "Earthquake history of the United States" (National Oceanic and Atmospheric Administration, 1970).

Nearly every wooden house at Keiawa, Punaluu, Ninole, and beyond was knocked off its foundation or tumbled over, and straw houses with posts in the ground were torn to shreds. It shook down almost every wall in Hilo and caused landslides beyond Hilo, as far as Waipio and Hamakua. Fissures opened and brooks became muddy. In one place a fissure opened about a foot, and, when it closed, the two sides were several in. from coincidence. At Kealakekua, strong trees were bent backward and forward like reeds in a storm. At Kohala, it was reported that the force of the shock stopped all sugar mill engines, even the large 75-horsepower engine which was running at the time with a full head of steam. Ground waves estimated at 1 to 2 feet from trough to crest were observed at Kohala. The shock was strong on Maui. At Ulupalakua, the motion was so violent it was difficult to stand. On western Maui and Lanai (130 to 160 miles from the epicenter), houses shook and rocked and rumbling sounds were heard. The shock was distinctly felt on Oahu and Kauai (about 350 miles from the epicenter). Clocks stopped at Honolulu.

A tsunami struck the Kau-Puna coast, adding to the devastation. It was reported that the wave rolled in over the tops of the coconut trees, a height [estimated to be] at least 60 feet. Most houses were swept from the beach, and a number of persons were drowned. At Hilo, the height of the wave was 10 feet, and at Kealakekua, 8 feet. [The] small tsunami also was observed on Maui and Oahu.

There were extensive surface effects in the epicentral region. Fissures extended from Pahala to Kilauea. At Kahuku, a fissure nearly 3 miles long was reported. A volcanic eruption took place from this fissure on April 7. Foreshocks began on March 27. One on March 28 at 13:28 was strong enough to throw down stone walls.

Volcanic activity was induced at both Kilauea and Mauna Loa volcanoes, and significant coastal subsidence relative to sea level was observed along the Kau-Puna shoreline.

Kiolakaa XII: The southeast side and summit of the hill was thrown the distance of 1,000 ft over the top of the trees landing in the valley below, the turf covering the hill apparently undisturbed.

Keaiwa XII: Frame building thrown off foundation, racked and strained. People thrown upon the earth, where they were tossed up and down like balls. Duration estimated at 2 minutes. Animals thrown down. People found it impossible to stand, had to sit on ground bracing with hands and feet to keep from rolling over. First ground moved north to south, then east to west, then round and round, then up and down and in every direction for several minutes. "Everything crashing around us" and the trees thrashing about. In places the ground was all cracked up. Rockfalls and landslides.

Kapapala XI: The vault of the cistern was shot off like a quoit, cistern smashed totally. Landslides. All frame buildings moved off their foundations. Earth is torn up in seams in every direction.

East of Ninole Hills, Reed and Richardson's station XI: Large cistern built in solid masonry and covered with an arched stone roof was rent to pieces, and the roof was entirely broken away. Not a single stone fence left standing, flat belts of stone on the ground mark them. A good wooden frame house exhibits a wrench across its roof so that the gutters empty themselves in the sitting room. Cookhouse thrown off foundation, other outbuildings completely overturned. Large land and mudslide.

Punaluu XI: Road to Honuapo has sunk in some places. Tsunami 20 ft high. Stone church shaken down. Almost every wooden house at Punaluu, Ninole, and beyond were shot off their foundations or tumbled over.

Shore Road XI: From Puna to Kau 9 miles south of Kilauea, country was terribly rent. Travelers were obliged to deflect widely from the old track to avoid fissures. For several miles the cracks were so numerous and so wide that a stranger would be utterly unable to find his way. Animals often refused to go. Coan searched for and found evidence of eruption from 1-mile-long fissure 11 miles southwest of Kilauea.

Waiohinu XI: Roads were broken up everywhere and dangerous fissures were opened throughout the district. All in ruins, 20 lives lost. On the Waiohinu fault

> ***a crack has been opened from one to seven feet extending to the beach and mauka (landward) as far as the eye can reach.

Road cut by this was laterally displaced by width of the road.

> Our dwelling has not fallen but is a perfect wreck. We have left it.

Everyone thrown off their feet including horses and cattle.

Apua X: The sea stands some 6 ft deep where the houses once stood.

Honuapo X: The sea occupies the site of former dwellings. Tsunami 20 ft high.

Kahuku X: The walls of the great stone church were shaken down and the roof was lowered standing over the ruins. Frame buildings moved off their foundations.

Kaimu X: Coconut-palm trees now stand 8 ft deep in sand and many stand in the water.

Kalapana X: Sunk about 6 ft, water now 4–5 ft deep covers some 20 acres of what was once dry land. The old stone church is buried nearly to the eaves in sand and the tides rise and fall within it.

Kapoho to Apua X: Coastal subsidence 4–7 ft varying in different locations.

Kealakomo X: Salt works destroyed and the fountain on the shore sunk.

Keauhou X: Men were thrown off their feet and walls of stone buildings were thrown outward. In some places the ground subsided and the sea was flowing a fathom deep where houses formerly stood. Coconut trees stood 7 ft in the water.

Paliuka, near Waiohinu X: Twenty deaths due to the earthquake and thirteen due to tidal wave. Several families left Kau.

South Coast X: Most of the towns and villages were totally destroyed, but it is difficult to assign intensities because it is not known how much damage was done by the earthquake and how much by the tsunami. This is the case for Punaluu, Honuapo, Apua, Kaimu, etc.

Hilo VIII: Shook down almost every stone wall in town (even the foundation stones were moved), cracked basement of church in several places, and knocked down most brick chimneys. Knocked down sugar house chimneys on Spencer, Kaiwiki, and Onomea plantations. Many landslides between Hilo and Waipio. Loud rumbling noises. Observer felt seasick and found it difficult to stand, other thrown off his feet. Fissures opened. Frightened people ran from houses. Trees swayed like ship masts in a storm. The few stone buildings were ruined. Furniture, clocks, mirrors, and crockery was thrown down and broken. Cellar walls and underpinnings were damaged. Physician lost his stock of drugs.

Kealakekua VIII: Strong Kukui trees were bent backward and forward, stone houses thrown down, large landslides. Walls fell in all directions. No damage except to stone buildings and walls.

Kilauea VIII: The Volcano House was abandoned by the occupants but judged minimally damaged by another observer. Roads to Kau and Puna near Kilauea summit rendered impassable by large ravines. Ground rocked like ship at sea. Many rockfalls.

Off Kona Coast VIII: Whaling bark was violently shaken to unseat the captain from the rail and the jib-boom was broken from plunging into the sea.

Hamakua VII to VIII: Millions of tons of earth seen falling into the sea.

Kohala VII: Ground waves seen, hard to keep balance, all mill engines stopped, very little damage, tall chimney of sugar mill did not fall.

Kona Plantation VII: Cistern cracked. Shocks severe but less so than in Kau.

Onomea VII: Rockfall killed a woman.

Ulupalakua (Maui) VII: Very strong, duration estimated at almost 2 minutes. Water swashed over top of nearly full cistern. Difficult to stand.

Wailoa River—Hilo VII: Several fissures appeared.

> The earthquake waves all moved from southwest to northeast, and overturned objects stood at right angles with that line. A heavy bookcase***holding that relation to the wave was overturned, while another heavy case filled with shells and minerals which stood parallel to the wave remained standing.

Kawaihae VI: Duration estimated at 30 seconds. Rumbling noise heard. Rockfalls in Honopueo (Kohala) gulch. Stone walls tumbled down.

South Point, Halii VI: Many of the stone pens were not very damaged and at Kalae there was no sign of any disturbance.

Lanai Island V: People were shaken and rocked, crockery rattled in cupboards, booming sounds were heard.

West Maui (Maui) V: Room, furniture, and pictures shook and clattered. Rumbling sounds. Estimated at 90-second duration.

Honolulu (Oahu) IV to V: Felt sensibly. Light and noticed mostly by those in stone buildings. The majority did not feel it. Motion was lateral and quick. Estimated lasting 30 seconds. Clocks stopped.

Molokai Island III: Felt.

1868 April 4 (0030 and 0045)

Two earthquakes of comparable strength were reported, but their effects cannot be separated. A report from Lanai of an earthquake on April 3 at 0315 may also refer to these earthquakes (Wood, 1914).

Kawaihae VII

> They were so violent that the stone store and dwelling at the beach was abandoned.

Kealakekua VII: Described as VVH very very hard by Mr. Williamson (as reported by Wood, 1914), who gave this same classification to the shock of March 28, 1868, but to no other event.

Lahaina (Maui) VI: House shaken violently. Duration estimated as 30 seconds and exceeding 30 seconds for the two shocks, respectively. More violent than the shaking on April 2, 1868.

Lanai Island VI: (Date given as 3rd, hour as 0315). Awoke everyone, seemed to lift us up and toss us. Duration estimated at 3 minutes.

Kaneohe (Hawaii) VI: Planter rushed out to check chimney.

Hilo: Not mentioned specifically.

1868 April 30 (0615)

Kohala VI: Very severe.

Hilo IV: Felt.

Maui IV: Felt.

Honolulu (Oahu) IV: Felt.

1870 August 7 (0413)

Molokai VI: Shook crockery from shelves, rattled doors and windows, awoke people. Reported as more severe than in Oahu.

Oahu V: It woke up many from sleep. A severe shock felt in Honolulu and all over the island.

Waimea V: Strongest since April 1868, awoke people.

Hilo V: Awoke people, most protracted shaking since 1868, but it was not severe.

1871 February 19 (2205)

Lanai Island VII: Landslides, difficult to stand, stronger than 1868, duration 40 seconds.

Maui Island VII: More severe in West Maui than in East Maui (VI). At Lahaina some adobe houses in ruins, walls shattered, most stone and adobe houses seriously damaged goods thrown off shelves, fences down, clocks stopped, duration 1.5 minutes, cracks in road, sugar mill chimneys not damaged.

Molokai Island VII: Kalaupapa trail destroyed by slides and cracks in the rock, massive stone wall at Kalamaula broken down in several places, damage to houses, stonewalls, furniture, movables, duration estimated at 45 seconds.

Oahu Island VII

Ewa—Belfry of church thrown down.

Honolulu—Crockery thrown down, building wall severely damaged, one building severely damaged, none of the large buildings damaged, rocks fell on Pali Road, wall of church fell in. At least six clocks stopped. Duration estimated at 1 minute. Stone fences down. Heavy furniture displaced.

Punahou—All buildings more or less damaged, walls severely cracked, chimneys thrown down.

Waialua VI—Comparatively slight intensity (Alexander, 1871).

Kauai Island V: Felt for 30–40 seconds, no serious damage.

Hawaii Island

Kawaihae VI—Nearly all stone walls thrown down.

Hilo IV—Felt, no damage, lasted 2 minutes, its duration alarmed people. Part of the time it was quite hard, yet nothing displaced.

1872 April 22 (1630)

Hilo VI: People rushed out of doors, crockery broken, a few stone walls leveled, the backs of some water holders caved in. Noticeable to startling for people out of doors. Furniture overturned.

1874 December 29 (0430)

Hilo V: A protracted and somewhat severe shock (three separate ones).

Honolulu (Oahu) IV: Two very perceptible tremors, sleepers awakened.

1877 May 31 (0420)

Hilo VI: A severe and protracted shaking, some things thrown down and displaced, walls damaged. Two aftershocks felt.

Kohala V: A smart shock, sleepers awakened.

Maui V: A smart shock felt in some parts of Maui, sleepers awakened.

1881 September 30 (0453)

Kailua VI: Three shocks felt. Crockery damaged, some stone wall pieces thrown down; Kapalua's stone building, the church buildings and several others were cracked. People frightened.

Kona, Waimea and Manakua areas V to VI: Numerous stone walls cracked, considerable damage to crockery, several large water cisterns cracked.

Hilo V to VI: Duration almost a minute.

> Most violent shaking ever felt [since 1832] yet strange to say very few things were displaced in the house.

Honolulu (Oahu) IV to V: Pendulum clocks stopped, a roll and heaving of the earth which made some parties feel slightly disoriented. Crockery and window sashes clattered. A jar and rattle of the ground as though a great train of cars were moving past.

1885 January 13 (0630)

Laupahoehoe: Tidal wave with marks on the bluffs 20 m above sea level dislodged a large quantity of rock and earth.

Hilo IV: A hard shake more protracted than usual.

Kohala IV: More severely felt than on Oahu.

Honolulu (Oahu) III: Plainly felt.

1887 January 13 (0500)

Honolulu (Oahu) V: Rattling of small articles on shelves, banging of doors, pendulum clocks stopped, window flung open.

1887 January 17 to 22

Hawaii Island V to VI: A volcanic crisis at Mauna Loa was associated with numerous earthquakes of intensity equal to and larger than V.

1887 January 23 (1130)

Kapapala Ranch VIII: Water tanks broke, building was moved 20 cm, stone fences were thrown down.

Kahuku VII to VIII: Every house moved some in. from its foundation and the contents smashed.

Kau (throughout) VII: Stone walls leveled, the crockery in every house has ceased to exist, stove broken in pieces.

Hilo VI: Doors and windows nearly torn off their bases. Many frightened persons ran out of doors and left their houses for the night. Vases, ornaments, dishes were thrown down and broken. In stores glassware, china and bottles broken. A chimney thrown down, slight damage throughout Hilo. Clocks stopped, stoves upset, chandeliers were swinging. Awakened sleepers and kept them awake.

Pahala VI to VII: Considerable damage. Newly set timber was disrupted. Large water tank thrown down and pipes broken about the mill. Residents severely frightened.

Kohala V: No damage. People frightened.

Mauna Kea V: Felt outdoors (25 shocks counted).

Laupahoehoe IV: Felt as severe.

1888 August 20 (0735)

Hilo V: Water thrown out from vases full of flowers, milk thrown out from the pans. Many things fell down.

1890 August 6 (2310)

Kau: Reported more severe here than in Kona, with Hilo not mentioned.

Kona: Two severe shocks experienced.

Hilo V to VI: All sleepers awakened. Small things were thrown down in nearly every room. In some houses tables and pianos were moved half a foot from the wall.

1896 September 13 (0559)

Hilo VI: Dishes and bottles were thrown from shelves and tables. Hundreds of bottles of medicines and drugs broken. Statuary broken. In general store goods were upset generally. Church bells sounded. All sleepers awakened and frightened. Clocks stopped, milk was splashed out of pans, and water out of fish bowl.
Olaa (Puna) V: Sleeper awakened, caught lamp in danger of falling down.
Kohala V (?): Felt and described as severe, but no damage.
Hawaii Island (general) V (?): In all stations of Hawaii reported as severe.
Maui Island V: Same as in Hawaii and Oahu. Most severe shock in many years.
Honolulu (Oahu) IV to V: Many sleepers awakened, estimated as two shocks lasting about 20 seconds together.

1900 June 27 (0530)

Kau IV to V: Heavy.
Hilo III: Felt.

1905 May 3 (1520)

Hilo V: Damage to furniture, bric-a-brac, and china. No damage in drug store.
Volcano House (?): Break up of sulfur banks. No change in volcanic activity. Felt.

1908 September 20 (2015)

Hilo and Puna V to VI: The earthquake was violent in Hilo and Puna. In the Hilo area the shock was severest in Puueo. Crockery and bric-a-brac broken. Glass goods, liquor bottles, vases and pictures thrown down and broken. Windows broken and plaster cracked. Strong.
Kilauea: Lava dropped 100 ft 1 hour before the quake and returned to the top of the pit immediately before the shake.

1918 November 2 (2333)

"Bulletin of the Hawaiian Volcano Observatory "(Bevins and others, 1988a, p. 840, 843)

> Press reports indicate that the earthquake of 11:33 p.m. Nov. 2 was most strongly felt at Kapapala Ranch on the southeast flank of Mauna Loa 15 miles south west of this station. There was some damage done to such objects as water tanks and stone walls. The first two shocks at Hilea are reported as lasting minutes and throwing down some objects such as small bottles. Mrs. de la Nux there reports the first shock at 11:36 p.m. and three others at 11:38, 11:46, and 12 midnight. Another pronounced shock was felt at 05:01 a.m. Kona and Hilo both reported strong shocks without damage and apparently somewhat stronger effects were noted on the north flank of Mauna Kea in the line of the Mauna Loa–Mauna Kea axis. At Kilauea the earthquake was prolonged with strong east-west rocking, and numerous avalanches were started from the cliffs. The very intense initial motion lasted for about a minute. All phases of the movement were registered on different instruments in the Whitney Laboratory. Like the earthquake of June 14, 1918, this shock kept the ground in vibration as recorded seismometrically for over 40 minutes. There were recurrent intense spasms during this period and three small earthquakes during the after midnight hours. The weather was still and foggy at the time of the earthquake, strong northeast wind springing up after it. The whole occurrence strongly resembled the night shock of Oct. 25, 1913***The strong shock occurred at 11:33 p.m. Nov. 1 with a first movement west-northwest, the direction of Mokuaweoweo. The seismic swaying of the ground in waves of long period continued until 12:26 a.m. Nov. 2, fifty-three minutes. There were recurrent quick-period shocks at 11:44, 11:52, and 12:07 superposed upon the long waves. Other shocks Nov. 2 were at 02:18 a.m., 03:01 a.m., 05:00 a.m., and 06:30 p.m., and two feeble shocks. Nov. 3 there were two weak shocks; Nov. 4 two feeble spasms of trembling; Nov. 5 one very feeble spasm; Nov. 6 one spasm; Nov. 7 a sharp felt shock at 12:05 p.m.: two weak shocks in the afternoon, and two feeble spasms near midnight; Nov. 8 no earthquake.

Kapapala VII: 26 shocks counted, waterpipes broken, one stone wall shaken down for half a mile, water tanks smashed.
Kau VI: Furniture (piano) moved inches to 1 ft, everything loose thrown to ground, worst since 1887.
Kilauea VI: Very intense, initial motion 1 minute, 40 minutes of records of long periods, many aftershocks recorded.
Hilea V: Objects such as small bottles thrown down, estimated as lasting minutes.
Hilo V: Small amount of crockery broken in Japanese part of town.
Honokaa V: Frightened people.
Honokohau V: Water spilled from water tanks.
Kawaihae V: Chairs slid around, standing objects toppled, subterranean noise.
Kealakekua V: One clock stopped, people alarmed, no damage.
Mahukona V: Doors slammed, sleepers ran outside.
Napoopoo V: One clock stopped, people alarmed, no damage.
North Flank Mauna Kea V: Somewhat stronger than Kona and Hilo.
Waiakea House Lots (Hilo) V: Water tank swayed, water sloshed, but practically no damage.

Waimea V: Some sleepers ran outside, others did not wake.

Hamakua Coast IV: No damage.

Kailua-Kona IV: Strong, of swaying motion, 30 seconds.

Kona IV: Strongly felt.

Waiohinu, Naalehu, Pahala, Maili, IV to V: No damage.

North Kona III: Felt.

1919 September 14 (1720)

"Bulletin of the Hawaiian Volcano Observatory" (Bevins and others, 1988a, p. 1001)

> The principal seismo-volcanic event of importance at Kilauea Volcano during the week ending September 19, 1919, was a strong earthquake which occurred at 05:20 p.m. on September 14. This was a prolonged twisting movement felt generally throughout the Island of Hawaii and slightly felt on Maui and Oahu. The maximum damage yet reported appears to have been in the Kau section, where chimneys fell and walls cracked, making the intensity approximately No. 8 of the Rossi-Forel scale. At Hilo also, objects were thrown down and much glass broken. At Kilauea crater there was strong swaying of hanging objects and a slow cumulative twisting movement which stopped a clock having torsional pendulum escapement. Rock slides were started, notably strong at the north wall of Kilauea Iki. A fairly complete record was written by the seismographs, and as in the case of some former local earthquakes registered here, the movement of the ground continued for over an hour in slow-period swayings strongly suggesting a teleseism. A similar effect was registered by Dr. Romberg in Honolulu. That the earthquake was of deep origin was indicated by the swarm of felt after-shocks which continued, gradually decreasing, for twenty-two hours at Hilea. A second strong local shock was registered at the Observatory in the very early morning of September 18 (03:37 a.m.).

Kau VII: Chimneys fell, walls cracked, Rossi-Forel VIII, at Hilea swarm of felt aftershocks for 22 hours.

Hilo V to VI: Objects thrown down, much glass broken. Felt by all, some frightened, lumber piles fell, bottles thrown from shelves in drugstore, one plate glass window broken, clocks stopped all over city, doors opened and shut, dishes fell from cupboards and broke.

Kilauea V: Strong swaying of hanging objects, one clock stopped, rockslides, one hour of long period record, aftershocks not felt.

Hawaii Island—Regional IV to V: Felt, minor damage to all districts.

Kohala IV to V: Felt, some stonewalls fell.

Puna IV: Not sharp but strong and long.

Maui and Oahu Islands II: Slightly felt.

1924 May

Earthquake swarm associated with explosive eruption at summit of Kilauea.

1924 August 20 (0620)

"Bulletin of the Hawaiian Volcano Observatory" (Bevins and others, 1988b, p. 592)

> About 06:20 a.m. an earthquake centering near Kapapala was felt here, at Hilo, Pahala, and Kona, but not at Kapoho.

Pahala V: Dishes knocked off shelves, no real damage, felt violently.

Puueo—Hilo IV: Particularly sharp.

Hilo III: Generally rocked.

Honokaa III: Not pronounced, but felt.

Kilauea III: Felt.

Kona III to IV: Sharp.

Kapoho I: Not felt.

1926 March 19 (2230)

"Bulletin of the Hawaiian Volcano Observatory" (Bevins and others, 1988b, p. 798)

> About 10:30 p.m. a long swaying earthquake dismantled the seismographs and caused loud squawking of pheasants. The apparent distance to origin, 80 miles, corresponded to the Hawaii channel off Kohala. The earthquake was severe at Kohala and was strong enough in Hilo to knock over ink bottles at the Tribune-Herald office. The earthquake was felt at Honolulu, and was specially noticed at the Wailupe Naval Station near Koko Head, Honolulu, where also small tidal waves were reported. The following morning an aftershock was felt at Kohala.

Kohala V: Felt by nearly everyone, quite strong, extraordinary strength, shook even the strongest buildings, no damage.

Kukuihaele V: Felt by nearly all, many alarmed, duration 30 seconds.

Maui Island V: Some people were awakened by the quake and left their homes.

Hilo IV to V: Shaking a number of ink bottles off a shelf in the upper story of the Tribune building. Not strong enough to do any serious damage. Lasted about 10 seconds. Buildings swayed slightly.

Kalihi (Oahu) IV to V: Light pieces of furniture moved, rattling of windows.

Wailupe Naval Station (Oahu) IV: Especially noticed, small tidal wave.

Hamakua IV: Felt by many, loud sound.

Kohala IV: Felt by many.

Ewa (Oahu) III: Some people did, some did not feel it.
Honolulu (Oahu) III to V: Hundreds aroused from sleep, excitement but no alarm. Noticeable in hotels, but not felt by some in the streets.
HVO III: Felt.
Kona III: Weak rocking.
Hawaii Island: Generally felt in other parts of island.

1927 March 20 (0452)

"The Volcano Letter" (Fiske and others, 1987, p. 117)

> The beginning of this shock was recorded at the Hawaiian Volcano Observatory abruptly at 04:52:00 a.m. Hawaiian Standard Time. The Instruments show no preliminary phase, the motion breaking abruptly into a strong movement of about 10 millimeters per second per second acceleration. This continued for about 10 seconds, and then became stronger, dismantling the instruments, so that the maximum acceleration and the subsequent details of the shock were not recorded. The shock was perhaps the strongest and most widely felt that has occurred for a year. Reports from other islands indicate that it was felt with about the same intensity throughout the group. Its beginning was recorded in Honolulu by the seismological station of the Coast and Geodetic Survey at the University of Hawaii, at 04:51:07, reaching its maximum there as 04:51:50. That also reports a second shock at 05:59 a.m. The extent of damage in Hilo was limited to a few broken dishes and small articles thrown from shelves in various localities.
>
> The fact of its abrupt beginning, without preliminary phases, at any of the places where it was recorded in the islands, makes localization of the epicenter a difficult problem. It is worthy of note that Washington, D.C., reports an earthquake 4,800 miles away for the same morning, but the time is not given.

Some of the observations and intensities listed below are from Neumann (1931).
Hilo V: Dishes and bottles thrown from shelves, some broken. Some frightened people fled from their homes. Awakened many people.
Honokaa V: Very sharp.
Honolulu (Oahu) IV to V: Rattled dishes and windows. Guests alarmed, rushed outside, no damage, residents awakened.
Hawaii Island—Regional IV: Strongly felt all over the island.
Hilo IV: Felt by several, three clocks on higher level stopped (Neumann, 1931).
Maui Island IV: So severe that most sleepers were awakened, buildings creaked, no damage. Severest in Haiku, felt by many. In Wailuku nearly every dog in town was making itself known. In Lahaina and in west Maui generally the shock was severe, but felt not as severely in Hana.
Oahu Island IV: Roused sleepers on various points.
Other islands IV: Felt with about the same intensity throughout the group.
Volcano IV: Wilson of HVO awakened, but guests at Volcano House not disturbed.
Waiohinu IV: Felt by many, trees and poles swaying slowly, ground swaying.
Waimanalo (Oahu)IV: Felt by many, moderate sounds before shock.
Molokai Island: Felt widely.

1929 September 25 (1820), M=5.5 (NOAA)

"The Volcano Letter" (Fiske and others, 1987, p. 249)

> The development of swarms of earthquakes, as reported last week, on the west side of the island of Hawaii, has continued throughout a second week without the appearance of lava activity to date (noon, October 1). The concentration of local shaking in frequency and intensity has remained about Hualalai volcano. In general until September 26 the frequency mounted to a maximum, and thereafter it systematically declined. The intensity of individual shocks has occasionally been extremely strong between September 25 and September 30, but no shock has exceeded grade IX R.F.
>
> The strongest shock of the series to date appears to have been at 06:20 p.m. September 25, felt generally throughout the inhabited Hawaiian Islands. This inaugurated groups of heavy shocks which have occurred in west Hawaii 6:20 to 11:00 p.m. Extremely severe shocks have occurred (other than 6:20 p.m. September 25) at 10:50 a.m. September 27, 07:08 a.m. and 03:18 p.m. September 28, and 11:55 a.m. September 30. All of these have added greatly to damage of tanks, masonry, stone fences, chimneys, roadways and weak buildings on slopes. There have been numerous other wrenching shocks in the North Kona district which would rank as very strong.

Felt generally throughout the inhabited Hawaiian Islands. Entire island of Hawaii was severely shaken by a heavy earthquake at 06:20 p.m. Kona region was strongest hit. Hundreds of persons, especially in Kona, fled from their homes. In the Kona district, many houses were damaged. Water tanks, pipes and fences throughout the Kona district were demolished. Aftershocks were reported being felt about every 15 minutes in the Kona area on September 27. Magnitude 5.5 (NOAA).
Hualalai Volcano VIII: Climbers who had reached the 4,000-ft level (west side?) when the tremor occurred found stone walls and water tanks on the slopes of the mountain wrecked by the force of the earthquake.
North-central Kona VII to VIII: Houses in Holualoa, Kailua, and Keoupua were destroyed and the stone walls were knocked down. Seismograph at Kealakekua was destroyed. Stone walls, water tanks, and foundations to buildings were damaged. Old stone house in Kailua was destroyed.

Puuwaawaa VII: Landslide caused by the earthquake plunged down onto the Hind ranch house, smashing part of the foundations. All buildings in Puuwaawaa were immediately evacuated, and the occupants, fearing a larger slide, refused to return for several hours. Some spent the night outdoors, sleeping was almost impossible due to the constant trembling of the earth. Stone walls, water tanks, and foundations to buildings were damaged.

Hawi V: Many earthquakes felt in North Kohala. Since Monday there has been a steady procession of tremors, some of them heavy enough to break dishes and dissipate sleep for the residents of the district. Monday night was perhaps the worst experienced here for years, for the quakes began at 7:30 p.m. and kept up until dawn.

Hilo V: Considerable damage to crockery was reported by residents of Puueo and Waiakea.

Makawao (Maui) IV: Severe earthquake shock felt at 6:10 in the evening. Duration of the vibration about 10 seconds. No damage reported.

Oahu Island IV: The most severe earthquake shock felt in Honolulu in several years was registered by the University of Hawaii Seismograph at 18:21:30 according to Lt. J.H. Peters of the Coast and Geodetic Survey. The seismograph recorded the waves for a duration of 1 hour. The Advertiser office received felt reports from every section of Honolulu, and from Kaneohe on the windward side of Oahu. Most of those who felt the shock estimated its duration at 30 seconds. W.J. Cooper of Cooper Ranch Inn, in the Hauula district, reported two distinct shocks felt there at 6:24 in the evening. Both were slight but the first was considerably more noticeable than the second.

1929 October 5 (2122), lat 19.7° N., long 155.9° W.

"The Volcano Letter" (Fiske and others, 1987, p. 250)

> The outstanding event of the first week of October was a very strong earthquake at 9:22 p.m. October 5, 1929, which was more disastrous than the one of September 25. There is good reason for believing also that it was more intense, as its effects in cracking roadfills and overthrowing embankments at the road spurs in North Kona introduced new phenomena. For the rest, the effects on buildings extended the damage for masonry and water tanks to Waikii and Waimea, while in Kona the long siege of shaking had weakened foundation posts, walls, and tanks with some 200 shocks recorded as sharp prior to October 5. Many of these had been very hard jolts, usually with maximum fling down the mountain slopes as shown by the collapse of hundreds of stone walls in a seaward direction.
>
> Thanks to the Naval Air Service the writer inspected the districts of South Hilo, Puna, Kau, Kona, and South Kohala from an airplane at elevation 10,000 to 12,000 feet in the early morning hours of October 3, traveling approximately 160 miles from Hilo over Kilauea, across the south flank of Mauna Loa, and across the divide between Mauna Loa and Hualalai. The visibility was good, and all the upland of the three active volcanoes was revealed as showing not a trace of new outbreak. Other flights have since been made by the airmen, and the mountains have been clearly seen repeatedly including this date, October 9. Moreover the seismographs show no trace of continuous harmonic tremor, which is characteristic of fountaining lava.
>
> The big shock of October 5 was reported by an observer in Hilo as no more severe than one of an earlier date. It seemed to last fully a minute, nothing in that house was overturned, no water was spilled from a glass three-quarters filled, and the cement basement was not cracked. Cement is reported cracked in the Federal Building.
>
> In the concrete basement of the Observatory the writer perceived a long, gentle, swaying motion which dismantled the seismographs and subjected them to much strain: there was no jerking. Rocks were heard falling from the Kilauea cliffs and several fresh scars were seen on the high northwestern walls and elsewhere. One or two small cracks in the soil were reported.
>
> In Kealakekua the motion was a heavy jerk, somewhat prolonged, and applied very suddenly. Vertical retaining walls broke on the downhill side of roads and of filled land, stone houses were cracked, tanks burst or were thrown off their foundations and some weak structures collapsed. Furniture was moved and loose objects were thrown about.
>
> Puuwaawaa Ranch received the brunt of the disturbance as usual, unbraced foundation posts went over, the masonry of the basement of the main house was partly thrown down, new avalanches fell in the gulches of Puuwaawaa hill, boulder fences were generally prostrated, and a chimney stump was broken for the second time. The effects suggest Grade IX Rossi-Forel for a radius of nine miles around Puuwaawaa Hill, and Grade VIII for a radius of 20 miles around a point northeast of that hill. Grade VII appears to include the Kohala sugar district and the region of Kealakekua Bay.

North Kona—Holualoa VIII: Cracks in roadfills and road embankments overthrown at road spurs. Structural damage of masonry and water tanks. Furniture completely overturned, dishes broken, water tanks destroyed, people panicked and fled from homes, a woman knocked to the ground. Telephone poles were loosened and tipped over throughout North Kona. Water pipes broken and water ditch caved in. At Kona Hotel, guest in second floor needed to slide to ground by pole, impossible to stand on second floor.

Puuwaawaa Ranch VIII: Maximum disturbance. At ranch unbraced foundation posts went over, masonry of the basement of the main house was partly thrown down, new avalanches fell in the gulches of Puuwaawaa Hill, boulder fences were generally prostrated and chimney stump was broken for second time.

Kawaihae VII: Large crack opened near sea.

Kealakekua VII: Motion was a heavy jerk, somewhat prolonged and applied very suddenly. Vertical retaining walls broke on downhill side of roads and of filled land, stone houses were cracked, tanks burst or were thrown off their foundations, and some weak structures collapsed. Furniture moved and loose objects were thrown about.
Waimea VII: Homes suffered greatly; much damage to furniture. Chinaware destroyed and all houses suffered minor damage.
Hilo—Downtown VI: Cement reported cracked in the Federal Building. Dishes fell from shelves and people left motion-picture theater. No serious damage. Residents in all sections rushed into street. Bottles were knocked down in drugstores. Broken dishes and cracked wall plaster. At Hilo Hospital jars knocked off shelves and walls cracked.
Hilo VI

Halaulani Place—Most people left to spend the night elsewhere.

Puueo—Wallpaper cracked, many houses littered with broken articles, residents fled from buildings. Stampede in Empire Theater and Palace Theater: Some people moved beds into the open.

Hilo Harbor—Felt sharply on board: Rattling of sheds so hard people expected them to collapse.

Hilo County Jail—Prisoners frightened, those who wanted out were let out.

Honokaa VI: Tombstones were knocked over.
HVO VI: Seismographs dismantled, long swaying motion, no jerking. Rocks were heard falling from the Kilauea cliffs and several fresh scars were seen on the high northwestern caldera walls and elsewhere. One or two small cracks in the soil were reported.
Kohala VI: Greater than any previous quake, some structural damage suffered by most houses.
Volcano House VI: Panic, very severe, people rushed from their rooms.
Lanai City (Lanai) V: Force 5 on Rossi-Forel Scale.
Maui Island V: Force 5 on Rossi-Forel Scale.
Waiohinu V: Not unusually severe.
Honolulu (Oahu) IV: Some sleepers awakened but others did not feel it (see Cox, 1986a).
Waimanalo (Oahu) IV: Fairly strong, people were frightened.

1930 May 25 (2017), lat 19°25.5' N., long 155°20' W.

"The Volcano Letter" (Fiske and others, 1987, p. 283)

The moderate shock occurred at 08:17 p.m. May 25, was strongly felt all over the island, no overturning of objects has been reported, and the accounts indicate stronger motion in Kau and Puna than in Kohala and Kona. At the Kilauea Observatory (HVO) all the seismographs were dismantled, but the Uwekahuna instrument restored its pens and recorded the declining vibrations. The vertical component instrument showed a heavy downward fling as though the earthquake were epicentral at Kilauea. The first movement flung off all the pens instantly at Kilauea, but is reported to have written a short preliminary on the seismograph at Kealakekua in Kona. The first fling of the ground at Kilauea was downward to the south and east, and the restoration of the pens indicated tilt to the south and west. Keaau Beach in Puna, where the Hualalai shocks of 1929 were barely felt, perceived, this shock strongly. At a Hilo theater the motion began with a swaying, followed by strong jerks that quickly ended, first to the northeast then to the southwest. The motion was not prolonged like the Hualalai shock of October 5, 1929. Puuwaawaa reports a long vibration not particularly strong, Honokahau a moderate shock accompanied with thunderous noise, Kealakekua an alarmingly sudden quake, but without the overturning power of the Hualalai shocks. All of these facts suggest a deep movement somewhere under Kilauea and Mauna Loa.

"United States Earthquakes": Felt strongly on eastern side of Hawaii and also in Kona district to the west. A similar shock occurred May 25 at 20:17.
Keaau Beach—Puna IV: Strongly felt.
Kealakekua IV: Alarming sudden quake, nothing overturned.
Hilo III to IV: In theater swaying followed by jerks.
Kau and Puna IV: Stronger motion than in Kohala and Kona (III).
Hawaii Island III to IV: Strongly felt but no overturning of objects.
Honokohau III to IV: Moderate shock, thunderous noise.
Puu Waawaa III: Long vibration, not particularly strong.
HVO: All seismographs dismantled.

1935 January 2 (0647), lat 19°25.5' N., long 155°17' W.

"The Volcano Letter" (Fiske and others, 1987, p. 419)

Reports indicated that it was felt generally over the island of Hawaii, objects fell in Hilo, and a landslip was started in Halemaumau.

"United States Earthquakes"

Felt generally over the island of Hawaii. Smashed dishes and pictures, and started a landslip in Halemaumau.

Hilo VI: Drugstore—Broke many bottles, items off shelves. In some homes broken dished and pictures; elsewhere reported as slight IV, felt by several.
Hakalau V: Large landslides blocking road.
Kilauea V: Slides, strongest shake here and in southern part of the island.
Kona V (?): Very strong.
Volcano V: Awakened and disturbed nearly everyone.
Holualoa IV: Felt by many.
Honokaa IV: Quite strong, shaking furniture.
Honomu IV: No damage, felt by many.
Hookena IV: Moderate, felt by many.
Kau IV: Felt by many.

Puna IV: Sharply felt.
Kailua III: Slight, felt by some.
Waimea III: Less severe.
Kalapana II: Oil in lamps moved, very slight.
Kohala II: Least severe.

1935 June 28 (0900), lat 19°36' N., long 155°11' W.

"The Volcano Letter" (Fiske and others, 1987, p. 424)

A moderate to strong earthquake began to record on the Observatory seismographs. The strong motion seismograph was the only instrument on the island not dismantled. The secondary wave did the dismantling. Some damage was caused in Hilo. The selected location was on the Mauna Loa northeast rift, 19°36' N., 155°11' W., and five miles deep. It was felt generally on Hawaii.

"United States Earthquakes"

The quake did some damage in Hilo and was felt generally on Hawaii.

Hilo VI: Shifted typewriter table, desks at Hilo High School, clocks stopped, objects fell off shelves, dishes broke, two men jumped through windows, frightened many. County building rendered unsafe, plaster cracked.
Glenwood V: Broken connection from eaves to tank at one house.
Hakalau V: Felt by everyone, very strong.
Kapoho V: Unusually hard, residents ran from their homes, no damage, very hard.
Kilauea V: Slide at HVO, not severe, dismantled seismographs.
Honokaa IV: Felt generally but not especially hard.
Kohala IV: Heavier than usual, not hard enough for damage.
Kurtistown IV: Workers in the field noticed.
Kona III: Noticeable.
Puu Waawaa III: Lasted long time.
Hookena II: Slightly felt by several.

1935 November 21 (0141), lat 19°31' N., long 155°31.5' W.

"The Volcano Letter" (Fiske and others, 1987, p. 429)

A moderate earthquake was generally felt on the island of Hawaii and was reported felt at Waikiki on the island of Oahu, and at Hana on the island of Maui. It was most strongly felt at Kapapala Ranch where the shock lasted one and a half minutes, made a noise like an explosion, knocked objects from shelves, broke one window, knocked over bottles and caused a tube of toothpaste to fall into a wash basin. In the Kilauea area, people were generally awakened, pheasants called, and in one case books were reported knocked from shelves. The seismographs at all stations were dismantled. Location in NE rift of Mauna Loa five miles SW by W from the rest house at Puu Ulaula and an equal distance NE by E from the center of Mokuaweoweo Crater. This quake was evidently caused by the opening of the NE rift in this vicinity resulting in the Mauna Loa eruption which started seventeen hours later. The depth of the quake is uncertain but is estimated to be not more than five miles and was probably less.

"United States Earthquakes"

Moderate earthquake generally felt on the island of Hawaii and at some places on other islands. Broke one window at the Kapapala Ranch. Located by the Hawaiian Volcano Observatory in the northeast rift of Mauna Loa at 19°31' north, 155°31.5' west; depth probably less than 5 miles. Caused by opening of the northeast rift, which resulted in the Mauna Loa eruption 17 hours later. Further shocks of slight intensity occurred with the eruption. High seas caused some damage on the beach at about the time of the earthquake but the tide gauge record at Honolulu showed no evidence of a seismic sea wave.

Kapapala VI: Knocked over bottles, and things off shelves, broke one window.
Honomu V: Violent, lasted over a minute, no damage.
Kilauea V: People generally awakened, books fell off shelves.
Pahala V: Very sharp.
Volcano V: Rather strong, felt generally, some alarm, books off shelves, building creaking.
Hakalau IV: Severe, felt by many, lasted a few seconds.
Hookena IV: Moderate, felt by many, no alarm, building creaking.
Kamuela IV: Quite a quake. House rattled 15 seconds. No damage.
Puu Waawaa IV: Felt very strongly (stronger than any in past 2 years).
Waiohinu IV: Big.
Hilo III to IV
Halai Hill III—Slight, felt by several.
Hospital IV—Felt generally.
Oahu and Maui Islands II to III: Reported felt (see also Cox, 1986a).

1938 January 22 (2203), lat 21.2° N., long 156.1° W.

A strong submarine earthquake off the north coast of Maui was felt throughout the Hawaiian Islands and caused considerable damage on Maui. Maximum intensity was VII to VIII and damage was estimated at $150,000. A few persons were injured by landslides. The location was recalculated by Holman (1982), who estimate M=6.9.

No tsunami was generated. Tide gauge at Honolulu Pier showed no change. Also the Dollar Liner *President Coolidge*, 136 miles north of Honolulu at lat 22.53° N., long 155.19° W., felt two sharp tremors from the earthquake. Among the usual phenomena reported were flashes of light in the sky before and during the earthquake. Some reported flashes after the shock, and one observer reported a meteor fall. Earthquake lights were reported from Maui, Oahu, Molokai, and offshore Lanai. Maui residents reported three separate shakes, simultaneously with a brilliant electrical display of green light in the sky extending from Kula to Paia. One Waikiki resident who rushed out of her home at the first quake also reported flashes of light over Diamond Head in the direction of Maui. Fishermen on the windward side of Lanai reported seeing first a bright flash between Maui and Molokai seaward, then the earthquake was felt. The noise of the objects moving or falling was accompanied by barking of dogs.

The earthquake was felt on three ships in the Hawaiian waters. The liner *President Coolidge* reported two distinct and severe shocks north of Hawaii. The officers and those familiar with normal motion of the ship on the *Chichibu Maru* enroute to Honolulu from San Francisco felt the earthquake; effect on the ship according to the chief officer was as though the propellers had suddenly been thrown into reverse with engine vibration but no roll or pitching of the ship. Aboard the *Waialeale*, enroute from Nawiliwili to Honolulu, most passengers slept through the earthquake, but 9 miles east of Kauai the captain felt a sudden change in the ship's vibration.

Hana (Maui) VIII: Two large oil tanks owned by the Standard Oil Co. were shattered. Thirty thousand gallons of oil flowed into the nearby sea from the damaged tanks. Damage to the old Wanalu church, leaving the walls caved in. The quake threw the power house of the Kaeleku Sugar Co. (5 km northwest of Hana) out of commission. Several days were required to make the necessary repairs to restore electric power in the Hana area. Flashing lights were seen by many immediately after or during the earthquake, brilliant as lightning but steadier.

Kula (Maui) VII: Cracks appeared on the Haleakala road, the widest being 1.5 in. Pipe lines running in all directions were damaged. Windows were broken and walls cracked. Many vases, dishes, etc., fell from shelves. Pictures fell in a few instances. Small slides were reported on nearby roads.

Lahaina (Maui) VII: A landslide broke the intake pipe near the Lahaina River. Lahaina was without water following the rupturing of 300 ft of pipeline in a gulch back of the town. Concrete buildings in Lahaina were cracked. Some damage to fruit orchard by falling boulders, one of which penetrated a caretaker's house several in. One chimney fell and a few walls were cracked. Some plaster was thrown down. Water in aquarium spilled over and many loose objects were displaced. Chairs, pianos, and ice boxes moved 6 in. to a foot.

Maui Island VII

North coast of East Maui was probably hardest hit in the Hawaiian Islands. Landslides occurred in the Lahaina Pali section, on the road between Hono Kahua and Hono Kahu, on the Kahakuloa Road, along the Hana belt road from Kapika gulch to Waikane bridge beyond Wailua, on the Kipahulu-Kaupo trail on the Ulupalakua Road towards Kanaio, and on the road to the Waikamoi intake. In many cases the roads were blocked and emergency crews worked day and night to clear them. There were many bad cracks in the road beds all over Maui, and occasionally boulders rolled into the roads.

The Olinda reservoir was so badly cracked that its capacity dropped from 8 to 1 million gallons. The steel storage dam on the Wailuku-Kahului line was damaged. Pipelines broke and water washed out the foundation causing the tank to buckle. The Kaupo waterline was broken and buried under large slides. About 250 ft of pipe on the Lahaina intake were broken by a rockslide. The Kaupahulua water tank was demolished. There was considerable damage of similar nature at other places of the island. Residents were asked to boil water used for drinking. At Hamakua Poko some jewels and ornaments were thrown to the floor and broken. Cracks appeared in an old stone stable. There was general panic.

Pauwela Point Light (Maui) VII: At the U.S. Coast Guard reservation, a flange casting on the lantern footing cracked but the light still operated. Water tanks shifted on foundations. Keeper reported that motion was so strong he could hardly stand. Ground nearby cracked and there were some landslides.

Puuohoku Ranch (Molokai) VII: Cement floors cracked in several range buildings, and all jars, tins, etc. fell from shelves in the ranch store in all directions. Some large stones fell on nearby roads. There was general alarm.

Spreckelsville (Maui) VII: Much china and glassware was broken. Water pipes were broken and a few chimneys fell. Landslides occurred on the nearby roads. A few plate glass windows were broken. Power lines were damaged, and some bridges cracked. General alarm prevailed.

Wailuku—Kahului (Maui) VII: Water storage tanks between Wailuku and Kahului were damaged. Kahului was without water for a brief period. At Wailuku the Hollister drugstore, the Kress store, Wailuku Armory, and the Courthouse showed some damage to the interior of the buildings. In some instances plaster was shaken loose and cornices damaged. The Kress Store and Wailuku Armory were relatively new structures. Walls of the Kahului Theater were cracked by the quake, and the fire station tower was moved one-half in. Windows of the Maui Drygoods and Grocery Company in Wailuku were shattered. Crowds rushed from theaters and many left their homes, some panic stricken. The audience at the Iao Theater staged a minor panic as the quake shook the structure. The new cutoff road between Wailuku and Kahului was closed to traffic by the landslides from the sand dunes bordering the highway. Large boulders and tons of sand poured onto the road. Hundreds of persons attending the Fernandez circus remained in a "paralyzed condition" during the shock which shook the center poles of the large tent. At the Wailuku Bar, bottles were knocked from the shelves and glasses tipped from the tables. Patrons left "without the slightest delay." A new grade crossing elimination structure in Wailuku apparently settled, cracking the concrete guard rail and masonry abutment. Two fishermen were partly buried by a landslide at Maliko gulch but suffered only minor bruises.

Hilo VI: People were awakened and ran out into the streets. Only damage reported was in the Puueo area, which usually feels all earthquakes stronger than any other section of the city. In that area some homes reported that stoves and ice boxes moved as much as 2–3 in., and dishes, vases, and lamps were broken. In the Haili Hill area, another section which usually experiences strong earthquakes, it apparently was not so strongly felt this time as no damage was reported in homes.

Honolulu (Oahu) VI

A great deal of excitement occurred. Telephone communications were temporarily disrupted, as residents of the island started calling residents and friends. Light boxes and crockery were jarred from shelves. In a building of the University of Hawaii some plaster fell and old cracks appeared to have widened considerably. Some organ pipes at the Central Union Church were thrown out of their sockets, the seismographs at the University of Hawaii were dismantled. Power line on River Street was knocked down. The building housing Borthwick's Mortuary was damaged to the extent that between 45 and 50 small cracks opened up in the masonry. The building is of hollow concrete tile with reinforced concrete beams. The Aloha Tower swayed back and forth almost 3 in., pilots and other employees in the building said. Everyone in the structure dashed out at the first movement. One kamaaina, who has been through several quakes, said it probably felt like 3 ft of swaying to whoever was at the top when the temblor came.

At Oahu Prison a 4-lb strip of ceiling fell in one cell. The strip of ceiling was about an inch thick and 2 ft long by 10 in. wide. The cell was on the third floor of the jail. Waikiki Theater was completely emptied in a few minutes.

Rafters creaked and the wooden floor swayed at the Outrigger Canoe Club where a dance was in progress. It was intermission and dancers started for the stairs leading down to the ground. The shaking stopped before more than a handful had descended.

Many young people were at a dance at the Waialae Golf Club. As the roof of the pavilion rustled and shook the men and women in formal attire left the floor in masse but without running. Standing on the lawn, they watched the trembling trees and pavilion.

Honomu VI: Many dishes were broken, and china cabinets swayed as their contents crashed to the floor. A large crack appeared in the ceiling, running straight through the house from front to back in the home of John F. Ramsey, manager of the Honomu plantation. Loose objects were disturbed and a piano moved.

Kailua (Maui) VI: Some chimneys were cracked and plaster fell. A few windows were broken and concrete steps cracked.

Kalaupapa (Molokai) VI: Cracks appeared in the walls of the Kalawao Catholic church. Six breaks in 8-in. pipeline along base of Waikolu Pali (cliff) were caused by falling boulders. Several landslides were reported. There were no reports of displaced objects.

Kaneohe (Oahu) VI: Fish leaped from the water in Kaneohe Bay. A sound like the roar of many airplanes was heard. The wall of the pond quivered. The bottom trembled underfoot. Some plaster fell from buildings and dishes were broken. Droplights swayed. Many were alarmed.

Kaumalapau Harbor (Lanai) VI: There was a 2-in. crack in the breakwater 20 ft leeward of the light, accompanied by slight settling.

Kaunakakai (Molokai) VI: One steel 4-in. pipe was pulled apart at one point and damaged at several joints. Empty pop bottles fell over on floor. Felt by everyone except those in moving automobiles. School clocks stopped at 10:05.

Keanae (Maui) VI: Light fixtures swung and dishes and supplies were thrown to the floor. Stone crusher at Keanae was covered by a landslide. The Haiku-Hana road was completely blocked by a landslide at Waikane. The earthquake caused the worst slides between the CCC camp and Honomanu. The Kaupo-Kipahulu trail was blocked by a landslide.

Kihei (Maui) VI: Visible swaying of trees and general alarm, no damage.

Kipapa Gulch (Oahu) VI (?): Forty rocks rolled onto the Kamehameha Highway off a steep roadcut; the largest was about 2 ft in diameter.

Lanai City (Lanai) VI: Stock on the shelves in stores was thrown over. Bottles were thrown off shelves in a number of houses. Pictures on walls were displaced. Many rushed outdoors and there was general alarm. Some glasses were broken and chips were knocked from a few fire places. Slides generally occurred on bare spots with sparse vegetation.

Maunalei (Lanai) VI: Pipelines of the Maunalei Gulch above and below the pumphouse were broken in several places from falling rocks. A crack 10 ft wide and 15 ft deep was reported in the Maunalei region.

Makapuu Point Light and Radio Beacon Station (Oahu) VI: Several minor cracks appeared on plaster walls and two storm panes of tower lantern cracked. Everyone rushed outside.

Manoa Valley (Oahu) VI: Residents reported three separate shocks. The first at 10:03 was felt generally, another at about 10:08 was of slight effort and brief duration, and a third at 10:23 was vigorous but short. The first shock caused power lines to quiver, hedges and large trees to shake as though grasped by a giant hand, and the ground shuttered convulsively. The motion was not rolling, but a series of vigorous shocks. One resident who rushed outdoors reported power line wires and hedges vigorously shook. There was no rolling motion, but hard continuous shaking, with a thumping sensation and sound of a pneumatic drill or jackhammer. Loose objects thrown off shelves.

Molokai Island VI: Cracks opened between 2 and 3 in. in width and 25 and 100 ft in length on the east Molokai Road at Mapulehu. From Ohia to Mapulehu stone walls collapsed, otherwise damage was confined to crockery and other household possessions.

Molokai Light Station (Molokai) VI: The mechanism was deranged and the light was out about 15 minutes. One and one-half quarts of mercury were thrown out of the mercury vat. Dishes rattled. Landslides occurred about 4–5 miles southeast of station.

North Kohala VI: Small landslides occurred in roadcuts along the ocean cliffs and the Kohala Mountain road, and one crack appeared in the ground at the edge of Pololu Valley. Slight cracks appeared in one building. Some cement poles were chipped, and one old flume fell. Dishes were broken, some chandeliers fell, and refrigerator doors opened. A few were alarmed. Series of three quakes were felt at 10:03, 10:10, and 10:25.

Paia (Maui) VI

> Except for a book, a picture, a globe, and tea dishes found on the floor, and a small chip out of the concrete around the fireplace opening there were no signs of disturbance.

South Maui (Maui) VI: Ranches in southern Maui suffered heavy damage to tanks and stone walls.

Waimea (Kauai) VI: At Waimea Hotel, it was very strong and caused some damage in the cottages where loose glass objects and crockery were broken. It was described as long and strong.

Holualoa V: Strongest felt since 1929. One woman reported that it was very long with a swinging motion.

Honokaa V: Everyone was awakened but no damage was reported by police.

Kailua V: Very little disturbance at the Kona Inn; long and strong movement.

Lanikai (Oahu) V: Severe shocks which dislodged cans and bottles from shelves. Awakened people who had gone to bed.

Lihue (Kauai) V: Swaying motion was felt by many. Cracks were reported to have appeared in a plantation store.

Mahalehua V: Light objects were displaced in east-west direction; standing plates rolled east to west. A small amount of soil fell from cliffs along nearby roads.

Oahu Island V: Damage limited mainly to breakage of crockery and glassware. Hanging objects swung from ceilings and some small articles were knocked from shelves. Honolulu Board of Water Supply reported no significant damage to water supply system, except many clocks at pumping stations were stopped. No damage except loose objects moved.

Offshore north of Hawaii V: Dollar liner *President Coolidge* radioed Globe Wireless that at 10:05 p.m. H.s.t. in lat 22°53' N., long 155°19' W., two distinct shocks were recorded, lasting about 10 seconds each and spaced 30 seconds apart. Passengers on the liner called the trembler "very severe." Passengers and crew on the American steamer *Montebello* at lat 22°20' N., long 155°34' W., also felt the earthquake. Both vessels were enroute from Honolulu to California.

Olaa V: The quake was severely felt.

Wahiawa (Oahu) V: One loose object fell from molding on a wall and a few other loose objects were disturbed. Nearby all residents ran outdoors.

Waianae (Oahu) V: Severely shaken by the tremor. Storekeeper reported merchandise tumbled from the shelves to the floor.

Waimea V: A 6-in. drop cord and shade swayed about 3 in. in an east-west direction. The shock was felt by most of the population, and many rushed to the streets.

Waipahu (Oahu) V: Canned goods and other loose objects were displaced. A 6-in. pendulum clock stopped. Telephone wires swayed. Many were awakened and alarmed, but those walking outside failed to notice the shock.

Alewa Heights (Oahu) IV: Continuous motion lasting about 30 seconds with an apparent recession of the shock and a stronger continuation. No serious damage reported. Houses creaked and windows rattled.

Kapoho IV: The shocks distinctly felt. No reports of damage.

Kauai Island IV: Felt by many but no reports of damage.

Kilauea Point Light Station (Kauai) IV: Felt distinctly by the station personnel. Only a few were alarmed.

Maunalani Heights and Wilhemina Rise (Oahu) IV: Shocks were widely felt, but caused no severe damage. There was a general exodus from homes.

Naalehu IV: Moderately strong and additional quivers felt after initial shock. No damage in the Kau section.

1939 May 23 (1414), lat 19°28.5' N., long 155°22.0' W.

"The Volcano Letter" (Fiske and others, 1987, p. 464–6)

> May 15, 10:28 a.m., moderate to strong, strongly felt over entire Island of Hawaii with exception of Kohala district. Probably most strongly felt in Hilo where there was slight damage to some masonry structures plaster work. Also quite strongly felt in Hawaii National Park. Located 10.0 miles deep, 2.5 miles E. of Makaopuhi Crater. 19°22.0' N; 155°08.0' W.
>
> May 23, 02:14 p.m., moderate to strong, felt over entire Island of Hawaii and registered on University of Hawaii seismograph at 2h 16m 03s p.m. All instruments at the Observatory except the strong motion seismograph were dismantled. Subsidiary stations at Hilo, Kona on Mauna Loa, and around Kilauea Crater likewise were dismantled. Source of origin was apparently 7.5 miles NW of Kilauea

Crater from a depth of 12.0 miles, 19°28.5' N.; 155°22.0' W.

May 24, 12:59 p.m. moderate to strong. Similar to quake of preceding day in that it was felt throughout Island of Hawaii and dismantled all seismographs except strong motion instrument at the Observatory. Registered at University of Hawaii, Honolulu, "S" wave at 01h 00m 29s p.m. Location 15.0 miles deep, 2.5 miles SE of Observatory, E rim of Kilauea Crater, 19°25.0' N.; 155°14.0' W.

Kilauea V: Felt strongly, flight from buildings, objects knocked off shelves.

Hawaii Island IV: Generally reported strongly felt except in the Kohala district.

Hilo IV: Felt by many, slight alarm.

Hookena IV: Felt by many, no alarm, buildings creaked, hanging objects moved.

Kealakekua IV: Felt by many to generally.

Kohala III: Felt.

Waimea III: Felt by several, building shook distinctly, windows rattled.

Oahu Island II: Felt.

1939 July 14 (0351), lat 19°19.5' N., long 155°07.0' W.

"The Volcano Letter" (Fiske and others, 1987, p. 465–5)

Moderate to strong, 5.0 miles deep, Hilina fault system about 5.0 miles SE of Makaopuhi crater. All instruments at the Observatory were dismantled with the exception of the strong motion seismograph. The quake was generally felt on the island with the greatest intensity centered in the Kau-Puna area. Most sleepers were awakened in Hawaii National Park and in Hilo. Reported unusually strong at Pahoa.

Honokaa V: Everyone awakened.

HVO V: Felt by nearly everyone, particularly strong.

Pahoa V(?): Unusually strong.

Hamakua Coast IV: Strongly felt.

Hookena IV: Moderate, felt by many, no alarm.

Kona IV: Felt generally throughout, quite a big one.

Pahala IV: Very sharp, 10–15 seconds, moderately strong.

Hilo III to V: Hundreds awakened, doors and windows rattled, no cracks, felt by several in other locations.

Halai St.—Felt by several, duration 30 seconds.

Holualoa III: Felt by several.

Kealakekua III: About same as at Pahala by person who estimated III.

1940 June 16 (2357), lat 21.0° N., long 155.3° W., M=6

"The Volcano Letter" (Fiske and others, 1987, p. 468–12)

A strong earthquake was felt throughout Hawaiian group and particularly Hawaii, Maui, and Oahu. No damage reported. Reported as major earthquake of grade 7 by seismological laboratory of California Institute of Technology at Pasadena. All seismographs in Territory dismantled with exception of strong motion instrument at Hawaiian Volcano Observatory. Awakened most sleepers on islands referred to. Most people report roaring noise preceding felt portion. Dogs howled, pheasants squawked and loose objects in or attached to buildings rattled violently. Location as worked out in cooperation with Lt. E.O. Heaton of the U.S. Coast and Geodetic Survey in Honolulu was: depth probably normal; epicenter 21.0° N. latitude; 155.3° W. longitude. This would place epicenter approximately 85 miles N. of Hilo and 185 miles E. of Honolulu. The main shock was followed by many after shocks.

"United States Earthquakes"

Strong submarine shocks north and east of Hawaiian Islands reported felt on all islands. Epicenter, as determined with the cooperation of the Hawaiian Volcano Observatory reported 19 aftershock epicenters in the same general area through June 28. Aftershocks were felt on Hawaii, Maui, and Oahu at 07:47 and 12:39 on the 17th. Many residents of the islands were awakened by the main shock but damage was insignificant.

The earthquake was reported felt at sea by the American Steamer *Monterey* in latitude 22°27'00' north, longitude 155°45'00'' west. The ship experienced a very heavy vibration.

At Hilo, on the island of Hawaii, all residents were awakened, and small objects moved. At Kaunakakai vases overturned, glass was cracked, and water spilled from containers, Maui experienced sharp shocks, all residents being awakened, many jumping from their beds. Some medicine bottles were broken and clocks were reported stopped. On Molokai dishes were displaced and, as on the island of Lanai, all residents were awakened. On Oahu and Kauai the earthquake was generally felt and many residents were awakened. In Honolulu the intensity seemed about as great as on the islands closer to the epicenter.

Hilo V to VI: Many families ran from their houses. Windows rattled, dishes dropped from their shelves. Residents awakened. Strongest since 1938.

Lanai Island V: All residents awakened.

Maui Island V: Felt strongly (most sleepers awakened).

Molokai Island V to VI: On Molokai, dishes were displaced, and all residents awakened. At Kaunakakai, vases overturned, glass was cracked, and water spilled from containers.

Offshore V: Felt on SS *Monterey*, lat 22°27' N., long 155°45' W. Strong vibration.

Hamakua IV to V: Felt distinctly (most sleepers awaken).

HVO IV: Loose objects rattled violently.

Kau IV to V: Felt distinctly (most sleepers awaken).

Kohala IV to V: Felt distinctly (most sleepers awaken).

Kona IV to V: Felt distinctly (most sleepers awaken).

Oahu Island IV to V: Many awakened, rattled dishes and windows.

Kauai Island IV: Felt, residents awakened.

1941 September 25 (0718), lat 19°21' N., long 155°27' W., M=6.0, depth=11 km

"The Volcano Letter" (Fiske and others, 1987, p. 473–3)

> Moderate to strong, SE flank of Mauna Loa 4.0 miles north of Kapapala Ranch House, depth 7.0 miles. Felt sharply over the whole island of Hawaii and by some persons in Honolulu. Dismantled all seismographs on the island of Hawaii (low magnification instrument not in operation) and at Haleakala on Maui. Several thousand dollars worth of damage done at Pahala where safes were moved over 1 inch northward, plaster cracked, pipes were sprung, roadfills cracked and some shoulders failed, furniture overthrown and dishes were broken in homes, pharmaceuticals at the Pahala hospital, chemicals in the Pahala Sugar Laboratories and package goods in stores were thrown from shelves. Some persons were injured in flight from houses. At Kapapala Ranch two windows and many dishes were broken, several stone walls were partially thrown down. No disturbance of the sea was reported observed at Punaluu. At Kealakekua a few books were thrown from shelves but no damage was reported. Boulders were shaken loose from steep slopes at the head of Wood Valley and on Hilina Pali. Numerous slides from Halemaumau's walls caused great dust clouds, but no damage was reported in the Kilauea area. Hilo also was strongly shaken but with only slight effect; an old earthquake crack in one building reopened. Residents in the Pahala and Kapapala area were agreed that this earthquake was stronger than any since 1929 and many claimed it was the strongest in 30 to 50 years.

Kapapala VII: Several stone walls partially thrown down, dishes and windows broken, water tank fallen down.

Pahala VI: Safe moved 1 in., plaster cracked, pipes broken, furniture overthrown, dishes and bottles broken, goods thrown from shelves, people frightened ran outside, water spilled from tanks, aftershocks were felt.

Hilina Pali and Wood Valley V: Boulders shaken loose from steep slopes.

Hilo V: Strongly shaken, slight cracks in plaster, clock stopped, windows broken, furniture moved, objects overturned, felt generally.

Kau District V: Small landslides on roads.

Kealakekua V: Few books thrown from shelves, no damage.

Kilauea V: Landslides, no damage.

Puu Waawaa V: People frightened ran from house, objects fell from shelves, furniture shaken hard.

Honokaa IV: Felt by nearly everyone, building swayed strongly, objects on shelves rattled, duration 30 seconds.

Kohala IV: Felt strongly.

Naalehu and Puna IV to V: Strong.

Waiakea (Hilo) IV: Felt strongly.

Hakalau III: Felt by many.

Haleakala (Maui) III: Dismantled seismograph.

Honolulu (Oahu) II: Felt by some.

Keaukaha—Hilo II: Felt slightly or not at all.

1948 June 28 (0141), Oahu, lat 21.2° N., long 157.9° W.

Cox (1986b) estimated that the depth was shallow and the magnitude 4.8. A few of the damage and felt reports given in more detail by Cox are summarized below.

Tantalus (Honolulu, Oahu) VI: Heavy water tanks were moved from their foundations. A fireplace chimney cracked, a grand piano was moved and heavy furniture was jarred from the wall. Canned goods, dishes, chandeliers, pictures, mirrors and lamps were broken. Plumbing was jarred from its connections.

Honolulu (Oahu) V: Many residents awakened and ran into the streets, although some slept through it. Plaster cracked and windows broken in several buildings. In libraries books thrown from shelves and stacks overturned. A large clock stopped. At a museum specimens and exhibits were thrown down. At the airport a traffic controller in the tower was thrown from his chair. At Kaimuki sidewalks were cracked.

Oahu V: Broken windows, cracked foundations, loosened boulders, landslides, and water as well as telephone service interruptions.

Molokai IV: Felt as "sharp tremblor."

Hawaii II: Felt.

1950 May 29 (1516), Kona, lat 19.5° N., long 156° W., depth=8 km

"The Volcano Letter" (Fiske and others, 1987, p. 508–12)

> Widely felt, damage to water tanks, stone walls etc. in Kona

According to Fitch the location was under the southwest rift of Mauna Loa.

"United States Earthquakes"

> Strong. Origin at upper southwest rift of Mauna Loa. Hilo residents reported chinaware broken and pictures and light fixtures swayed. At Kona canned goods in several stores toppled to the floors. Three trucks rocked in a field at Papaikou. Small sections of stone around the rim of Halemaumau were shaken loose and hurtled to the bottom of the crater. Seismographs were dismantled at the Hawaiian Volcano Observatory and broken at the Konawaena station.

Captain Cook VII: Machado's store shifted approximately 1 in. from its foundation (clearly visible). Four large water tanks split open. Goods tumbled from the shelves.

Honaunau to Captain Cook VII: Cracks 1 in. wide visible along highway, and shoulders gave way.

Kona VI: Water tanks and stone walls damaged, extensive but minor damage, canned goods knocked off shelves.
Hilo V: China ware broken, pictures and lamps swinging.
Kilauea V: Small slides; dismantled seismographs at the Observatory.
Hawaii Island III to IV: Most parts of the island: clearly felt.
Kealakekua: Mechanical seismograph at Konawaena School was broken.

1951 April 22 (1452), lat 19°25' N., 155°15' W., M=6.3, depth=35 km

"The Volcano Letter" (Fiske and others, 1987, p. 512–1) contains a long description of felt effects of which a short summary is given. Strongest earthquake since 1929, and possibly since 1908, experienced in the southern part of the island of Hawaii. Uniformity of intensity over a broad area between Hilo and Naalehu indicated a focal depth of 25 to 30 miles. All seismographs of the local Hawaiian Observatory network were dismantled by the P-waves. Generally felt throughout the island of Hawaii and by many persons on the island of Maui and Oahu. Many but not all pendulum clocks were stopped. Small earth slips occurred in road cuts between Kilauea caldera and Hilo, and north of Hilo along the Hamakua Coast. Water slopped over rims of water tanks in southern parts of the island of Hawaii.

Volcano—Hawaii National Park, Kilauea Summit Region VII

> Electric power outage. At Kilauea caldera and Halemaumau, rockslides along the walls of the caldera and Halemaumau started by the terrific jolt, dust clouds generated by the rockfalls rising above the crater viewed from Volcano House. At the Volcano House, lamps and furniture were knocked down. Settling of the road bed between the Volcano House and Kilauea overlook and considerable damage to roads in the National Park. Water pipe was broken at Hawaiian Volcano Observatory. Cracks which crosses tourist area at the southeastern rim of Kilauea crater opened 6 millimeters at the time of the earthquake and 3 millimeters more during aftershocks. At Uwekahuna vault, wire suspensions on both components of semiportable tiltmeter were broken.

Glenwood VI: Plate glass window broken, earth slips along road.
Hawaii National Park—End of Mauna Loa jeep road VI: Wire suspensions for one of the masses of one component of the Hawaiian Type seismograph at Mauna Loa Station (east flank of Mauna Loa) was broken.
Hawaii National Park—Hilina Pali VI: Many slides and big rocks shaken into the sea.
Hilo VI: In downtown Hilo, plate glass seriously cracked, buildings and parked cars moved noticeably, loose items fell off shelves, plate glass window broken at 60 Waianuenue St., Hilo station (radio) went off air temporarily, golfers at the Hilo municipal golf course felt the fairways "moving," widespread reports of minor household damage. At Wainaku, several bottles were knocked off shelves at a liquor store.
Kulani Prison Camp VI: Very strong effects reported by Hilo Police Department. No specific details.
Oahu Island—Honolulu area IV: Flood of calls to the Advertiser's switchboard indicated that the tremor was strongly felt throughout Honolulu. The Royal Hawaiian Hotel switchboard rocked for almost 40 seconds. Felt reports from Woodlawn, Manoa Valley, Nuuanu Valley, and downtown Honolulu. Cox (1986a) estimated the average intensity at Honolulu as IV±one unit.
Maui Island III to IV: Felt by many persons.

1951 August 21 (0057), lat 19.5° N., long 155.95° W., M_S=6.9, depth=10 km

"The Volcano Letter" (Fiske and others, 1987, p. 513)

> Probably strongest since 1868. Felt strongly over entire island of Hawaii, and weakly by many persons on the islands of Maui, Molokai, and in Honolulu on the island of Oahu. Many aftershocks until September 6 and continuing thereafter at decreased rates. Most violent in central Kona, from Kealakekua to Hookena. Near epicenter, the initial motion was reported to be mostly up and down, with some east-west swaying. Horizontal swaying rapidly increased in intensity, and changed to somewhat vertical motion. Few persons who were awake before the earthquake reported the shaking of the ground was preceded by a dull roar that seemed to come from the ground. Observers near the epicenter reported that the shaking was almost continuous for an hour or more after the major shock.
>
> Noise during the main shock was intense. Dishes, furniture, and canned and bottled goods crashed to the floor, doors and windows rattled, water tanks collapsed, rocks rolled from stone walls and banks, and landslides and rockfalls rushed down cliffs.
>
> Within moments, several houses, churches, and a school building were partly or entirely destroyed, and many other houses slightly damaged. Water tanks collapsed, miles of stone walls were thrown down, roads partly blocked by rockslides and road pavements and shoulders badly cracked. Headstones in cemeteries were shifted or overturned, waterlines broken, and telephone and electric service disrupted. Two small fires broke out, and two persons received minor injuries from broken glass.
>
> Kona police estimated about 200 homes in the area suffered some damage. Most houses in the area near the epicenter were of frame construction, set on knee-braced timber underpinnings. Such supports were capable of undergoing the shaking and distortion without sustaining serious damage. Some houses shifted from a fraction of an inch to 3 or 4 inches on their foundations. Many were suf-

ficiently twisted to make it difficult or impossible to close windows or doors. In almost all houses dishes and other objects were thrown from shelves. Direction of maximum ground shaking and structural failure was east-west, normal to the direction of maximum slope in terrain.

The most serious damage was that to water tanks. Kona's water supply came from rain caught on roofs and stored in the tub-type wooden tanks. Of a total of more than 1,000 such tanks in the heavily shaken area, about 200 were destroyed or badly damaged. Tank damage extended from Keauhou to Milolii, but was most severe from Captain Cook to Hookena. Tanks showed all degrees of failure, from the development of slight leaks to complete collapse.

Loose stone walls were greatly damaged by the earthquake. Principle damage occurred in the area from Keauhou to 3 miles south of Hookena, and isolated instances of wall damage were observed all the way from Naalehu to Honokohau, 5 miles north to Holualoa.

Damage in cemeteries included the shifting, rotation, or overturning of headstones and the breaking of some grave caps. In cemeteries from Kealakekua to Honaunau most of the overturned headstones fell westward, though in a few cemeteries almost as many fell eastward. This was attributed to, partly to generally, the north-south orientation of the longer dimension of the bases of the terrain and the east-west direction of the shaking.

Rockslides in highway cuts in Kona were many. Most came from cuts on the inland side of the highway, probably because the cuts were higher on that side. Most slides were small with blocks less than 2 feet across, and few were larger with blocks weighing several tons. Other rock avalanches took place along steep cliffs and crater walls. Road bank cavings and pavement cracks were focused as far away as Kilauea caldera. However, most road damage was concentrated within 25 miles of the earthquake epicenter.

Minor damage extended from Holualoa, 10 miles north of the epicenter, to Pahala, 37 miles southeast. As far away as Naalehu, many dishes fell to the floor in homes, groceries and bottles toppled from shelves in stores, and the stone walls collapsed.

Responsible persons at Naalehu and Pahala reported bright flashes of white light at the time of the major earthquake. These persons believe the flashes were not the results of electric sparks that were distinctly blue rather than white caused by broken circuits, as observed by Macdonald at Naalehu.

Shortly after the mainshock, a distinct odor of hydrogen sulfide, apparently coming in intermittent waves, were reported by persons in central Kona. Source of the odor was not known. No increase in fume emission was detected by aerial observers at the vents of the 1950 lava flows on the southwest rift of Mauna Loa.

All mechanical seismographs on the island of Hawaii, except the Bosch-Omori seismograph at Whitney Laboratory were dismantled by the preliminary waves.

The direction of first ground movement was east-southeast and up at Kilauea caldera, east-northeast at Mauna Loa station, and east-northeast at Kealakekua station.

The earthquake was accompanied by a small tsunami. At Napoopoo wharf the sea water withdrew and lowered the level by about 4 feet, and then rose to about 2 feet. At Milolii wharf the water level lowered about 3 feet and then raised 3 or 4 feet above normal (floating a canoe off the beach), one large fall and rise of the water level was apparently followed by many small oscillations. The Honolulu tide-gauge showed oscillatory disturbance of the water starting at about 01:35, 38 minutes after the mainshock. Seven more oscillations were detectable, with an average period of 14 minutes and maximum crest-to-trough amplitude of 3.6 inches. Time of the beginning of the water disturbance at the Hilo harbor was about 02:38, and this late arrival was attributed to a slower average speed of wave travel along a refracted path around the island in comparatively shallow water.

Napoopoo VIII: (Note: MM intensity of IX in central Kona was estimated in "The Volcano Letter" at the time.)

Intense noise as doors and windows rattled, dishes and furniture crashed to the floor, water tanks collapsed and rocks rolled from banks and stone walls. Landslides along the burial cliff Pali Kapu to Keoua at Kealakekua Bay. A 12-ft wave caused by a cliff falling into the sea damaged a small boat dock at Napoopoo. Minor cracking of the lintels and interior plaster of Kahikolu church. In the Kahauloa area, about 1.7 miles east of Napoopoo village, the walls of a store partly collapsed as a result of distortion caused by shifting on its foundation. The warehouse of another store was badly damaged.

Along the adjacent portion of the Kealakekua faults the maximum amount of road cracks, caving of road banks, and collapse of stone walls occurred.

Road fills slipped and cracked and shoulders for long stretches had separated anywhere from 1 to 6 in. and dropped below the road as much as 8 in. in several 80-ft sections. In a spot near Machado's Store, the road surface carried a 4-in. step for about 40 ft. Four tanks at one house nearby in Captain Cook were demolished and sent their loads of water through the home of the owner.

Honaunau VIII

Failure of the underpinning at Honaunau School caused the building to collapse partly and slump to the ground, deforming the building so badly that it was considered a total loss. The failure appeared to have resulted from very inadequate bracing in an east-west direction, approximately parallel with the direction of sway during the earthquake. Road cracks and bank cave-ins and damage to stone walls were common. Overturned head stones in cemeteries.

At the ancient City of Refuge about 20 ft of the seaward side of the main outer wall of the enclosure collapsed. Damage was restricted to a reconstructed part, whereas the remaining parts of the original enclosure wall and walls of the heiau (temple) platforms were undamaged. Occasional broad slabs of rocks that extend entirely or largely through the wall and sometimes bridge open spaces beneath in the old portions of the wall were believed to be responsible for their greater resistance to earthquake damage.

A landslide opened new burial caves and swept away shrubs that had hidden others.

Hookena VIII

At Hookena beach two old frame houses were destroyed. The first collapsed when its timber underpinning failed. The second one also was dropped onto the ground by failure of its underpinning and apparently dropped straight downward. This building was somewhat twisted but not otherwise seriously damaged.

The Pukaana Church at Hookena beach was badly damaged. The building consisted of masonry walls, and a sheet-iron roof supported on heavy handhewn beams. These were supported by east-west beams resting in niches on the upper edge of the front and back walls. During the earthquake most of the front (west) wall was thrown out, some debris falling as much as 25 ft from the building. The other walls were not appreciably damaged, even the interior plaster showed little cracking.

A small building nearby, which had long been without a roof, similarly had the end walls thrown outward, to the west and east, whereas the side walls remained standing though somewhat cracked.

A church 0.6 miles north of Hookena was badly damaged. The upper parts of the eastern and western walls were thrown down and the interior plaster was cracked. The walls were built of loose stones laid together without mortar between them except near the faces where the interior and exterior plaster had penetrated a short distance.

Some road cracks, caving of road embankments, and damage to stonewalls occurred.

Hookena school was seriously damaged.

Keauhou VIII: Principal damage occurred in the area from Keauhou to 3 miles south of Hookena.

Kealakekua VII: In the church at Kealakekua, interior plaster on the eastern and western walls cracked, but the masonry showed little or no cracking. At the back of the church is a small lean-to addition, the roof of which is supported by beams with one end set into niches in the wall of the main building. During the earthquake the two parts of the building pulled the beams out of their supporting niches and allowed the roof of the addition to drop a few in. The front of the church is covered with exterior plaster that was badly cracked. St. Paul's church at Honalo, 1.9 miles north of Kealakekua suffered severe cracking of masonry in the main building and in the rectory. Considerable amount of road cracks, caving of road banks, and collapse of stone walls was reported in the area. Stone buildings at the Kona Meat Market were also badly cracked. Mutual Telephone Co. reported damage to its power system that kept south Kona telephones out most of the day and the system was not in complete operation Tuesday night. Overturned head stones in cemetery.

Holualoa VII: A toilet tank top was thrown across a bathroom. Stonewalls were damaged. Loose objects thrown from shelves.

Kealia VII: Underpinning of two houses gave way and the houses dropped to the ground. At Kaumalino, 0.3 miles south of Kealia, a shop building slumped downslope when high posts supporting it at the back gave way. This building was on timber supports level with the highway at the front, but 6 ft above ground level at the back, without adequate crossbracing. Failure of the underpinning allowed the building to tilt backward and slump to the ground. A similar situation existed at Keokea, 1.2 miles north of Kealia, where a service station building slumped downslope from the highway and partly collapsed when high posts supporting it at the back gave way.

Milolii VII: Water tanks and stonewalls damaged. Loose objects thrown off shelves.

Naalehu VII: Car driven by Gordon Macdonald (volcanologist) through Naalehu, 36 miles from the epicenter, swerved violently as though it struck deep mud on the road. Immediately afterward dead branches snapped from trees overhead and fell on the pavement. Suspended signs and electric wires swung violently, the few visible lights went out, and blue sparks from broken wires were observed. Bright flashes of white light observed at time of main shocks. Many loose objects fell from shelves, and stone walls collapsed. One house was shifted several in. off its foundation. Stone walls damaged.

Honokohau VI: Stonewalls damaged. Loose objects thrown from shelves.

Honuapo VI: Earth slide at a high road cut west of Honuapo. Damage to stonewalls. Loose objects thrown from shelves.

Volcano—Hawaii National Park VI: In the vicinity of Kilauea caldera, few objects toppled from shelves, pavements were cracked, and many landslides were started.

Waiohinu VI: Disruption of mains cut off water. Damage to stone walls. Loose objects thrown to floor.

Hamakua area V: Strongly felt. Some loose objects shaken off shelves.

Hilo V: Strongly felt. Loose objects and dishes fell off wall.

Kohala V: Strongly felt.

Pahala V: Loose objects thrown to the floor.

Puna area V: Strongly felt. Some loose objects shaken off shelves.

Maui Island IV: Felt by many residents, but no damage.

Molokai Island IV: Felt by many residents.

Oahu Island—Honolulu IV: Strong enough to awaken sleeping persons, but caused no damage. Resident in Manoa Valley reported feeling the earthquake for 10–15 seconds, along with a long low roar. Mildly felt near Makiki Fire Station (see also Cox, 1986a).

Kauai Island III: In Lihue and Koloa, slight window rattling was reported. In some cases, not recognized as an earthquake.

1952 May 23 (1213), lat 19°29' N., long 155°59' W., M_S=6.0, depth=10 km

"The Volcano Letter" (Fiske and others, 1987, p. 516–8)

Strong. Kealakekua fault, about 3.5 miles west of Napoopoo, central Kona, about 6 miles deep. Coordinates: lat 19°29' N., long 155°59' W. Magnitude 6 assigned at Pasadena, California. Felt all over island of Hawaii and on the island of Maui. Minor damage in central Kona.

Captain Cook to Napoopoo road VI: Slides blocked road, old cracks reopened, repair work undone.
Hookena VI: Underpinning of teachers cottage broken and braces cracked. Concrete floor in school cafeteria caved in at several places.
Kealakekua Bay VI (?): Two landslides, knocked out the police transmitter.
Konawaena School VI: Bottom fell out of a water tank, three were leaking badly and six others slightly damaged, stone retaining wall broken.
Kona V to VI: Merchandise swept off shelves.
Hawaii Island IV (?): Felt all over the island.
Hilo IV to V: Quite a strong one.
Maui Island III to IV: Felt all over the island.

1954 March 30 (0841), lat 19°21' N., long 155° W., M_S=6.5, depth=10 km

"The Volcano Letter" (Fiske and others, 1987, p. 523–5)

Both earthquakes were felt over the entire Island of Hawaii, and at least the second, which was the larger of the two, was felt on parts of Maui. Extensive, but mostly moderate, damage was caused in the Hilo and Puna districts. Although the shaking was most intense in the Puna district, where water tanks were thrown down and stone fences were damaged, the most spectacular damage occurred in and near Hilo, where many windows were broken and portions of a few houses were deranged or thrown down.

"United States Earthquakes"

06:40:03 and 08:41:54. Between the east rift of Kilauea and the sea near Kalapana, W. Strong. Magnitudes 6 and 6.5. Both earthquakes were felt over the entire island of Hawaii, and at least the second, which was the larger of the two, was felt on parts of Maui. Extensive, but mostly moderate, damage was caused in the Hilo and Puna districts. In the Puna district, where the shaking was more intense, water tanks were thrown down and stone fences damaged. In the Hilo district the schools were evacuated. At one school 54 windows were smashed. Walls cracked, floors buckled, pillars were knocked askew. Short circuits cut off power to some residential areas. In a rickety county building, books tumbled from shelves and plaster rained from the ceiling. Huge dust clouds rose from inside Kilauea Volcano as landslides poured down the almost perpendicular cone. A long crack opened up under the lookout position at Halemaumau, Hawaii's "drive-in volcano," where cars normally park on the rim to watch the fiery display. Several smaller aftershocks were felt in Puna and Hilo on March 30 and 31.

Downtown Hilo VII

Palace Theatre downtown—Shook down half the wall plaster.

Downtown offices and stores—Frightened people ran outdoors, buildings swayed and items were shaken off shelves.

New Tribune-Herald building at corner of Kinoole and Mamo Streets—Building swayed causing persons in newsroom to hang onto desk while light fixtures swung overhead.

Hilo High School on Waianuenue St—Heavy structural damage, plaster cracked from ceilings and walls, window panes broken, chemistry glassware broken.

Puueo-Hilo VII: Dishes rocked off shelves, floors of old houses buckled, house moved 2 in. along wooden foundations, small cracks in ground.
Hawaii National Park—Volcano VI: Crack in Chain of Craters Road. Broken water pipe at Volcano House.
Kulani Prison Camp—Near Kulani Cone VI: Bottoms dropped out from four 50,000-gallon redwood water tanks, strongest ever felt among inmates at the camp.
Kapapala Ranch V: Loose objects knocked to floor.
Keaukaha—South Hilo V: Shaken but not enough to break dishes.
Naalehu IV: Frightened resident ran out of house and felt the ground sway back and forth, lasted long, no damage.
Holualoa—Kona III: Felt gently, no damage.
Kohala III: Felt gently, no damage.
Maui Island III: Felt gently in parts of Maui.

1955 August 14 (0228), lat 19.3° N., long 155.3° W., M=6.0, depth=29 km

(Epicenter as recalculated by Eaton (1962)).
"The Volcano Letter" (Fiske and others, 1987, p. 529–12)

Strong at Uwekahuna. On the Hilina fault system south of the Volcano Observatory at a depth of about 25 kilometers. Felt over the entire island of Hawaii, on Maui, on Oahu, and by a few persons on Kauai.

"United States Earthquakes"

Epicenter 19.5° north, 155.5° west, island of Hawaii, W.V. Felt over the entire island of Hawaii, on Maui, and on Oahu, and by a few persons on Kauai. Dishes were knocked from shelves, and walls were cracked at a farm

40 miles southwest of Hilo. Origin Hilina fault south of the Volcano Observatory.

Kapapala VI: Cracked paint and plaster, a few articles knocked off shelves.
Hawaii National Park V: Awakened people generally.
Kilauea Volcano V: (Estimated by G. Macdonald.)
Hawaii Island IV: Many people roused from sleep.
Hilo IV: No reports of overturned or broken objects, felt strongly by many.
Kona and Pahoa IV: Strongly felt.
Maui and Oahu Islands III to IV: People awakened.
Kauai Island II: A few people felt it.

1957 August 18 (0042), lat 23.8° N., long 155.47° W., M=5.6

Maui and Hawaii: Felt widely.

1962 June 27 (0127), lat 19.40° N., long 155.45° W., M_S=6.1, depth=8 km

The effects of this earthquake are described in a detailed paper by Koyanagi and others (1966).
Kapapala VI: Ice box moved, drawers opened, dishes and everything fell to the floor, large kitchen appliances moved.
Pahala VI: Clock stopped, dishes fell and broke, everyone ran outdoors, heavy but no damage.
Wood Valley VI: Bottles and dishes fell from shelves.
Keaau V: Mangoes shaken off tree.
Captain Cook V: Felt by everyone, water slopped out of tanks, plants swayed, mirror fell off wall and broke. Elsewhere not felt outside walking, while noticeable indoors. Near Highway junction windows rattled, candle fell on floor, water splashed around.
Kealakekua V: Cabinet doors flew open, small items fell over, rattled windows, felt by all including people in a car, slide on pali (cliff) at Kealakekua Bay.
Laupahoehoe V: Slides.
Pohakuloa V: Very severe.
Waimea V: Water pot fell off the stove, people were frightened.
Hilo IV to VI: Jars and dishes broken in some places, things fell from shelves and tables (in some locations extensively). Felt reports range from "felt by persons at rest" and "not felt except by very few" to "quite noticeable indoors" and "very strongly felt." Windows broken, plaster chipped, water splashed out of bowl.
Holualoa IV: Felt by all, frightened.
Honokaa IV: Felt strongly by some, not by others.
Kailua IV: Water splashed out of tank.
Kohala IV: Strongest in years.
Makawao IV: Windows and doors rattled.
Mountain View IV: Felt in the area.
Naalehu IV: Rattled objects on shelves but none dislodged, felt by all, water in aquarium disturbed, very strong. Kau police station reported shock hard enough to shake desk, but nothing fell.
Pahoa IV: Felt, no breakage.
Puna IV: Felt as "very light" to "strongest in a long time," dishes rattled, 10 seconds long, thought of running outside in Mountain View area.
Waiohinu IV: Very strong.
Puuanahulu III to IV: Felt moderately by students at school.
Puunene (Maui) III: Upstairs felt and furniture trembling.
Honolulu (Oahu) II: Sitting man on seventh floor felt it, whereas standing wife did not.
Nanawale II to III: Very light.
Waiakea Village II: Felt but no one else in same house did.

1963 January 8 (0939), lat 19°23.4' N., long 155°13.1' W., M=4.6, depth=31 km.

Kulani Honor Camp V: During day felt indoors by many, outdoors by few. Building rocked and cracked, wash basin came loose. Felt like the ground would push on through floor, shook building badly.
Alae School—South Kona V: Felt quite noticeably indoors, many outdoors. Inside schoolroom, children all felt and heard it. Duration 8 seconds. Doors and windows rattled.
Hawaiian Paradise Park V: Small objects fell.
Hilo V

Halai Hill—Felt by all, 1.5-second duration.

Waianuenue—Motion seemed pulsating, pictures on north-south wall tilted at slight angle as is usual with Kilauea earthquakes. Pictures on east-west wall not shifted. Felt strongly.

Downtown—Two quakes, first stronger.

Hilo Technical School—Felt strongly.

Kamuela V: Duration estimated at 3 minutes. Rather severe. Strongly felt. Very strong, felt as though "island was sinking." Another very slight quake about 15:45.
Kukuihaele V: Felt indoors by many, outdoors by a few. Ground and house shook noticeably. Two minutes later felt a second earthquake of similar intensity as the first indoors.
Pahala V: Two quakes a few minutes apart, knocked a few things off shelves, dishes rattled.
Pahoa School V: Very severe.
Volcano V: Wall pictures shifted. Thump-bump and then shake, all fairly strong. House creaked and windows rattled. Duration about 3 seconds. Strong at Keakealani School and Volcano residential area.

Captain Cook IV: Rather good and long shake about 2 seconds. Began in the buildup, tapered down to barely nothing, and then final brief buildup. Felt quite noticeably indoors.
Kapoho IV: Rumble preceding quake.
Kaumana—Hilo IV: Felt moderately.
Kau Police Station IV: Rocked hard enough to shake desk, nothing fell. Felt in Naalehu.
Kealakekua IV: Felt quite noticeably indoors. First very slight, then 15 seconds later positively noticeable.
Laupahoehoe IV: Sharp quake followed by lesser one.
Paauhau Mill IV: Strong quake.
Puuanahulu School IV: Students felt earthquake moderately.
Maui Island III: Felt.
Oahu Island III: Felt.

1973 April 26 (1026), lat 19°52' N., long 155°09' W., M_S=6.2, depth=40 km

Felt over a very large area, from the east coast of Hawaii Island northwest through the principal islands of Maui, Kahoolawe, Lanai, Molokai, Oahu, and Kauai, a distance approximately 595 km. Property damage in and around the Hilo area was estimated at about $5.6 million. No fatalities occurred, but 11 persons were injured. Damage to buildings, roads, water, gas, and power facilities caused authorities to declare a state of emergency over most of the northeast coastal areas of the island of Hawaii. Landslides, including ground cracks from lateral displacement and local subsidence. Landslides caused damage to roads and structures over a wide area. A few buildings collapsed and many were displaced slightly on their foundations.

The following is summarized from a press report. Through the afternoon of April 27, 200 homeowners covering an area from Hilo northwest to Waimea, a distance of approximately 64 km, had reported losses exceeding $700,000. About 70 "Big Island" business firms, many of which lost their display windows, reported damage totaling $375,000. State facilities sustained at least $950,000 damage. Figures included at least $500,000 damage to four schools, which were closed temporarily.

State roads sustained more than $100,000 in damage, the heaviest damage occurred along the Laupahoehoe Gulch areas where the Belt Highway was closed at three points during most of the day on the 26th and limited to local traffic on the 27th. County losses were estimated at $893,000. County roads sustained the heaviest damage with an estimated $600,000 needed for immediate repairs: $300,000 damage to Wainaku and Kaiwiki county roads near Hilo; $15,000 in the Waimea area; $90,000 in the Hamakua district; $135,000 in North Hilo; and $60,000 elsewhere. The next highest damage were for waterworks in the Kaiwiki, Kaiele, and Papaikou areas, where 10 major problems cost $278,000 to repair. Several hundred residents north of Hilo remained without water through the 27th. Many powerlines were down between Hilo and Hakalau. The telephone company reported that the exchange at Kawailani was out of order. On the 27th, most electric, telephone, and gas services had been restored to all areas of the island except for isolated outages at Wainaku, Kaiwiki, Amauulu, and Kaumana areas. Seven major landslides occurred on the Hamakua Highway, closing off three gulches and completely cutting off the Laupahoehoe Point Beach Park. The makai (seaward) side of Waihau Lane in Puueo (Hilo) collapsed, damaging the roadway, chain-link fence, and a telephone pole and breaking a waterpipe, which sent a geyser of water into the air. Police barricaded the entrance to Wainaku Overlook because of the ever-widening cracks of 20–25 cm in the roadway. There were 46- to 68-m-long cracks in the earth along Kaiwiki Road in Wainaku.

On the Amauulu slopes, just north of the Wailuku River, an older plantation house collapsed. It was reported that 17 homes were shaken off their foundations and that 5 collapsed completely.

Haaheo, near Hilo VIII: Heavy damage to waterlines. Haaheo School was closed due to a major water leak.
Hakalau VIII: Felt by and frightened all in the community. Loud earth noises. Ground crack; landslides; water disturbed. Tombstones overturned. Electricity off; telephone out. A television fell off stand.

> Nearly every home suffered loss. We live in a sugar plantation community. The water systems were poor. Damage to our pipelines was heavy; all required repair. Residents were without water for about 4 days. Even schools were closed for 2 days owing to shortage of water. It's back to normal now (May 4). Some people are still scared, even when a small shock occurs.

Hilo VIII

Felt by and frightened all in community. Building creaked severely. Loud earth noises. Trees and bushes shook; vehicles rocked. Ground cracked; landslides occurred; water was disturbed. Chimneys, tombstones, elevated water tanks cracked, twisted, and overturned. Hanging objects swung violently. Furniture shifted and overturned. Plaster cracked, broke, and fell. Windows broke. Cement cracked.

> Many residents on this island sustained considerable damage to kitchen goods. Cabinet and refrigerator doors were opened and food was lost along with glassware and dishes.

One downtown building collapsed. Buildings cracked and shifted on foundations. The Federal Building was roped off because of wide cracks at all three levels. Hilo College buildings sustained structural damage. Damage at the Central Fire Station was estimated at $10,000; County Building, $5,000; Hilo Processing Corporation, $159,000; and Mauna Kea Sugar Company, $260,000. At Hilo Union High School, plaster fell and some acoustical panels popped open in the school's newest building; one student was hit in the head by a flying panel.

Downtown Hilo was ordered closed. One man was pinned in the rubble of the collapsed Typewriter Center. Traffic lights were knocked out. All around the block bordered by Kamehameha Avenue, Haili Street, Keawe Street, and Kalakaua Street many plate glass windows were shattered. There were no reports of damage at Hilo Airport, but cracks were observed in the airport restaurant walls. In the control tower, men were forced to hold on to a rack to keep their balance. The Malia Apartment Building (Hilo), a two-story cinder-block building, was damaged. The outside walls on the two ends of the rectangular-shaped 24-unit building were torn loose and cinder blocks fell. The tops of the building's underground cesspool collapsed, leaving a gaping hole in the ground. The Hawaiian Telephone Company building on Kinoole Street sustained structural damage. A house in the Puueo district reportedly collapsed. Damage to homes on Halaulani Street was extensive. Most homes on Halaulani Street have rock foundations. The houses were shifted several centimeters from their original locations. Most rock walls around the foundations caved in. Much fallen merchandise in stores along Puainako Street. Water pipes broke at Naniloa Hotel.

Damage at Pier 1 was estimated at $350,000 for necessary repairs alone. A 366-m-long concrete pier was split from end to end by a 1.27- to 2.54-cm-wide crack. Two other piers sustained damage to a lesser degree.

Honomu VIII: Felt by and frightened all in community. Buildings creaked very loudly. Loud earth noises. Trees and bushes shook; vehicles rocked; woman driving truck was frightened. Ground cracks; many landslides along with fallen trees; water disturbed. Many tombstones twisted and overturned. Hanging objects swung violently, north-south, and fell. Furniture moved, some broke; freezer and refrigerator moved and doors opened. Windows cracked. Plaster cracked, broke, and fell. Concrete floor cracked. Damage great.

> Many items fell from my store shelves. It took me 3 days to clean up the mess. My TV and transistor also were damaged.

Kaumana (about 8 km southwest of Hilo) VIII: The press reported heavy damage to waterlines. Some houses were shaken loose from foundations.

Ninole VIII: Felt by and frightened all in community. Trees and bushes shook; vehicles rocked. Ground cracks; landslides; water disturbed. Chimneys, tombstones, elevated water tanks cracked, twisted, and overturned. Hanging objects swung violently. Small objects shifted, overturned, and fell. Plaster cracked, broke, and fell. Damage moderate.

Ookala VIII: Felt by and awakened all in community, frightened many. Faint earth noises. Trees and bushes shook; vehicles rocked. Ground cracks, landslides, water disturbed. Chimneys, tombstones, elevated water tanks, etc., twisted and overturned. Furniture shifted. Plaster cracked. Some houses shifted slightly off foundations.

Papaaloa (north Hilo) VIII: Felt by, awakened, and frightened all in community; general panic. Loud earth noises. Trees and bushes shook; vehicles rocked. Ground cracks; landslides; water tanks cracked and overturned. Hanging objects swung violently. Furniture shifted and broke. Plaster cracked, broke, and fell. Windows cracked. Roofs leaked. Damage great.

Papaikou (about 6 km north of Hilo) VIII: Felt by, awakened, and frightened all in community. Loud earth noises. Trees and bushes shook and swayed; vehicles rocked. Ground cracks, landslides, water disturbed. Main waterline broke, cesspool caved in. All hollow-tile concrete steps crumbled and fell to the ground. Hanging objects swung violently east-west. Furniture shifted and overturned. Plaster broke and fell. Windows cracked. Foundation moved about 7.6 cm.

> Many concrete buildings had ceiling and wall cracks. Wood frame structures moved from foundations.

Damage great. The press reported some homes were shaken loose from foundations. The front door of one home came completely off and back door was damaged. One report to police stated a telephone pole was "hanging" and a water tank had collapsed. Heavy damage to waterlines. The most severe structural damage to schools occurred at Kalanianaole School at Papaikou, one of the hardest hit areas. The roof dropped 7–10 cm, and a ceiling warp appeared between the two principal sections of the main building.

Pepeekeo VIII: Felt by, awakened, and frightened all in community. Loud earth noises. Trees and bushes shook, vehicles rocked. Ground cracks, landslides, water disturbed. Chimneys, tombstones, and water tanks were shaken severely. Stone wall overturned. Hanging objects swung violently. Furniture shifted, overturned, and broke. Plaster cracked and settled. Windows cracked. Damage moderate.

Honokaa VII: Felt by all and frightened many in community. Building swayed and seemed as though it would collapse. Loud earth noises. Vehicles rocked. Ground cracks, landslides, water disturbed. Some tombstones and elevated water tanks cracked and overturned. Hanging objects swung violently. Small objects shifted, overturned, and fell in some buildings. Plaster cracked, broke, and fell in some buildings. Furniture shifted. Damage moderate. The press reported that the 3-year-old State Building had extensive interior damage. At the Honokaa School, electricity and water were off for a while, steam pot plumbing dislodged, one building was vacated temporarily owing to conspicuous looking cracks.

Kamuela VII: Loud earth noises. Ground cracks, landslides. Chimneys and tombstones cracked, twisted, and overturned.

Kapaau-Kohala VII: Felt by and frightened all in community. Building creaked loudly. Loud earth noises. Trees and bushes shook, vehicles rocked. Small objects shifted, overturned and fell. Furniture shifted. Damage slight. The press reported that the damage to the Kalahikiola Congregational Church was estimated at $75,000; to Kohala High School, $20,000; and to Mahukona Bridge (north Kohala district), $20,000. Miscellaneous damage to a number of houses in the North Kohala district was estimated at $45,000. Damage at Pololu Valley Lookout was estimated at $40,000. Rocks fell off roadways.

Keakealani—Volcano VII: School building and water tank shifted on foundation.

Laupahoehoe VII: Felt by, awakened, and frightened all in community. Loud earth noises. Small objects fell. Furniture shifted. At the Laupahoehoe School, press reported the damage to the community-school library was estimated at $25,000. Nearly all of the minor columns were split. Also, there was much shattering of glass panels facing makai (seaward).

Paauhau VII: Felt by and frightened all in the community. Loud earth noises. Trees and bushes shook, vehicles rocked. Landslides. Tombstones cracked, twisted and overturned. Hanging objects swung violently. Small objects fell. Furniture shifted. Windows cracked.

Waimea VII: In the Waimea area, road damage was estimated at $15,000. At the Waimea School, damage was estimated at $25,000, owing to broken lenses and light fixtures. A stone chimney fell through the roof at the Waimea Steakhouse. Police reported shattered glass and other minor damage at various other places, including two schools. At the Parker Ranch Shopping Center, damage to fallen merchandise was estimated at $500.

Crater Rim and Chain of Crater roads—Hawaii Volcanoes National Park VI: Cracks in upper domain widened significantly at the ledge overlooking Mauna Ulu vent. Considerable rubble in Thurston lava tube.

Halaula VI: Windows were cracked in residential houses.

Hana (Maui) VI: Landslides along steep coastline road. Old stone walls surrounding pasture crumbled. Papaya trees were knocked down in east Maui area.

Hauula (Oahu) VI: Underground pipeline broke.

Hawaii Volcanoes National Park and HVO VI: Considerable rubble fell into Thurston lava tube; required closing off tube and eruption area near Mauna Ulu to visitors. At the eruption site, crack widened significantly at the ledge overlooking Mauna Ulu vent. Landslides occurred at Kilauea caldera. There were ground cracks in the Kilauea summit area and pipes shook loose at the Hawaiian Volcano Observatory. Rocks fell off shoulders along Volcano Highway.

Keaau VI: Plaster cracked in several houses.

Kealakekua Bay VI: Rockfalls along steep coastal cliffs. Stonewalls collapsed in the Kona area.

Kurtistown VI: Strongly felt and water tank nearly overturned.

Naalehu, Pahala, Mountain View VI: Slight damage, rocks fallen onto highway, collapsed stonewalls. Ceiling panels in Mountain View school loosened.

Paauilo VI: Walls cracked and plaster fell. Moderate damage.

Pahoa VI: Damage to fallen merchandise.

Aiea-Hickam AFB, Honolulu, Kaneohe, Kaneohe Marine Corp Air Station, Waimanalo, Wahiawa, Wheeler AFB (Oahu) V: Cracks in the wall and plaster, small slides of loose rocks along highway. People were frightened, buildings were evacuated. One clock stopped.

Captain Cook, Holualoa, Honaunau, Kailua (Kona) V: Slides of loose rocks, cracks in wall plaster.

Haiku, Kahului, Kaunakakai, Kihei, Kula, Lahaina, Makawao, Mt. Haleakala Summit, Puunene, Ulupalakua, Wailuku (Maui) V: Cracks in wall plaster and plaster joints opened.

Hawi V: Plaster cracked in several homes.

Kualapuu-Kaunakakai (Molokai) V: Plaster cracked, slight damage.

Ewa, Haleiwa, Kaawa, Kahuku, Kunia, Laie, Makapuu Point, Mount Kaala, Pearl City, Wahiawa, Waianae, Waipahu (Oahu) IV: Felt by many, movement of hanging and loose objects.

Haliimaile, Kahakuloa, Makawao (Maui) IV: Felt moderately, movement of loose objects and noise.

Hanalei, Kokee Ranger Station, Puhi (Kauai) IV: Movement of loose objects and moderately felt.

Hoolehua, Kalaupapa (Molokai) IV: Movement of loose objects and creaking of house and noise from chinaware.

Lanai City (Lanai) IV: Moderately felt.

Eleele, Hanamaulu, Hanapepe, Kapaa, Kilauea, Waimea (Kauai) II to III: Felt slightly to moderately.

1974 November 30 (0354), lat 19.44° N., long 155.42° W., M_L=5.5, depth=8 km

HVO V: Felt noticeably indoors. From the sounds that were coming from the roof, the antenna was expected to come cracking down, but it didn't. Earthquake had strong vigorous action; it was the most pronounced and prolonged earthquake felt for quite sometime. Duration estimated 30 seconds (more or less). All persons awakened, and walls and furniture rattled; felt 30 seconds gentle→strong→ gentle.

Keokea V: Felt by everyone, many awakened. Awakened out of sound sleep by severe rattling of whole house—doors, windows, etc.—lasted 2–3 seconds but no damage.

Hilo IV to V

Halai Hill V—Felt by everyone, many awakened.

Waianuenue—Strongest felt for some weeks. Awakened from deep sleep; a second tremor at 04:08. Felt by everyone, many awakened.

Akolea Road, Piihonua V—Few small items fell in cupboard and on table, no damage, many aftershocks as long as 20 minutes later.

Kealakekua IV: Awakened from sleep. Heard it coming from mauka, nothing fell down, phone calls received from mauka and makai.

Hawaiian Acres—Puna IV: Vigorous shock.

Captain Cook—Kona III: Felt quite noticeably indoors. Not a hard quake but a fairly strong tremor that lasted for 4–5 seconds.

Honuapo III: Felt.

Kamuela III: Felt quite noticeably indoors. Felt two aftershocks.

Puuloa III: Strong and lasted a long time.

Naalehu III: Felt.

Waiohinu III: Felt noticeably indoors, no damage or objects moved. Was awake about to go for a drink of water, when came a sudden strong quake followed by a gradually fading tremor that lasted more than 10 seconds.

Kealakekua II: Not felt except by very few, light vibration, sound for 1–2 seconds.

1975 November 29 (0447), lat 19.34° N., long 155.04° W., M_S=7.2, depth=9 km

Largest earthquake in Hawaii since 1868. It ruptured beneath the south flank of Kilauea Volcano with the epicenter near Kalapana, causing subsidence of the south coast (fig. A5), ground rupture, a tsunami, and a small eruption at the summit of Kilauea. Damage from the earthquake and tsunami amounted to about $4 million. Two persons were killed at Halape, where the tsunami, coastal subsidence, rockfalls, and ground motion were most severe. The earthquake was preceded by a **M**=5.7 foreshock at 03:36, followed by aftershocks that continued until the major event 72 minutes later.

Numerous reports of earthquake lights from the Hilo, Puna, and Kona areas, during or immediately after the mainshock. Most people reported intense white or bluish flashes, and others saw effects of yellow, pink, greenish and orange. Most people saw the lights during the earthquake, and few saw them immediately after. Duration of the lights were mostly reported to be 1–5 seconds and some indicated about 20 seconds to more than a minute. A woman in Hilo reported,

> immediately after the very first tremor, the whole sky lighted up by a brilliantly white light, lasting probably for over 45 seconds; it took probably another 15 seconds to dim away into the distance; the farther away it went the more yellowish it became.

Unusually large numbers of aftershocks followed the Kalapana mainshock. The sequence lasted for more than a year and contained several hundred events with 3<**M**<4, many of which were felt.

The earthquake caused two deaths and more than $4 million in damage. The effects of this earthquake are described in more detail in Tilling and others (1976).

Hilina Pali and Kipuka Nene VIII: Numerous cracks, depressions, holes throughout Hilina Pali road.

Hilo V to VIII: Extensive damage in downtown area. Cracks in road, water pipes, concrete walls and floors, plaster. Cracks and floor-to-wall separations a few millimeters wide and bowing of the walls were observed in steel-reinforced concrete structures at the hospital, several schools, and libraries. Some of these buildings had 5–10-mm vertical drops in some floor sections. Churches in Hilo reported damage to a pipe organ, cracks in hollow tile blocks, breaks in a swimming pool, and waterlines. Hotels, apartments, and business buildings suffered structural and equipment damage. Shelved items in markets fell or tumbled over. Fifty-one home owners in Hilo reported loss due to broken water pipes, windows, plate glass, water gutters; cracks in concrete walls and steps; cupboards torn away from walls and breakage of chinaware; collapse of stone walls and fences; plumbing damage and cesspool cave-ins; house and garage shifting from foundation; doors and doorways distorted; leaks in roofs; minor ground cracks, chipping of ceramic tile floors; collapse of stairways; cracking or crumbling of brick fireplace chimneys (from Tilling and others, 1976).

Kaiulani St. VI—Felt strongly by all and all frightened. Overhead track lights rattled, ironing board tipped over in closet, tipped some pictures, and some canned goods moved. Many objects fell off shelves, loosened paint chips from ceilings and walls in most rooms, strong on Reed's Island area. Brick wall moved, dishes fell out of cabinets and broke. Fireplace shifted, dry wall cracked, glassware and artifacts broken, drainage pipes disturbed. Furniture and appliances moved, indoor brick barbecue separated from wall, moldings loosened, books fell off shelves, stonewall damaged outside, unable to close three doors, broken gutters. Cupboard doors flew open and objects fell from shelves. Crack in stone foundation and walls, cracks in fish pond, tipped hot water heater. Living room wall came apart, firebrick patio cracked, bottle collection and china fell and were broken.

Amauulu Rd. above Puueo VI—Felt by all and all frightened. Objects fell off shelves in bathrooms and bedrooms, food shifted and fell in kitchen. Rumbling in building followed by a jolt, canned goods fell off their stacks in shelves, masonry or plaster dust made little piles on base boards.

Civic Auditorium VI—Felt by everyone, carnival booths felt like they went up and down, lights swayed, people indoors ran outdoors, shook quite awhile.

Halai Hill VI—Felt by all and all frightened, objects thrown from shelves, furniture moved.

Kauila St. VI—Felt by all and all frightened, pictures fell off walls, items in medicine chest fell in bowl, water in vases splashed out, glasses broke on floor when doors opened in cupboard and bottles broke that fell from shelves, refrigerator opened and frozen meat and other

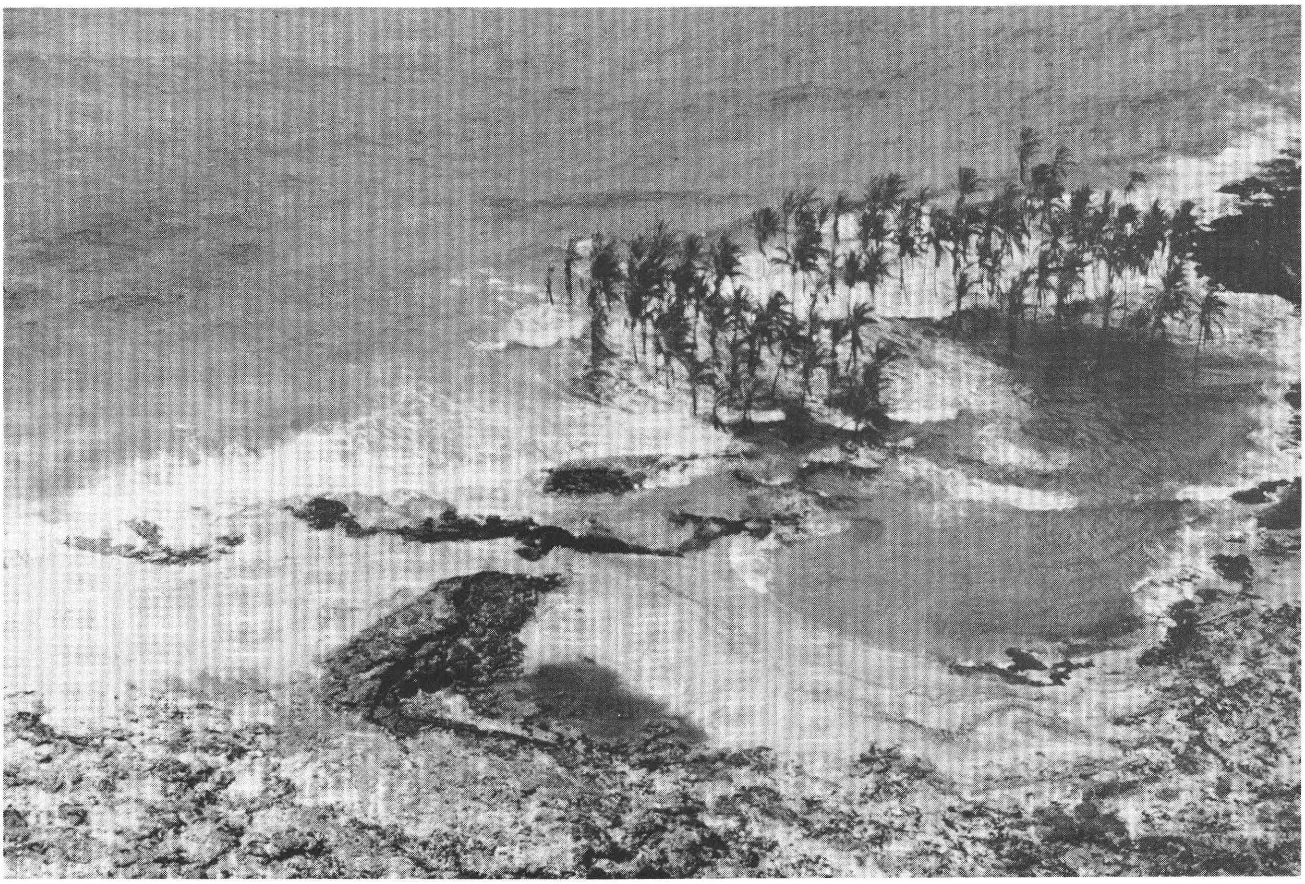

Figure A5. Coastal subsidence at Halape, south flank of Kilauea, due to the Kalapana earthquake of November 29, 1975 (M_S=7.2). Photographed by P.W. Lipman.

items fell out, books fell out of cases, stove moved 2 in. from original spot.

Makakai Pl. (Paukaa–Honolii Cove) VI—Felt by all and all frightened, in house pictures tilted, drinking glasses overturned, cupboard doors opened, broken vase, no structural damage.

Waiakea Uka VI—Felt by everyone, cars in carport were rocking back and forth.

Desha Ave. V—Felt by all, no broken objects.

Kalanianaole St. V—Felt noticeably, bottle fell over, two items fell from closet, only severe quakes felt in this area.

Keaukaha V—Felt noticeably, no broken objects.

Kinoole St. V—Felt by all and all frightened.

Kumakoa St. V—Felt by all and many frightened, shook house a moderate shake followed by a big jerk toward end, chandelier swayed for a few minutes.

Lyman Ave. V—Felt by all and all frightened, room wall swayed, closet doors rattled, clothes in closet swayed, cracking sounds in house.

Wailuku Drive V—Felt by all, few objects fell out of medicine cabinet.

Kurtistown VIII: Damage in seven residential homes: cracked concrete steps, house and garage moved from foundation, 10-cm wall separation, chinaware broken from falling out of cupboards. Rock wall damaged.

Opihikao VIII: Two water tanks at church destroyed.

Pahoa VIII: Three homes moved from foundation. Other damage included a broken waterline, collapsed water tank, and toolshed.

Volcano and Hawaii Volcanoes National Park at Kilauea VIII: Extensive ground cracking caused heavy road damage in the National Park. On the Crater Rim Road, damage was reported at Waldron Ledge, Kilauea Military Camp, Halemaumau, and Keanakakoi sections. Damage was noted on the Chain of Craters (fig. A6), Ainahou, and Hilina Pali roads. Water tank at the Youth Conservations Corps and Kipuka Nene was damaged. Waterlines in several areas broke. Fireplace chimneys at Kilauea Military Camp and at a residential home in Volcano collapsed. About three wooden water tanks were destroyed, and several others were partly damaged at Volcano. At the Volcano Observatory, violent ground motion lasted about half a minute, many

Figure A6. Damage to the Chain of Craters Road at the Hawaii Volcanoes National Park due to the Kalapana earthquake of November 29, 1975. Photographed by R. Holcomb.

loose objects moved or turned over, sounds were heard from rockfalls in crater and water sloshing in water tank.

Black Sands Subdivision VII: Damage reports from two homes. One house dropped 7.5 cm, walls cracked, loose objects fell. At other residence, water tank fell and house beams cracked.

Hawaiian Paradise Park VII: One house shifted off foundation; cabinets toppled off walls.

Kalapana VII: A wood frame house shifted 1 m from foundation. One water tank damaged. Residents reported strong shaking and loose objects falling off shelves.

Kapoho VII: Minor cracks and small rockfalls from walls of cinder cones.

Mountain View VII: Foundation of water tank cracked, Plexiglass cracked, television set shifted off stand and fell to the floor, rock wall damaged.

Pahala VII: One homeowner reported doors were distorted, house moved from concrete foundation, furniture and stereo were overturned.

Glenwood VI: Loose objects fell off shelves, water splashed out of fish bowl.

Hawaiian Beaches VI: A garage concrete slab cracked.

Honomu VI: Heavy rolling ground motion, loose objects fell off shelves, landslides.

Kulani Prison VI: No structural damage, possibly some loose objects, books, vase, fell off shelves. Several clothing cabinets held by wood screws fell off the walls.

Laupahoehoe VI: Landslides at steep roadcut along coastal road between about Laupahoehoe and Honomu. Loose objects fell off shelves in homes. Heavy rolling ground motion.

Naalehu VI: Foundation of one ranch house cracked and road damaged.

Hakalau, Honalo, Keaau, Kukuihaele, Ninole, Ookala, Paauhau, Paauilo, Papaikou, Pepeekeo, Pohakuloa Training Area V: Moderate ground shaking and unstable objects moved.

Holualoa V: Landslides reported along steep roadcuts. Hanging objects and small loose objects in homes moved.

Honokaa Police Station V: No damage, rolling sensation and few objects moved. Possibly very small cracks in hollow tile structure. Damage was considerably more following the April 1973 earthquake. Rockslides (November 29) were mostly south of Laupahoehoe-Honomu.

Hoolehua (Molokai) V: Moderate ground shaking and movement of unstable objects.

Kealakekua V: Strong shaking and rockfalls along steep cliffs at Kealakekua Bay.

Mauna Loa Observatory V: No structural damage, all equipment were in operation, no damage to water or electric lines. A few small objects moved.

Pearl City (Oahu) V: Moderate ground shaking and movement of unstable objects.

Kaaawa (Oahu) IV: Windows and doors rattled.

Kalaupapa (Molokai) IV: Windows rattled and felt by many.

Kamuela IV: Felt by many, noises heard, and loose objects shaken.

Kaunakakai (Molokai) IV: Noises heard and loose objects rattled.

Kohala—Hawi IV: Some loose objects moved, shaking felt by many people.

Kualapuu (Molokai) IV: Loose objects rattled.

Maui Island IV: Felt by many, no significant damage.

1979 September 21 (2159), lat 19°21' N., long 155°04' W., M_L=5.5, depth=9 km

Felt over the whole island of Hawaii. Most damaging earthquake since November 29, 1975. Several hundred homes in the Hilo area were damaged and several businesses suffered losses. Damage was reported heaviest in Ainako, Wainaku, and Wailuku Drive neighborhoods in Hilo. There were no reports of injuries.

Honomu VII: Living room wall separated, bedroom wall separated, patio floor cracked, garage floor cracked and separated from wall, ground on makai side of house opened up about a foot (the length of the house), lost more than 500 old bottles.

Honolii Pali VI: Woodframe residence on level ground and cinder fill: windows, doors, and dishes rattled, building creaked and shook, hanging pictures swung or fell, small objects overturned or fell, interior walls separated from ceiling or floor, exterior walls had hairline cracks.

Captain Cook V: Felt by everyone, frame house shook vigorously.

Glenwood, Laupahoehoe, Kurtistown, Mt. View, Papaikou V: Felt noticeably, movement of loose objects.

Kealakekua V: Residence felt vigorously with rumble, then vibration, then stronger vibration about three seconds in duration.

Keokea V: Woodframe house shook vigorously, felt by everyone in house.

Volcano V: Felt noticeably, sound from house, table lamp vibrated and wall rocked, pictures shifted.

Honokaa, Ninole, Keaau, Naalehu, Ookala, Pahala, Waimea IV: Noticeably felt by many, loose objects rattled.

Holualoa, Papaaloa, Kamuela, Paauhau III: Felt by persons at rest.

1982 January 21 (1152), lat 19.23° N., long 155.59° W., M_L=5.5, depth=10 km

This event caused two small landslides onto a road in Laupahoehoe Gulch and widespread minor damage in Kau area; many items were knocked from shelves and in some cases shelves were broken. Accompanying heavy rains contributed to some of the rockfalls along the Hamakua Coast; a person reported injuries when a 30-lb boulder struck his car at Kaawalii Gulch near Waipunalei while he was driving to Hilo. Several rock walls were also knocked down. Most descriptions of the effects from this earthquake were combined with a second shock from the same locality registering M_L=5.4 at 12:29. The shaking from the second event was described as not being as strong as the first one. See also Cox (1986a).

Hawaiian Ocean View Estates, Naalehu, Pahala VI: Light furniture was overturned, many small objects were overturned and fell, many dishes were broken, many items were thrown from store shelves, trees and bushes were strongly shaken, chimneys were cracked, rock walls fell, felt by all. At Kau hospital, part of the ceiling in the hallways fell, some glass broke and there were cracks in the windows. Pick 'n' Pay Supermarket in Pahala reported goods fell off shelves. Sea Mountain Resort in Punaluu reported very strong jolt and frightened visitors.

Hawi, Hilo, Honaunau, Honomu, Naalehu, Ninole, Ookala, Pepeekeo, Pohakuloa Army Training Area, Volcano, Kukuihaele, Napoopoo V: A few small objects overturned and fell, few glassware items were broken, few items were thrown from store shelves, felt by all. In Hilo, one report indicated things were falling down and people were running outside into the courtyards, buildings swayed for perhaps five minutes. There were reports of school children being excited and crawling under tables for cover. The quakes caused damage to at least one office wall in the Tribune-Herald Building. Some residents reported objects fell off shelves, liquid spilled from open vessels, furniture moved. At Kukuihaele, one house shook badly, dishes and plants in the house almost fell. At Napoopoo, dishes fell from cupboards.

Captain Cook, Hakalau, Holualoa, Keaau, Honokaa, Kapaau, Kealakekua, Laupahoehoe, Mountain View, Paauhau, Paauilo, Pahoa, Papaaloa, Papaikou,

Kalapana IV: Noticeably felt, rattling of small objects and windows. Felt by many. Loose objects displaced.
Haiku (Maui) IV: Noticeably felt, rattling of small objects and windows. Felt by many. Loose objects displaced.
Kaunakakai (Molokai) IV: Noticeably felt, rattling of small objects and windows. Felt by many. Loose objects displaced.
Honolulu, Laie (Oahu) III to IV: Felt moderately by few persons with movement of loose objects.
Kohala District IV: Mildly felt, some movement of loose objects.
Kahului, Kihei, Wailuku (Maui), Kualapuu (Molokai) III: Noticeably felt by some.
Kauai, Maui, and Oahu Islands II: Felt mildly by persons at rest (see also Cox, 1986a).

1983 November 16 (0613), lat 19.43° N., long 155.45° W., M_S=6.6 (NEIS), depth=11 km

The mainshock was centered beneath a zone of high seismicity between the active volcanoes of Hawaii, Mauna Loa, and Kilauea. Earthquake damage was estimated at $7 million. The effects of this earthquake were described by Buchanan-Banks (1987) and Koyanagi and others (1984). Seismographs at the Hawaiian Volcano Observatory recorded more than 10,000 aftershocks by the end of November. Of these, more than 800 had a magnitude of 1 or greater. The aftershock area had a radius of about 10 km. The highest accelerations recorded on strong motion equipment were at the Hawaiian Volcano Observatory and at Kau Hospital, Pahala, with peak accelerations of 0.87 and 0.59 *g*, respectively (Lum and others, 1984, updated in text table 7).

The intensities listed below were based primarily on damage to manmade structures or other works. Most of the houses in the area are of single-wall wood construction supported 2–4 ft off the ground by 4-in. by 4-in. post mounted on 16-in. by 16-in. concrete foot blocks. Homes of this type built after 1940 had a 6-in. by 6-in. concrete block between the posts and the foot block; most of these post-1940 homes were the ones damaged when they fell off the concrete blocks (Lum and others, 1984). The pre-1940 homes suffered little damage. Some houses with masonry chimneys that were anchored to the house were cracked by the movement of the chimney; anchored chimneys fell (Stover, 1987). Damage descriptions at some locations that are in Buchanan-Banks (1987) are not repeated here. A typical crack of the surface rupture is shown in text figure 53.
Hawaii Volcanoes National Park—Kilauea Summit area VIII: Substantial ground cracking and ground failures resulted in extensive road damage (fig. A7). On Crater Rim Drive damage was severe at the Waldron Ledge, Kilauea Military Camp, the Southwest Rift Zone, Keanakakoi Overlook, and Puu Puai. The main highway was damaged at the entrance of Kilauea Military Camp. Ground cracking also occurred on the Chain of Craters, Ainahou Ranch, Hilina Pali, and Mauna Loa roads. Many hiking trails were damaged by slope failures that removed parts of trails and buried other trails. Some instruments at the Hawaiian Volcano Observatory were temporarily out of order and others were damaged, books were tossed from shelves and bookcases fell over, file cabinets shifted. There was some cracking and minor offsetting of concrete foundation slabs. Dishes and loose objects on shelves fell and broke.
Kapapala Ranch VIII: Main house moved almost 17 cm off its foundation toward the southeast. Hot-water tank torn from pipes and thrown over, partly collapsed rock walls.
Volcano—Residential and farm area VIII: Houses and garages were moved off foundations as much as 1 m. Masonry was broken and house frames cracked. Carports were leaning and a few collapsed. Many water tanks were damaged and some collapsed, others were moved as much as 0.5 m and pipes were broken. Three fireplace chimneys at residential homes collapsed. Ground cracks opened about 2 cm, pavement cracks occurred, and small soil slips were observed in steep road cuts. Doors of cabinets and refrigerators opened and contents spilled out, dishes broke, objects fell off shelves, cabinets overturned. Chest drawers opened. Books fell from shelves, and furniture moved. A driver traveling northeast on Wright Road felt as if his car had a flat tire, then it turned at right angle to the road. He saw the ground undulating. Houses and farm greenhouses shifted from foundations.
Volcano Golf Course VIII

Many houses and garages were moved off their foundations toward the southwest. Hairline cracks occurred in concrete slabs. People reported difficulty in standing or walking. Water tanks moved across their gravel beds as much as 5 cm, and some of their roofs were knocked off or damaged, water sloshed out of many tanks, water heaters were moved, and PVC lines to the water tanks were snapped. Refrigerator and cupboard contents were dumped on floors, cabinet drawers opened, books and tools were thrown off shelves, television sets were overturned, and bookcases toppled. Lamps and canned goods fell to the floor. Heavier furniture moved. A kitchen counter was separated from wall. Many walls were cracked and windows broken. Wooden beams 2 in. by 4 in. and 4 in. by 4 in. cracked. Impossible to stand or walk.

Loose objects fell off shelves, items fell from cupboards and freezer, contents of closets spilled, television overturned, and books were dumped off bookshelves, large appliances moved, drywall was cracked in some places, stacked lumber was unstacked, full doughboy water tank moved about 5 cm. Felt by all and many were frightened.
Hilo VII: Extensive damage in downtown area. Minor cracks in roads and water pipes, concrete walls and floors, and plaster. Connecting pipes to an underground gasoline storage tank were ruptured. Most public buildings sustained damage to architectural plaster and acoustic-tile ceilings.

Figure A7. Damage to the Crater Rim Road due to the earthquake of November 16, 1983. Photographed by J.D. Griggs.

The public library also had plate glass windows broken. Hilo Hospital suffered structural damage, roofing, and architectural-plaster damage estimated at $250,000. Apartments and business buildings suffered structural and equipment damage. Numerous plate glass windows broke. Shelved items in markets fell or tumbled over. Homeowners reported losses because of houses and garages shifting from foundations, cracked windows, retaining walls, driveways, and concrete house pads, broken windows, water pipes, and water heater fittings, collapse of rock walls and fences, steps torn away from houses, plumbing damage and septic tank cave-ins, doorways, window frames and cupboard doors distorted, chimneys separated from walls, lightweight furniture and table lamps fell over, loose and hanging objects fell and broke. Several people experienced difficulty standing. A driver described his car trying to wander as if it had a flat tire. Another observer described undulating ground waves with crest and troughs approximately 0.3 m high and 0.5 m across.

Mauna Loa Observatory VII: Maximum acceleration of 0.59 *g* horizontal registered.

Mountain View VII: One house shifted 2 cm on its foundation piers, pulling away from back wall. A resident reported water pipe to toilet broke and fitting to water heater was damaged and leaking; water sloshed in water tank; cupboard doors opened and contents fell out; dishes and lamps broke; bookcases overturned and books were scattered; furniture was moved; loose objects tumbled off shelves. Hand-stacked rock wall collapsed in some places. A driver traveling at about 50 miles per hour uphill on Highway 11 between Mountain View and Glenwood found it impossible to maintain control of the car and reported that it felt as though the car had several flat tires. He observed two other cars coming downhill whose drivers also stopped and got out to examine their cars.

Wood Valley VII: A few wood-frame houses moved off their foundations, PVC pipes broken and minor cracks in stucco facing, almost every headstone in the cemetery was overturned. Some people ran outdoors.

Hawaiian Paradise Park VI: A few knickknacks tipped or fell, 5 percent of the water in a large pool was lost through sloshing. There was one report of a destroyed water tank.

Honaunau VI: Rocks tumbled from stone walls, houses shook vigorously, loose objects tumbled from shelves and cupboards, and some broke, bookshelves fell over, filing cabinets moved, a few water pipes were broken. Wave action was observed in a pond and a concrete water tank. Water spilled out of a toilet tank.

Honomu VI: Felt by all and all frightened. Objects fell from shelves, broken dishes and bottles.

Hualalai VI: Strong shake, movement of rocks, rockfalls in summit area.

Ka Lae VI: Part of cliff fell into ocean, a large sand hill subsided, rock walls in north-south direction were damaged. One house was moved about 1.5 m off its foundation. North of the highway, a few water pipes were broken, refrigerator doors opened and contents fell out, loose objects on shelves fell, damage to bookshelves, table lamps, and glassware, stone walls were severely damaged.

Kurtistown VI: Television, lamp, and statue fell off shelves. Dishes broke and pictures fell off wall.

Laupahoehoe VI: Landslides from slopes along the circum-island highway and on the road down to the coastal village blocked roads. Buildings swayed, cupboard doors opened and items fell out, loose objects fell from shelves and broke, items inside cabinets fell over. At the school library, ceiling tiles fell, books fell off shelves and scattered, bookcases were loosened from walls.

Pahala VI: In Kau Hospital, bookshelves fell over, ceiling panels dislodged, patients beds moved as much as 1.5 m, wall clocks dangled by wires and contents of cabinets were displaced. Dishes fell from cupboards and loose objects fell from shelves, pictures and mirrors fell from walls; bookcases, books and shelving fell; tables and floor lamps were broken as well as dishes and an aquarium. Cabinet, refrigerator, and freezer doors opened and contents fell out. Appliances and furniture moved as much as 10 cm from original locations and small appliances fell from stands. A few water heaters were knocked over and one was moved about 0.3 m and its connecting pipes were broken. At a store, 75 percent of the merchandise fell from the shelves and was damaged.

Papaikou VI: Felt by all and many were frightened. Objects fell off shelves. Walls and wall partition cracked.

Pepeekeo VI: Dishes and bottles broken. Felt by all and all frightened.

Ainaloa V: Cupboard doors opened and dishes toppled out, book shelves fell, two support beams for a deck moved 10 cm off blocks.

Captain Cook V: Lamp, vases, bottles and books fell from shelves.

Hawaiian Ocean View Estates V: Cabinets and drawers opened, objects on shelves fell to floor, rocks fell into driveway.

Hawi, Kapaau, Kamuela V: Buildings shook, rattling dishes, pictures fell, loose objects fell from shelves, hanging plants swayed.

Honokaa V: Wood-frame buildings shook severely. A few objects fell from shelves, rocks fell from roadcuts.

Keaau V: House rocked, objects on shelves and in cupboards fell over but few broke. Water sloshed out of catchment tank. Felt noticeably indoors.

Kealakekua V: Landslides from cliff into bay discolored water and caused substantial dust cloud over bay. Rock falls also occurred off slopes into some driveways. Loose objects tumbled from shelves and there was little breakage.

Kukuihaele V: Houses shook and dishes rattled, a few dishes and loose objects fell from shelves, a stone wall cracked. There was one report of house siding splitting and clocks being damaged.

Naalehu V: Table lamps, bookshelves, and knickknacks tipped over and the dishes broke; television and microwave oven were moved, water splashed out of fish tank, slight leak in water pipe.

Ninole V: Report spoke of weird rumbling noise accompanied by vigorous rolling and shaking, bottles and pictures fell.

Orchidland Estates V: Many objects on shelves fell. Nothing broken.

Paauhau V: Minor damage to objects on shelves.

Paauilo V: Some objects fell off shelves, houses shook. Driver on main highway did not feel quake while driving his truck but noted rock debris on highway.

Punaluu V: Felt by all, and some were frightened. Loose objects fell off shelves.

Maui Island IV: Felt moderately in Haiku, Kahului, Lahaina, Makawao, Wailuku, and Kihei.

Oahu Island IV: Felt generally throughout the island, no reports of damage.

Kauai Island III: Felt slightly at Kekaha and Lihue.

Molokai Island III: Several reports from Kaunakakai, Mauna Loa, and Kualapuu.

1989 June 25 (1727), lat 19.36° N., long 155.03° W., M_L=6.1, depth=9 km

Kalapana-Kaimu VI to VII: Two houses collapsed (fig. A8) with total damage, and several houses had minor damage. Ground breakage occurred with about 1-ft widening on pre-existing crack across coast road at Kalapana; inch-wide ground cracks across Chain of Craters Road about 3 km west of Kalapana (between Kalapana and Kapaahu). Strongly felt by residents and many loose objects displaced. Loose boulders displaced along embankment on highway between Kaimu and Opihikao. At a home in Kalapana Gardens objects on shelves and cabinet walked and fell down, and outdoors, stone walls collapsed and roads cracked; numerous aftershocks felt up to about 12 hours later.

Figure A8. Residential house in Kaimu, southeast flank of Kilauea, that collapsed during the earthquake of June 25, 1989 (M_L=6.1). Photographed by J.D. Griggs.

Another resident at Kalapana Gardens reported

> movement strong enough and long enough (about 20–30 seconds) that everyone ran outside, had trouble walking.

Three other residents at various houses in Kalapana Gardens reported some structural damage, loose objects knocked over and broken, cars rocked back and forth, felt aftershocks, and ran outdoors. Inland from Harry K. Brown Park (Kaimu), the corner of a house was knocked off its foundation; the resident in the house reported that the structure first started to shake, then rocked and rolled, and when the corner pier shook free from its pad the house "shook like crazy" and many objects fell from shelves and tables. Another Kaimu resident reported his house resting on 9-ft posts shook vigorously, while he was outside and his wife inside; everything fell out of the refrigerator and pictures and mirrors fell from the walls. Many of the residents in the area reported several aftershocks felt during the evening and night.

Royal Gardens Subdivision—Wahaula Visitor Center VI to VII: In Royal Gardens subdivision (west side) houses were toppled and destroyed; minor structural damage to other residential houses and loose objects displaced. As reported by an observer,

> large house on posts hurled 6-ft makai (downslope toward the sea) off its pier blocks during final seconds of long lasting quake; total loss probably; stone wall damaged.

West of Kupapau Point near oceanfront lava flow from continuing eruption of Kilauea Volcano,

> severe ground movement, some persons unable to stand, marked increase in breakout of lava activity at perimeters and on surfaces of active pahoehoe lava flows; increase in burning vegetations around flows; anomalous ocean-wave activity near lava entering sea several minutes after the earthquake, appeared as rushing current and turbulence moving along shore toward Kau (westward), 5-ft swell moving same direction.

Opihikao VI: Felt strongly, one house destroyed.

Devil's Throat (Hawaii Volcano National Park along upper Chain of Craters Road) V: Three or four rockfalls from the crater's walls.

> Ground shaking like on a boat in a harbor about 15 seconds in duration, sound like far away heavy surf after the ground shook from ESE.

Glenwood V: Felt by many and frightened. Loose objects on counter tops and shelves moved and some fell to floor, a garage post moved about 3 in.

Hamakua Coast (between Hilo to Honokaa) V: At least four landslides along coast road causing partial obstruction to traffic.

Hawaiian Paradise Park V: Resident near ocean at end of Makuu Drive

> heard steam-roller like noise 5-seconds prior to quake, and everyone ran outdoors.

On 30th Ave., between Makuu and Paradise Drives, there was

> significant swaying and creaking (wooden structure), some items fell from shelves and several glass items were broken.

Hilo area V: Strongly felt by many, some frightened and ran outdoors, loose objects in houses were displaced. Some reports of cracked wall plaster, shelves thrown open and kitchenware scattered.

> At Prince Kuhio Theaters, looking toward parking lot, all the parked cars bounced around and some looked like they might hit each other; power failure after earthquake.

At Prince Kuhio Shopping Center parking lot, a

> car shimmied, and groceries fell off shelves and power went out in Safeway.

In front of home on Ala Muku Street, the

> house shook, parked cars bounced; some contents on shelves fell off or fell over or just shifted to side and/or forward, mailbox lid flipped open; couldn't tell which way(s) the shaking was—up/down or side-to-side; across the street at neighbor's house, could hear neighbor's shrieks and breaking of china or glassware.

At upper Piihonua home, a

> few objects fell off shelves, easily perceptible sideways ground movement outside.

At home in Waikea-Uka, things fell over and light fixtures swayed. At Kaumana Terrace, house shook but no damage and nothing fell from shelves. At Nohoana Place home, they

> saw waves in the street but miraculously nothing fell off or out of any cabinet.

At Huali Place home, loose objects moved, but none fell off shelves, and dogs outdoors barked. At home on Kupualani Street

> nothing fell off shelves and hanging pictures remained straight, but cars bounced up and down and cement tub in laundry room cracked, no other damage.

In Upper Wailuku Drive home,

> hanging pictures were crooked, bottles fell, doors opened and stone chimney across the road was damaged; duration seemed very long.

Reports from a home on Laukapu Street and another on West Kawailani Street indicated strong sensation, but no objects were moved out of place. Residents on Haihai Street reported

> extremely lots of movement and objects fell.

Resident at Panaewa Farm Lot near 5-mile marker reported very noticeable movement outdoors and one small vase tipped over in house.

Keaau V: Large boulder displaced at Keaau solid-waste transfer station. Felt noticeably, new construction in framing state swayed but was not damaged. At Keaau shopping center Sure Save market, liquor bottles fell off shelves, mirrors on walls fell, much damage to goods that fell off shelves, some persons ran out of the building.

Kurtistown V: Home in Hawaiian Acres, glass fish tank fell and broke, house shifted 0.5 cm on wooden post foundation. Resident on 13-mile road reported

> broken pottery, snapped braces under house, broken windows, books fell off shelves, animals escaped from cages, and water from toilet splashed out across room.

Pahoa V: Very noticeably felt. At Pahoa Cash and Carry store

> wooden walls seemed to have sound of wood cracking, merchandise fell off shelves.

Pohoiki V: Strongly felt. Many loose objects displaced.

Volcano—Hawaii Volcano National Park (Kilauea summit area) V: Felt noticeably. Minor cracks occurred on the Volcano Road (Highway 11), and the shoulder of the road collapsed at the 29-mile marker, but the road remained passable. At Volcano Golf Course residential area, a

> house swayed strongly, motion felt more up/down, everything rattled, cats were upset, but nothing fell off shelves.

Two other residents near the golf course reported that

> house swayed smoothly with large motion, pictures tilted, hanging lamps swung but nothing fell off shelves, ladder leaning against house fell, water sloshed and stirred up sediment in outdoor water-tank, animals were excited, trees and shrubbery shook, heard rocks falling off cliff 20 ft away and large roar maybe from a landslide, outdoors towards caldera.

Shaking was from northwest to southeast with rolling motion (not sharp jolts) felt for 15–20 seconds. Resident near Volcano village reported long-period rolling motion lasting 1–2 minutes felt by, and frightened, all in the household. At the Hawaiian Volcano Observatory, people

> heard deep rumbling sound possibly from movement of building joists, felt irregular rolling motion, relatively long-period seismic waves, lights in the lobby shook violently for about a minute, gauge on main water-tank next to parking lot still moving up and down within a 3–4 point interval about 10–15 minutes after the mainshock.

At a Park residential house, strong shaking up and down movement lasted 30 seconds to a minute but nothing fell off shelves. At two other houses in the park residential area

> ground swayed side-to-side with little or no vertical motion, substantial shaking but no falling objects or damage and power outage.

Honokaa IV: At Kaapahu Homesteads, house shook, felt strongly by everyone in household.

Kona IV: Felt by many. At a residence in Holualoa (Keopu Mauka), the

whole house rocked for 20 seconds, chandelier continued swinging for five minutes, strongest felt for several years.

At Kealakekua residence, felt noticeably indoors by many.

Pahala IV: Felt by many, long movement "over 60 seconds," objects fell off shelves, concrete block fell from bell tower at Pahala United Methodist Church.

Waiohinu—Discovery Harbour subdivision IV: Felt by everyone, house shook hard for about 30–45 seconds, chandeliers and hanging objects swung for 3–4 minutes, dishes rattled in cabinets and moved in refrigerator.

Kamuela III: Felt mildly at many homes.

Lahaina (Maui) III: Felt quite noticeable indoors, long shaking motion lasting about 3 minutes.

Kohala II: Felt by few persons.

Makawao (Maui) II: Felt by very few persons.

Oahu Island II: Felt slightly by few persons.

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Appendix 4—Population Distribution of the County and the State of Hawaii

Table A5. Resident population of counties and districts, 1970, 1980, and 1985

[From "The State of Hawaii data book 1986, A statistical abstract," Hawaii State Department of Planning and Economic Development, December 1986, table 7, p. 17, Honolulu, Hawaii]

County and district	April 1, 1970	April 1, 1980	July 1, 1985
State total	769,913	964,691	1,053,884
Hawaii County	63,468	92,053	109,159
Puna	5,154	11,751	17,522
South Hilo	33,915	42,278	44,621
North Hilo	1,881	1,679	1,525
Hamakua	4,648	5,128	5,288
North Kohala	3,326	3,249	3,451
South Kohala	2,310	4,607	6,310
North Kona	4,832	13,748	18,962
South Kona	4,004	5,914	6,937
Kau	3,398	3,699	4,543
Maui County	46,156	70,991	85,303
Hana	969	1,423	1,654
Makawao	9,979	19,005	22,129
Wailuku	22,219	32,111	39,270
Lahaina	5,524	10,284	13,577
Lanai	2,204	2,119	2,178
Molokai	5,089	5,905	6,354
Kalawao	172	144	141
City and County of Honolulu	630,528	762,565	814,642
Honolulu	324,871	365,048	381,676
Koolaupoko	92,219	109,373	114,600
Koolauloa	10,562	14,195	16,367
Waialua	9,171	9,849	10,922
Wahiawa	37,329	41,562	43,099
Waianae	24,077	31,487	34,029
Ewa	132,299	191,051	213,949
Kauai County	29,761	39,082	44,781
Hanalei	1,182	2,668	4,327
Kawaihau	7,393	10,497	12,104
Lihue	6,766	8,590	9,219
Koloa	6,851	8,734	10,520
Waimea	7,569	8,593	8,611

Table A6. Private residential construction and demolition authorized by permits by counties, 1980–1985
[From "The State of Hawaii data book 1986, A statistical abstract," Hawaii State Department of Planning and Economic Development, December 1986, table 592, p. 545, Honolulu, Hawaii]

Year authorized	State total	City and County of Honolulu	Other counties: Total	Other counties: Hawaii	Other counties: Kauai	Other counties: Maui
New one-family dwellings						
1980	4,072	1,650	2,422	1,192	427	803
1981	2,551	768	1,783	1,032	353	398
1982	2,451	891	1,560	800	230	530
1983	3,387	1,562	1,825	880	398	547
1984	4,117	2,197	1,920	900	382	638
1985	4,663	2,313	2,350	979	387	984
New duplex units						
1980	84	46	38	12	24	2
1981	164	42	122	18	38	66
1982	32	32	—	—	—	—
1983	138	60	78	58	6	14
1984	146	112	34	28	4	2
1985	208	112	96	64	—	32
New apartments						
1980	5,163	1,854	3,309	727	769	1,813
1981	3,135	1,873	1,262	267	60	935
1982	3,038	2,553	485	245	118	122
1983	1,341	1,220	121	38	73	10
1984	1,134	942	192	153	35	4
1985	2,388	1,744	644	129	84	431
Units demolished						
1980	766	665	101	63	6	32
1981	686	521	165	21	70	74
1982*	568	443	125	34	1	90
1983**	505	385	120	54	4	62
1984	528	429	99	50	5	44
1985	555	455	100	38	12	50

*Data exclude housing units destroyed by Hurricane Iwa on November 23–24, 1982 (127 in the City and County of Honolulu and 543 in the County of Kauai).

**Data exclude 16 structures destroyed by volcanic activity in Hawaii County.

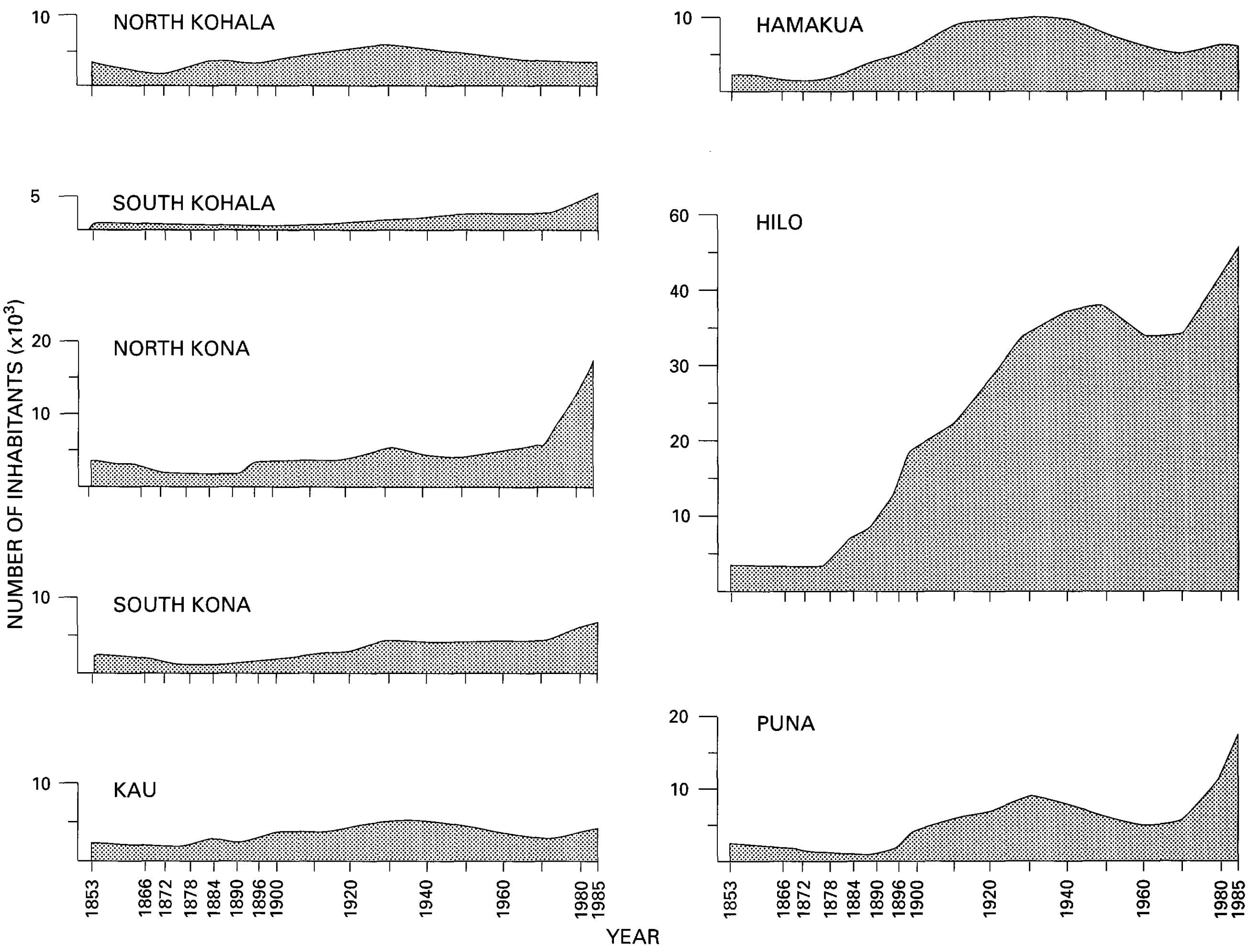

Figure A9. Number of inhabitants as a function of time for districts of the island of Hawaii.

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