THE TSUNAMI OF APRIL 1, 1946

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ABSTRACT

THE TSUNAMI which devastated the shores of the Hawaiian Islands on April 1, 1946, was caused by a movement of the sea bottom on the northern slope of the Aleutian Trough, south of Unimak Island. The waves traveled southward to Hawaii with an average speed of roughly 490 miles an hour, a wave length of nearly 100 miles, and a height in the open sea which is thought to have been 2 feet or less. The height and violence of the wave attack on Hawaiian shores varied greatly: at some points the waves dashed up on the shore with great violence and to heights as great as 55 feet above sea level; elsewhere they rose slowly and without turbulence. A detailed account is given of the heights the waves reached on the shores of the major islands, and damage done is described. Waves were generally highest on those sides of the islands which were toward the wave origin, and at the heads of submarine ridges projecting into deep water. They tended to be lower at the heads of submarine valleys, along shores protected by wide coral reefs, and at the ends of peninsulas projecting into deep water without corresponding submarine ridges. Waves were refracted around circular or nearly circular islands much more effectively than around elongate and rectangular islands. Locally, storm waves superimposed on the crest of the broader swells of the tsunami did considerable damage.

The areas suffering heavy damage in the 1946 tsunami are in general those most subject to damage by future tsunamis originating in the North Pacific. Eastern and southern coasts are subject to damage by tsunamis from South America. Western coasts are comparatively safe, although they have suffered some damage from Japanese tsunamis. All Hawaiian shores are subject to possible damage from tsunamis of local origin. Damage from future tsunamis can be lessened by avoiding construction in known danger areas; by construction of suitable sea walls, with open strips behind them; by limiting construction in heavily populated areas of danger to reinforced concrete or other wave-resistant structures; and by raising on stilts the frame structures in rural areas. Loss of life can be lessened or eliminated by establishing a suitable warning system, the warnings being based on instrumental detection of the small preliminary water wave, or the observation of ocean waves by shore stations around the borders of the Pacific Ocean and on mid-Pacific islands nearer the origin of the waves.

INTRODUCTION

ON THE morning of April 1, 1946, the Hawaiian Islands experienced the most disastrous tsunami in their history. More than 150 persons were killed, principally by drowning, and 163 others were badly injured. Hundreds of houses and other small buildings were destroyed or badly damaged. Property damage probably amounted to $25,000,000.

Many other tsunamis have struck the Hawaiian Islands. In fact, such waves are recorded on the Honolulu tide gauge on an average of about one a year. Most of them cause no damage, being so small that their arrival is generally unnoticed, but in the past 125 years several have been severe enough to cause loss of life and damage to property. The Hawaiian shores must, therefore, be recognized as subject to occasional attack by tsunamis.

The severity of the wave onslaught was not uniform along the entire shore, but varied greatly from place to place, and over short distances. Locally, one house escaped severe damage while another near by, situated as close to the strand line and at about the same altitude above sea level, was destroyed. Damage was severe on the shores of one bay, whereas in adjacent bays it was light. The reasons for some of these variations are obvious, but those for others are not immediately apparent.

Thus, the delineation of those areas which are most subject to severe damage during future tsunamis is highly desirable. To make it, however, it is necessary to understand as completely as possible the reasons for the variations in intensity of attack by past waves. If danger areas can be indicated, it may be possible to suggest means of protection for some areas and logical limitations to the extent and nature of construction in other areas. If, moreover, a suitable system can be devised for warning of the approach of dangerous tsunamis even a few minutes in advance of their arrival, it should be possible to effect a very considerable saving of life; and warnings an hour or more in advance would allow the saving of much easily movable property. The study of a single tsunami cannot be expected to indicate all the warning and protective measures for succeeding tsunamis, but it may contribute measurably to the body of knowledge from which such practical applications may be deduced.

For this reason, an intensive study has been made of the effects on Hawaiian shores of the tsunami of April 1, 1946. The present investigation has been carried out by the United States Geological Survey in coöperation with the Territory of Hawaii, the Scripps Institution of Oceanography under contract with the Office of Naval Research and the Hydrographic Office of the U. S. Navy, and the Experiment Station of the Hawaiian Sugar Planters' Association. The work was performed with the support of funds from the U. S. Geological Survey, the Office of Naval Research and the Hydrographic Office of the U. S. Navy under contract with the University of California, and the Hawaiian Sugar Planters' Association. F. P. Shepard represented the Scripps Institution; G. A. Macdonald, the Survey; and D. C. Cox, the Association.

The heights to which the waves dashed up on the shore have been measured at intervals along most of the coasts of the major islands of the Hawaiian group, the nature and extent of the damage has been investigated, and the

data have been studied in an effort to ascertain the causes of the variations in wave intensity from place to place. The results are incorporated in this report.

GENERAL FEATURES OF TSUNAMIS

Name.—The name *tsunami*,[1] of Japanese origin, is applied to the train of long-period gravity waves in the ocean probably set up by a large displacement of the sea bottom or shores. Severe earthquakes usually occur where the tsunami originates. The word tsunami means "large waves in harbors," but is used to cover the phenomena under discussion. The term is adopted in this report both because of its greater brevity than *seismic sea wave*, frequently used in recent literature, and because the latter term is not etymologically sound. Seismic, from Greek *seismos*, "earthquake," is defined as "pertaining to, produced by, or characteristic of an earthquake." However, waves of appreciable

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[1] Also spelled *tunami* in some Japanese reports, in accordance with the official system of transliteration prior to the Second World War. The *tu* is pronounced *tsu* by the Japanese.

magnitude do not accompany the great majority of submarine earthquakes. Presumably, tsunamis are not produced by earthquakes but are correlative phenomena produced by the same causes which produce the earthquakes. More properly, the term seismic sea wave might apply to the waves of compression commonly called "seaquakes." The term *maremoto* also has been applied to the phenomenon, but is less well known than *tsunami*.

Tsunamis are commonly and popularly called "tidal waves," a term which originated, no doubt, from certain resemblances between tsunamis and tides, particularly as contrasted with ordinary wind-generated waves. Along many coasts where deep water lies close to shore, the water appears to rise in a mass movement like the tide, but much faster. The bores which develop from tsunamis in estuaries are closely similar to tidal bores. Because of the difference in origin, however, the name "tidal wave" is considered a misnomer.

Origin.—Two hypotheses have been suggested to account for the occurrence of tsunamis. One points to faulting, or some other sudden movement on the ocean floor, and the other to submarine landslides. Until we have some positive evidence of what happens at the source, the origin must remain somewhat in doubt. However, indirect evidence, such as was supplied by the tsunami under discussion, provides some interesting tests of the two possibilities.

Submarine landslides are suggested by the large waves which are known to result from the falling of large masses from mountainsides into lakes. Also, Gutenberg (1939) has directed attention to the Atacama earthquake of 1922, which supposedly had an epicenter 100 miles inland and yet was accompanied by a large tsunami. Gutenberg explained this occurrence as the result of a submarine landslide. But there are serious objections to this hypothesis, as follows:

1. On land most of the large landslides have occurred without any accompanying earthquake, whereas so far as we know not one appreciable tsunami has occurred without a large earthquake or some catastrophic volcanic engulfment.

2. The investigation of submarine canyons off the California coast (Shepard, 1948, pp. 236–237)[2] has shown that landslides are not infrequent but that waves are not known to have been caused by these slides.

3. Earthquakes producing tsunamis almost invariably occur in deep ocean trenches. One is led to wonder why earthquakes occurring along steep slopes in other areas do not produce the necessary landslides. If earthquakes set off large slides, it is indeed strange that the earthquakes along and off the California coast have left only one record of an accompanying tsunami.

4. To produce waves which would cross wide oceans, movements of large volume are required. The source of the sediment for large-scale landslides in the Aleutian Trench, west of the Alaskan peninsula, is hard to imagine. Continental slopes off deltas have much larger sources of sediment, but lack tsunamis.

5. It is likely that submarine landslides are too slow to produce large waves. There are reasons for believing that the mud-flow type is the most common.

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[2] References in parentheses are to "Literature Cited" at the end of this paper. See pages 469–470.

6. Transfer of material without change of volume, as in submarine land-slides, will produce a dipolar type of disturbance. On the other hand, uplift or sinking of the sea floor results in a unipolar disturbance. In general, unipolar disturbances produce waves that will decay much less rapidly with distance than those from dipolar disturbances. Therefore it is unlikely that the waves which cross thousands of miles of ocean and produce large tsunamis on the other side come from a dipolar source.[3]

7. The tsunamis are directional, as was clearly shown by the intensity of waves in Hawaii in contrast to the small waves along western America and the Asiatic coast. Landslides might be expected to produce waves moving out from a point rather than a line. These circular waves should not be very effective in crossing a wide ocean.

8. The Atacama earthquake may have been followed directly by a large submarine movement which could not be located by seismographs because the machines had been set in motion by the first waves. Actually, the epicenter of an earthquake is only a record of the first point of appreciable crustal disturbance. Therefore, the Atacama earthquake is not a definite proof of landslide origin.

Although the foregoing objections appear to eliminate landslides, the case for submarine fault movements is not necessarily established. It is perhaps strange that these large waves, while relatively rare, occur much more often than appreciable vertical displacements of the land surfaces. It may be that this greater frequency means that movements within the great ocean trenches are actually more common than in any place on land. The trenches are quite different from any features of the lands and are the locus of more world-shaking earthquakes than occur in any of the seismic belts on land. Fault movements would at least account for the characteristics of the waves so far as they are understood. The line source and the slow decay of the waves is thus explained. Nevertheless, it may be that the movement on the sides of the deep trenches may be other than faulting.

Another cause known to produce large waves is the collapse of volcanic mountains, which is a unipolar disturbance. The huge waves accompanying the eruption of Krakatoa in 1883 are said to have been the result of such a collapse (Williams, 1941). In 1792 the collapse of a mass of about one cubic kilometer into the sea on the eastern side of Unzen volcano, in Japan, caused a local wave 30 feet or more in height which did enormous damage to coastal villages and took a toll of more than 15,000 lives (Ogawa, 1924). Submarine volcanic explosions also set up waves, although no large waves from this source are known to have traveled far. Explosive eruptions probably do not occur in very deep water, because of the confining pressures resulting from the weight of overlying water.

Nature of the waves.—The outstanding characteristics of tsunamis are their great wave length and rapid propagation. The wave length in the deep ocean is of the order of tens of miles, probably most commonly from 40 to 125 miles.

[3] From personal discussion with Dr. Carl Eckart.

Because of this great wave length the height in the open ocean must be very low, probably never exceeding about 7 feet. This is based on Green's Law, which may be written in the form (Lamb, 1932, p. 275):

$$H_1 = H_2 \left(\frac{h_2}{h_1}\right)^{\frac{1}{4}}$$

where H_1 and H_2 are the respective wave heights in water of depth h_1 and h_2.

Assume that this law is applicable to tsunamis, and further assume that a wave height of 30 feet in water of 30 feet depth is an extreme near-shore wave height for tsunamis after traveling several thousand miles from their source; then Green's Law gives a wave height of 6.8 feet in water of 2,300 fathoms depth (average depth of the Pacific).

Although the tsunamis develop strong currents in shallow water along the shore, their effectivenesss decreases rapidly with depth. In long waves of the Stokes type the horizontal bottom velocity under the crests of the waves, where it reaches a maximum of short duration, is given by the formula: $Q = CH/(2h)$, where Q is the velocity of the bottom current, C the wave velocity, H the wave height, and h the depth of water. To obtain the wave velocity, use is made of the formula $C = \sqrt{gh}$, where g is the acceleration of gravity. Using these formulas and considering a tsunami 10 feet high at the coast, we find that the maximum currents would have values approximately as follows: at 5 fathoms depth, 95 cm/sec.; at 10, 62 cm/sec.; 100, 11 cm/sec.; 300, 4.5 cm/sec.; and at 500, 3 cm/sec.

As mentioned above, the velocity of long waves is given by $C = \sqrt{gh}$. Calculations based on this formula are in general agreement with the observed travel times. For example, the Sanriku waves of 1896 crossed the Pacific Ocean from Japan to San Francisco in 10 hours, 34 minutes, with an average velocity of about 450 miles an hour (Byerly, 1942); and the tsunami of February 3, 1923, which originated off the coast of Kamchatka, traveled to Hilo, Hawaii, at about the same speed (Finch, 1924). The average speed of other tsunamis in the North Pacific has ranged from about 430 to 500 miles an hour. These are, however, average speeds for the entire distance of transit, and since the speed of the waves is much less in shallow water near shore than in deep water, the actual speed in the open ocean must be somewhat greater than the average.

As the wave enters shallower water, its speed is greatly reduced and it becomes higher and steeper. Green (1838) states that the wave height varies inversely as the fourth root of the depth of the water. Approaching shore in shoal water, and especially in funnel-like bays, the front of the wave appears as a steep wall of water with a broad, rather flat crest behind it, having many of the characteristics of a tidal bore. The speed of these borelike waves observed advancing up Kawela Bay on April 1, 1946, did not appear to exceed 15 miles an hour.

A tsunami consists not of a single wave, but of a whole series of oscillations. Near the origin the first wave is commonly the largest of the series, but at a greater distance from the origin it is generally smaller than the immediately succeeding waves. In some tsunamis the waves increase in size up to the third or fourth, or even the seventh wave, but in others the first wave appears to be

the largest. After the maximum the waves gradually decrease in size over a period of hours or days.

In bays, a tsunami sets up a forced oscillation which may give rise to a seiche, an oscillation in the natural free period of the bay. The seiche oscillations exist not to the exclusion of, but in addition to, the later waves of the tsunami, and greatly complicate the later part of the record of the tsunami on tide gauges. If late waves of the tsunami arrive in phase with the seiche oscillation they are greatly augmented, whereas if they happen to arrive directly out of phase they may be largely or entirely obliterated.

There seems to be substantial evidence that some of the waves of a tsunami arrive at their destination after reflection from a submarine slope. Hart (1931) referred to three tsunamis which reached Sydney, Australia, after reflecting off the North American continental slope. Similarly, waves representing reflections from North America were recorded at Hanasaki, Japan, at the time of the tsunami of April 1, 1946. Some of the late-arriving waves in the Hawaiian Islands can best be explained by reflections off the submerged slopes around Asia. Also, more local reflections among the Hawaiian Islands seem to be required to explain the direction of approach of some of the waves. The mechanics of reflections are discussed in a manuscript by J. D. Cochrane and R. S. Arthur, "Reflections of Tsunamis" (in press). Referring to wave heights, they note that the reflection from typical continental slopes would be of the order of 20 to 40 per cent where the incidence was normal and of 15 to 30 per cent for an incidence of 45 degrees. Reflection from the steep walls of the great trenches of the Pacific would probably be considerably higher.

GEOGRAPHIC AND GEOLOGIC SETTING OF THE HAWAIIAN ISLANDS

The Hawaiian Islands lie along a ridge which extends northwestward for 1,600 miles across the central Pacific Ocean (fig. 1). The small islets of the northwest part of the chain are composed entirely of coralline limestone and calcareous sand, presumably built on a volcanic base. The principal ports of the Territory, Honolulu and Pearl Harbor, are situated on the southern side of the island of Oahu. Secondary ports are Hilo and Honuapo on the island of Hawaii, Kahului and Lahaina on Maui, Kaunakakai on Molokai, and Ahukini, Nawiliwili, and Port Allen on Kauai.

The large islands at the southeastern end of the chain are very largely volcanic, built up from the ocean floor by repeated flows of fluid basaltic lava. Mauna Loa and Kilauea volcanoes, on the southernmost island, Hawaii, are still active. Minor amounts of coral reef border parts of the shores of the volcanic islands. On the northeast and southwest, the islands rise steeply from typical oceanic depths of 2,500 to 3,000 fathoms. Here the water separating the islands is much shallower, ranging from 1,500 fathoms between Kauai and Oahu to less than 150 fathoms between Maui, Molokai, Lanai, and Kahoolawe (fig. 2). The submarine topographic forms appear to be largely constructional, although there is some evidence of erosion. A few recently discovered submarine canyons, extending outward to depths of 500 fathoms

or more, are found off some of the older, deeply eroded volcanoes. Other large valley-like depressions, extending outward to oceanic depths, are probably structural depressions between lava ridges built along volcanic rift zones.

The present study of the effects of the tsunami has covered only the major volcanic islands at the southeastern end of the Hawaiian Ridge.
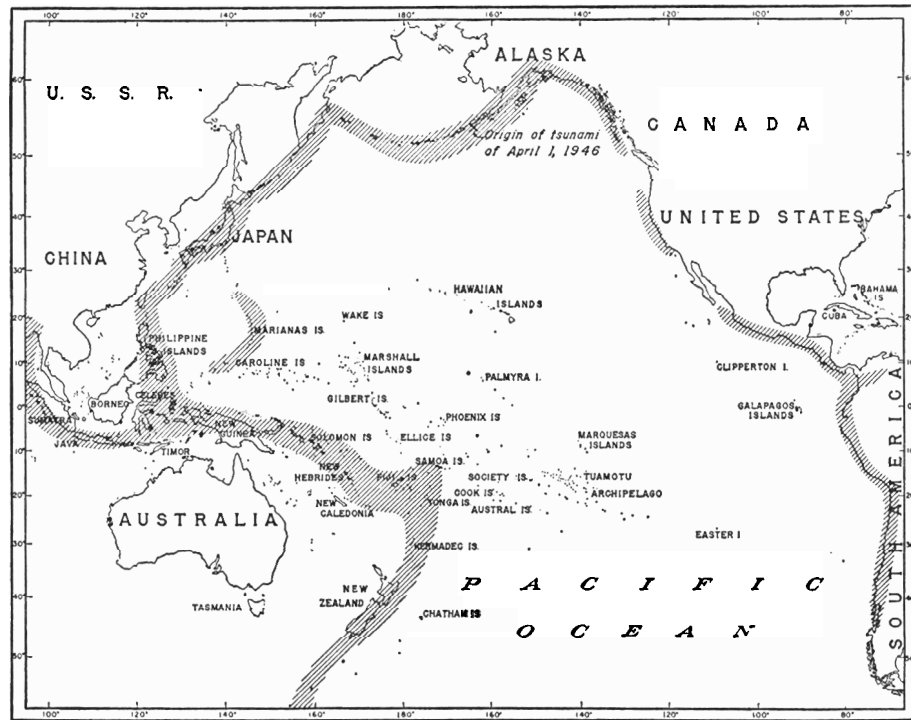
Fig. 1. Map of the Pacific Basin, showing the position of the Hawaiian Islands, the place of origin of the tsunami of April 1, 1946, and the distribution of seismically active belts around the Pacific in which tsunamis are likely to originate.

HISTORY OF TSUNAMIS IN HAWAII

Brief histories of tsunamis in the Hawaiian Islands have been published by Jaggar (1931) and Powers (1946). These accounts have been freely used in the preparation of the present chapter. Data for four of the small tsunamis are from the paper by Zetler (1947) and for one they are from Heck (1947).

In table 1 (see page 401) are listed the principal tsunamis recorded in Hawaii. Many others of small size are known to have struck the coasts, and still others must have done so without attracting attention.

It is obvious from an inspection of the table that most of the tsunamis which reached the Hawaiian Islands originated around the borders of the Pacific Basin. Of the 36 tsunamis listed only 3 originated in the Hawaiian area, and of the 5 severe ones listed only 1 was of local origin. Three of the severe tsunamis originated near the coast of South America and 1 in the Aleutian area.
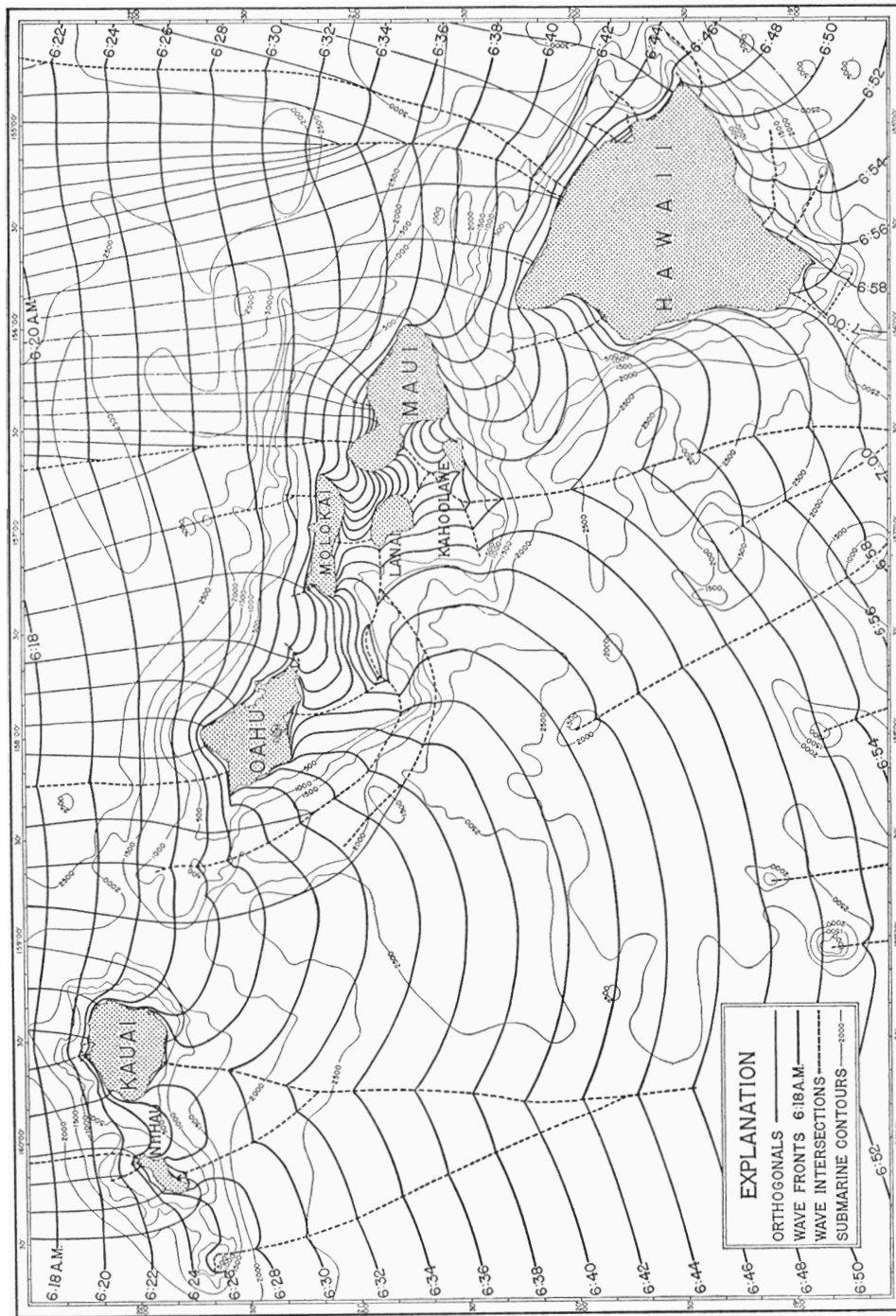
Fig. 2. Map of the Hawaiian Islands, showing submarine topography (contours in fathoms), wave fronts, and orthogonals of the tsunami. Times refer to computed time of arrival of first wave.

One moderately severe wave came from near Kamchatka. One wave from Japan caused a small amount of damage along western coasts. Judging from the descriptions, the waves of 1837, April 2, 1868, and 1877 were probably nearly or quite as severe as those of April 1, 1946.

The earliest record of a tsunami in Hawaii is for April 12, 1819, when a recession of the water was followed by several risings and fallings. On the western coast of Hawaii about 9 oscillations occurred, at intervals of 10 or 11 minutes, the fall being as much as 7 feet.[4] A severe earthquake and tsunami occurred in Chile on April 11, and it is probable that the waves seen in Hawaii were from that source (Willis, 1929).

On November 7, 1837, a violent tsunami occurred. At Honolulu, on the leeward side of the island of Oahu, about 6 P.M., the sea suddenly dropped about 8 feet below its normal level, leaving reefs dry. The water rose again, but, surprisingly, only to a height a few inches above normal high-tide mark. In the second recession the water level fell only 6 feet. Oscillations continued, with a period of 28 minutes, until the morning of November 8. Similar behavior was observed at Lahaina, on the leeward side of Maui. At Kahului, on the windward side, the water first receded, leaving the bottom of the bay bare for 120 feet from shore, and then rolled landward as a wall of water which swept persons and houses before it. Two lives were lost. At Hilo, on Hawaii, recession of the water left a broad expanse of harbor bottom dry. Many persons ventured out on the dry sea floor in search of fish, only to be caught by the returning wave, which moved shoreward at a rate reported as 7 or 8 miles an hour and swept up on the coast to a height of 20 feet above normal high-water mark. Many houses and animals were washed away. Fourteen persons were drowned; but many others were saved by the boats of an English whaler which was anchored in the bay. This ship reported that the water level sank 9 feet during recessions (Bennett, 1869; Jarves, 1843).

On May 17, 1841, at Honolulu, the water withdrew suddenly at 5:20 P.M., leaving the reef bare. Two such oscillations occurred within 40 minutes, the fall in water level being about 3 feet. A similar withdrawal occurred at Lahaina, where the water rose and fell several feet (Bennett, 1869; Jarves, 1843).

The tsunami of local origin which struck the southern shore of the island of Hawaii shortly after the violent earthquake of April 2, 1868, caused very great damage all the way from the South Cape to the East Cape, but was not severe elsewhere in the islands. Data on this wave have been collected by Wood (1914). The wave swept as much as a quarter of a mile inland along the south coast of Hawaii, reached a height of 50 or 60 feet above sea level, destroyed 108 houses and killed at least 81 persons. At Hilo the sea first receded, then returned, reaching a mark 10 feet above normal high tide. At Kealakekua, on the western coast of Hawaii, the range of the fluctuation was about 8 feet from crest to trough; at Honolulu, about 5. At all places remote from the origin the first phenomenon observed was a withdrawal of the water, although at localities near the origin the first reported movement was a rise of the water.

On August 13, 1868, a tsunami originating off the Peruvian coast reached a height above normal low tide of 15 feet at Hilo and 12 feet at Kahului.

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[4] Don Francisco Marin, unpublished journal in the Archives of Hawaii, translated by R. C. Wiley.

TABLE 1

HAWAIIAN TSUNAMIS

Year	Month and day	Source (nearest coast)	Damage in Hawaii	Average speed of waves (statute miles per hour)
1819	Apr. 12	Chile (?).................	Unknown	...
1835	Feb. 20	Chile.....................	Moderate	...
1837	Nov. 7	Chile.....................	Severe	...
1841	May 17	Kamchatka.............	Small	...
1868	Apr. 2	Hawaii..................	Severe	...
1868	Aug. 13	Peru and Bolivia......	Severe	...
1869	July 25	South America (?)......	Moderate	...
1872	Aug. 23	Hawaii..................	Small	...
1877	May 10	Chile.....................	Severe	...
1878	Jan. 20	....	......	...
1883	Aug. 27	....	Small	...
1896	June 15	Japan....................	None	478
1901	Aug. 9	Japan (?)................	None	...
1906	Jan. 31	Colombia................	None	...
1906	Aug. 16	Chile.....................	Small	...
1913	Oct. 11	New Guinea............	None	...
1914	May 26	New Guinea............	None	...
1917	May 1	Kermadec Islands......	None	...
1917	June 25	Samoan Islands.........	None	...
1918	Aug. 15	Philippine Islands......	None	...
1918	Sept. 7	Kurile Islands..........	Small	456
1919	Apr. 30	Tonga Islands..........	None	...
1922	Nov. 11	Chile.....................	None	450
1923	Feb. 3	Kamchatka.............	Moderate	432
1923	Apr. 13	Kamchatka.............	None	438
1927	Nov. 4	California................	None	462
1927	Dec. 28	Kamchatka.............	None	438
1928	June 16	Mexico...................	None	462
1929	Mar. 6	Aleutian Islands.......	None	492
1931	Oct. 3	Solomon Islands.......	None	447
1932	June 3	Mexico...................	None	...
1933	Mar. 2	Japan....................	Small	477
1938	Nov. 10	Alaska...................	None	496
1943	Apr. 6	Chile.....................	None	...
1944	Dec. 7	Japan....................	None	425
1946	Apr. 1	Aleutian Islands.......	Severe	490
1946	Dec. 20	Japan....................	None	...

Oscillations continued for 3 days. A large wave, probably of South American origin, is reported to have swept in to heights about 30 feet above sea level along the southeastern Puna coast on July 25, 1869, reaching 1,000 feet inland southwest of Cape Kumukahi, and destroying some houses (Coan, 1870).

On August 23, 1872, a small tsunami was observed at Hilo, the water rising 4 feet above normal level in the first wave. The second wave was 3 feet high, and other waves, diminishing in size, occurred at intervals of 6 minutes (Dana, 1890).

At the time of the violent Iquique earthquake in Chile, on May 9, 1877, a large tsunami was generated, possibly by submarine landslides (Gutenberg, 1939, p. 519). The waves reached Hilo, Hawaii, at 4 A.M. on May 10. Water swept completely over Coconut Island and up on the shore as far as the second business block near the Wailuku River, reaching a height of 12 feet above normal low water. In the Waiakea district of Hilo, near the Wailoa River, every house within 100 yards of the shore was washed away. Five persons were killed and 7 were injured. The waves were reported to measure 14 feet vertically from trough to crest (Hitchcock, 1911, pp. 294–295). The same tsunami was recorded at Hakodate, in Japan, as an oscillation with a maximum range of 8 feet, a period of about 20 minutes, and a duration of several hours (Byerly, 1942, p. 73).

During the collapse of the cone of Krakatoa volcano, in the East Indies, on August 26 and 27, 1883, great sea waves were generated. In Honolulu and on the western coast of the island of Hawaii, starting about 3:20 A.M. on the 27th, waves were observed which had a maximum height of nearly 1 foot.[5] However, the time of arrival was far too early for any route from Sunda Strait, and hence another source may have given rise to these waves.

On August 9, 1901, at 11:30 A.M., a wave about 4 feet high swept up on shore at Kailua, on the western coast of Hawaii. A house was swept away at Keauhou, 5.5 miles farther south. The source of the wave may have been in the Japanese area. No disturbance was noticed elsewhere in the Hawaiian Islands.[6]

On January 31, 1906, a wave dashed up on shore at Hilo, reaching 12 feet above sea level. The water covered the floor of the old wharf at the foot of Waianuenue Street, and the railroad tracks between there and Waiakea, and temporarily reversed the flow of the Wailuku River. Before the rise the water receded, leaving the bottom of the bay bare for a considerable distance from shore. At Kahului, on Maui, the coastal road was covered.[7]

The great Valparaiso earthquake of August 16, 1906, was accompanied by a tsunami which swept over the entire Pacific Ocean. On the southern coast of Maui the water rose 12 feet, damaging the wharfs at Maalaea and McGregor's Landing. At Hilo the rise was only 5 feet, and no destruction occurred at Kahului[8] although the lowlands in the vicinity of the town were flooded.[9]

A small tsunami from a source near the Tonga Islands was observed at Punaluu and Hilo, on the island of Hawaii, on the morning of April 30, 1919. At Punaluu the whole bay became dry at 7:30 A.M. The water gradually returned, "but went out rapidly again about 9 A.M. and 10:30 A.M." (Jaggar, 1919). The long period of the waves is noteworthy.

The tsunami of February 3, 1923, which originated off the coast of Kamchatka, was predicted 4 hours in advance by the Hawaiian Volcano Observatory, on the basis of seismograph records of the earthquake (Finch, 1924). The sea waves reached Haleiwa, on the northern shore of Oahu, about 12:02 P.M.,

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[5] *Daily Bulletin*, Honolulu, August 29, 1883.

[6] Honolulu *Daily Advertiser*, August 10, 1901.

[7] Honolulu *Daily Advertiser*, February 3, 1906.

[8] Honolulu *Daily Advertiser*, August 17 and 18, 1906.

[9] J. N. S. Williams, personal communication.

and Hilo at 12:30 P.M. (Jaggar, 1923). At Honolulu the water receded suffi-
ciently to lay bare the reefs, and oscillations continued with a period of 15
or 20 minutes. At Kahului, Maui, the recession left a vessel stranded on the
harbor floor. When the water returned it flooded into the town, reaching
heights of 6 to 12 feet above normal water level and doing damage amounting
to about $1,500,000.[10] At Hilo there was first noticed a recession of the water,
followed by a series of oscillations which continued for several hours. The
third wave was the largest, the water rising more than 20 feet at the mouth
of the Wailoa River. Much damage was done, and one man lost his life.

The violent tsunami which devastated the Sanriku district of Japan on
June 15, 1896, left a record on the Honolulu tide gauge. This wave reached
extreme heights of nearly 100 feet on the coast of Japan (see fig. 19, p. 446),
but the height of the wave at Honolulu was only about 0.3 foot from crest
to trough.[11] The wave is reported to have been several feet high as it struck the
Kona coast of Hawaii. It is interesting to note that, as in the wave of April 1,
1946, the record on the Honolulu tide gauge began with a rise although the
first manifestation on the Japanese coast was reported to be a withdrawal. The
lesser tsunami, which struck the Sanriku district on March 2, 1933, also
reached the Hawaiian Islands. At Kailua, on the western coast of Hawaii, a
series of 10 large waves started at 3 o'clock on the afternoon of March 2. The
last wave was the highest, reaching about 9 feet above ordinary water level
and causing minor damage.[12]

On October 3, 1931, a tsunami from the Solomon Islands region in the
southwestern Pacific was recorded on the tide gauge at Hilo. The speed of the
waves as they moved from their origin to Hilo averaged about 447 miles an
hour. The first manifestation at Hilo was a lowering of the water of about 3
inches, followed by a rise of about 4.5 inches. Pulsations continued at about
15-minute intervals for the next 2 days (Jones, 1931).

The Japanese wave of December 7, 1944, was recorded on the Honolulu
tide gauge with an amplitude of 8 inches, but it did no damage in the Hawaiian
Islands. Small waves reached Hawaii from the vicinity of Kamchatka on
April 13, 1923, and December 28, 1927; from California on November 4, 1927;
from Mexico on June 16, 1928; from the Aleutian Islands on March 6, 1929;
and from the mainland of Alaska on November 10, 1938. None of these did
any damage, but they do indicate that Hawaii is subject to waves from those
areas, some of which may be severe enough to cause damage in the future.
Some other violent waves termed "tidal waves" in the newspapers were prob-
ably heavy storm waves; for example, those which struck Maliko, Maui, on
January 28, 1895, and those which did damage at Kaumalapau on Lanai, and
Nawiliwili on Kauai, on May 30, 1924. In January, 1947, storm waves rose
higher in many areas of the Hawaiian shores than did the tsunami of April 1.

[10] Honolulu *Daily Advertiser*, February 4, 1923.
[11] *Pacific Commercial Advertiser*, June 16, 1896.
[12] Honolulu *Daily Advertiser*, March 3, 1933.

THE TSUNAMI OF APRIL 1, 1946

GENERAL FEATURES

Source of the waves.—The crustal movement which caused the tsunami of April 1, 1946, occurred on the northern slope of the Aleutian Deep, south of Unimak Island (fig. 3). The movement also gave rise to a violent earthquake which was recorded on seismographs all over the world. The United States Coast and Geodetic Survey has placed the epicenter of the earthquake at $53°5$ north latitude and $163°$ west longitude, and has fixed the time of occurrence as 58.9 minutes past 1:00 A.M., Hawaiian time (12^h28^m9 Greenwich time). This epicenter is approximately 2,240 statute miles N, $8°5$ W of Honolulu, and 2,370 miles N, $12°$ W of Hilo. Presumably the tsunami originated at or very near the epicenter, and at approximately the same time as the earthquake.

Time of arrival in Hawaii.—Computed times of arrival of the first wave are given in figures 2, 3, 6, 9, 12, and 16, assuming the time of origin in the Aleutian Trough as 2:00 A.M. The only reliable record of the time of arrival of the tsunami at the Hawaiian Islands is given by the tide-gauge record in Honolulu Harbor, which shows the beginning of the first rise to be at 6:33 A.M., Hawaiian time. The drum of the water-stage recorder near the mouth of the Waimea River, on Kauai, was revolving too slowly to give an accurate indication of the time of arrival, but indicated that the first rise started there a little before 6:00 A.M., or about half an hour earlier than at Honolulu. No direct instrumental record of the time of arrival of the waves at Hilo is available. Observers at Hilo reported a marked recession of the water shortly before 7:00 A.M., and the arrival of the first wave crest soon after 7 o'clock. Electric clocks along the damaged water-front area of Hilo were stopped at 7:06. Powers (1946) has interpreted a short power failure recorded on the drums of the Hawaiian Volcano Observatory seismographs at Kilauea at 7:18 as probably resulting from the second wave. It is possible, however, that the clocks were stopped not by the first wave, but by a second or even later wave, a small earlier wave or waves having escaped notice. This hypothesis is strengthened by the fact that a distinct withdrawal of the water was seen at Hilo preceding the crest at 7:06, whereas the instrumental records at Honolulu and Waimea River show the first movement to have been a rise. It appears more probable that the crest at 7:06 was actually the second wave at Hilo, being preceded by a smaller wave crest at about 6:54, the initial rise starting about 6:50. The average speed of the waves from the origin to Hilo calculated on the basis of this earlier time of arrival is in good accord with that calculated from the arrival time at Honolulu.

Data on the time of arrival of the waves at other places in the Hawaiian Islands are very poor. No witnesses have been found who noted the time on a reliable timepiece. Most of the people living along Hawaiian shores, especially fishermen and others familiar with the sea and conscious of its behavior, are not concerned with great accuracy of time. Estimates of the time of arrival of the waves in a given area vary by as much as half an hour; moreover, there is frequently no assurance that the first wave observed was actually the first

an interval of 12 minutes between stoppages of electric power, which represents an interval between two waves but not necessarily between corresponding parts of the waves. At Kolo, on the southern shore of Molokai, the interval between the first waves was reported to be about 10 minutes, but later waves arrived at shorter and very irregular intervals. At Waimea River, on Kauai, the average interval between crests during the first hour was a little more than 7 minutes, but this interval is about that of the normal seiche of the Waimea estuary and may not be significant. A period of about 15 minutes was reported between crests at Kaumalapau on Lanai, but it was not accurately timed.

The interval between the first and third wave crests, as recorded on the Honolulu tide gauge (fig. 4), was about 25 minutes, indicating an average interval between early wave crests of approximately 12.5 minutes. The interval between the first wave crest and the succeeding trough was 7.5 minutes, however, indicating a wave period of 15 minutes at the beginning of the disturbance. This corresponds with the mean wave period of 15.6 minutes found by Green at Honolulu and eight other stations on the coasts of North and South America (Green, 1946). At the mouth of Nuuanu Stream in Honolulu, C. K. Wentworth observed an interval of approximately 15 minutes between successive bores ascending the stream, and a wave period of about 15 minutes was observed by J. B. Cox and D. C. Cox at Waikiki about 7:45 A.M. Observations elsewhere were poor, but in general they indicated an interval of about 15 minutes between the early waves of the series. The interval between later waves at Honolulu (see fig. 3, p. 405) and elsewhere was shorter and less regular, probably because of the arrival of trains of waves which traveled by somewhat different routes. Some waves traveled by the most direct route; others were refracted around different sides of islands, or were reflected from various submarine slopes. Wind waves and also the free oscillations (seiches) in harbors and channels probably contributed to the irregularity of later waves.

Wave length.—Assuming an average speed of approximately 490 miles an hour for the waves in the open ocean, and a period of 15 minutes, the wave length from crest to crest was about 122 miles. When it is taken into consideration that the height of the waves in the open ocean, from crest to trough, was theoretically of the order of a few feet, it becomes obvious that the waves would not have been perceptible to ships at sea. This is substantiated by the fact that no extraordinary waves were felt on a ship lying off Hilo although the master could see the heavy waves breaking on shore. Fishermen at sea off the southwestern coast of Hawaii also felt no waves, and a ship crossing between Oahu and Molokai experienced only a very rough sea which was in existence before the arrival of the tsunami. Large waves on the open ocean which were reported by a few vessels were probably wind waves; they certainly were not the tsunami.

Because of their great wave length, the effect of the waves extended to the ocean bottom along all their paths. The movements of water along the bottom at great depth were, however, probably negligible, as explained above.

Relative size of successive waves.—At most places the third or fourth wave was reported to have come highest on shore and to have done the most damage. The Honolulu tide gauge recorded the third peak as definitely higher than any
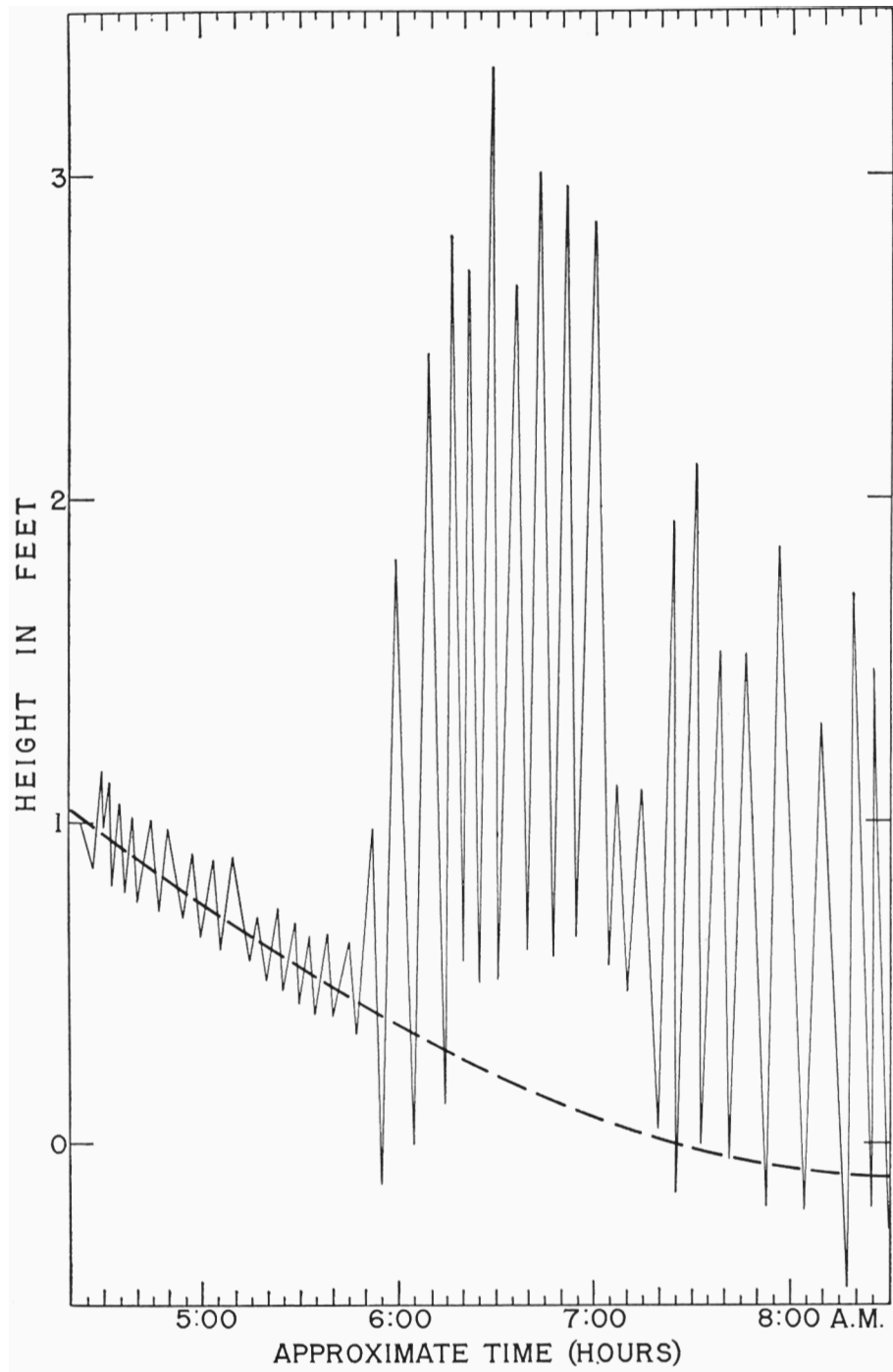
Fig. 5. Record of the tsunami of April 1, 1946, on the water-stage recorder in the estuary of the Waimea River, Kauai.

other (fig. 4). Elsewhere, the sixth, seventh, or eighth peaks were reported as highest. The gauge at Waimea River, Kauai, recorded the sixth as highest (fig. 5). At a few places, such as Nanakuli, on the western shore of Oahu, witnesses state that the first wave was the highest, but at such localities it is not certain that the earliest waves did not escape notice. Following the maximum the waves in general decreased gradually.

Occasional later waves were larger in size than those immediately preceding, but not as large as the third to eighth waves. Such increases in size probably resulted from the additive effect of two or more waves which had followed different paths but arrived simultaneously. Locally also, the size of any wave in the series may have been increased by its coinciding with storm waves.

Nature of the waves striking Hawaiian shores.—The nature of the waves sweeping up on Hawaiian shores varied greatly, even over short distances. Accounts of the character of the waves have come from many sources, and though many of the observers were closely familiar with the normal behavior of the sea, few were trained in scientific observation. However, photographs and moving pictures confirm the great variation (see pls. 6–12, pp. 473–485).

Part of the variation was in the height reached by the water. The measured heights ranged from 55 feet to half a foot. At places in Kaneohe Bay, on the northeastern side of Oahu, no evidence could be found of any rise at all.

The violence of attack was related only in part to the water height. In some places the water rose quite gently, gradually flooding the low coastal lands, and no steep wave front was observed. At these places the damage, if there was any, resulted from the flow incident to the wave's movement on shore, or more often from the swift draining back of the water during the time of the succeeding wave trough. At some localities the general water level rose gently, but ordinary wind waves rode in on the crest and did some damage.

At many places on directly exposed coasts the waves swept toward shore with a steep front and great turbulence (pls. 6 and 7). Locally at least, this wave front was closely similar in appearance to a tidal bore (pls. 8 and 9), the steep front rolling in over comparatively quiet water in front of it. Behind the steep front the wave crest appeared broad and nearly flat but still turbulent, and the general surface was modified by smaller, steplike fronts (perhaps of the nature of hydraulic jumps). The picture shown in plate 11 was presumably taken during the advance of one of the later waves onto the coast northeast of Hilo. The turbulent effect of the wave in crossing a reef is indicated. Plate 12, *a* shows the relatively level surface at the crest of one of the waves southeast of Hilo. The only violent turbulence is shown where the wave is pouring over the sea wall in front of the Puu Maile Hospital.

Bores formed, apparently, in places where the waves were higher than average, or where the coast shelved very gradually or was fringed with coral reefs. Bores were seen mostly in bays or river mouths, but were not limited to them.

Bores associated with other tsunamis, such as those which followed the great Lisbon earthquake (Davison, 1936) and several accompanying earthquakes in Japan (Imamura, 1937), have been described most often as occurring in long, narrow inlets. Probably their development is dependent on the shape

of the bottom of the bays; bays with flat, shallow bottoms develop bores, those with a V-shaped cross section do not.

Commonly, the gentle rise occurred on shores facing away from the wave origin, but locally it was reported on directly exposed coasts. At some places the change from gentle rise to violent wave attack took place over very short distances. Thus at Haena, on Kauai, witnesses reported a gentle rise on the western side of the bay, whereas half a mile to a mile farther east the waves rushed on shore so violently as to flatten groves of trees (pl. 12, *b*) and destroy houses.

MEASUREMENT OF WAVE HEIGHTS ON SHORE

The height reached by the water on shore has been measured to points indicated by eyewitnesses, to clearly defined lines of flotsam and swash marks, to the upper limits of consistent scraping and barking on trees, and to the upper levels of staining on buildings, scouring of soil, and stripping or salt poisoning of vegetation. These heights are plotted on figures 6 to 18 (pp. 412–442 *passim*). Water may have extended a few inches or even a few feet higher than these marks in some places, without leaving measurable traces. The height in Honolulu Harbor is that measured on the tide gauge, and that at the head of the East Loch of Pearl Harbor was measured on a water-stage recorder.

All heights are stated, both on the figures and in the ensuing text, in feet above mean lower low water, which in the Hawaiian Islands generally approximates 1 foot below mean tide. Mean lower low water is 0.7 to 1.2 feet below mean sea level for points in the Hawaiian Islands. The heights measured are therefore about a foot greater than elevations above mean sea level to which the waves washed. Measurements were made by means of hand level and eye height, or sometimes with steel tape, above estimated tide level, and the heights corrected to the lower low-water datum by means of the published tide tables of the U. S. Coast and Geodetic Survey. Some inaccuracy undoubtedly has entered in the estimation of tide level on coasts exposed to large waves, but it is believed that the resultant error probably nowhere greatly exceeds 1 foot.

When the tsunami washed on the shores of the islands the tide was falling and had reached from half tide at some locations nearly to low tide at others. The predicted tide height above mean lower low water for the time of arrival of the tsunami ranged from −0.1 foot at Hanalei, Kauai, to +0.7 foot at Waianae, Oahu.

It should be clearly recognized that the heights measured are those to which the water dashed on shore, and not the actual height of the waves of the tsunami. It should also be recognized that the measured heights involve certain variables not directly related to the tsunami. As indicated below, at most places in the Hawaiian Islands large storm waves were running on the day of the tsunami, and these waves, riding on the broader swells of the tsunami, added to the height to which the water dashed on shore.

In judging the significance of high-water marks, account should be taken of the height to which storm waves of the type prevalent on the day of the tsunami could be expected to reach. Several storm waves would ride in on each of the broad swells of the tsunami. There is, of course, a great difference in

height above normal sea level which will be reached by wind waves striking different parts of the coast. Even on the high general levels of tsunami crests the storm waves would be lower in bays where projecting points and protecting islands and shoals intervened. However, on open points the storm waves would make their usual concentrated attack, but would rise from a higher level. Several places were seen where the storm waves of the past winter had risen higher than the high-water marks of the tsunami. At those places the implication is, of course, that the tsunami was not very high. Similarly, at places where, during the period of investigation, the wind waves were seen to dash up almost to the height reached by the water during the tsunami, the conclusion was reached that the sea had risen only enough to permit the storm waves to attain this slight extra height. An illustration of this is Keanae Point, on the northern side of East Maui, where the level reached by the tsunami was only a few feet higher than that reached by large wind waves under typical trade-wind conditions.

Another complication arises from variations in the angle of slope of the shore upon which the combined tsunami and storm waves impinged. Storm waves which strike essentially vertical cliffs dash high up them, and often bring solid water (as distinguished from spray) to heights twice that of the breaking wave. Abundant spray even may be thrown much higher than that. Thus, if the tsunami raised the general water level along the shore, say 15 feet, and a storm wave 15 feet high rode in on top of the tsunami, the water from the breaking storm wave might dash up on a cliff to a height of 45 feet above see level. The 45-foot mark at Kilauea Point, on the northeastern side of Kauai, could be explained in this way.

DESCRIPTION OF EFFECTS ON INDIVIDUAL ISLANDS

ISLAND OF KAUAI

Kauai is the most nearly round of any of the Hawaiian Islands (fig. 6). The Napali coast, on the northwest, is steeply cliffed except at the mouths of deeply entrenched valleys. Much of the rest of the coast is formed of lower cliffs. At Haena, on the northern side of the island, and between Mana and Kekaha on the southwestern side, the coast is low, consisting of a broad shore platform of coral reef and terrigenous sediments formed at a time when the stand of the sea was higher. North of Mana, on the western coast, the shore line is closely paralleled by a row of high dunes of calcareous sand, and between Wailua and Hanamaulu on the eastern coast there is a row of similar but lower dunes. The largest bays are Hanalei Bay on the northern shore, Hanamaulu Bay and Nawiliwili Bay on the southeastern shore, and Hanapepe Bay (Port Allen) on the southern shore.

Coral reefs fringe a small part of the coast of Kauai. Their greatest development is along parts of the north coast, notably between Haena and Wainiha Bay and between Hanalei and Kalihiwai. Reefs occur also around Kekaha and Waimea on the southern coast. These reefs, however, are inconsequential as compared to those of Oahu and the south coast of Molokai.

The most impressive features of the submarine topography off Kauai are the three ridges which extend respectively from the northwest, the north, and
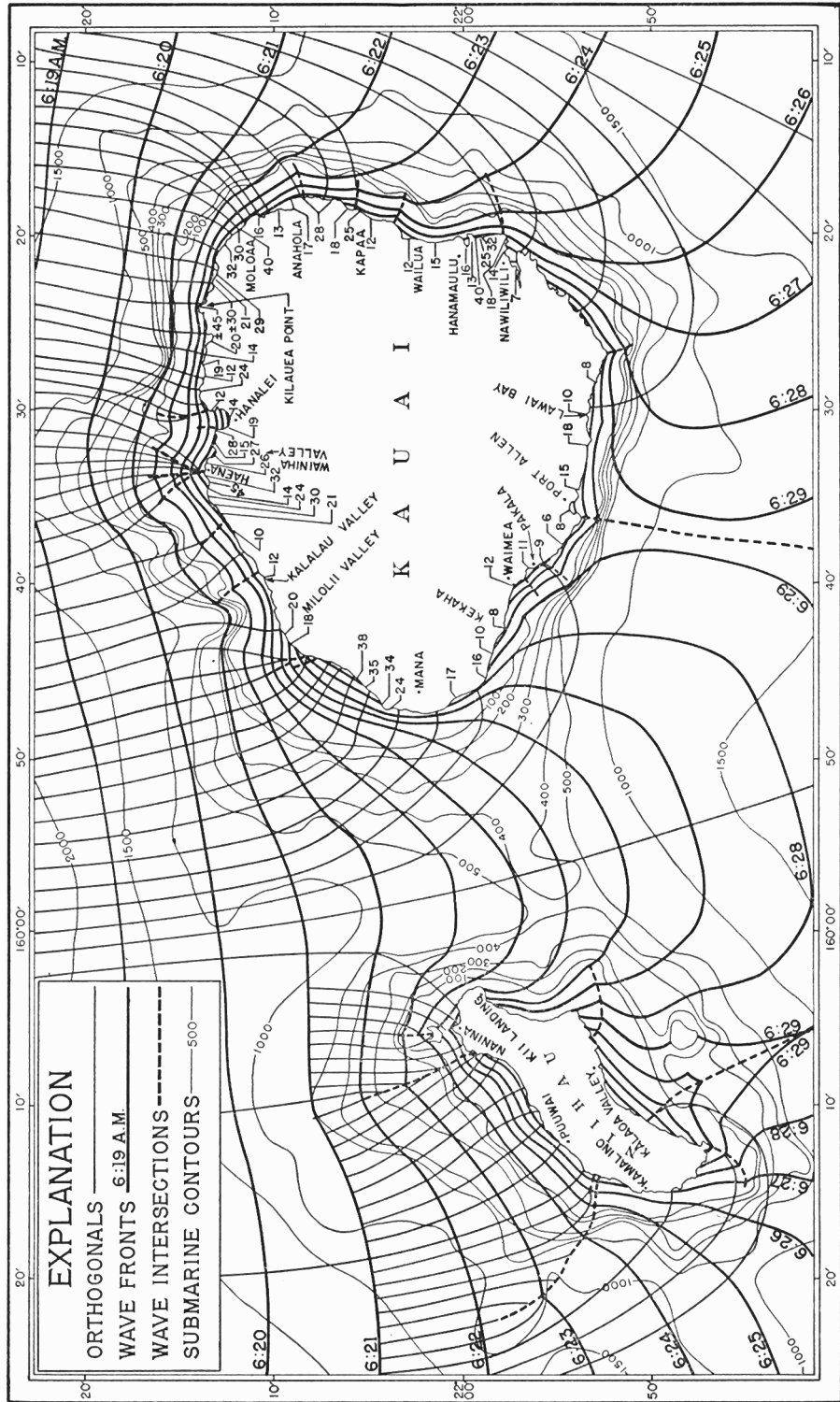
Fig. 6. Map of the islands of Kauai and Niihau, showing heights (in feet above lower low water) reached by the water during the tsunami, wave fronts, orthogonals, and submarine contours (in fathoms). Times refer to computed time of arrival of first wave.

the northeast coasts. The Kauai ridges are not related to points of land except for a slight bulge at Haena inside the middle ridge. Between these ridges are broad valleys. The westerly valley shows some resemblance to the submarine canyons along continental coasts, but appears to be more troughlike than the typical submarine canyons.

The insular shelf around Kauai is very narrow off the southern half of the island, averaging little more than a mile in width and having no impressive steepening at its outer edge. A more pronounced shelf is shown to the north, and particularly to the northwest off the cliffed Napali coast. Widths of 4 or 5 miles are found off Haena and Makaha points. Off Haena the shelf terminates at about 75 fathoms, which is deeper than is usual for oceanic insular shelves. The shelf off Makaha Point and to the south has a submerged ridge, presumably of coral, which runs parallel to the coast and rises to within 8 fathoms of the surface.

Submarine valleys of small depth head near the entrances of Hanalei and Kalihiwai bays on the north side of the island and toward Hanamaulu and Nawiliwili bays on the east side.

The greatest measured heights to which the tsunami dashed up on shore on Kauai are 45 feet at Haena and approximately 45 feet on the cliffs at the head of the small bay just east of Kilauea Point. Both areas of extremely high waves lie at the head of long submarine ridges. In general, the heights are greatest along the northern coast, decreasing southward along the eastern and western coasts, and are lowest along the southern coast. Near the middle of the southern coast, however, approximately on the opposite side of the island from the direction of approach of the waves in the open ocean, we found a zone several miles wide in which the heights were much greater than along the coast farther east and west (see fig. 6). The heights to which the water rose along the southern coast of the nearly round island of Kauai average much greater than those along the southern shore of the very elongate island of Molokai, even though the average height along the northern shore of Molokai is greater than that along the northern shore of Kauai.

In the vicinity of Haena the water rose to heights generally between 20 and 30 feet (fig. 7). At the head of Haena Bay it crossed a shore platform about 3 feet above sea level and 0.1 mile wide, and rose on the cliff at the landward side of the platform to a height of 45 feet. On the point just west of the bay the water rose only 14 feet, but on the next point to the west it rose 24 to 30 feet. Near the head of the bay, on the western side, witnesses reported that the rise of the water was gentle. Two women, one of them carrying a baby, were standing in front of their houses, undecided about what they should do, when they were engulfed by the rising water. They swam without much difficulty to some near-by trees, and thus saved themselves and the baby. The houses were floated off and wrecked.

At the head of Haena Bay the sand beach was strongly eroded and the sand was carried inland and deposited 4 feet deep across the highway at the base of the cliff. On the point just east of the bay the water rose 32 feet. On the eastern side of the bay the head of the beach was cut back 30 to 50 feet, leaving a scarp 4 to 12 feet high (pl. 13, *a*). Coral blocks, some of which were 12 feet
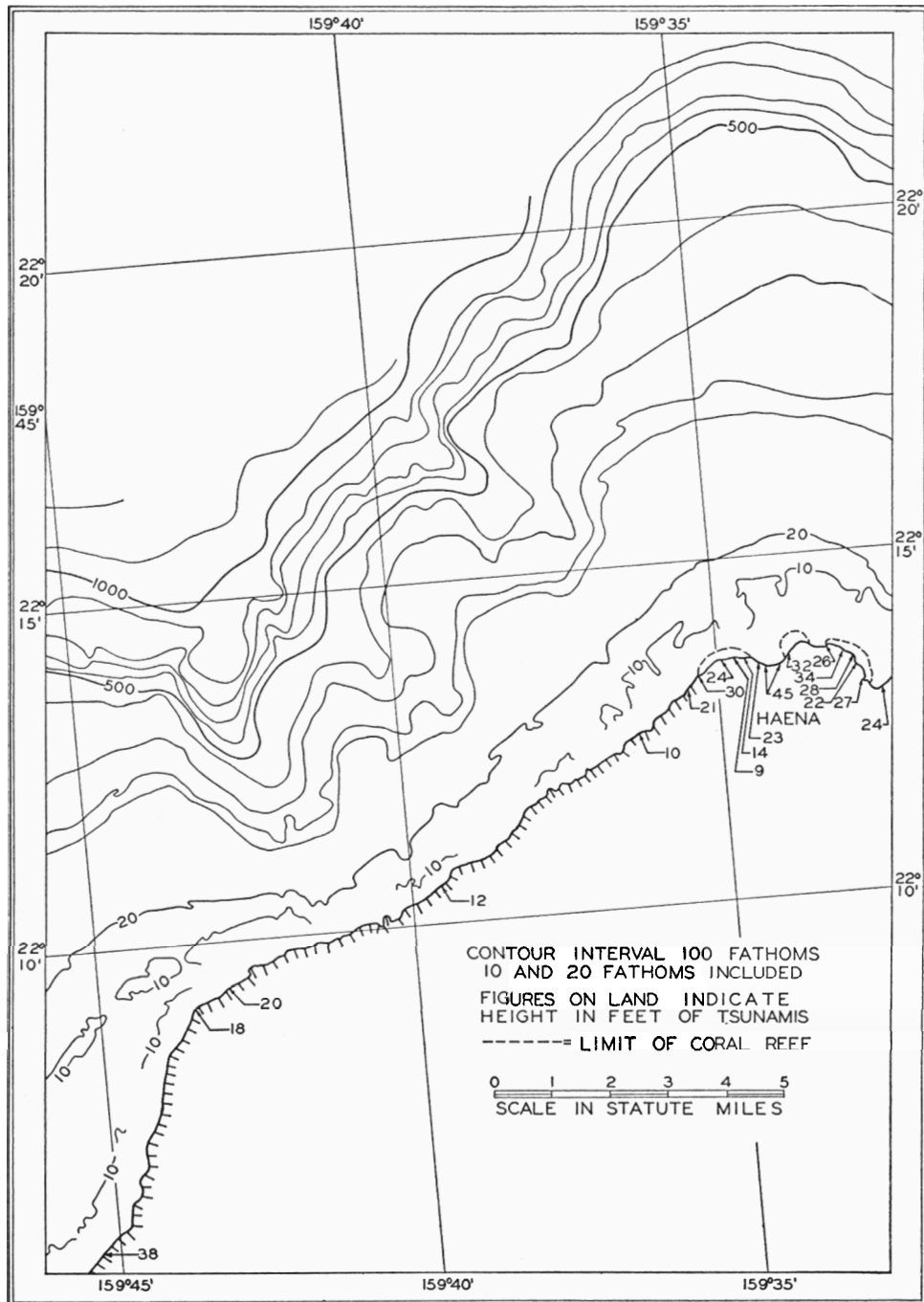
Fig. 7. Northwest corner of Kauai, showing relation of heights to submarine
topography and to coral reefs.

in diameter, were carried as much as 500 feet inland, and blocks of limestone which must have exceeded 10 tons in weight were tossed up on the reef. A large block of concrete and reef limestone, more than 200 square feet in area and 2 feet thick, which had been the porch of a house, was carried 200 feet out on the reef by the receding water (pl. 13, *b*). Houses standing 22 feet above sea level were demolished, and several persons lost their lives.

Half a mile east of Haena Bay the water swept inland 1,600 feet, knocking over trees, and a little farther east it smashed through a dense grove of pandanus, laying the trees over in parallel rows (pl. 12, *b*), much as did the devastating blasts of gas on the eastern slope of Lassen Peak, California, during the eruption of 1915. Fishes were carried far inland, as at many other places; and 11 days after the wave, small fish were found still alive in a pool 1,000 feet inland.

Wave intensities and directions at Haena bear an interesting relationship to the distribution of reefs. The extreme height of 45 feet at the head of Haena Bay occurred at a place where the reef was absent, whereas the lower heights on both sides occurred where the shore is fringed with reef. On the eastern side of Haena Bay the waves everywhere advanced to shore over the fringing reef but struck shore most violently at the head of a small channel through the reef, and spread laterally, carrying debris alongshore.

At the head of Wainiha Bay the water rose 24 to 27 feet above normal sea level. Several houses were wrecked, and some loss of life occurred. At the mouth of the Lumahai River, half a mile east of Wainiha Bay, the water rose only 15 feet. However, extensive alteration of the beach profile took place, the beach being cut away at high levels and moved inland 50 feet or more. When the beach was visited on April 11 a broad, whale-backed bar had been built just above normal water level; but this was probably built by normal waves after the tsunami.

On the western side of the point at the west edge of Hanalei Bay the water dashed up 28 feet, whereas on the eastern side of the point it came up only 10 feet. Near the head of Hanalei Bay the water rose 9 to 14 feet, and on the eastern side only 12 feet. Hanalei Bay is partly sheltered by small reefs which project from each side near its mouth, and by a shoal farther offshore. On the cliffs east of Hanalei Bay the water rose 24 feet. At Kalihikai, on the eastern side of the small bay at the mouth of Anini Stream, 2 miles east of Hanalei Bay, the water rose only 12 feet above normal sea level, but several houses were damaged and carried as much as 150 feet inland. Observers there reported that the water first receded, then came up again turbulently, but with no big wave. The third wave was the most violent, rolling in with a steep front like a big breaker.

In Kalihiwai Bay the water rose 20 to 22 feet. Houses as much as 10 feet above sea level and 300 feet inland were destroyed, and some loss of life occurred. One house was carried 1,000 feet up the valley and left not badly damaged. Between waves the water receded until the river bed was left practically dry for 500 feet inland. The incoming waves struck the western wall of the bay near the beach, and were reflected back at an angle across the valley, missing a house which stood near the western wall of the valley 500 feet inland.

The beach at Kalihiwai was cut back 300 feet by the waves. In connection with the violence of wave attack there, it is important to note that Kalihiwai is not protected by reefs.

The zone from Kilauea Point to a mile southeast of Moloaa is in general one in which the waves dashed on shore to great heights. In the small cove just east of Kilauea Point the water rose on the cliffs to about 45 feet above sea level. On Mokolea Point, 1.5 miles farther east, the water rose about 30 feet. A mile farther southeast the water rose 29 feet on the cliffs, although a fringing reef 150 feet wide lay in their path offshore. At the stream 0.1 mile southeast of Pakala Point, a mile northwest of Moloaa, the water rose 32 feet at the shore, but rushed 750 feet up the valley to a height of 38 feet.

Violent destruction was caused at Moloaa, though without loss of life. Every one of the dozen houses was destroyed. The shore line at the head of the bay was cut back about 70 feet, leaving cliffs of alluvium 6 feet high (pl. 14, *a*). Rocks weighing about 5 tons were thrown up on the beach. Near the beach the water rose to heights of 30 to 35 feet above sea level. It swept inland along the valley, carrying debris from the houses at the beach as much as 0.7 mile inland, to a height of about 40 feet above sea level.

For 2 miles northward from Anahola Bay the heights reached by the water were comparatively low, ranging from 13 to 17 feet, although the waves did some damage to houses near Anahola. Along the cliffs southeast of Anahola Bay the water reached heights of 28 feet. From Kapaa to Hanamaulu Bay it rose only 12 to 16 feet.

At Hanamaulu Bay, according to F. X. Thiel, captain of the port at Ahukini, the water rose 9 feet at the breakwater and wharf, and during recessions between waves it dropped about 18 feet below normal sea level, exposing the anchor of a buoy at that depth. About 7 waves of large size were noticed, the third being the largest. Most of the damage was caused by the violent withdrawal of the water, between waves, which damaged a small launch, washed the tug against the breakwater, with minor damage, and shifted several buoys. At the head of Hanamaulu Bay the water rose 16 feet and washed 500 feet inland. The beach was cut back 30 or 40 feet, leaving scarps 3 feet high. On the headland just south of Hanamaulu Bay the water rose only 13 feet.

The small bay just south of Hanamaulu Bay presents an interesting example of how high the water rose at the head of certain funnel-shaped bays. It is shown in detail in figure 8. At the mouth of the bay, on both the north and south sides, the water rose only 25 feet, but at the bay head the water rushed up the small valley to a height of 40 feet above sea level. A mile south of Hanamaulu Bay the water dashed up 32 feet on the precipitous sea cliff; but heavy storm waves reach at least 20 feet above sea level at that point.

In the northern arm of Nawiliwili Bay the waves reached a height of 14 feet above sea level and did considerable damage to frame structures. At the head of the bay the water rose only 7 feet, washing a small boat onto the mud flats but doing only minor damage to structures ashore.

Along much of the southern coast of Kauai the waves reached heights on shore of only 6 to 10 feet above sea level. Near Koloa Landing, 2 miles east of Lawai Bay, the height was 8 feet, at Lawai Bay 10 feet, at Port Allen 8 feet,

at Pakala 7 to 11 feet, a mile and a half farther southeast at a point south of the town of Makaweli 6 feet, and south of Kekaha 8 feet. However, in Wahiawa Bay, a mile east of Port Allen (see fig. 6), the water rose 12 to 17 feet; and at the mouth of Kalaheo Gulch, 2.5 miles farther east, it reached a height of 18 feet. At the mouth of Waimea River the water dashed up 12 feet on the beach ridge, but at the U. S. Geological Survey stream gauging station on Waimea estuary, 0.3 mile from the mouth, the water rose a maximum of only 2.8 feet (see fig. 5).

Mr. Aylmer F. Robinson was just leaving the wharf at Pakala in a small boat of the type known in Hawaii as a sampan when the water started to recede in the first trough. In realization of what was happening, the boat was
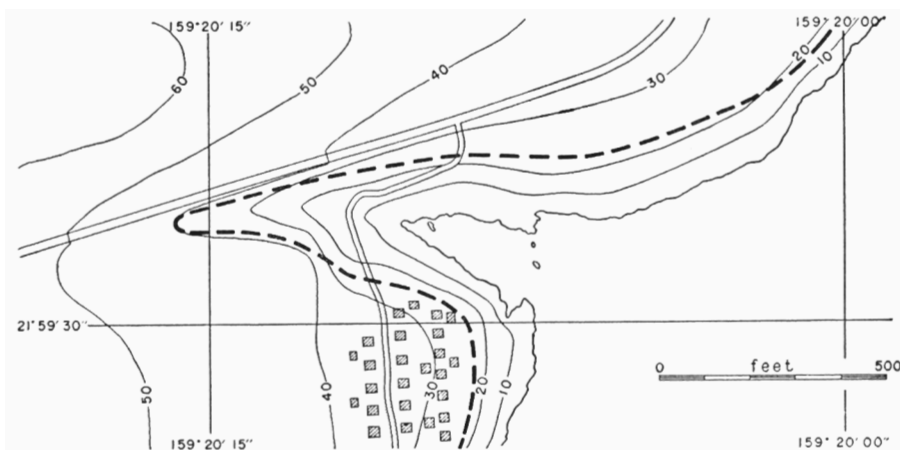
Fig. 8. Map of the small inlet and valley just south of Ahukini, Kauai, showing the height reached by the water during the tsunami (indicated by the dashed line). Altitudes are in feet above lower low water.

hurriedly put to sea and met the succeeding waves coming up the bay. The waves were not particularly large, but Mr. Robinson noticed that on going over a wave the boat did not drop into a trough but appeared to "stay at the greater height on a very full inrush of water behind the wave."[13] Obviously, the waves had the form characteristic of tidal bores, with broad, nearly flat crests behind steep fronts. From Kekaha to Waimea well-defined breakers were observed nearly parallel to the coast and crossing the wind waves which were coming in from the east. Three well-defined large waves were seen, with smaller intervening waves.

West of Kekaha, the heights increased to 17 feet near the Mana airport, 24 feet at the southern end of the Barking Sands dunes north of Mana, and 33 to 38 feet on the outside of the dune ridge farther north (see fig. 6). Near the northern end of the dunes the water flowed inland through a break in the dune ridge and flooded cane fields for a distance of 1,000 feet inland, damaging the cane to a degree which made it necessary to cut several acres of cane prematurely.

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[13] A. F. Robinson, letter of May 11, 1946, to G. A. Macdonald.

The three observations on the Napali (northwestern) coast of Kauai, made by H. W. Beardin of the U. S. Geological Survey, suggest that the wave heights were distinctly lower than those to the northeast and southwest. On the western side of Kailio Point, at the northeastern end of the Napali coast a mile west of Haena Bay, the water reached a height of 30 feet; and at the northern end of the Barking Sands dunes, at the southwestern end of the Napali coast, it reached a height of 38 feet. However, at the mouth of Hana-kapiai Stream, 2 miles southwest of Haena Bay, it rose only about 10 feet; on the beach 0.4 mile southwest of the mouth of Kalalau Valley, only 12 feet; and only 18 to 20 feet in the vicinity of Milolii Valley. It should be noted that this zone of low wave heights lies opposite a broad, valley-like swale which extends outward on the sea floor to oceanic depths, whereas the zones of high waves to the northeast and southwest lie at the head of broad offshore ridges.

ISLAND OF NIIHAU

The writers have not visited Niihau (see fig. 6), and no other scientist has made a study of tsunami effects on that island. The following general statement is based on a letter from Mr. Aylmer F. Robinson.

According to Mr. Robinson, the wave impact was most severe on the northern side of the island. Around the entire shore line of the island the water reached, in general, heights of more than 10 but less than 20 feet above sea level. Only at a few places were the heights outside these limits.

The waves did a large amount of damage but caused no loss of life or injury to persons. At Nanina, on the northern coast (see fig. 6), they destroyed a cottage which had stood for probably more than sixty years, and so severely washed the ground that it was difficult even to recognize the place where it had stood except in a general way. At Kii Landing they destroyed the small wharf, damaged houses and fences, washed cobbles inland over part of the area, and at other places stripped away the surface soil down to the hardpan layer. At Nonopapa Landing they badly damaged the wharf and damaged some houses. Apiaries in the bay south of Kamalino and at Kalaoa Valley were almost destroyed. At Puuwai the water barely came over the low parts of the sand-dune ridge along the coast.

For some time Mr. Robinson was unable to land from a sampan at Niihau because of the extremely heavy surge. About noon the water was alternately withdrawing so far as to leave the reefs on the northern shore bare to depths never before seen by him, and flooding inland to the sand dunes behind the beach. The surge continued all day.

ISLAND OF OAHU

The shore line of Oahu (fig. 9) is much more angular than that of Kauai. The island consists of two elongate northwesterly-trending shield volcanoes which have been joined together and deeply eroded. Later volcanic cones cluster around the southeastern end of the eastern shield. There are four prominent points on the island, all of which are prolonged as ridges below sea level. These are Kaena Point, which forms the sharp western end of the island; Kahuku Point on the north; Mokapu Point on the northeast, which partly encloses
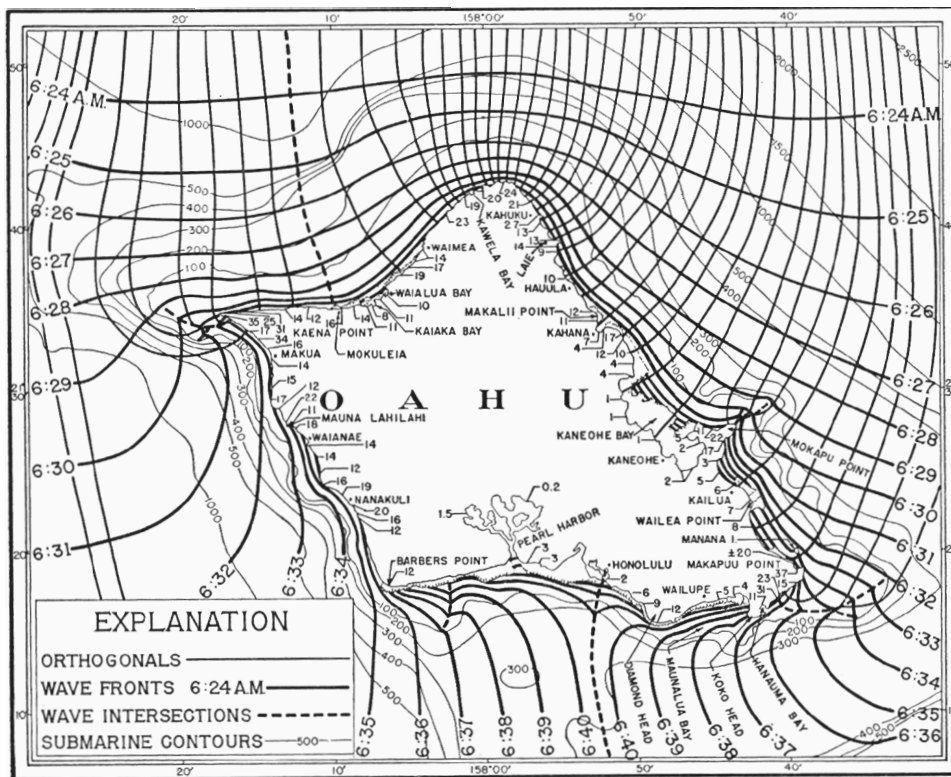
Fig. 9. Map of the island of Oahu, showing heights (in feet above lower low water) reached by the water during the tsunami, wave fronts, orthogonals, and submarine contours (in fathoms). Times refer to computed time of arrival of first wave.

Kaneohe Bay; and Makapuu Point on the east. Almost all the greatest heights reached by the tsunami were in the vicinity of these promontories. The southern side of the island is notable for its low coastal plains, on which most of the population of the island is concentrated, and for the two natural harbors, Pearl and Honolulu. Narrower coastal plains are found around much of the rest of the island. On the northern coasts a number of beach communities and army camps are situated on the outer edges of the narrow plains a few feet above sea level.

Coral reefs surround most of the northern, eastern, and southern coasts but are inconspicuous on the western side of the island. These reefs are of the fringing type and are not actively growing at the present time. They extend from half a mile to a mile out from shore and inside their seaward edge they have some small channels parallel to the shore. Reefs are absent off all the prominent points of the island, and a number of other gaps are to be found. The area of greatest reef development is Kaneohe Bay.

It is worth noting that the submarine topography off Oahu accords with the contour of the shore line and bears some resemblance to the land contours. As already mentioned, the four principal promontories on the windward coast are all prolonged seaward by submarine ridges; on the leeward side the same is
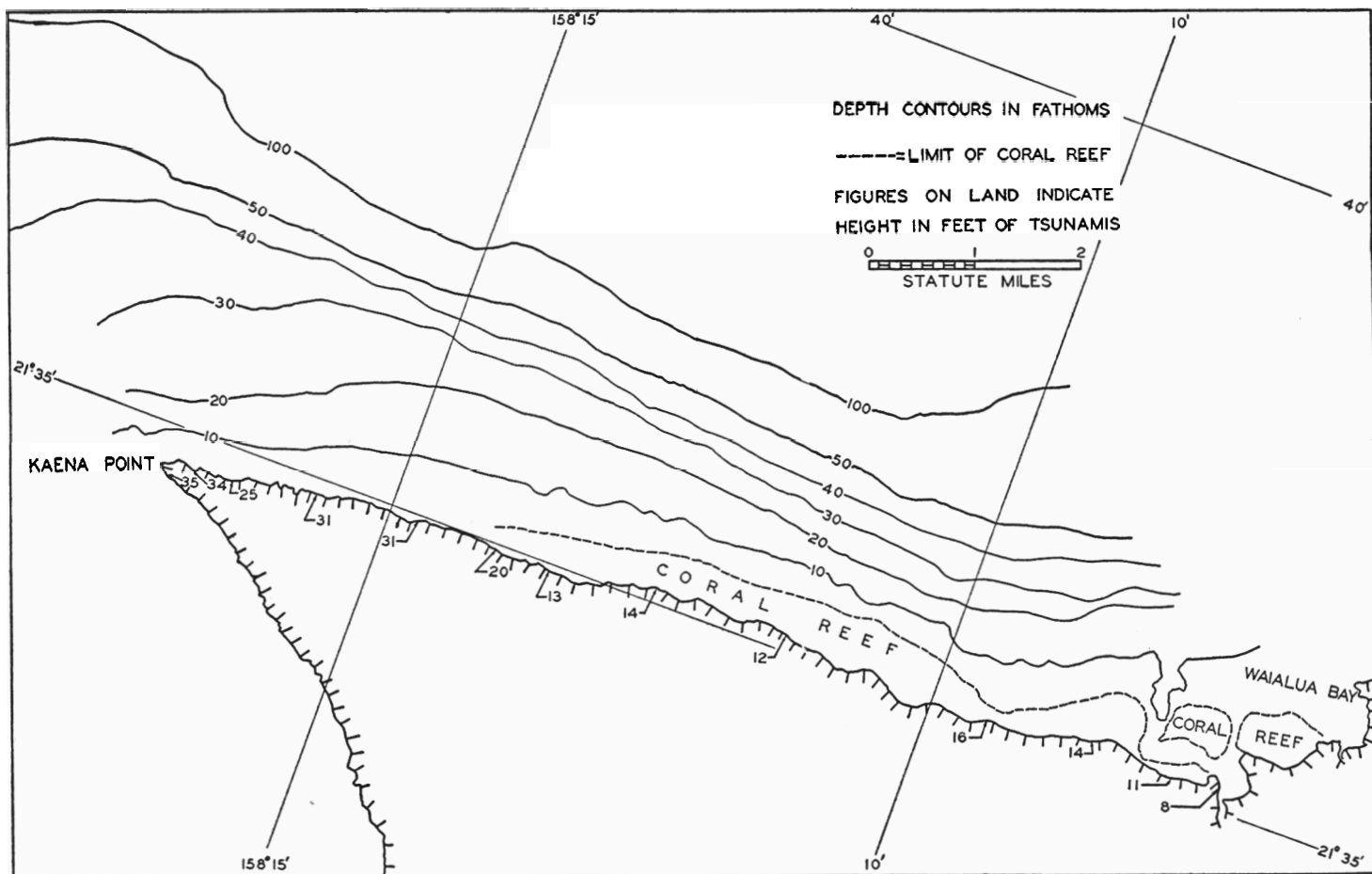
Fig. 10. Northwest corner of Oahu, showing relation of coral reef to heights reached by the water.

true of Koko Head and, to a less degree, of Diamond Head. Along the north side of the island there are several submarine canyons, discovered in the course of recent naval soundings. Shallow valleys cut the coral reef at both ends of Kaneohe Bay. A shallow submarine valley also enters Kahana Bay, and another enters the north side of Waialua Bay. Along the west coast there are broad sea-floor indentations which follow the coastal indentations. However, between Barbers Point and Pearl Harbor the coast line is almost straight and does not affect the broad ridges and valleys on the sea floor.

A narrow insular shelf surrounds most of Oahu. Off the northwest and northeast coasts it appears to terminate at a depth of about 50 fathoms and has a width of about 2 miles. The slope beyond is about three times as steep, a contrast not nearly as great as is usual between continental shelves and continental slopes. On the southern side of the island the shelf terminates at a shallower depth, steepening being evident at about 25 fathoms or less. The slope beyond the shelf is particularly steep out to 150 fathoms and then becomes gentle down to the 300-fathom depth of the Kaiwi Channel. Along much of the southern coast the shelf has the same 2-mile width as on the north side of the island, but there is no shelf at all off Koko Head. Along the western coast there is only a narrow shelf less than a mile wide, which shows signs of steepening at a depth of 15 fathoms or less. Beyond this, a 10° slope extends down to depths of over a mile.

The high-water marks reached by the tsunami on Oahu have been determined partly by the present writers and partly by John Isaacs and H. W. Iversen of the University of California. A more complete coverage has been made of this island than of any of the others. The most striking feature of the measured heights on Oahu (see fig. 9) is the generally low altitude reached by the water on the northwestern and northeastern coasts. This contrasts strongly with the findings on the northern coasts of all the other islands. The levels are consistently high, however, on the prominent points of Oahu.

Starting at the western end of the island, altitudes as great as 36 feet were found at Kaena Point, the greatest being just south of the point. Along the northern coast for more than 2 miles east of Kaena Point, where the coral reef is absent, the high-water marks were about 30 feet above sea level, but in the next mile to the east the heights reached by the water decreased rapidly to 20 feet, and in the next half mile to 13 feet. This decrease in height coincides with the beginning of the coral reef (fig. 10). Still farther east, at Mokuleia, the water rose more than 16 feet and considerable damage was done to houses along the beach. Elsewhere in the long bight, which includes Waialua Bay, the heights were low. At Kaiaka Bay the water rose only 8 feet, but in Waialua Bay it rose 10 to 11 feet.

At Laniakea Spring, 2 miles east of Waialua Bay, opposite a break in the reef, the water rose 19 feet, but at the barred entrance to Waimea Valley it rose only 14 feet. The bay-mouth bar at Waimea Bay was breached by the waves but was rebuilt by normal waves in less than a week. Three miles northeast of Waimea, at Paumalu, the water rose 23 feet above sea level and threw sections of the railroad track inland across the adjacent highway.

At Kawela Bay, damage was done to houses by the waves which came across

the off-lying reefs and rose as high as 19 feet just west of the bay. Occurrences in this area will be discussed at length later.

At the airport just east of Kahuku Point the waves drove inland across the dunes, flooding the lowlands inside the coastal dune ridge and causing extensive damage. The water rose 24 feet in crossing the dunes. Farther east, opposite the town of Kahuku, a high level of 27 feet was recorded by debris lines along the dunes. Southeast of Kahuku, heights of only about 13 feet were observed. Half a mile south of Laie the water rose only 9 feet, leaving the houses on the low terrace virtually intact as far as Hauula. However, the water rose slightly higher to the southeast and caused extensive destruction to houses at Haleaha and at Makalii Point. Sugar cane on 123 acres of Kahuku Plantation was damaged or destroyed by the force of the waves and by salt poisoning.

The water levels at Kahana Bay are instructive. The waves swept in violently against both sides of the entrance to the bay, wrecking houses which were as much as 12 feet above sea level on the western side, but reached not more than about 7 feet above sea level at the head of the bay. However, the return of the water from the bay head swept a house into a fishpond on the southeastern side of the bay and drowned three children. On the headland east of the bay the water rose 17 feet, and threw large blocks of coral onto the beach and even across the road.

At Kaaawa, a mile southeast of Kahana Bay, the water rose 12 feet and damaged barracks in an abandoned army camp. About 2 miles farther to the south the height of the high-water marks decreased from 10 to 4 feet in a distance of 1.5 miles. Around the point in Kaneohe Bay the waves must have been still lower. Along this shore the waves left intact houses on the fishpond walls at altitudes of less than 3 feet (pl. 14, *b*.) Low piers with decks not more than 3 feet above sea level also were undisturbed. A boat beached at Kaneohe only about a foot above sea level appeared not to have been moved. Observers on the shore saw nothing out of the ordinary. Few places on the five major islands examined showed so complete a lack of indication that a tsunami had struck the shore.

A very different situation was found by Isaacs and Iversen at Mokapu Point. Here, the waves swept in on the outside of the northern end of the point to altitudes of about 22 feet, and caused some damage to outlying buildings and roads around the Naval Air Station. No observation was made at the outermost point. To the south of Mokapu Point the heights reached by the waves decreased to $3\frac{1}{2}$ feet in a distance of 3 miles in the lee of Kapoho Point, and a rise of only a few feet was recorded in Kailua Bay. At Wailea Point the waves rose 7 feet. Motion pictures of the waves were taken at this point, showing the waves coming in around both sides of the Mokolua Islands and meeting inside. Damage to the beach houses was not great.

On the north side of Makapuu Head the high-water mark was 37 feet above normal, the highest for Oahu. At this point there is an indentation, flanked on the southeast by Makapuu Head and on the northwest by Manana and Kaohikaipu islands. The shore rises steeply at this place (pl. 15, *a*).

At Kaloko, a mile southwest of Makapuu Point, the water rose only 15 feet

but demolished a group of houses just inland from the beach. In spite of the high seas which are characteristic of this area, the water came in rather gently, at least in the first two waves. Mr. A. S. Davis, whose home there was destroyed, waded to his armpits ahead of the advancing second wave, holding a picture above his head. This suggests that no great turbulence existed in this wave. The wreckage indicates that later waves probably were more violent. The houses were swept away and left as a heap of debris against a row of trees 500 feet inland.

Southwestward toward Koko Head the heights reached by the waves were greater, attaining a height of 31 feet near the famous Blow Hole. Much of the road was washed out in this area (pl. 15, *b*). The steep sand beach was greatly eroded, and a series of steep cusps with truncated ends was left (pl. 16, *a*).

Much lower heights, with a maximum of 14 feet, were found in Hanauma Bay, a breached crater just northeast of Koko Head. West of Koko Head the water rose only 3 to 5 feet. At the head of Maunalua Bay two waves were seen to move up parallel channels across the reef and turn toward each other along the shore, water shooting upward like a geyser where they met. Moderate damage was done at Wailupe, where houses only 4 or 5 feet above low tide were hit by the waves. At Diamond Head the water rose as high as 12 feet but came in very gently. The largest wave there was said to be the fourth.

At the eastern end of Waikiki Beach, 1.5 miles northwest of Diamond Head, the water flooded over the sea wall and attained a height of about 9 feet. All along the south side of Oahu the reefs were laid bare between waves. Water rushing up the Ala Wai Canal, at the western edge of Waikiki, damaged boats moored to the walls of the canal, and yachts in the yacht harbor were thrown up on the reef or against the shore.

In Honolulu Harbor the tide-gauge record shows that the water rose 4 feet in the third wave (see fig. 4). At the entrance to Pearl Harbor the water reached 4 feet above normal, but it rose only 18 inches at the docks in the West Loch and 0.2 foot at the head of East Loch. Most people at Pearl Harbor did not know that a tsunami was occurring until they heard radio reports.

At Barbers Point the water reached 12 feet above sea level, but along the Waianae Coast much higher levels were found (see fig. 9). Near the mouth of Limaloa Gulch, 1.5 miles southeast of Nanakuli, the waves pushed one house inland across the beach ridge and the returning water carried another house seaward, leaving it near the normal high-tide mark (pl. 16, *b*). Near the southern edge of Nanakuli Valley the water rose 16 feet, flooding gently up a valley and returning across the adjacent terrace. A house was carried seaward and deposited with its occupant, an elderly Hawaiian, near the edge of a low bluff along the shore. The large effective wave here was said to have been the first, and to have been preceded by a large withdrawal. As elsewhere, it is probable that the first wave was overlooked, and possibly also the second.

At Nanakuli the water attained an elevation of 20 feet above sea level in a park pavilion. Here also it came in gently and the first wave was reported to be the largest. To the north, heights of about 14 feet were found as far as Waianae, where the water damaged houses on a low terrace. Farther north,

an appreciable variation in heights was found. Just north of the promontory of Mauna Lahilahi the water rose 22 feet, but on the south side of the same point it rose only 11 feet, and in the bight north of the point 11 to 12 feet. It rose 17 feet south of Kepuhi Point, but appears to have reached 34 feet at the point north of Makua Valley, with only 16 and 17 feet recorded on either side.

At Makua the water rose 14 feet above sea level, but the beach appeared to have suffered little erosion. A few days after the tsunami a swimming party
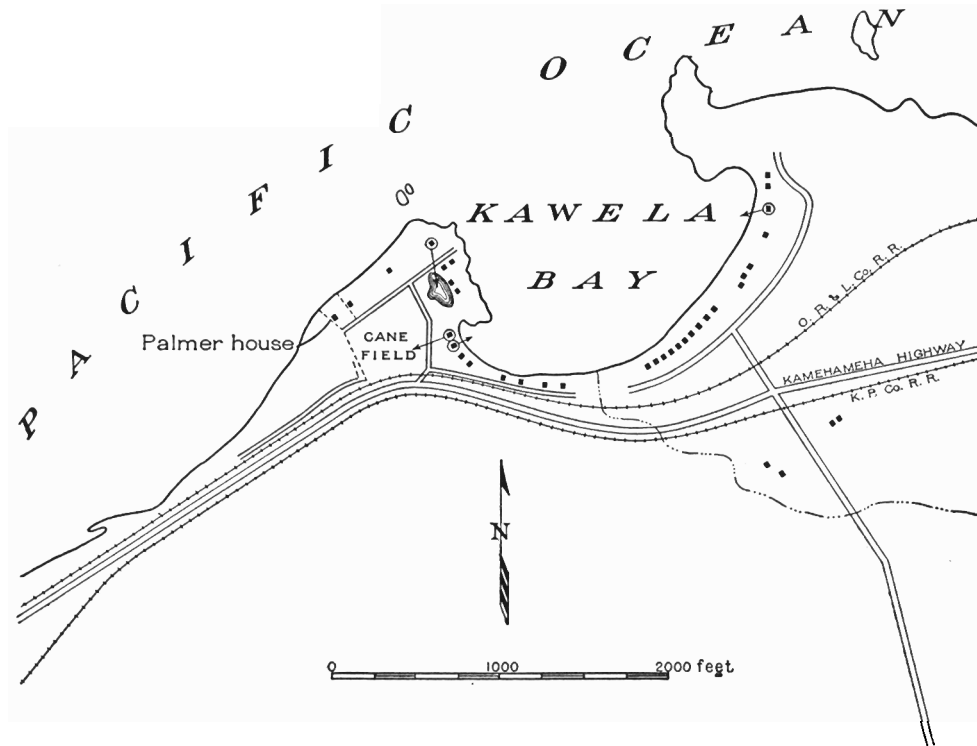
Fig. 11. Map of Kawela Bay, Oahu (after H. S. Palmer). The arrows show the direction of movement of houses shifted by the tsunami.

of marines noticed outside the beach a shallow bar which had not been present when they had swum there several weeks earlier.

Waianae Plantation lost 15 acres of sugar cane, mostly by the force of the waves.

Wave at Kawela Bay, Oahu.—Kawela Bay is an indentation in a nearly horizontal terrace, 5 to 20 feet above sea level, which extends from the slope of the Koolau Volcano to the shore. The terrace appears to be essentially a fringing reef formed when the sea stood higher than it does now. Irregularities on the reef platform have resulted from accumulation of beach and dune sand and from solution of the limestone. Just west of Kawela Bay a sinkhole 50 feet across extends below sea level. Along the shore west of Kawela Bay, where the Palmer house stands (fig. 11), a beach ridge rises several feet higher than the surface of the terrace behind it. Offshore lies a fringing reef about a quarter

mile wide. At the outer edge of the reef a ridge rises nearly to sea level, but inside the ridge deeper water occupies a lagoon parallel to the shore.

At the time of the tsunami, Shepard and Mrs. Shepard were living in a house just west of Kawela Bay belonging to Professor H. S. Palmer of the University of Hawaii. Following is a narrative by Shepard of their experiences during the waves.

Mrs. Shepard and I were awakened by the first large wave. According to a Filipino fisherman, who was camped near by, the water withdrew from shore before that wave, leaving many fish stranded on the reef. The returning wave brought water up to about 14 feet above sea level at the Palmer house, awakening us by a hissing noise like a group of engines blowing off steam. Just to the east, the water crossed the beach ridge with enough volume to wreck the unoccupied house next to us [pl. 17, *a*]. The water was moving westward with considerable turbulence along the front of the beach ridge. The second withdrawal also exposed the reefs, leaving pools of water in the lagoon. I watched the coming in of the second wave as closely as possible under the alarming conditions. Nothing unusual was visible until the wave front broke over the outer edge of the fringing reef. The crest of the wave did not rise more than about 20 feet above normal sea level. It swept westward diagonally with a steep and very turbulent front across the lagoon inside the outer ridge [pl. 6], but did not appear to move faster than an ordinary wind wave. The slow rise over the beach ridge is indicated by the fact that 2 photographs, showing only a small change, were shot with an interval long enough to wind the camera, probably about 5 seconds. The second wave reached a height of about 17 feet, wrecking the front of the Palmer house [pl. 18, *a*].

A considerable flow of water coming down the road from the east, inside the beach ridge, made escape in that direction impossible. Passage through the cane field behind the house was also out of the question, so that the beach ridge to the west was the only route open. We had ample time to reach the railroad (a trip later repeated in 5 minutes), and then go back to persuade two Hawaiian women to leave the ridge, before the arrival of the next wave. The third wave was observed from a point on the railroad at a height of 24 feet. It broke just outside the terrace, rising slightly above the horizon at eye level, so that this breaker must have been about 25 feet high. Crossing the terrace with a terrific noise of breaking cane, it swept across the railroad track to the west of us and left a mass of debris on the highway inland from the railroad. In walking to the head of Kawela Bay, we encountered several refugees. Four of them had ridden in a house which was floated 200 feet from the beach into a cane field [pl. 19]. Their breakfast was left still cooking on the stove, and china was still intact on the shelves. Obviously the wave was not very turbulent at that point. However, this represented only the farthest advance of the wave coming up the bay. Our observations of subsequent waves in the bay itself showed that they had a steep, turbulent front and were advancing like bores over relatively smooth water inside. The rate of movement in the bay we estimated as being about 15 miles per hour. Several crests appeared on the wave, probably representing wind waves.

After the fourth or fifth wave, the magnitude of the waves appeared to be decreasing, and after the eighth wave, leaving my wife on the road, I made a return trip to the remnants of the Palmer house [pl. 18]. However, as I was arriving, a large wave roared in and rose to heights considerably exceeding the second wave, so that I had to climb an ironwood tree behind the house. Water rushed by, 2 feet deep underneath the tree, where no water had come during the second wave. The waves continued to have alarming dimensions for the remainder of the morning, although I saw none come up onto the terrace after that. I could not time the wave periods because we had lost our watches. During the afternoon, after about 1:30, the waves were so small that I did not observe them while working in the ruins.

Examination of the beach after the waves showed that the sand was approximately the same in level below the house as before but had more coral and shell debris in it. However, the bank at the head of the beach had been considerably undercut, leaving scarps up to 6 feet in height where only minor scarps had existed before. Large pieces of beach rock weighing up to about a ton had been thrown up onto the shore.

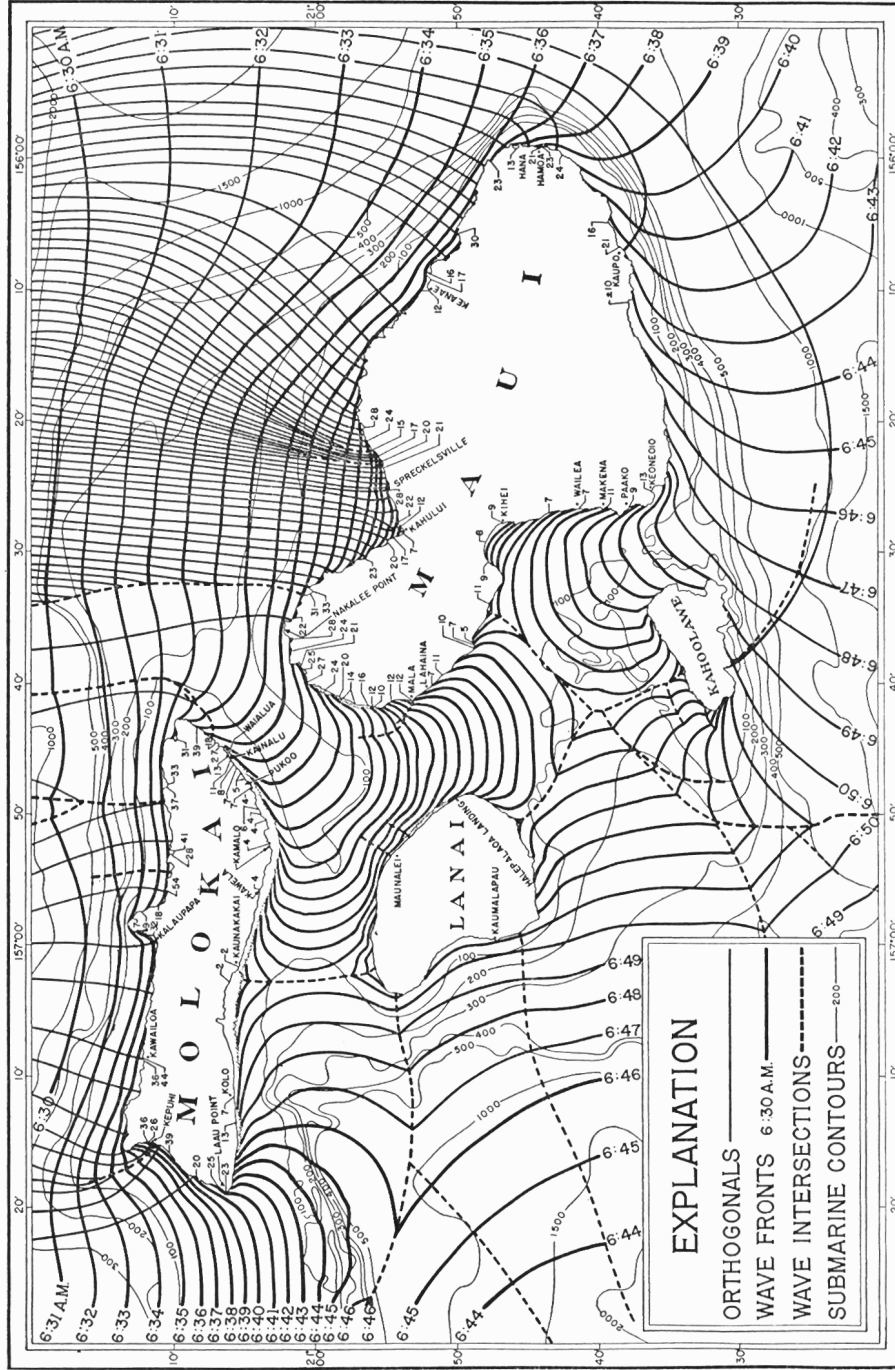Toward Kawela Bay we found that two houses had been washed into the small pond in the

Fig. 12. Map of the islands of Molokai, Maui, and Lanai, showing heights (in feet above lower low water) reached by the water during the tsunami, wave fronts, orthogonals, and submarine contours (in fathoms). For detailed submarine topography see figure 13. Times refer to computed time of arrival of first wave.

sinkhole [pl. 19]. Along the shore of the bay, sand had been swept toward the west so that the beach was wider at that end, but in the center the beach had been considerably reduced in width. Also at the center of the bay numerous large coral blocks had been lifted onto the shore and carried up onto the terrace about 9 feet above sea level [pl. 17, *b*], and even through the front of one of the houses. Near the east end of the bay a house was carried out into the water, leaving only its roof emerged.

ISLAND OF MOLOKAI

Molokai differs from other islands of the Hawaiian chain in being very elongate. It is 35 miles long from east to west and 6 miles across from north to south (fig. 12). This elongation is even greater below sea level, where the shallow Penguin Bank extends west of the island for an additional 35 miles. The straight northern side of the island is precipitous, particularly in the eastern part where the highest mountains are found. Near the center of the northern side a low volcanic cone juts out 2 miles beyond the cliffs, forming Kalaupapa Peninsula (pl. 20, *a*). Judging from the recent navy soundings (fig. 13), this peninsula was built out onto a steep slope and does not have any appreciable submarine ridge extending beyond it. This is in contrast to the points at the ends of the island, which are greatly prolonged below sea level. Along the northern side of the island there is a narrow submerged shelf with a width of about 2 miles, except at the western end of the island, where it widens to 3 miles. The shelf does not exist off Kalaupapa Peninsula, where it apparently has been covered by the late cone of Kalaupapa volcano. The northern slope beyond the shelf is cut by a series of submarine canyons which compare somewhat with the great land canyons of East Molokai. Off West Molokai the submarine canyons are absent, just as are land canyons of any important size. The lack of canyons on the slope of West Molokai must be attributed to aridity, as the volcanic structure is older in time of extinction than the deeply dissected mass of East Molokai (Stearns and Macdonald, 1947). No coral reefs or shallow submarine platforms are known to exist along the northern side of the island.

The southern side of Molokai is characterized by a smoothly curving coast with a broad convexity south of the eastern mountain mass and a broad concavity south of the low isthmus between East and West Molokai. The southern slopes are much more gentle and much less dissected than those of the north side. In the concavity west of Kaunakakai there is a low terrace, and at the apex of the concavity there is a broad mud flat. A mile-wide coral reef extends along the southern side of the island except at the extreme eastern and western ends. Beyond the reef the bottom slopes gently into the Pailolo and Kalohi channels, which separate Molokai from Maui and Lanai, respectively. The water in these channels averages about 100 fathoms in depth, but off southwestern Molokai there is a trough leading down to oceanic depths.

The short western coast of Molokai also has a simple outline, with a broad indentation to the north. The mountain slopes on land are gentle and are continued seaward with no appreciable change.

The high-water marks left by the waves have been determined at scattered points all around the island (see fig. 12). They are high on the northern side of the island and low on the southern side. The extreme range, from 54 feet

Fig. 13. Bottom topography along the north side of Molokai.

at Waikolu Valley on the north to 2 feet at Kaunakakai on the south, is greater than the range on Kauai and Oahu. Also, the heights along the northern coast in general were consistently high, mostly more than 30 feet; and along the southern coast they were consistently low, except near the east and west ends. It will be noted that south of both the east and west points of the island the water rose to highs of 39 and 38 feet, respectively, higher than the average for the north side of the island. These high levels are in keeping with similar high levels found south of both the east and west points of Oahu and the east point of Maui.

The most striking feature of wave-height distribution on Molokai was found around Kalaupapa Peninsula (see fig. 13). At the outer end of the point the waves left driftwood concentrations 7 or 8 feet above normal sea level, whereas winter storms had left wood 20 feet above the same datum plane (pl. 20, *b*). Similarly, winter storms occasionally wash onto the air field near the end of the point, which has an altitude of about 20 feet, but the tsunami did not touch the airport. Away from the point, on both sides of the peninsula, the tsunami attained much greater heights. The measurement of 43 feet just west of the peninsula appears higher than the average along that part of the shore, but the average probably exceeds 30 feet. Eastward from the peninsula the height increased to 54 feet at the eastern side of Waikolu Valley, where the highest mark on the island was measured (pl. 21, *a*). At the center and western side of Waikolu Valley the waves reached lower levels, probably about 30 feet. The high point at Waikolu Valley has a topographic setting similar to that of the highest point reached on Oahu, both being in coastal indentations with a point on one side and an islet on the other. This situation suggests that funneling action was important. Probably the irregular submarine topography acted in such a way as to produce wave convergence at those points.

According to measurements by Mr. Howard S. Leak of the U. S. Geological Survey, the water rose 28 feet on the western side of Pelekunu Bay, and 41 feet at the head of the bay. Old taro patches and the abandoned village of Pelekunu were obliterated, and the water running back to the ocean scoured out large holes on the beach. At Wailau Valley, 5.5 miles east of Pelekunu, Mr. M. H. Carson of the U. S. Geological Survey measured high-water marks of 33 to 37 feet. Large amounts of beach sand were carried into the mouth of Wailau Valley and deposited 4 to 5 inches deep at altitudes up to more than 25 feet. At high levels on the valley walls, trees were pushed inland by the force of the inrushing water; but along the axis of the valley, debris was washed seaward by the returning water.

The waves were observed at the town of Kalaupapa by many persons, some of whom lost their homes. The fourth wave was the highest. The withdrawals between waves were said to have been much greater in magnitude than the rises. The waves rose gently, like an excessively high tide, and the most violent flow came during the return of the water seaward. The backwash undermined a road and washed away several houses. One house which was washed to sea at Kalaemilo Point, three quarters of a mile north of Kalaupapa, bobbed about on the waves for several minutes before it finally broke up.

In contrast, at the northeastern end of the island, at Halawa, the water came in with great violence, and washed a large area so clean that it could almost serve as an airport (pl. 21, *b*). Photographs indicated that the beach at the head of the inlet had been cut back several feet by the waves.

It is interesting to compare the heights reached by the water along the axes of valleys with the heights on the valley sides near the mouth. In the short, steep valley at Honouliwai, 1.25 miles northeast of Waialua, the water rose at least 6 feet higher on the sloping valley floor than on the valley walls. This is comparable to the greater rise along the valleys at Moloaa and just
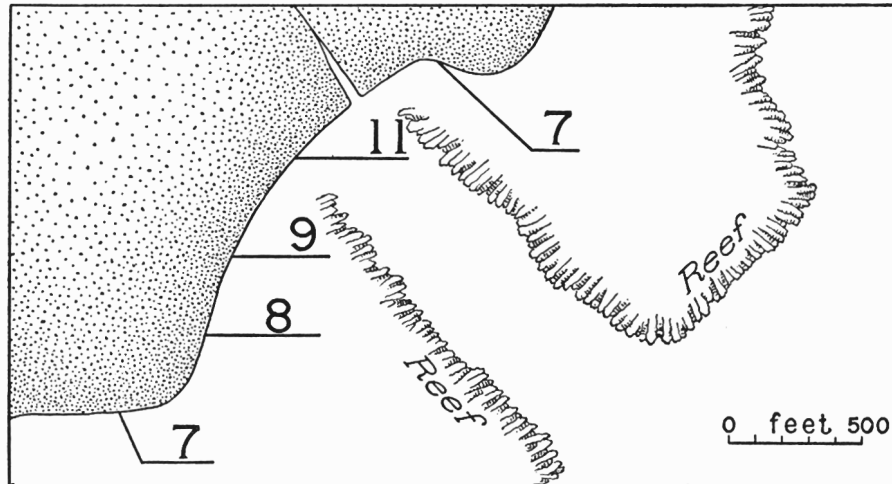
Fig. 14. Map of Kainalu area, on the southern coast of East Molokai, showing heights reached by the water during the tsunami (in feet above lower low water) in relation to a channel through the fringing coral reef.

south of Ahukini on Kauai. At all other places measured on Molokai the water reached somewhat higher on the valley walls near the mouth than on the valley floors.

The heights reached by waves on the southeastern side of the island showed some relation to channels in the coral reefs. The water appears to have risen somewhat higher at channel heads, and just west of the channel heads, than elsewhere. For example, at the head of the channel at Pukoo the water rose 6 feet above sea level, whereas inside the broad reef to the west it rose only $3\frac{1}{2}$ feet, and to the east the water did not rise the $4\frac{1}{2}$ feet necessary to cover the floor of a house built on the wall of the fishpond. Similarly, at Kainalu, 1.2 miles southwest of Waialua, the waves came in along a channel, crossed the reef and moved westward, shifting houses in that direction (pl. 22, *a*). At the channel head and just west of it the waves attained a maximum height of 11 feet, but away from the channel farther east and west they reached only 7 to 8 feet (fig. 14).

At Waialua, on the southeastern coast of Molokai, the waves were described as coming in from the east but returning directly seaward down the slope. Apparently the fourth wave was the most severe. A huge pine log 5 feet in

diameter, which had lain on the beach for many years, was moved westward along the beach and carried inland across the road.

At Kaunakakai the water was observed to rise gently, but to flow back seaward with more violence. The waves were still in evidence more than 2 hours after the first ones arrived. At Kolo, on the southern shore of West Molokai, the first two waves were said to be separated by an interval of about 10 minutes, but subsequent waves were much closer together. The water reached a height of about 7 feet above normal sea level. The return of the water seaward was more violent than the inflow. The water level during the troughs is reported to have dropped about 6 feet below normal sea level, leaving the sea bottom bare for 500 feet offshore.

At Kepuhi, 2 miles south-southeast of Ilio Point, the northwestern corner of Molokai, the waves swept inland to a height of 35 feet above sea level with force enough to uproot and wash inland a grove of algaroba trees (pl. 22, *b*).

ISLAND OF LANAI

Lanai was not visited by the authors in the course of the present investigation. For an account of the effects of the tsunami on the island of Lanai we are indebted to Mr. Dexter Fraser, plantation manager of the Lanai division of the Hawaiian Pineapple Company.

No severe damage was done by the tsunami on Lanai. At Manele Bay, on the southern coast (see fig. 12, p. 426), the largest wave knocked over a stone wall and swept inland about 150 feet. On the northeastern coast, from Maunalei to Halepalaoa Landing, the waves swept inland 50 to 100 feet, leaving a line of flotsam at their position of farthest advance. At Manele Bay and Hulopoe Bay on the southern coast, and at Kaumalapau on the southwestern coast, the height reached by the waves was estimated by Mr. Fraser to be about 7 feet.

At Kaumalapau, from 7:15 A.M. until about noon, a general rise in ocean level followed by a recession occurred at intervals of approximately 15 minutes. Fishing boats moored in the harbor lay first with their bows pointed toward the ocean, then swung 180° so that their bows pointed shoreward. No damage was done, and the rise and fall of the water was so gentle that the loading of pineapples onto barges continued uninterrupted all day.

ISLAND OF MAUI

The island of Maui is composed of two volcanic mountains connected by an isthmus only 7 miles across (see fig. 12, p. 426) and so low that several times in the past ships have been beached in attempting to pass between the two mountains. Maalaea Bay lies between the volcanoes and south of the isthmus. Kahului Harbor is at the head of the corresponding bay north of the isthmus.

The northern coast of Maui is unprotected against waves from the north, but the southern coast is sheltered not only by Maui itself but also by the adjacent island of Molokai. The two islands are separated by the Pailolo channel, which is 8 miles wide. Probably the neighboring islands of Lanai to the west, Kahoolawe to the south, and Hawaii to the southwest also helped to shelter the southern coast of Maui from refracted and reflected waves.

Except at the isthmus, the northern coast of Maui consists generally of cliffs. The only lowlands on the northern coast of West Maui are the bottoms of a few large valleys. On the northern and eastern coasts of East Maui there are even fewer large valleys, but in places late lava flows have made low coasts and peninsulas, as at Keanae and for several miles both west and south of Hana.

The southern coasts are in general low, except the southernmost point of West Maui and the southeastern coast of East Maui, which consist of low cliffs.

Maui is connected with Lanai by a shallow submarine platform with a sill about 20 fathoms deep. The island is connected with Kahoolawe, and indirectly, through Lanai, with Molokai, by platforms less than 100 fathoms deep. The Pailolo channel between Maui and Molokai is 140 fathoms deep. The 100-fathom contour around this group of islands shows, besides the narrow reëntrant of the Pailolo channel, a large reëntrant between Kahoolawe and Lanai south and southwest of West Maui. This reëntrant is indicated to a lesser extent by the 200-fathom contour. The bays north of the central Maui isthmus are barely represented by the 50-fathom contour, and the 300-fathom contour, outside the northern bay, shows a large ridge opposite the bay and West Maui, about 25 miles north of Kahului. The submarine slopes off East Maui are steep and contours on them in general parallel the shore line. The Alenuihaha channel between Maui and Hawaii is more than 1,000 fathoms deep. No submarine canyons have been found in the submarine slopes off Maui.

There are few well-developed coral reefs on Maui. North and east of Kahului there are reefs as much as half a mile wide but not very shallow. At Lahaina there is a narrower reef. Elsewhere there are only spotty reefs.

Kahului Harbor is protected by two breakwaters (fig. 15). The waves of the tsunami came over the point of land at the base of the eastern breakwater about 22 feet above low water, but the breakwaters so reduced them that the water in the harbor rose only about 12 feet above low water at Pier 1, which is built against the breakwater. Where the waves rushed across the point and cascaded into the harbor, the difference in height was plainly indicated by the heights to which trees were barked, rubbish washed up, and soil eroded. Just east of the breakwater, coral blocks as much as 4 feet in diameter were thrown on the shore. The Kahului Railroad Company reported damage amounting to about $10,000 to railroad tracks, cars, and warehouses.

The third wave was reported to be the largest at Kahului. Very accurate measurements were made of the waves at the piers by employees of the Kahului Railroad Company. At Pier 2, 0.2 mile inside the breakwater at the eastern end of the harbor, the lowest trough was 16 feet 3 inches below the pier deck, or 6 feet 7 inches below normal low water. The highest wave washed 2 feet over the deck of Pier 1, reaching a height of 11 feet 10 inches above low water. The total height from crest to trough was, then, about 18 feet 5 inches.

The effect of the breakwater in reducing the wave was seen also at the west end of the harbor. Inside the breakwater the rise was only about 7 feet, but just outside it was 17 feet. There was some erosion of soil and sand just land-

ward from the end of the rock breakwater, and the seaward edge of the high-
way was eroded even inside the breakwater. Several houses were damaged or
destroyed and a number of amphibious tanks parked in a marine camp near
the breakwater were floated off.

Along the beaches for about 6 miles east of Kahului (fig. 12) the waves rose
17 feet or more above sea level. At Spreckelsville the waves reached an eleva-
tion of 28 feet and swept inland as much as 800 feet, although there is a fairly
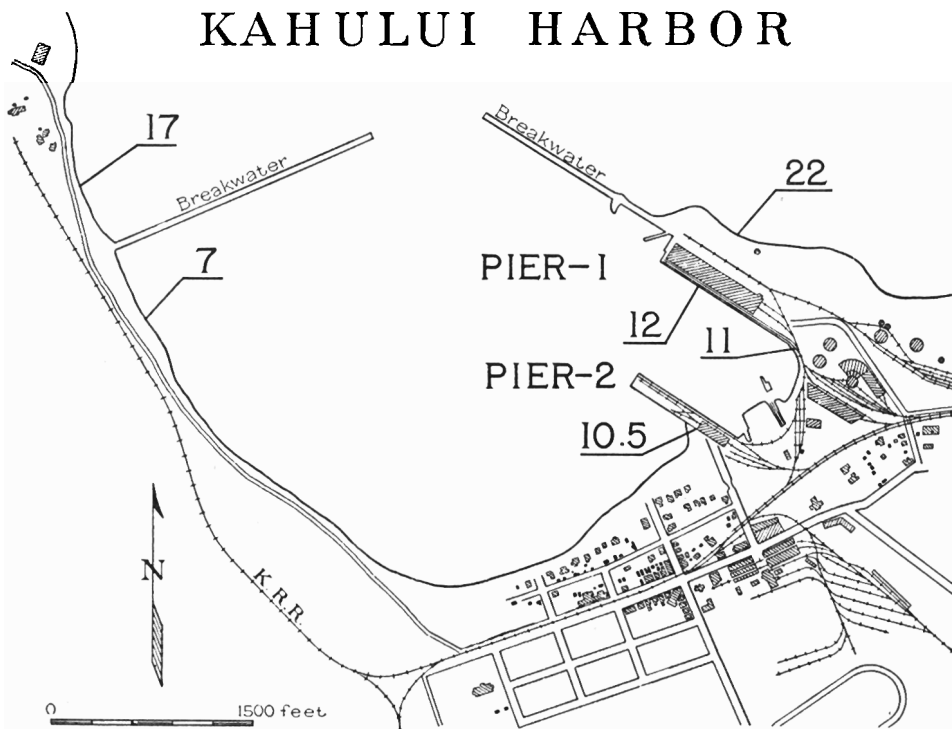
Fig. 15. Map of Kahului Harbor, Maui, showing heights reached by the water during the
tsunami of April 1, 1946. Heights are in feet above lower low water.

wide reef offshore. Several residences were destroyed and many were badly
damaged. Erosion was noticeable in many places. At one place the lawn and
the tennis-court pavement on a sand base were stripped off for a width of 150
feet. At Lower Paia, where the waves reached to 20 feet above low water,
several buildings 250 feet from shore and 10 feet above sea level were wrecked,
and some buildings were carried 50 to 100 feet farther inland. In places the
waves swept into cane fields about 800 feet inland, damaging the cane and
making necessary a premature harvesting.

West of Lower Paia the shores are rockier and higher, and only a few inlets
have low shores. At Kuau, a mile northeast of Paia, there is a reef about 1,000
feet offshore with deeper water inside, and there the wave heights dropped to
15 feet. There was no damage at Kuau. At Maliko Bay, which is a drowned
and partly alluviated valley, there is no reef. There the waves swept the sides

of the valley to a height of 28 feet and washed 0.2 mile up the valley to and over the highway. Houses below the highway were destroyed, and an automobile parked near the beach was rolled up on the highway.

No examination was made of the coast from Maliko Bay to Honomanu Bay. The shores have high cliffs, and there are few places where good wave measurements could be made. No damage was reported from this area.

Honomanu Bay is a drowned, partly alluviated valley in a coast line which consists mostly of cliffs several hundred feet high. Although there is no reef, the waves washed to a height of only 12 feet. The low height may be related to a small submarine valley, between 50 and 100 fathoms deep, which is suggested by sparse soundings about 2½ miles north of Honomanu.

Keanae Peninsula is a low lava delta extending about half a mile beyond the cliffed coast line. It is on the northern side of a large submarine ridge which extends to a depth of between 100 and 200 fathoms. The height reached by the waves at the head of the bay west of the peninsula was 17 feet, and that at the end of the peninsula 16 feet. Although the waves swept over the entire end of the peninsula, damaging several buildings and killing two persons, the wave heights were not great, considering that normal storm waves dash up nearly to the level of the top of the peninsula, 13 to 15 feet above sea level.

Nahiku Landing is at another, older, lava delta which extends beyond the general line of cliffs but is itself cut back to 25-foot cliffs. Here the waves washed up as much as 30 feet above low water, the greatest height on East Maui, and cut a low scarp in soil only a couple of feet below that level. This great height may not be significant, since wind waves were breaking up to 16 feet at the time of examination.

From 5 miles west of Hana eastward and southward past Hana the cliffs become somewhat lower, but no damage was reported except at Hana. Just east of Kapakaula Point, 2.5 miles northwest of Hana, the waves washed to 23 feet above sea level. At the head of Hana Bay, just north of Kauiki Head, the easternmost point on Maui, the waves were up only 13 feet above low water, although several houses on low ground at the north side of the bay were damaged. At the north end of Hamoa, 2 miles south of Hana, the waves reached 21 feet above low water, and at the south end 23 feet. The houses, which were only about 10 feet above sea level, were almost all destroyed. One, however, was floated intact for a distance of 200 feet (pl. 25, *a*). Several lives were lost.

There was little damage on the coast south of Hamoa because the shores are cliffed and the houses well above sea level. However, the waves continued high for some distance. At Puuiki the waves washed up on cliffs on the open coast to a height of 24 feet, and in a little cliffed cove to 28 feet above low water. At Kaapahu Bay, 3 miles east of Kaupo, a shack was wrecked, and the water rose over the highway to a height of 16 feet above sea level. At Kaupo the height was 21 feet, but no damage was done. These considerable heights in the lee of a protecting point resemble the great heights in similar locations on Oahu and Molokai, mentioned previously.

Along the southern and western coasts of East Maui the heights were much less. At Nuu, 3.5 miles west of Kaupo, the wave came up only about 10 feet.

No examination was made of the coast between Nuu and Keoneoio, on La Perouse Bay. There is no road, and the coast is uninhabited. At Keoneoio the water came up 13 feet and damaged or destroyed three houses. At Paako the waves rose only 9 feet, but a long stretch of low road was badly eroded or covered with sand. At Makena the waves came up 11 feet, but there was no apparent damage. At Wailea the level rose only about 7 feet, though the marks recording the maximum were poor. At Kamaole, 3 miles north of Wailea, the height was 7 feet. Photographs taken there by Joe de Lima at both maxima and minima show no noticeable wave, only an apparently flat sea. Fourteen waves were counted between 6:45 A.M. and 9:30 or 10:00 A.M. The sixth was the largest. Pictures of the recession indicate no very great withdrawal, the water level falling probably only 2 or 3 feet below normal low water.

At Kihei the waves covered the dock with 1 foot of water, rising thus to a height of 9 feet. There the first wave was reported to have been the largest. The recession was not so marked as to expose the bottoms of the dock piles, which are at a depth of about 10 feet. Opposite the middle of Kealia Pond at the head of Maalaea Bay the rise was only 8 feet. At the town of Maalaea the waves rose gently to 9 feet above low water and floated a garage a few feet inland. The third wave there was said to be the largest.

From Maalaea Bay westward there is a gradual increase in the measured heights. This may be related to the greater exposure of the coasts to the direct approach of the waves to the north. Two miles east of Papawai Point, the southernmost point on West Maui, the height was 11 feet above low water. At Olowalu there was evidence of a southeastward longshore component to the wave direction. Just west of the pier the wave covered the beach and rose to 10 feet above low water. The water washed over the pier, which is 7 feet above low water, and covered some of the level land just behind it. However, alongside and just east of the pier the water came up only 5 feet.

At Launiupoko, 3 miles northwest of Olowalu, the wave height was 11 feet, and at Mala it was 12 feet; but between them, at Lahaina, the water rose only 7 feet. Two possible reasons for the low rise are indicated. Perhaps the Lahaina shore was sheltered by the short Puunoa Point just south of Mala; or perhaps it was somehow sheltered by a part of a long submarine ridge at 14 to 20 fathoms depth that runs west from Puunoa Point for 5 miles, or about two-thirds of the distance to Lanai. At Lahaina the third wave is said to have been the largest. All were gentle except for a little dash at the foot of the pier. There was no damage. At Mala and along the shore for a mile to the north many houses were destroyed or damaged. The wave height was 12 feet at Hahakea Gulch, 1.5 miles north of Mala.

At Kaanapali Landing, north of Kekaa Point, the wave covered the dock to a depth of 1 foot, having thus a height of 12 feet. Around the point to the south the height was only 10 feet. The decrease southward may be ascribed to the sheltering effect of the point. On the beach about a thousand feet north of the landing the waves washed to 16 feet. There is no apparent reason for this increase except the local influence of storm waves.

At Honokowai, 1.5 miles north of Kaanapali, the waves washed to 14 feet above low water and ruined or damaged several houses. Northward the heights

increased fairly regularly to Hawea Point, 2 miles west of Honolua. In the small bay 3.8 miles north of Kaanapali the height was 14 feet. In the next small bay, 0.3 mile farther north, the height was 20 feet. In both bays the narrow beaches were strewn with coral blocks. In the bay north of Alaeloa Point, 4.5 miles north of Kaanapali, the height was 24 feet and a house was destroyed. Wave heights were poorly marked on Hawea Point, but on the northern side the waves apparently reached 27 feet.

East of Hawea Point the observed heights, which were all in bays, dropped slightly. In Honolua Bay a height of 24 feet was measured at the east end of the beach and a height of 21 feet near the center. One house was destroyed. In a little bay a mile to the west the height was 25 feet. At Punalau, a mile east of Honolua, the height was 24 feet. However, at Honokohau, 2 miles east of Honolua, the waves rose 28 feet, smashed a bridge, eroded the upper beach, and destroyed some taro patches.

No measurements were made on the northernmost points of West Maui, which are cliffed, and except at Keawalua and at Kahakuloa none were possible along the 7.5 miles of coast southeast of Nakalele Point. At Keawalua, 3 miles northwest of Kahakuloa, the height was only 22 feet, but at Kahakuloa the greatest heights on Maui were found. In the western gulch entering the bay the waves reached 31 feet, destroying a house and making scarps in the soil about 20 feet above sea level. In the eastern gulch the waves rose to 33 feet, destroying 2 houses and uprooting or smashing many plum and hau trees.

At the mouth of Waihee Valley, halfway between Kahakuloa and Kahului, the water was up 23 feet but no damage was done. At the northern side of Paukakalo, 2.5 miles nearer Kahului, the water rose 20 feet. Some of the many beach houses there were damaged, but most were on land too high to be reached or were built well off the ground on stilts so that the water flowed under them.

ISLAND OF HAWAII

Coastal geography.—The island of Hawaii has roughly the shape of an equilateral triangle, with one corner toward the north-northwest. The city of Hilo is situated on its northeastern side at the head of a broad, funnel-shaped bay (fig. 16). Approximately three-quarters of the northeastern coast, northwest of Hilo, consists of high sea cliffs, notched by a few large valleys cut below sea level at their mouths and subsequently alluviated. Along the other coasts the sea cliffs are lower, but in general their height is greater than that attained by the waves of the tsunami which washed up on shore. On such cliffs the waves left little or no record of their height. Only along the few stretches of low coast, and in the mouths of the stream valleys cut to sea level, were there good indications of the height to which the water dashed up on shore.

The largest embayments along the coast of Hawaii are at Hilo on the northeastern coast and Kawaihae on the western coast. Smaller bays exist at other localities, such as Kailua and Napoopoo on the western coast, Honuapo and Punaluu on the southeastern coast, and Keaau on the northeastern coast.

Laupahoehoe Peninsula, on the northeastern coast, is a low lava delta jutting 1,500 feet beyond the general coast line, without any appreciable corresponding bulge in the submarine topography.
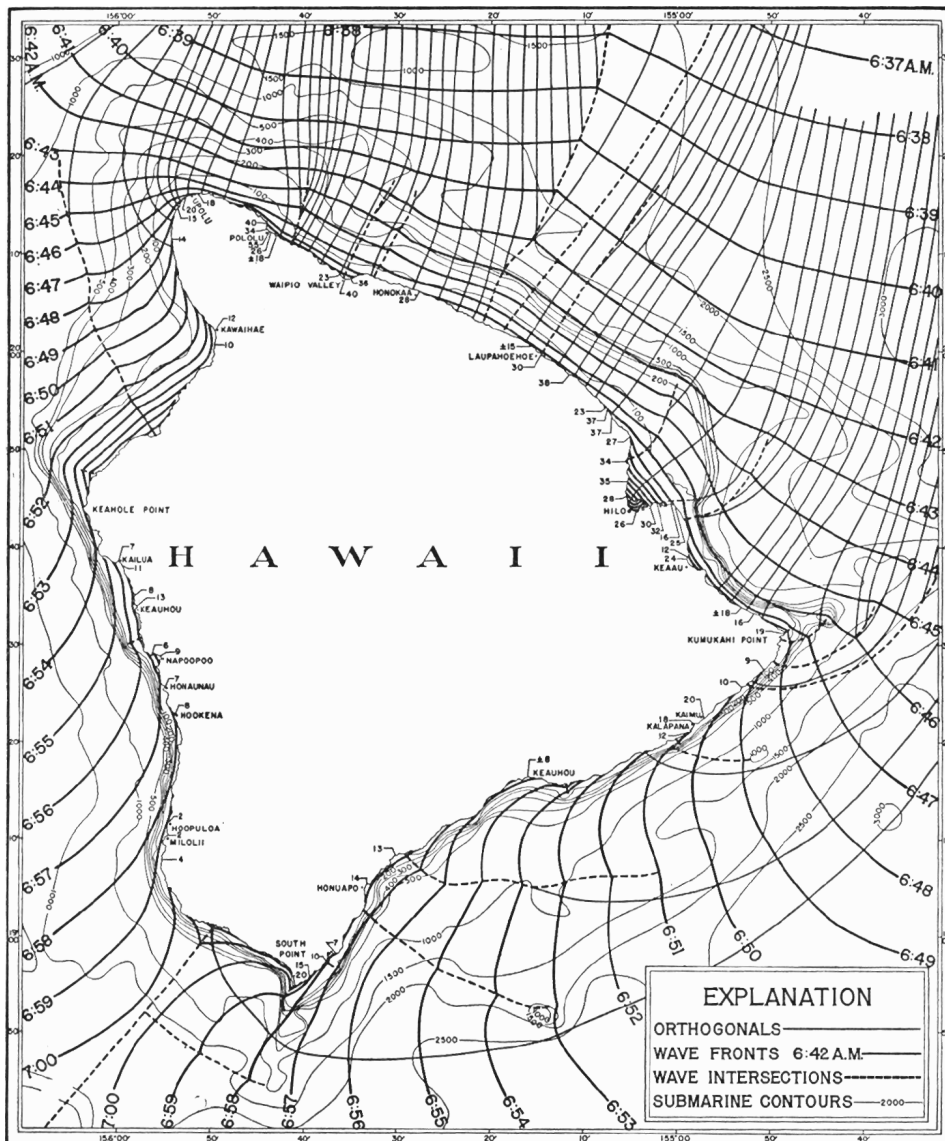
Fig. 16. Map of the island of Hawaii, showing heights (in feet above lower low water) reached by the water during the tsunami, wave fronts, orthogonals, and submarine contours (in fathoms). Times refer to computed time of arrival of first wave.

Sea-floor topography.—The only noteworthy development of coral reefs on the coasts of the island of Hawaii occurs at Kawaihae, where a reef half a mile broad extends alongshore for a mile south of Kawaihae wharf.

The topography of the sea floor surrounding the island of Hawaii is shown in figure 16, so far as it can be deduced from the soundings, which in most areas are inadequate. A broad ridge projects northwestward from Upolu Point, conforming in contour with the coast. Another broad, blunt ridge

extends nearly eastward from the north coast of Kohala Mountain, 8 miles east of Upolu Point.

A recent detailed survey off the Hilo area indicates that there is a broad projecting shelf about 200 fathoms deep which is terminated by steep intersecting escarpments with trends which join at an angle of about 75°. This zone off Hilo Bay is in a sense a flat-topped ridge. It lies in the prolongation of the east rift zone of Mauna Kea, and was undoubtedly built by eruptions along that rift. However, the scarps which truncate it are far too steep for the normal slopes of a basaltic volcano, and suggest faulting. A more typical ridge extends eastward from Cape Kumukahi along the east rift zone of Kilauea volcano; another extends southward from South Point along one branch of the south-
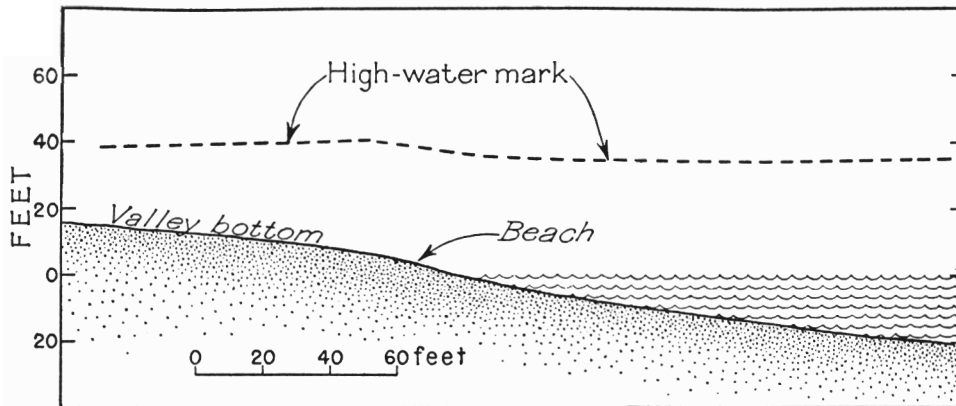
Fig. 17. Profiles of the high-water mark along the northwestern wall of Pololu Valley, Hawaii, and of the valley bottom. Note the hump in the high-water mark just above the beach.

west rift zone of Mauna Loa volcano. The western side of this southern ridge is very steep, undoubtedly because of downfaulting of the crustal block to the west. The displacement is clearly seen above sea level. The submarine slope along the western side of the island south of Keahole Point is exceedingly steep, and probably represents a fault zone along which the westerly side has moved downward. Broad valleys, probably of structural origin, extend from depths greater than 1,000 fathoms to the coast between Hilo Bay and Cape Kumukahi, and on the northeastern shore of Kohala Mountain, northwest of Honokaa. A less prominent depression extends from a depth of 300 fathoms to the shore at Kawaihae.

Elevations attained by the tsunami.—The heights attained by the tsunami on the shore of the island of Hawaii are shown in figure 16, and in greater detail for the Hilo area in figure 18 (p. 442). The greatest height measured anywhere in the Hawaiian Islands was 55 feet, on the sand dunes just southeast of the mouth of Pololu Stream (pl. 25, *b*). However, on the valley wall north of the stream mouth the greatest height was 41 feet. This height was found almost directly opposite the beach, the high-water mark dropping both landward and seaward, as is shown in the profile in figure 17. Similarly, in Waipio Valley, the greatest height, 40 feet, was reached on sand dunes in the center of the

valley mouth, as compared to 36 feet on the valley wall to the southeast and 23 feet on the valley wall to the northwest. At the mouth of Honokane Nui Valley, 0.8 mile southeast of Pololu Valley, the water rose 26 feet; and 0.3 mile farther southeast, at the mouth of Honokane Iki Valley, it rose only about 18 feet. At Pololu Valley the beach was cut back about 150 feet, and cliffs 7 or 8 feet high were cut on the northwestern end of the dune ridge (pl. 25, *b*). The water swept inland with great force for about 1,000 feet, destroying houses and rice paddies. At Waipio Valley the water pouring over the dunes near the southern edge of the valley cut a channel in the sand 100 feet wide and 15 feet deep. It rushed inland more than half a mile, destroying houses and taro patches. About 2,000 feet inland the water was still 23 feet above sea level on the southern wall of the valley.

Southeastward from Waipio Valley, the heights to which the waves dashed continued high all the way to Hilo Bay. At Laupahoehoe Peninsula the water reached a height of 31 feet above sea level and swept over the whole seaward end of the peninsula, doing great damage. Some houses were swept 500 feet inland diagonally to the northwest, and left more or less intact (pl. 26, *a*). Others were torn apart, and one was swept a considerable distance out to sea by the returning water before breaking up. Several persons were drowned; others were rescued by men in a small boat. The naval air service dropped a raft to some of the victims (pl. 11). The first three waves are reported to have approached the shore from the northeast, but succeeding larger waves came in from the east or southeast. The violence increased until the seventh or eighth wave, after which it again decreased. Between the waves the water receded from shore far beyond the normal low-tide mark.

At Maulua Gulch, 4 miles southeast of Laupahoehoe, the water reached a height of 38 feet above sea level. At Hakalau Gulch, 6 miles farther southeast, the water reached 37 feet above sea level on the south side of the valley mouth, and 23 to 29 feet on the north side. This suggests that at that locality the wave approach was from the north, in contrast to the direction of approach at Laupahoehoe. The Hakalau Sugar Company's mill, which stood less than 10 feet above sea level and near the water's edge, was badly wrecked. A large clarifier tank, small steel girders, and sheet-iron roofing from the mill were carried 800 feet inland. Steel girders in the railroad trestle, inland from the mill, were bent by the impact of the debris-laden water. Fourteen noticeably large waves, at intervals of about 10 minutes, were counted at Hakalau Mill, the seventh or eighth wave being the largest. At Kolekole Stream, 1.4 miles southeast of Hakalau Gulch, the water reached 37 feet above sea level, tearing away the middle trestle of the railroad bridge and leaving it, greatly twisted, 500 feet inland (pl. 27, *a*).

At Pepeekeo the water rose 27 feet, and at Onomea Bay it rose 34 feet both on the headlands and at the bay head. On the cliff just south of the mouth of Honolii Stream, 2 miles north of Hilo, the water rose 28 feet, and 500 feet up the stream it rose 12 feet. (Discussion of the effects in Hilo Bay will be found further on.)

Along the coast from the east side of Hilo Bay to Cape Kumukahi the heights were less than along the coast north of Hilo. At Cape Kumukahi the

water rose 19 feet, which is not very high, considering the great height attained by ordinary trade-wind waves at this point. Along the coast southwest of Cape Kumukahi the heights were in general low, ranging from 8 to 10 feet, but at Kaimu and Kalapana they reached 18 to 20 feet and water swept in violently, destroying houses at Kaimu, undercutting the highway, and stripping away soil to a depth of 1 foot 50 feet inland. At Kalapana, houses behind the sand dunes were protected from the waves. Along the western part of the southeastern coast the heights again increased. The water rose 13 feet at Punaluu, 14 feet at Honuapo, 7 feet in the bay at Kaalualu, 9 miles southwest of Honuapo, and 20 feet on the east side of South Point.

The southern part of the western coast of Hawaii is inaccessible, and no measurements were obtained along it. The southernmost measurement on the western coast was made at Milolii. At that place the water rose only about 2 feet above normal sea level, the waves being much less violent than those of southerly storms. The water rose gently, resembling a tide rather than a storm wave. It is reported that during recessions between waves the water dropped 4 feet below normal sea level. A Hawaiian fisherman reports that 3 miles south of Milolii the water rose about 4 feet. To the north the waves attained heights of 9 feet at Hookena, 7 feet at Honaunau, 9 feet at Napoopoo, and 6 feet at Captain Cook's Monument, across Kealakekua Bay from Napoopoo.

At Hookena, at the time of the violent waves elsewhere, the water is said to have risen about 6 feet, doing no damage, but the townspeople report that at 8 o'clock in the evening a much higher wave came in, damaging the dock and rising on shore to 9 feet above sea level. At Napoopoo there are said to have been at least two recurrences, one corresponding in time with that at Hookena, and the other about 2:00 A.M. on April 2. Both swept over the pier, which is about 8 feet above low tide. These late-arriving waves may represent double reflections off the walls of submarine troughs off the Asiatic coast, their height at these particular localities being due to especially good wave convergence.

At Keauhou Bay the water rose 13 feet, badly damaging one house and washing several boats ashore. At Kahaluu, 1.3 miles north of Keauhou Bay, the water rose 8 feet. At the southern edge of Kailua Bay, near the Kona Inn, it rose 11 feet, damaging masonry sea walls; but at the wharf on the northern side of the bay it rose only 7 feet.

Kawaihae wharf is situated just north of a small area of coral reef. At the wharf the waves rose on shore to a height of 12 feet above sea level. The third wave is reported to have been the largest. Between the waves, and reportedly before the first wave, recession of the water uncovered the reef for 1,000 feet offshore, the lowering of water level being estimated by one observer as about 20 feet below normal sea level. The old wharf was almost completely demolished, even pilings being carried away. However, the new wharf, which stood much higher above water, was unharmed. Many blocks of coral several feet across were thrown up onto the reef, and one about 3 feet in diameter was carried to the roadway 5 feet above sea level. For half a mile south of the wharf, houses along the shore, inside a half-mile-broad reef, were damaged or

destroyed. However, these houses were built less than 5 feet above sea level. At the park at the southern end of Kawaihae the water rose 10 feet, but it caused no damage there because all structures were on higher ground. Several waves were observed, the fourth being the largest. The water withdrew far out from shore between the waves.

At Mahukona the water rose on shore to 14 feet above sea level but did no damage. It is reported that before the first wave the harbor was dry as far out as the inner buoys, which would require a lowering of water level of about 35 feet. The water rose gently, like a tide, without breakers. The third wave is said to have been the largest. North of Mahukona the height to which the waves dashed on shore increased to 20 feet, and locally to 24 feet near Upolu Point.

Effects in Hilo Bay.—The heights to which the waves of the tsunami dashed up on the shores of Hilo Bay, and the extent of flooding inland, are shown in figure 18. The heights in the head of Hilo Bay mostly range from 21 to 26 feet. The third wave is reported to have been the largest. At the mouth of the Wailuku River the water rose about 17 feet, destroying the railroad bridge and carrying one of the steel spans 750 feet upstream (pls. 8 and 9). Most of the frame structures on the seaward side of Kamehameha Avenue were destroyed, and the few that remained were shifted and badly damaged (pl. 28). Two reinforced concrete buildings remained structurally undamaged, although they suffered water damage from flooding. Structures on the inland side of Kamehameha Avenue also suffered extensive damage, although they were somewhat protected by the buildings on the seaward side of the street. The buildings on the inland side of the street suffered much more heavily at places where there were none of these protecting structures.

East of the breakwater, at its landward end, the water rose 29 feet; at Pier 1, just inside the breakwater, it rose 27 feet. Westward from Pier 2 the wave heights rapidly decreased to less than 10 feet in Reed's Bay. This decrease appears to have been at least partly the result of protection of this part of the shore by the landward end of the breakwater and the docks.

The part of the breakwater which projected above sea level was more than half destroyed (pl. 27, *b*), but destruction generally extended to a depth of only 2 or 3 feet below sea level; as on the beaches, the force of the waves was exerted mainly at high levels. Although it suffered severely from the wave onslaught, the breakwater undoubtedly played an important part in lessening the severity of the waves in the head of Hilo Bay. Had there been no breakwater, water levels would probably have been several feet higher.

An interesting example of increase in height of the water above sea level as the waves dashed up on the shore was seen just north of the mouth of the Wailoa River. At the water's edge clear marks were left on an ironwood tree up to only 13 feet above sea level, whereas 150 feet directly inland the water marked another tree up to 23 feet.

At the small basin known as Radio Bay, between Pier 1 and the breakwater, several small boats were washed ashore and more or less damaged to various degrees. The water swept over Pier 1 (pls. 23 and 24), severely damaging the superstructure of the pier, but a ship which had been moored alongside suc-
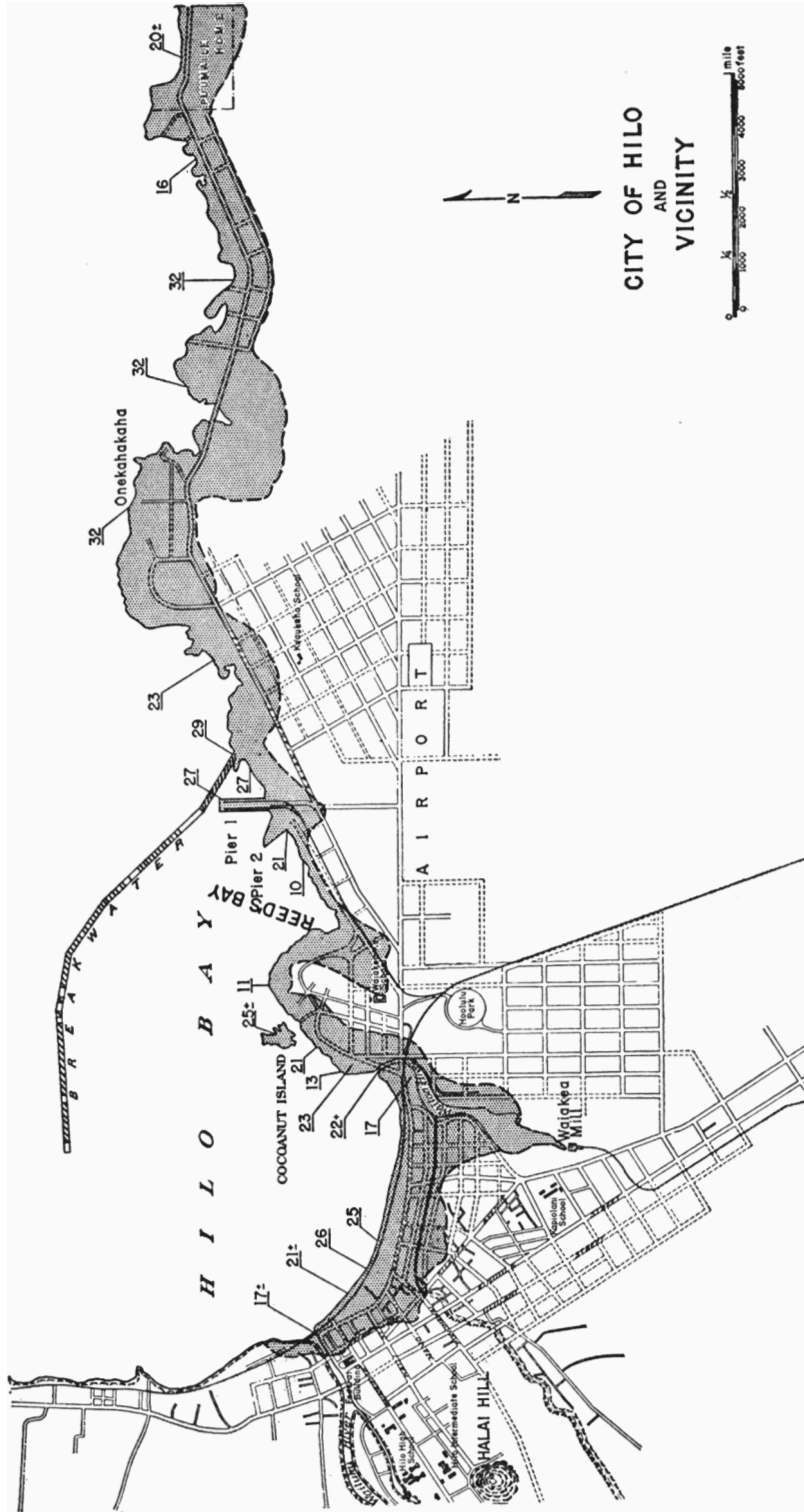
Fig. 18. Map of the Hilo area, Hawaii, showing the heights reached by the water, the area of flooding, and the sections of breakwater destroyed, during the tsunami of April 1, 1946. Heights are in feet above lower low water.

ceeded in casting off and escaped undamaged. Pontoons moored near Pier 2 were swept onto that pier, causing considerable damage.

Half a mile east of the head of the breakwater the waves dashed up on shore to a height of 23 feet. Farther east, for a distance of more than a mile, the water reached a height of 32 feet above sea level and caused great damage in the residential suburb of Keaukaha. Mr. Wendell Carlsmith reports that one wave came in from the north and another from the northeast, which met offshore and built up a high crest. Mr. Clarence Lyman states that at Oneka-hakaha the third and fourth waves were high, and the seventh the highest of all. He states that although the crests were high, during the troughs the water did not drop appreciably lower than at very low tides. At most places near Hilo, however, the troughs were marked by recessions of the water from shore which left the shallow sea bottom exposed far beyond the usual tidal range.

At a small inlet about 2,000 feet west of the Puu Maile Hospital the water rose only 16 feet and did little damage. The mouth of this inlet is nearly closed by a ridge of rock which rises nearly to or slightly above sea level, the water being 10 feet or more deep in the lagoon behind it.

Puu Maile Hospital is protected by a strongly built concrete sea wall along the seaward side of the road. There the water rose about 20 feet, flooding over the wall (pl. 12, *a*). The wall broke the force of the wave by throwing it up and partly back on itself, and the rest of the wave energy was largely dissipated in turbulence and minor soil erosion and rock quarrying along the inner side of the wall (pl. 30, *a*). The wall itself was undamaged, and buildings sheltered by it were undisturbed except for minor damage by flooding. However, at the end of the wall the water came round with force enough to wash away one house and damage another. Mrs. Pearl Welsh reports that at Puu Maile Hospital the third wave was the largest, and that it approached from the northeast. A few months after the tsunami, storm waves destroyed parts of this wall (pl. 30, *b*) and damaged the lower floor of the hospital.

THE TSUNAMI ALONG THE EASTERN SHORES OF THE PACIFIC

High-water marks.—The Aleutian Islands and much of the Alaskan coast are situated much nearer the source of the disastrous waves of April 1, 1946, than are the Hawaiian Islands. The effects of the waves on these near-by points are not well known, chiefly because the area was uninhabited. Dutch Harbor is the nearest settlement of any size, but this was protected from the waves by islands and a narrow passage, and hence no significant effect was reported. However, at Scotch Cap Lighthouse, on the exposed south side of Unimak Island, the waves reached their greatest recorded height, depositing debris on a plateau 115 feet above sea level and destroying a radio mast 105 feet above sea level (pl. 31). The lighthouse, a heavily reinforced concrete structure, its base 45 feet above sea level, was destroyed. Apparently there was also erosion of alluvial cover on the land slopes. The significance of this high-level erosion should be considered in relation to the problem of marine terrace cutting above sea level.

Along the rest of the Alaskan coast no evidence of appreciable waves has been reported, so far as the writers are aware. Along the western coast of the

TABLE 2
DATA ON TSUNAMI, FROM TIDE GAUGES

Name of station	Time of arrival of waves (Greenwich Civil Time)	Distance from epicenter (statute miles)	Travel time from epicenter to station	Average velocity of waves (miles per hour)	Initial rise of water level (feet)	Initial fall of water level (feet)	Period of initial oscillations (minutes)	Maximum range of ensuing oscillations (feet)	Time interval between arrival and maximum oscillations	Difference of observed from computed arrival time (minutes)
Honolulu, Hawaii	17h03m	2,241	4h34m	490	0.7	2.2	12.5	4.1	30m	−4
Yakutat, Alaska	......	974	......	......	...	...	...	2.4	......	...
Sitka, Alaska	15h25m	1,108	2h56m	378	...	...	...	2.6	9h25m	...
Clayoquot, Canada	16h47m	1,610	4h18m	374	0.7	1.0	9.0	1.9	4h10m	−1
Victoria, Canada	17h48m	......	......	...	0.1	0.2	9.0	0.7	1h30m	...
Neah Bay, Wash.	17h00m	1,687	4h31m	373	0.3	0.4	10.0	1.2	2h40m	0
Crescent City, Calif.	17h07m	1,950	4h38m	421	1.0	2.2	12.0	5.9	1h55m	+6
San Francisco, Calif.	18h00m	2,197	5h31m	398	0.5	1.1	15.0	1.7	2h25m	+6
San Luis Obispo, Calif.	18h05m	2,392	5h36m	427	1.3	3.3	18.0	8.5	1h25m	−2
Port Hueneme, Calif.	18h23m	2,504	5h54m	424	0.5	1.1	11.0	5.5	2h40m	+1
La Jolla, Calif.	18h40m	2,646	6h11m	428	0.5	1.1	10.5	1.4	45m	+8
San Diego, Calif.	19h15m	......	......	...	0.2	0.3	10.5	1.2	2h40m	...
Talara, Peru	27h00m	6,132	14h31m	422	0.5	1.3	15.0	3.2+	......	+2
Matavani, Peru	28h55m	7,193	16h26m	438	0.3	0.6	...	5.0+	......	+23
Antofagasta, Chile	29h50m	7,622	17h21m	439	0.4	1.6	19.0	5.9	2h00m	−3
Valparaiso, Chile	30h36m	8,066	18h07m	445	0.8	2.4	18.0	5.0+	......	+30

United States, at distances from the wave source comparable to the distances to the Hawaiian Islands, wave heights were investigated to a limited extent by E. A. Robertson of the U. S. Army Engineers, San Francisco District, and Willard N. Bascom of the University of California. They found that the water had risen to heights as much as 11 feet above those normal for the state of the tide. The greatest heights were observed at Halfmoon Bay and at Santa Cruz, both of which places are on the central California coast. At most places, however, the rise was small. There appeared to be some indication that water rose higher on the south sides of points, which might have been expected to furnish some protection from the approaching waves, than it did on the directly exposed north sides. This observation recalls the high altitudes reached by the waves on the southern sides of the east and west points of the islands of Oahu and Molokai, in the Hawaiian Islands. It is noteworthy that observers at Moss Landing at the head of Monterey submarine canyon could detect no rise.

Tide-gauge records.—Records produced by the tsunami of April 1, 1946, on tide gauges along the Pacific coast of North and South America have been compiled by the U. S. Coast and Geodetic Survey. The results have been published by C. K. Green (1946) and will be only briefly reviewed here.

Records are available from some 20 stations, from Yakutat Bay in Alaska to Valparaiso in Chile, ranging in distance from 1,000 to 8,000 miles from the epicenter of the earthquake. Using the velocity formula for long waves ($V = \sqrt{gh}$), and the depths from Chart 9,000 of the Coast and Geodetic Survey, of the northeastern Pacific, Green computed travel-time curves at half-hourly intervals. Theoretically, the greatest velocity attained by the waves was 600 miles an hour, in crossing the Aleutian Trough. At most stations the time of arrival actually observed checked quite closely with the arrival time calculated on a theoretical basis, thus upholding the validity of the velocity-depth formula. At Valparaiso the wave arrived 30 minutes ahead of the calculated arrival time. The travel time to Washington, Oregon, and northern California is about the same as to the Hawaiian Islands.

Data on the waves from the records at 23 stations are summarized in table 2, taken from the paper by Green. Computed travel times in the shallow waters of San Francisco Bay also checked closely with observed times. The speed of the waves in the shallow bay was about 20 miles an hour, and the wave length about 6 miles.

The records appear to indicate a slight lengthening in period of the waves at the most distant stations. This lengthening is about 2 minutes in a distance of 5,000 miles. At most stations the records show the initial movement to have been a rise, generally with a magnitude of only about one-third that of the succeeding fall.

Comparisons with Observations of Japanese Tsunamis

The Japanese made extensive observations of the high-water marks attained in three of their great tsunamis. The most nearly complete surveys were made in 1933 (Tokyo Imperial University) after the waves of that date had wreaked havoc on the Sanriku Coast. Examination of maps taken from the Japanese
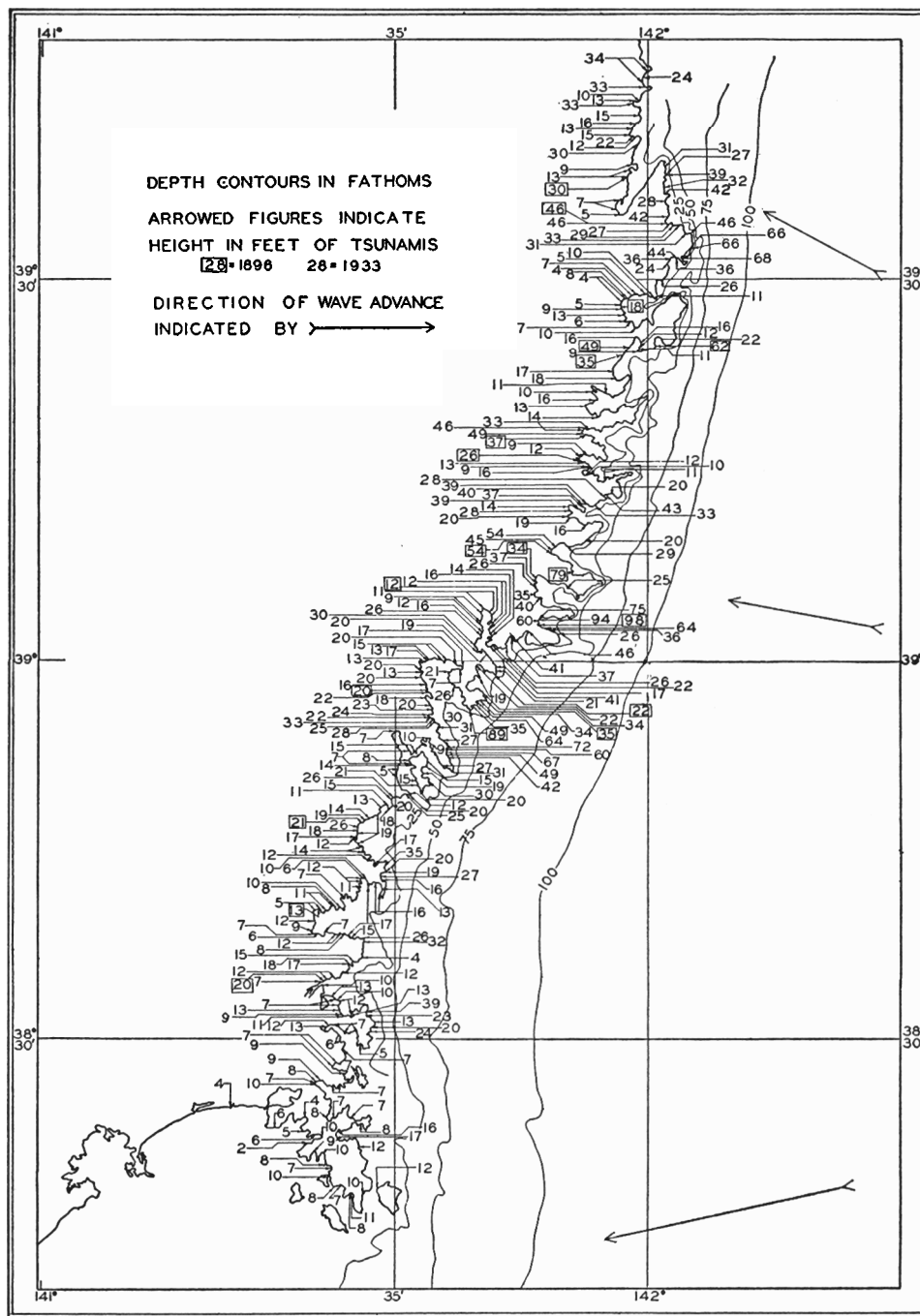
Fig. 19. Map showing the heights reached by the tsunamis of 1896 and 1933
in the Sanriku district, Japan.

data (figs. 19 and 20) shows that the greatest rises were in small bays indenting headlands. At the heads of most elongate bays, 5 miles or more in extent, the waves were considerably reduced in comparison with those on the exposed headlands. However, this was true only of bays which did not directly face the advancing tsunami. Those which did face the tsunami had about the same heights on the sides and at the head. The points trending in a direction diagonal to the advancing waves showed the greatest heights on the exposed sides, somewhat less on the ends, and decidedly lower heights in the lee. The waves which hit Hokkaido to the north of the Sanriku area were much lower, but they are interesting in showing a relationship to the valleys and ridges of the submarine topography. They rose about 10 to 20 feet inside a ridge and only about 1 foot inside of two submarine valleys. It is noteworthy that some of the heights measured after the tsunami of 1896 had similar heights in the same localities.

The tsunami of December 26, 1946, hit the southeast coast of Japan south of Tokyo Bay. The greatest heights were far less than those of the Sanriku waves. On the coast nearest the epicenter of the earthquake they attained a maximum of only 17 feet. The measurements indicate that, in general, intervening points of land considerably reduced the heights of the water rise, as was observed also of the 1933 waves. This is in contrast to the 1946 observations in Hawaii and along the California coast, where some of the greatest rises were observed in the lee of points. The reason for this contrast is not known.

Variation in Intensity and Effects of the Waves in Hawaii

The great variation in intensity and effects of the waves from point to point on the Hawaiian shores is clearly demonstrated in the preceding descriptions. The heights to which the waves washed ranged from 2 feet or less to 55 feet; their violence ranged from gentle rises and falls, almost entirely free from turbulence, to raging torrents. The variation in the heights reached by the water appears to be related to the following features:

1. Position of the coast in relation to the direction of wave origin.
2. Shape of the island.
3. Submarine topography.
4. Interference of parts of the tsunami from different directions.
5. Presence or absence of coral reefs.
6. Exposure of the coast to storm waves.
7. Shore-line configuration and topography.

Variation in the turbulence of the waves as they rose over the coast can be related partly, but not entirely, to the height reached by the water. If for no other reason, this is understandable on the basis that the greater height of water piled against the shore resulted in a steeper hydraulic gradient and consequent greater rapidity of flow inland, particularly where the water flowed over a barrier. Likewise, the greater depth of water on shore resulted in a steeper gradient and more violent run-back to the ocean during wave troughs. At many places where the water rose more than 20 feet, the effects were described as violent. As the water levels were generally higher on northern than on
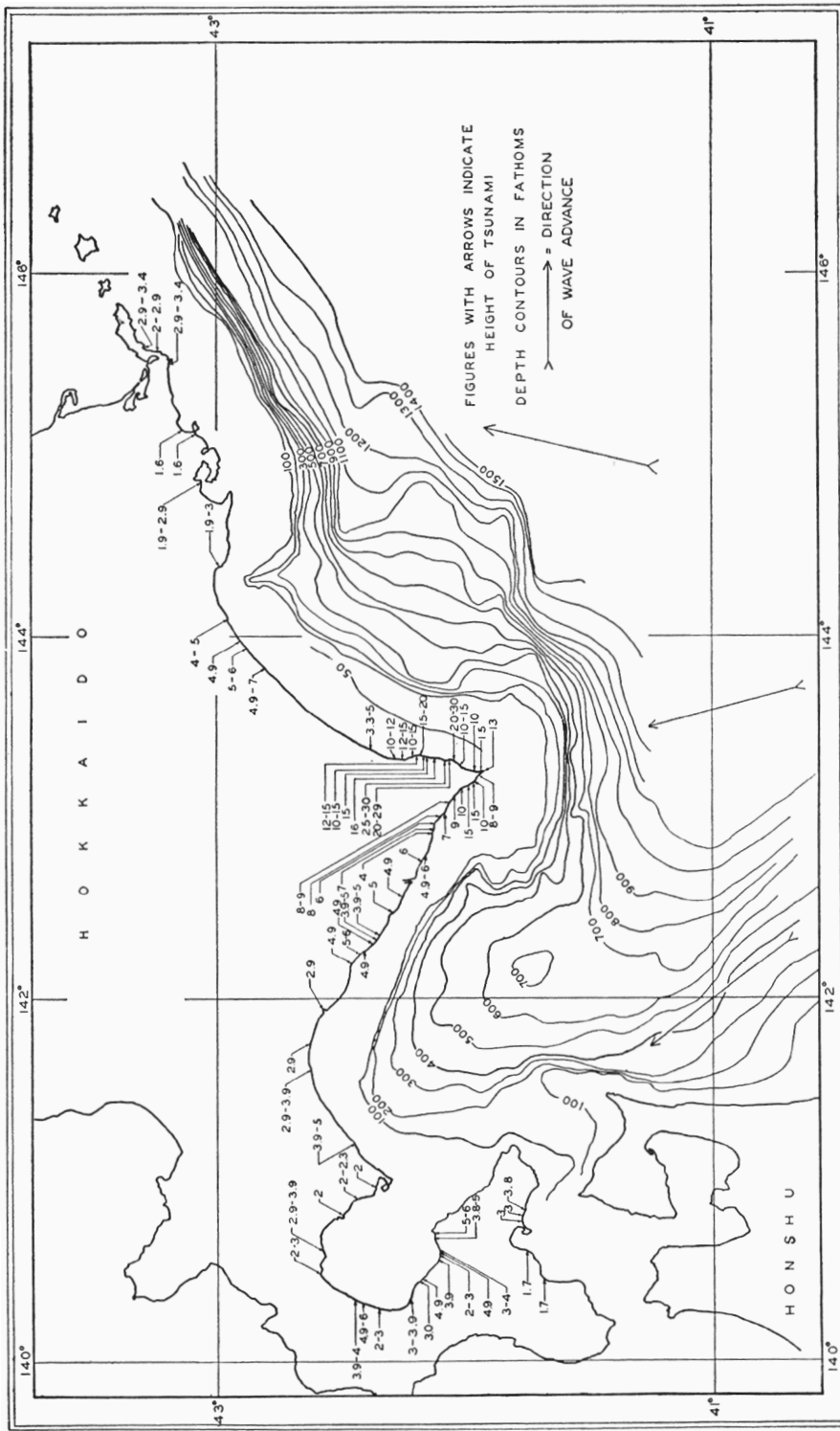
Fig. 20. Map showing the heights reached by the tsunami of 1933 in southern Hokkaido, Japan.

southern shores, violent waves were reported particularly from northern shores, whereas most of the reports of gently rising water level came from southern shores. The velocity of flow was also controlled by the area flooded and consequently by the steepness of the slope above sea level.

The heights to which the waves washed on the shore have been measured, as the best available indices to the relative intensity of the waves at the various points. The methods of measurement of these heights, the several features influencing the intensity of the waves, and the effects of the attack are discussed below.

Effects of coast-line orientation.—Because the waves approached the islands from the north, it is understandable that the water should have risen higher on the northern than on the southern sides of the islands. Heights reached by the water average consistently greater on the northern sides of all islands. On the other hand, heights on the southern sides of east- or west-facing promontories were almost as high, on the average, as on the northern side.[14]

North-facing coasts tended to receive the greatest amount of wave energy, other things being equal. Where a wave approached the coast diagonally, the wave was refracted and the energy of the wave was distributed over a greater length of shore line than where the wave moved directly toward the coast. Furthermore, refraction of waves around islands resulted in a considerable decrease of energy per unit length of crest.

Examples of the generally greater height reached by the waves on northern shores are supplied by all the islands studied in detail. The fact is evident in the most cursory inspection of the maps showing the high-water levels (figs. 6–18).

Effects of shape of the island.—Although on all the islands the waves reached generally lower heights and were less violent on the southern sides as compared with the northern sides, the diminution was much greater on some islands than on others. The difference in decrease of wave energy per unit crest in refraction around the island is related to the shape of the island. Waves were refracted around circular or nearly circular islands much more effectively than around angular or elongate islands. The importance of the shape of the island is illustrated best by the contrast in wave heights on the southern shores of the islands of Kauai and Molokai (see figs. 6 and 12). Kauai is a nearly round island, and the waves rose on its southern shore to an average height of about 10 feet. Molokai, on the other hand, is a long, narrow, angular island, and along the central part of its southern shore the waves reached a height of only 2 feet (partly the result of protection by coral reefs, as explained later). But the average height reached by the water along the northern coast of Molokai was as great or greater than the height on the northern coast of Kauai.

Exposure of the coast to storm waves.—The greater height and violence of the tsunami on the northern and northeastern coasts was probably in part the result of storm waves driven by the northeasterly trade winds. At the time of the tsunami, large storm waves had been running for several days. The

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[14] This was not true in Japan during the tsunami of December 23, 1946, when heights were markedly reduced on the lee sides of promontories.

windward (northern and northeastern) coasts were directly exposed to these waves, whereas the southern and southwestern coasts were in the lee. Storm waves riding in on top of the broad crests of the tsunami are apparent in several photographs (pls. 6, 7, 10, and 12, *a*). It is evident that a simple welling-up of the water along the shore could be accompanied by comparatively violent movement where a wind wave comes in on top. The general rise in water level caused by the tsunami allowed storm waves to attack the shore line at a higher level, and to move farther onto the land than usual.

Not only was the wave attack more violent on the windward than on the leeward side of the islands, but places on the windward side which were sheltered from the storm waves also were less violently attacked. Thus at Kalaupapa, on the sheltered side of Kalaupapa Peninsula on the windward side of Molokai (see fig. 13), both photographs and the testimony of observers indicate that, although the water level rose 25 feet, the rise was comparatively gentle. Such evidence suggests that wind waves probably were one of the chief contributing factors to the violence of attack. On windward coasts much of the rapid variation within short distances in intensity of wave attack may have resulted from the caprice of storm waves.

Presence or absence of coral reefs.—Well-developed fringing reefs reduced markedly the intensity of wave assault on the shore inside them. Reefs are better developed on the northern coast of Oahu than on the northern coast of any other of the islands. The average height reached by the water along the northern shore of Oahu (see fig. 9) is correspondingly less than along the northern shore of any other of the major islands except Lanai, which is well protected on the north by Molokai. A few small reefs lie along the northern shore of Kauai, and in general the waves were considerably lower inside these reefs than where the reefs are absent. Similarly, reef-protected coasts along the northern shore of Maui suffered less severe attack than unprotected parts of the same coast; and along the southern shore of Molokai it was probably the wide protecting reef that in part accounted for the low heights reached. An example of the relation of reefs to the high-water marks was found along the northern coast of Oahu east of Kaena Point. There the abrupt change from heights of 30 feet to heights of 13 feet coincides with the beginning of the reef. The best-developed coral reef in the Hawaiian Islands flanks and largely fills Kaneohe Bay, on the northeastern side of Oahu. There the reef attains a width of about 3 miles. Although the broad mouth of Kaneohe Bay opens toward the north and northeast, the effects of the tsunami at the head of the bay were imperceptible to observers, the rise in water level being certainly less than 2 feet, and probably less than 1 foot.

The reefs appear to have been most effective in reducing the size and intensity of the waves where channels or lagoons of greater depth lay between the shoalest part of the reef and the shore. Evidently the waves breaking on the reef and piling over it into the lagoon partly or largely dissipated their energy before reaching shore. This was observed at several places on both Kauai and Oahu. Coral reefs were not alone in producing these results. On Hawaii, the high-water mark was very low at a small bay west of the Puu Maile Hospital, in Keaukaha, where the entrance to the bay is nearly blocked by a ridge of

lava rising nearly to or just above sea level. Breakwaters appear to have had much the same effect; at both Hilo and Kahului the height reached by the water inside the breakwater was notably less than that outside of it (figs. 15 and 18).

The importance of the effect produced by the reefs is perhaps most clearly demonstrated by study of the effect of transverse reef channels, particularly those along the southeastern coast of Molokai. The waves striking the shore at the heads of the channels were distinctly larger than those reaching shore on each side of the channel. Thus, at the head of a small channel which crosses the reef just west of the mouth of Kainalu Stream the water rose 11 feet, whereas just east and west of the channel the water rose only 7 to 8 feet. The 17-foot high-water mark just southeast of Kahana Bay, on Oahu, probably was greater than the surrounding heights because it was directly inside a channel crossing the reef.

Shore-line configuration.—It has been stated repeatedly in the past that the waves of tsunamis are largest at the heads of large funnel-shaped bays. Embayments of this sort, such as the Bay of Fundy, greatly magnify ordinary tidal fluctuations, and it appears not unreasonable that they should act in a like manner on the similar long-period waves of a tsunami. Imamura concludes that tsunamis are most destructive in deep, broad-mouthed V-shaped bays, extending outward into deep water (Imamura, 1937). He states that as the waves of a tsunami move up a V-shaped embayment their height increases in inverse ratio to the width and depth of the bay. He cites examples of this during the Sanriku tsunami of 1933. In one of these the wave heights increased from 1.5 meters near the bay mouth to 12 meters at the head of the bay, and in another they increased from 3 to 23 meters. On the other hand, Nasu (Tokyo Imperial Univ., 1934, p. 226) states that the water does not always increase in height going inland (i.e., up bays) and that sometimes it decreases. Also, an examination of the map showing the heights reached by the waves during the Sanriku tsunamis of 1896 and 1933 (fig. 19) indicates rather that the greatest heights were not in bays but on islands along the open coast.

Special search was made for examples of the increase of wave heights toward the heads of V-shaped bays on Hawaiian shores, but no good examples could be found. Hilo Bay would appear to be an almost ideal example of a funnel-shaped bay extending into deep water and with a wide mouth facing the direction of wave origin. However, measurements around its shores show no systematic increase in heights reached by the water toward its head (see figs. 16 and 18). The broad embayment on the northern side of Maui, at the head of which lies Kahului Harbor, likewise showed no signs of an increase of height toward its head (see fig. 15).

Pololu Valley on Hawaii and Pelekunu Valley on Molokai both open onto small bays, at the head of which the water level was higher than along the walls near the mouth of the bay. The profile of the high-water mark at Pololu Valley is shown in figure 17. However, at Pololu Valley and probably also at Pelekunu Valley, this rise at the bay head resulted from a local upsurge where the waves crossed the beach. Several bays were found in which the heights reached by the water were distinctly less near the head than near the mouth.

The great height of 54 feet reached by the water at Waikolu Valley, Molokai, may have resulted partly from funneling between Kalaupapa Peninsula and the headland and small islands east of the mouth of the valley (see fig. 13).

Several small valleys of steep gradient were found debouching into small bays, in which the water rose notably higher along the axis of the valley than on the walls near the beach. At the small bay just south of Ahukini, on Kauai, the water rose only 25 feet on the bay sides but swept up the steep little valley at its head to a height of 40 feet above sea level. At Moloaa, also on Kauai, the water dashed inland along the valley axis to an altitude of 40 feet but reached heights of only 30 to 35 feet on the bay walls. At Honouliwai, on the southeastern coast of Molokai, the water rose 27 feet on the valley walls opposite the beach, but 33 feet along the axis of the valley. These are merely special examples of the rushing of water up on the shore, driven by the great volume of the broad wave behind it, in which the topography above sea level was such as to concentrate the inrushing water. The effect may be analogous to the increase of wave heights toward the head of funnel-shaped bays described by Imamura.

Submarine topography.—Because in waves of such great wave length the movement of the water extends to the ocean bottom, the effects of bottom topography were important throughout the course of the tsunami. However, the effects became much more pronounced as the waves moved into the shallower water over the slopes of the Hawaiian Ridge. As the waves entered shallow water, interference of the bottom with the wave motion resulted in an increase in the height of the waves, a lessening of their speed, and a steepening of their fronts.

As a result of the slowing of the waves in shallow water, submarine ridges and valleys projecting from shore toward or nearly toward the direction of wave origin were of great importance in their effects on the height and violence of the waves. The advance of waves moving toward shore parallel to the axial direction of a submarine ridge is retarded along the ridge more than in the deeper water on each side of it. As a result, the wave front becomes concave toward the head of the ridge and a large amount of wave energy converges at the head of the ridge. Similarly, in moving toward shore along a direction parallel to the axis of an underlying submarine valley, the part of the wave in the deeper water along the valley axis moves faster than that in the shallower water on the two sides, and the wave front becomes convex toward the valley head. Therefore, along the shore at the head of the valley the force lines or orthogonals of the waves are diffused or spread apart, and over any unit length of shore line the force of the waves striking shore is greatly decreased.

Some of the best examples of the effect of ridges in increasing the size of the waves striking shore at their heads are on the northern coast of Kauai. From Haena, a long ridge extends north-northwestward to a depth of about 1,200 fathoms (see fig. 7). Another ridge extends northeastward from Kilauea Point to even greater depths. At the heads of these two ridges the water rose on shore to heights of 45 feet, the greatest heights measured on Kauai. Still another ridge extends northwestward to oceanic depths from the western coast of Kauai, and probably accounted for the great heights of 35 to 38 feet measured at its head.

On Oahu, the long submarine ridges which project from Kaena and Kahuku Points (see fig. 9) appear to have caused distinctly greater wave heights than were found along the shores on both sides. However, on Oahu the effects of both ridges and canyons were partly masked and made less definite by the effects of coral reefs.

Submarine ridges projecting eastward north of Hilo Bay and at Cape Kumukahi on Hawaii had, however, no apparent effect on the heights of waves along the shore at their heads. These ridges extend not toward the general direction of wave advance but across it. On the other hand, the water reached greater heights at South Point on Hawaii than along the coast on the two sides of it. It is difficult to explain this as a result of focusing at a ridge head, how-ever, for although a submarine ridge extends outward from South Point, it projects away from the wave origin, not toward it. The effect of submarine ridges is therefore not demonstrable on the island of Hawaii.

The effect of submarine valleys or canyons is illustrated by the broad, valley-like swale which extends northwestward to oceanic depths from the northwestern coast of Kauai (see fig. 7). The heights reached by the water at the head of that swale are distinctly lower than those along the coast farther north and south, probably because the wave force was lessened by the effects of the canyon. The similar depression off the eastern coast of Hawaii south of Hilo Bay (see fig. 16) probably also had some effect in reducing the size of the waves striking shore at its head, for although the heights reached there were 16 to 19 feet above sea level, those heights were not much greater than those which are reached by ordinary storm waves.

The shallow submarine valley which enters Kahana Bay, Oahu, appears to have had some effect on the tsunami. The waves were higher and more violent on the sides of the bay and on the coast northwest and southeast of the bay than at its head. Similarly, the waves were lower directly shoreward from the head of the submarine valley off Haleiwa, on the east side of Waialua Bay, Oahu, than they were on either side. The submarine indentation south of Mokapu Point on Oahu may have been the cause of the low levels reached by the water at Kailua. Likewise, the low heights at Honomanu Bay, on the north shore of Maui, may have resulted from a submarine valley the existence of which is suggested by the few available soundings.

Submarine topography appears also to have influenced the wave heights attained during the 1933 tsunami off the Sanriku coast of Japan. At the head of a submarine valley which lies off the southern coast of Hokkaido the water rose to a height of only 2 feet, whereas at the heads of adjacent submarine ridges it rose 12 feet (fig. 20).

Promontories bordered by deep water.—In general, pronounced coastal prom-ontories are prolonged in submarine ridges. Some, however, like Kalaupapa Peninsula on the north coast of Molokai (see fig. 13), project into deep water. At such places the heights which the tsunami reached on shore were consider-ably less than those in adjacent areas, because of the short interval of transi-tion from deep water to shallow water conditions. At the end of Kalaupapa Peninsula the waves of the tsunami reached a height of only 7 feet. In contrast, along the coast east and west of the peninsula, where a moderately wide belt

of shoal water lies offshore, the waves rose to heights of 35 to 54 feet. The rise of only 7 feet at the end of Kalaupapa Peninsula contrasts with a height of 21 feet reached by winter storm waves at the same locality (pl. 20, *b*). Keanae Peninsula on the northeastern coast of Maui (see fig. 12) represents a similar situation, although there the submarine slope is less steep than at Kalaupapa. At the end of Keanae Peninsula the waves of the tsunami reached heights only a little greater than ordinary storm waves. At the end of Laupahoehoe Peninsula, on the northeast shore of the island of Hawaii, the waves rose to a height of 30 feet, despite the steep termination of the ridge. At Laupahoehoe the destructive waves are reported to have come in diagonally, which would give them a longer time in relatively shallow water than at the two other localities.

Interference of refracted and reflected waves.—Wave crests traveling by different routes may arrive at a given locality simultaneously, thereby giving rise to a wave of greater size than either. Likewise, the simultaneous arrival of a wave crest and a wave trough may essentially cancel out both. Thus variations in the size and intensity of the waves may result from the arrival, either in or out of phase, of two or more wave chains. This should have been true particularly among the later waves, on the sides of the islands away from the wave origin, and at places where the waves could have been reflected from one island to another.

At several places, waves from different directions were observed to arrive in phase and produce a larger wave. In the Keaukaha area, east of Hilo, witnesses described the simultaneous arrival of two waves, respectively from the north and northeast, which formed a very high crest at the point of joining. At the head of Maunalua Bay, on the southeastern shore of Oahu, two waves were seen to move up channels across the wide reef, turn, and approach each other parallel with the shore, and then meet, throwing water upward like spray from a geyser. In this area the water rose on shore to a height of only 3 feet except at the place of juncture, where it swept over the top of a sandspit 5 feet above sea level.

On the island of Kauai the heights reached by the water were greatest on the northern side, the average height decreasing southward. Along most of the southern shore the water reached only 6 to 12 feet above sea level. However, in a zone 3 or 4 miles wide near the center of the southern coast it ranged from 15 to 18 feet. This zone is almost directly across the island from the direction of origin of the tsunami, and is believed to represent the area in which waves that were refracted around the opposite sides of the island met and reinforced each other. The phenomenon is less apparent on the other islands, probably because waves were refracted around the other, more angular, islands less efficiently than around the nearly circular island of Kauai.

In general, later waves exhibited much greater irregularity of period and variation in height than the first three or four waves. The irregularity undoubtedly is in part the result of simultaneous arrival, both in and out of phase, of refracted and reflected waves which had traveled by different paths. At those places where the sixth, seventh, or eighth wave was reported as the largest of the series, it appears probable that this was due to reinforcement by the simultaneous arrival of two or more wave crests from different directions.

On steep shores the maximum heights reached by the tsunami were the points farthest inland reached by the waves. On gently sloping shores, however, especially where the movement of the water inland was restricted by vegetation, the heights reached by the waves dropped as the waves moved inland. The drops were recorded in many places by the lines of washing on the walls of valleys and by the levels of damage to trees on flat lands. A particularly marked drop was noted where the waves came in over a high beach and then flooded lower lands.
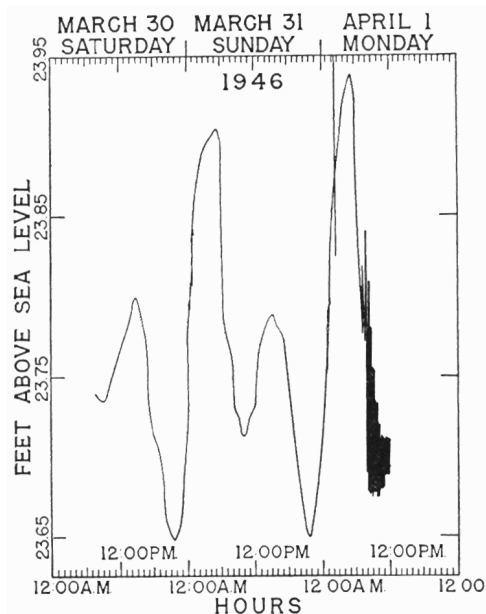
Fig. 21. Record of the tsunami of April 1, 1946, on the water-stage recorder in the Thomas Square artesian well (drilled well 83), Honolulu.

EFFECTS ON WELLS AND SPRINGS IN HAWAII

In general the tsunami had little or no effect on ground water in the Hawaiian Islands, even in the coastal areas. However, in Kailua Bay, on the island of Hawaii, a strongly brackish spring appeared about 50 feet from shore at the time of the tsunami and has continued to flow since then. The water issues from a small lava tube in a prehistoric lava flow of Hualalai volcano. The volume of water escaping is sufficient to dome up slightly the overlying ocean surface. Apparently the spring formerly discharged farther out to sea, but increased hydrostatic pressure in the tube at the time of advance of the tsunami waves over the seaward opening resulted in loosening a block of rock in the roof of the tube nearer shore, and in the formation of a new outlet. The existence of an opening of the tube farther seaward is demonstrated by a surging of the spring as a wave moves shoreward.

At Kahuku, on Oahu, a spring area about 3,500 feet from the shore, used by the plantation as a source of irrigation water, was flooded by the tsunami. On the morning of April 2 the water pumped from the spring area had a salt content of 1,700 grains per gallon, representing a proportion of roughly 85 per cent sea water. Part of the salt water drained away by seepage into the permeable coral reef, and by the morning of April 4 this seepage, together with pumping at a rate of 11,000,000 gallons daily and flushing by newly discharged fresh spring water, had lowered the salt content to 900 grains per gallon. Nearly a month of pumping at the same rate, however, was required to reduce the salinity to a level at which the water could again be used for irrigation.

Of particular interest is the effect produced in the artesian well at Thomas Square in Honolulu. The automatic water-stage recorder maintained on that well by the Honolulu Board of Water Supply recorded the tsunami and apparently also the earthquake which accompanied it at its source. A copy of the record is shown in figure 21. At slightly after 2 A.M. the well water was disturbed by an oscillation of more than 0.1 foot, which was probably caused by the arrival of the earthquake waves. The recording of earthquakes on water-stage recorders in wells is a common occurrence. About 6:30 A.M., the surface of the water in the well was again set in motion by the arrival of the tsunami, the oscillation gradually building up to more than 0.1 foot and continuing for several hours. A check on salinity of the water in wells in the Honolulu area showed no change attributable to the tsunami.

DAMAGE BY THE TSUNAMI

Structural damage.—A considerable part of the damage to buildings was due to the light types of construction customary in the island. No reinforced concrete buildings seen were seriously damaged, even at places where the attack was severe. Of scores of buildings on the water front in Hilo, for example, only two stood in place and intact, and both of these were of reinforced concrete.

Even steel-framework and sheet-iron-siding buildings generally stood up well except where the attack was severe and where there was a great deal of floating wreckage. However, in Hilo many buildings of this type were damaged. The wharf sheds on Piers 2 and 3 were badly battered by some large bridge-type pontoons that were moored in the harbor. The greatest single loss through building damage was the destruction of the boilerhouse and powerhouse sections of the Hakalau sugar mill on Hawaii (pl. 32, *a*). The steel frame collapsed; corrugated iron siding was ripped off; and machinery, pipes, and tanks were swept out of the building. A large clarifier tank was carried 800 feet inland. The loss at Hakalau was estimated at $375,000.

Most island houses are of wood-frame construction. They are generally supported on stilts which raise them a foot to several feet off the ground, but some, especially the newer ones, are anchored to a concrete floor platform, which is usually low and sometimes is flush with the ground. Unless they were struck by floating debris, or unless the water rose sufficiently to float them off their foundations, the houses on stilts were not seriously damaged. Even

some which were floated considerable distances were little damaged. Some houses of poor construction apparently broke up as they were lifted or while they were floating. Most of the houses that were destroyed were pushed against trees or rocks. Many were set down again without great damage, except as they were strained because the ground on which they came to rest was uneven. The gentleness of the floating was sometimes amazing. Thus, a house at Kawela Bay on Oahu was carried 200 feet inland and deposited gently in a cane field, leaving breakfast still cooking on the stove and dishes intact on shelves. Another house, at Kainalu, Molokai, was moved 50 feet without shaking any of the dishes from the shelves. It was possible to move many of the houses back on to their original foundations without much repairing.

Those houses on concrete floor platforms that were in areas of severe attack or that had weak frameworks were ripped off their foundations and broken up in the process. Those with strong frameworks and relatively light siding commonly had part of the siding pushed in or out, but stood with their frames and roofs intact. Floating debris and rolling or saltatory rocks broke in many walls and windows that might have been spared by water alone.

In a large proportion of the two-story houses—not a common type on the beaches—the second story was wholly saved from damage by the destruction of siding on the ground floor, since the skeleton structure remaining offered little resistance to the passage of the water. Some two-story houses were reduced to one story by the destruction of the first floor and collapse of the second to the ground (pl. 32, *b*), a type of damage common during earthquakes.

The number of homes demolished or damaged by the tsunami have been listed by Lewers & Cooke, Ltd., of Honolulu, as follows:

Island	Kauai	Oahu	Molokai	Maui	Hawaii	Total
Homes demolished	60	67	13	65	283	488
Homes damaged	130	335	14	144	313	936

There was, of course, great destruction of furnishings, personal property, and merchandise in buildings from breakage or wetting. Probably the largest item was 8,824 tons of sugar awaiting shipment on the docks in Hilo. Unlike most of the other losses, however, this one was covered by insurance. Many articles were lost simply by floating away or by burial.

Damage to roads and railroads was mostly of a nature common in any flood. In many places railroad and highway fills were cut partly or completely across. Blocks of undermined road pavement were rolled around like rocks. Railroad tracks, usually still attached to ties, were pushed out of line and in places were wrapped around trees and other obstacles (pl. 33, *a*).

An unusual type of damage was noted in pavement on the abandoned Kahuku airfield on Oahu, which was completely submerged. In roughly circular areas 3 to 5 feet across, blocks of pavement were tilted so as to make conical hills a foot or so high. The pavement rests on sand, and the raising of the blocks was doubtless a result of hydraulic pressure, but how the water

penetrated the pavement, and why the pressure was greater under the pavement than over it, is not known.

The foundations of some bridges were undermined, and the bridges collapsed. Others were pushed or floated off their foundations. One span of the steel railroad bridge across the Wailuku River in Hilo was pushed off its piers and carried about 750 feet upstream. Two of the four concrete piers under the center pier of the high steel railroad trestle over the Kolekole Valley on Hawaii were undermined. The trestle collapsed and was carried 500 feet upstream, leaving the bridge deck hanging by the rails (pl. 27, *a*). High flumes at Hakalau and Papaikou, Hawaii, were demolished, probably in a similar manner.

At several places, railroad cars were swept off the tracks or rolled over. Many automobiles by the shores of the islands were rolled or pushed around, thrown against obstacles, and battered by floating debris.

In many valleys the terraced, water-filled patches in which taro is grown were severely damaged by erosion of the valley walls and silting up of the patches. In the Waipio Valley (Island of Hawaii) alone the damage to the taro patches was estimated at $25,000.

Damage to piers, other than to the sheds on them, was slight, even in Kahului and Hilo harbors, where the water was high and the currents swift. In those harbors and in Honolulu Harbor most of the damage was done by ships battering the docks at which they were moored. At Waianae, Oahu, a pier was pushed shoreward several inches by the waves. The inner end of the pier and the pavement which abutted it were buckled. The movement was made possible by bending of the long offshore piles and by shearing of the pier deck over the inshore piles. Marine railways at Kahului and Hilo were smashed.

Most breakwaters were not damaged, or only very slightly damaged. Only the Hilo breakwater (pl. 27, *b*), which has often been damaged by storm waves, suffered greatly during the tsunami. Of the part of the breakwater above sea level, 6,040 feet, or about 61 per cent, was destroyed. The cap and outside face were composed of rocks weighing 8 tons or more, and the inside face of rocks weighing 3 tons or more. The rocks were thrown both shoreward and seaward by the waves. The average depth of scour in the gaps in the breakwater was 3 feet. The breakwaters at Ahukini and Nawiliwili on Kauai, at Kahului on Maui, and even at Hilo, in spite of the damage, probably reduced greatly the severity of the attack of the waves inside the harbors. The effect is easily shown by the drop in wave heights from 17 and 22 feet outside the breakwaters at Kahului to 7 and 11 feet inside the breakwaters, and from 29 feet outside at Hilo to an average of about 21 feet inside. The effect was similar to that of a coral reef with fairly deep water behind it.

Sea walls, where well constructed, were not materially damaged. Many small sea walls of loose or poorly cemented rocks were smashed by the waves. There was some erosion behind sea walls at Pier 1 in Kahului Harbor, where the water came from the sea side and cascaded over the walls into the harbor. Much more erosion occurred behind short, discontinuous sea walls at Hilo which had been designed merely to protect sewer outfalls. At the Puu Maile Hospital, east of Hilo, the water poured in great volume over the sea wall

(pl. 12, *a*), causing considerable erosion of the highway pavement just inside the wall (pl. 30, *a*). The wall undoubtedly protected the main buildings of the hospital from the full force of the waves, and probably saved them from severe damage.

Many fishpond walls of loose rock, particularly on Molokai, were damaged or destroyed, and some of the ponds were partly filled with silt, sand, and rocks from the walls.

No ships were greatly damaged, though one, the *Brigham Victory*, was moored at Pier 1 at Hilo during the first waves and did not clear the harbor until 9:20 A.M. Probably at least a hundred tugs, fishing sampans, yachts, and smaller craft were damaged by stranding or battering. The greatest number were in the Ala Wai yacht basin in Honolulu, where boats were torn from their moorings and thrown against sea walls and against each other, or on reefs or the shore. Several amphibious tanks and trucks were floated away from a parking area at a marine encampment at Kahului, Maui. A dredge was grounded at Kuliouou on Oahu. Boats at sea, where the waves were low and broad, were of course unaffected. The master of a ship lying offshore near Hilo said that he could feel no unusual waves, although he could see the great waves breaking on shore.

Damage to vegetation.—Vegetation was damaged by the tsunami in two ways: first, mechanically, by uprooting or breaking; and second, chemically, by salt poisoning. In general, grass and low shrubbery with closely interlocked roots and stems stood the wave attack so well that they supplied some protection to underlying soil and especially to sand. The effect was most plainly recorded in dune or upper beach areas where the erosive attack was heavy; yet the effects were limited to places where the water could locally penetrate the protective cover. In some unprotected spots excavations many feet deep resulted and these holes were probably much enlarged by undermining of the surrounding vegetation. The effect was greatly magnified, of course, where early erosion resulted in channels which directed the later flow.

Trees varied greatly in their resistance to the waves and in the degree of protection from the waves which they afforded to structures. Hala (*Pandanus odoratissimus*), a low tree with many supporting aerial roots, offered much surface but was too weak to stand intense pressure, and hence afforded little protection (see pl. 12, *b*). Hau (*Hibiscus siliaceous*), a tree growing characteristically in dense thickets with intertwining trunks and branches, offered more protective surface and stood up strongly against the attack. Groves of hau effectively shielded the lands behind them in many places. At Wainiha on Kauai, for example, the destruction probably would have been much greater had there not been thickets of hau on the beach and just behind it.

Other trees offered less surface to the waves. Chinese plum trees (*Eugenia jambolana*), though they grow fairly thickly in places, as at Haena on Kauai, did not stop the water and besides were rather easily broken. Kamani (*Terminalia catalpa*), which are trees with buttress roots, stood up well and in places apparently strengthened hau thickets, but did not themselves offer much protection. Coconut trees (*Cocos nucifera*) stood up well against water attack, and their dense, shallow root system protected the soil or sand, but

they were readily undermined and were easily sheared off by floating debris or rocks carried by waves. Ironwood trees (*Casuarina* sp.) offered similar protection and stood up strongly even against the impact of solid bodies. Ironwood trees supplied excellent records of the height of the waves because their tender bark was easily bruised, and where bruised it showed up red. Where these trees grew on the beach they afforded in many places the means of demonstrating the drop or rise in crest heights as the waves of the tsunami rolled inland.

The greatest losses through mechanical damage to plants grown commercially were in taro and sugar cane. Taro is grown principally in valley bottoms, in paddies flooded with fresh water. The waves easily uprooted the taro plants from the soft mud. Besides the damage to the plants, the taro patches themselves were damaged (see section on damage to structures). Sugar cane was easily crushed by the water, especially if the water carried floating objects. About 150 acres of sugar cane in the islands was killed or so badly damaged that it had to be prematurely harvested, including a small amount that was poisoned by salt but not mechanically injured.

Most plants living within the range of the waves are somewhat tolerant of salt water. At times they are covered by salt spray, and they depend either on phreatic water, which is likely to be brackish because of its proximity, or on vadose water subject to contamination by salt spray. None of the trees offering mechanical resistance as discussed above, and none of the typical beach plants, were hurt by salt poisoning. However, many plants were killed or injured as salt water attacked their roots, and a few bushes were noted on which salt-water contact had killed the leaves. From a few days to several weeks after April 1 the level of highest water was marked in many places by a sharp line between dead shrubs and grasses below and green vegetation above.

Of common crop plants reached by the waves, sugar cane and bananas were most easily poisoned. Some damage to cane was avoided by prompt irrigation with fresh water to wash out the salt. At Kahuku on Oahu the salt water flooded a spring area about 3,500 feet from the shore, from which irrigation water was pumped. The fact that it was flooded was not immediately known, and for about a day brackish water was used to irrigate a fairly large part of the plantation. However, the irrigation was stopped, and heavy pumping drained off the salt water from the spring area in time to save the cane, though its growth undoubtedly was set back.

Papayas were somewhat more tolerant of the salt water, and taro, though it is usually grown flooded with fresh water, did not seem to suffer from salt poisoning.

EROSION

The erosional effects of the tsunami were, in general, not as easy to determine as the damage to structures or vegetation. At high levels, where the waves cut into soil on stabilized and plant-covered sand, or buried such soil under a new layer of sand, the extent of the changes was not difficult to see. Unaffected patches or recognizable buried surfaces generally remained, indicating the old topography. However, on the beaches there were generally no indications

of the position of the surface as it was before the tsunami occurred. Even memory of the appearance of the beaches some time before the waves is of little value, since all beaches are subject to changes during ordinary storms. Commonly the beaches are cut shoreward by storm waves or large swells and are built back again during periods of small waves. Because of the distinct difference between wind and current directions during the stormy Kona (southwest wind) season and those during the trade-wind season, the changes on most Hawaiian beaches are great and show a marked annual cycle. There are also definite progressive changes on many beaches, indicating a longer cycle or cycles. The tsunami of April 1 was preceded by a strong trade-wind storm. Consequently only observations or photographs made within a very few days before April 1 were of any value in indicating what changes in windward beaches were attributable to the tsunami. Changes below sea level are even more difficult to determine than those above the sea.

Subaerial and shore-line changes.—In general the erosive effects were similar to those of storm waves. Beaches were cut landward and scarps were formed at their heads. Sand was carried away and rocks were either uncovered or left in place. Bedrock and even soil were little disturbed. However, in only a very few places were the changes greater than those produced during normal storm seasons or even by single severe storms, and in most places previously known to any of the writers the tsunami did not change topography or shore line appreciably.

The most extensive changes were on north coasts and may be ascribed both to the generally higher tsunami heights and the accompanying greater turbulence, or to the storm waves which rode in on top of the tsunami crests along those coasts. An exception was the beach at Lawai, on the south coast of Kauai, which was cut back at least 20 feet. This cutting was greater on the west than on the east side of Lawai Bay and resulted in a swing in the shore line which matched a swing that had been taking place at other beaches on the same coast for many years. It seems possible that the underwater portion of the beach had been cut away before the tsunami, and that the tsunami merely hastened slightly a swing about to take place normally.

The greatest retreat was generally not far above sea level, and at places the shore line retreated. The cutting resulted commonly in the formation of scarps in the upper parts of beaches. The formation of the scarps was aided by the anchoring of sand by vegetation and by the higher proportion of alluvium, which is generally less easily eroded. Such scarps are produced normally during storms, and existed on many beaches prior to the tsunami. At many places, however, they were cut back farther by the tsunami. The cutting of these scarps resulted in the undermining of many trees, particularly coconut trees and ironwoods (see pl. 18, *a*).

In one place, scarp formation on the upper part of the beach, combined with erosive effects of the water running back to the sea, left giant beach cusps with truncated ends as much as 6 feet high (see pl. 16, *a*).

The bases of all scarps formed by the tsunami were decidedly below the high-water marks reached by the waves. Extensive washed zones were usually found above the tops of the scarps (see pl. 15, *a*). At some places the scarp

bases were below mean sea level, but ordinarily they were well above, and often about halfway between mean sea level and the high-water mark of the tsunami.

Some of the most pronounced erosion was on beaches on the north shore of Kauai. At Moloaa the scarp which formed the front of the alluvial flat at the head of the beach retreated about 70 feet (see pl. 14, *a*); and at Haena a similar scarp was cut back about 50 feet. At Haena and at Lumahai the shore line retreated a similar amount, leaving exposed, in places at Haena, a cemented calcareous sandstone. Before the tsunami there had been a good beach at the head of Hanamaulu Bay, on the east coast of Kauai, but the beach was cut away, leaving escarpments and undercut trees along the shore.

So far as could be determined the beaches on Oahu were not much changed. At Kawela the shore line in front of the house where the senior author was living maintained approximately the same position (pl. 18, *a*). However, the bank above the beach was cut back about 8 feet and a scarp 5 feet high was left. Inside Kawela Bay the beach was somewhat narrowed by the waves, and an indentation was produced at the mouth of the stream valley entering the center of the bay. The sand of this beach returned within a few weeks.

Before the tsunami, along the straight coast just west of Kalaupapa Peninsula on Molokai, there was a beach which was used for swimming. This was mostly removed by the tsunami, but much of it had been rebuilt when the writers visited the area on May 3. The beach at Spreckelsville, on Maui, was cut back in places as much as 50 feet, undermining several houses and leaving a 5-foot scarp. At Pololu Valley on Hawaii, where the waves reached the record height of 55 feet, a sand beach said to have been 150 feet wide was cut away by the waves, leaving exposed an old boulder beach.

Where the waves rose over a high beach on a barrier of dunes and flooded lower lands behind, they eroded deep channels through the sand. At Waipio Valley on Hawaii a channel 100 feet wide and 15 feet deep was cut through high sand dunes. At Pololu Valley, also on Hawaii, the waves did not quite reach the tops of the dunes and no new channel was cut, but the river channel was enlarged by the waves. At the west side of Wainiha Valley on Kauai there is a row of dunes covered by grass and trees. The waves rose well above the dunes and in some places breached them. Where grass flourished, however, the waves were only able to scoop out elongate pockets about 5 feet deep. Though vegetated soil appeared more difficult to erode than sand, soil with plants was removed in a number of places, especially just behind the sand beaches.

At many places the sand excavated by the waves must have been carried seaward. Elsewhere, however, much of it was carried inland. At Haena, on northern Kauai, the highway was buried under 4 feet of sand. Thinner layers of sand covered roads at other places on Kauai, Oahu, and Maui. Many taro patches in Waipio Valley on Hawaii were completely covered by sand.

Submarine erosion.—Except in a general way, little can be told of the effects of the tsunami on the sea bottom. At the few places near shore where the writers were sufficiently well acquainted with the bottom configuration before the tsunami to hope to recognize changes, few could be definitely determined.

Off Waikiki the bottom appeared to be unaffected; in Kawela Bay, Oahu, Shepard could recognize only small changes in configuration of the reef rock and of the coral heads.

Obviously, however, the tsunami did have some effect on shallow bottom. A great many coral heads, ranging in size up to 12 feet across, were torn loose and thrown up on the beaches. At Kawaihae, on Hawaii, a coral head 3 feet in diameter was carried to the roadway 5 feet above sea level, and a great block about 8 feet long and 4 feet thick was torn loose at the outer edge of the reef and thrown up on the reef platform. Also near Haena, on Kauai, there were observed several large blocks of reef rock which had been thrown up on the reef. Large coral heads are characteristic of the seaward slopes of reefs rather than the tops. Presumably, much of the coral strewn about the beaches and the reef tops was derived from the seaward edges of the reefs. Some of the sand swept inland by the tsunami may have come from the shallow ocean bottom near shore, but most of it probably came from the beaches.

At many places the near-shore water became muddy as a result of the tsunami. At most places the water cleared again within a few days. The muddiness of the water may be attributable partly to the stirring up of fine terrigenous sediments on the shallow ocean bottom, but more largely to the result of washing away of soil cover on the temporarily inundated land areas.

It may be concluded that, although the tsunami did have some erosive effect in shallow water, the effect was very small. In deeper water it probably had little or no effect on the ocean bottom, because, as explained previously, the velocity decreases progressively with depth.

Casualties in the Tsunami

The accompanying table summarizes the number of persons killed and injured during the tsunami on the principal Hawaiian Islands. The figures were supplied by the American Red Cross.

Casualties	Kauai	Oahu	Molokai	Maui	Hawaii	Total
Dead...................	15	9	0	14	121	159
Injured................	8	0	0	2	153	163

Of the 159 listed as dead, only 115 bodies were recovered. The other 44 persons had, however, been missing for many months when these figures were compiled, and must be numbered among the dead. The number of injured includes only those hurt seriously enough to require hospitalization. The heaviest loss of life was at Hilo, where 96 lives were lost.

Most of the deaths were by drowning. The high ratio of dead to injured could be explained by the fact that any injury in the water increases susceptibility to drowning. Although drowning is listed as the direct cause of most deaths, probably many drownings were preceded and caused by disabling injury. Some of the persons drowned were known to be strong swimmers.

Undoubtedly the hour of arrival of the waves minimized the loss of life. If the waves had arrived two or three hours earlier, fewer persons would have

wakened and they would have had difficulty in picking routes of escape in the dark. Furthermore, the tide would have been higher, resulting not only in a corresponding increase in the heights to which waves dashed on all shores, but also in greater depth of water over reefs. This would have decreased the sheltering effect of the reefs and increased greatly the heights to which waves reached behind them. Particularly on Oahu, where the population is dense and the reef effect marked, this would have meant many more casualties.

No estimate has been made of the number of chickens, cats, dogs, pigs, and larger animals killed by the waves. Probably the numbers would be comparable with the number of human fatalities. Certainly thousands of fish were carried up and stranded on low land on all the islands (pl. 33, *b*). Kahuku and Kaneohe airfields and Waialae golf course, on Oahu, supplied many pounds of fish and lobsters. Eels were found in greatest abundance, probably because they live most of the time in crevices in the coral blocks and were carried on shore with the blocks. *Myripristis*, the fish shown in plate 33, *b*, is a nocturnal species that hides during the day in crevices on the coral reef.[15] Locally, fish lived for some time in pools left by the waves. Three small ocean fish were found in a few inches of very salty warm water 1,000 feet from the shore at Haena, Kauai, 11 days after the waves. One of these was identified as *Thalassoma duperrey*, a common reef fish.

CONCLUSIONS

Danger areas.—In general, it may be stated that no Hawaiian shore is exempt from possible damage by future tsunamis. Certain areas are, however, much less subject to damage than others. Waves of local origin, such as that of April, 1868, may strike any shore with great violence. However, the Hawaiian area is not highly active seismically, with the exception of the numerous small volcanic earthquakes on the island of Hawaii which are not accompanied by the generation of tsunamis. Tsunamis of local origin are rare in comparison with those developing in the highly seismic border regions of the Pacific (see fig. 1, p. 398). The greatest likelihood of damage to Hawaiian shores is from waves of distant origin.

The greatest danger appears to be from waves originating in the trenches or deeps off the coasts of Alaska, Kamchatka, and Central and South America. Only one tsunami can be definitely assigned to the area from Alaska to Mexico along the west coast of North America. There is some possibility of severe damage by a tsunami from the Japanese area, especially if it happened to arrive during a heavy Kona (southwesterly) storm, but judging from experience of past tsunamis from Japan there is little likelihood that Japanese tsunamis will be large enough on Hawaiian shores to do serious damage. Even the great Sanriku tsunamis of 1896 and 1933 caused little or no damage in Hawaii. There is still less probability of damage from tsunamis originating farther south in the western Pacific. The great Mindanao Deep off the Philippine Islands is less active seismically than the Tuscarora Deep off Japan, and the distance from Hawaii is even greater. Moreover, the Mariana, Caroline, Marshall, and Gilbert islands form a barrier between the Philippines and

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[15] C. L. Hubbs, personal communication.

Hawaii which would greatly reduce the force of a tsunami reaching Hawaii from the Philippines. Similarly, island chains form a screen between Hawaii and the southwestern border region of the Pacific.

The effects of past tsunamis indicate that the greatest damage is done, as would be expected, on the coasts facing toward the source of the waves. The Hawaiian coasts most likely to sustain damage are therefore the northern, the eastern, and to a smaller degree the southern coasts. Western coasts are in general less subject to severe damage. Northern and eastern coasts are probably more subject to damage than southern ones because of the shorter distance from the origin of Aleutian tsunamis as compared with those from South America. However, South American tsunamis have caused damage on southern coasts in the past and may be expected to do so in the future.

Along all coasts, local features make certain places more subject to damage than others. Places situated at and near the heads of submarine ridges which extend into deep water are more subject to damage than those at the heads of submarine valleys or canyons. Shores protected by wide reefs, especially where a moderately deep lagoon lies inside the reef, are much safer than unprotected shores. The ends of peninsulas projecting into deep water without appreciable submarine ridges, such as Kalaupapa on the north coast of Molokai, are less subject to damage than adjacent areas. Certain bays may have a funneling effect, forcing the water to high altitudes along the axis of the valley at the head of the bay, but this effect is not at all general. There also appears to be a tendency for the concentration of violent waves on shores of angular islands just in the lee of the headlands projecting across the course of the waves. Thus, in the 1946 tsunami the waves reached great heights on the shores just southwest of Makapuu Point and southeast of Kaena Point on Oahu, just southwest of the eastern and western points of Molokai, and just southwest of the eastern point of Maui.

The foregoing are generalities. It is more difficult to enumerate specific places which are in danger, or which are especially safe, partly because knowledge of the behavior of tsunamis is still incomplete and partly because of the inadequacy of knowledge of the submarine topography around the Hawaiian Islands. The effect of submarine topography on the intensity of all waves striking shore, and tsunamis in particular, is so marked that, if for no other reason, a detailed survey of submarine topography in the vicinity of the Hawaiian Islands should be undertaken as soon as possible.

It is safe to say that the places most severely damaged by the tsunami of 1946 are the most subject to severe damage by future tsunamis reaching Hawaiian shores, especially those from the northern Pacific. Hilo is so situated as to be in serious danger from tsunamis originating along the northern or eastern borders of the Pacific. Kahului, on Maui, will probably suffer damage from any severe tsunami from the northern or northeastern Pacific, but to a less degree than Hilo. Honolulu is protected by other islands and ridges and is not likely to sustain severe damage from any tsunami of distant origin. The western coasts of all the islands may sustain minor damage from tsunamis of Japanese or northern Pacific origin, but major damage by tsunamis of distant origin is not likely.

Mitigation of future damage.—Damage to property by future tsunamis can be avoided only by leaving vacant all the coastal belts subject to inundation. That, of course, would not be practical. Attention must, therefore, be directed toward keeping the inevitable damage to a minimum.

Locally, as in Hilo, construction of a sea wall is advisable. It is out of the question to attempt construction of a wall which would entirely stop the advance of a large tsunami. Such a wall would have to be very high, say 50 feet. Not only would the cost be prohibitive, but the wall would be so high that it would completely shut out the view of the sea from the first and second stories of adjacent structures. A small sea wall of proper construction would, however, reduce the force of the waves and help restrict damage in inundated areas to mere flooding. The water coming over would still retain a large amount of energy, which would be expended in turbulence and erosion in the belt just inside the wall. Should there be structures in that belt, they would be subject to damage or destruction. It would be advisable, therefore, to leave open, except for the planting of resistant trees, a belt one or two hundred feet wide along the inside of the wall.

Entire avoidance of construction in danger areas would undoubtedly be impossible. However, in all areas of heavy population, such as the water front at Hilo, structures should either be eliminated or restricted to those which will best withstand the wave impact. Experience has shown that well-constructed reinforced concrete buildings will sustain little if any structural damage. As pointed out by Imamura (1937, pp. 127–137), these wave-resistant structures will serve as a line of defense for weaker frame structures farther inland. In all types of multiple-story buildings, it is the lower story which is most subject to attack, and consequently the lower story should be especially well built. This is true also of resistance to earthquakes, and hence, in a seismically active area such as the island of Hawaii, it is doubly desirable.

In many coastal areas of the Hawaiian Islands, particularly those inhabited by fishermen and farmers, it is impossible to prevent the erection of cheap and often poorly constructed frame buildings. Experience with the tsunami of 1946 indicates, however, that frame houses have a much better chance of survival if they are built a little above ground level on strong stilts. This apparently allows the water to pass under the house without exerting its full force against the house. It is also better, if possible, to place the house on a hummock which is elevated even slightly above the surroundings. In many places, where it is feasible, a small sea wall will help protect the house from the full force of the wave. As is true also in earthquake territory, good construction is worth while. In the tsunami of 1946, some well-built frame houses were floated for considerable distances with comparatively little structural damage, whereas less well-built houses, and particularly houses which were poorly tied together, suffered much greater damage under less intense attack.

Future avoidance of loss of life.—Although loss of property in future tsunamis is probably unavoidable, it should be possible to minimize greatly the loss of life from tsunamis of distant origin. A suitable series of observation stations could be established to give warning of the approach of many of the tsunamis 1 to 4 hours before they strike Hawaiian shores. Loss of life in the

rare tsunamis of local origin is probably unavoidable, as no warning of them can be given unless they are characterized by the same large withdrawal of water from shore which precedes the damaging waves of distant tsunamis, and even then the warning must at best be short.

In the past, attempts have been made to warn of the approach of tsunamis on the basis of seismographic recording of submarine earthquakes. This procedure was successful on one occasion, but in general it would be unsatisfactory because of the very small proportion of submarine earthquakes which are accompanied by the generation of tsunamis. Repeated warnings of waves which do not materialize will soon negate, in large measure, the value of a warning for an actual wave. Although they are not satisfactory as a basis for broadcasting a general warning of the approach of a tsunami, seismographic recordings of severe submarine earthquakes might serve to alert local agencies responsible for issuing public warnings. Charts recently prepared by the Coast and Geodetic Survey show travel times of tsunamis to Honolulu from points of origin throughout a large part of the Pacific Basin (Zetler, 1947). Seismometric recording of a heavy submarine earthquake might be used to alert the responsible agency, which then could watch for signs of the arrival of a tsunami at the time interval indicated by the chart. Such forewarning greatly increases the probability of recognition of the small preliminary wave.

At present the only feasible method of giving warning that a tsunami is approaching is the establishment of shore stations to observe the ocean waves themselves, either directly or instrumentally. Existing Coast Guard and weather stations and lighthouses with permanent personnel could be utilized on the shores of Alaska and North America and on mid-Pacific islands. Arrangements could be made with other governments for stations to report waves on the Central and South American coasts and in Japan, Siberia, and the Philippines. The arrival of any unusually large waves could be reported from visual observation. It is also possible to build tide-gauge attachments which will record the first indications of the tsunami. Recording apparatus is being constructed to give an alarm whenever a long-period wave is detected. The arrival of such waves at each shore station should be reported immediately by radio, telephone, or telegraph to a central coördinating agency, on which would rest the responsibility of issuing warnings to places in the path of the waves. In a locality such as Hilo, the arrival of the preliminary wave could be announced by the blowing of a siren, giving most inhabitants time to escape.

Once a warning of distant waves is issued, means can be devised for spreading it rapidly among the populace. With warning an hour in advance of the arrival of the waves, people in the endangered areas could be moved, together with some easily portable property, to higher areas of safety. In general, the move required would be short and quickly made. After the arrival of the first wave, refugees should not return to their homes for several hours, as later waves are commonly larger than the first. The natural curiosity of humanity may lead some persons to stay in areas of danger to watch the waves. This should be discouraged by means of a suitable campaign of education. At any rate, warning would have been given, and the opportunity of saving life and property would have been made available.

PLANS FOR OBSERVING FUTURE WAVES

For many years the Japanese have had well-developed plans for obtaining observations during tsunamis. At the time of the disasters of 1933 and 1946 these plans were put into operation and extensive information was gathered. It would be well for American scientists to lay plans for observing future tsunamis in the Hawaiian Islands or in other accessible areas so that next time we can be in a better position to determine what actually happens during these inundations. All information of this type will tend to reduce the danger and the material losses from future waves. Observations of the nature of the waves and of the withdrawal of water between waves could be made by volunteer teams of residents who had been given some training; to keep up their interest, which is likely to lag during the long periods which usually occur between disastrous waves, they could be made responsible for observing storm waves such as can be expected annually during the stormy winter season. A second and very important means of obtaining information during tsunamis is with the coöperation of the air forces of the armed services. They could have photographic squadrons cover the shores during waves, taking moving pictures of the rising and falling sea levels. Plans could be made to have airmen cover specifically the most critical places and take note of the sequence of events. Such places as Hilo on Hawaii, Kahului Harbor on Maui, Laupahoehoe Peninsula on Hawaii, and Kalaupapa Peninsula on Molokai are areas where valuable information could be obtained.

Investigation of the effects of the waves after they have receded should also be planned. Teams of scientists should be ready to go to the areas of the disaster without appreciable delay, so as to obtain firsthand information while residents can still remember the details and while the evidence from the waves is still fresh. Also, the civil authorities should have questionnaires which they could fill out after the disasters while the information was easily available. No arrangements of this sort were made before the last Hawaiian disaster, and it was entirely fortuitous that the present writers were available to conduct the investigations in the islands and that observers from the war project of the University of California had stopped over en route to Bikini at the time.

LITERATURE CITED

BENNETT, C. C.
  1869. Honolulu directory and historical sketch of the Hawaiian or Sandwich Islands. Honolulu. Pp. 48–51.

BYERLY, P.
  1942. Seismology. Prentice-Hall, New York.

COAN, TITUS
  1870. The volcano of Kilauea and great earthquake waves. Am. Jour. Sci., 2d ser., vol. 49, pp. 269–271.

DANA, J. D.
  1890. Characteristics of volcanoes. Dodd, Mead, New York. P. 197.

DAVISON, CHARLES
  1936. Great earthquakes. Murby, London. Pp. 20–23.

FINCH, R. H.
  1924. On the prediction of tidal waves. Pan-Pacific Sci. Congr., Australia, 1923, Proc., vol. 2, pp. 1366–1368.

GREEN, C. K.
  1946. Seismic sea wave of April 1, 1946, as recorded on tide gages. Am. Geophys. Union Trans., vol. 27, no. 4, pp. 490–500.

GREEN, GEORGE
  1838. On the motion of waves in a variable canal of small depth and width. Cambridge Phil. Soc., Trans., vol. 6, pp. 457–462.

GUTENBERG, B.
  1939. Tsunamis and earthquakes. Seismol. Soc. Am., Bull., vol. 29, pp. 517–526.

HART, G. E. F.
  1931. Interesting oceanographic phenomena. The Australian Surveyor, December, 1931, pp. 192–198.

HECK, N. H.
  1947. List of seismic sea waves. Seismol. Soc. Am., Bull., vol. 37, pp. 269–286.

HITCHCOCK, C. H.
  1911. Hawaii and its volcanoes. 2d ed. Honolulu. Pp. 294–295.

IMAMURA, A.
  1937. Theoretical and applied seismology. Maruzen, Tokyo.

JAGGAR, T. A.
  1919. Observations on Hawaiian volcanoes. Hawaiian Volc. Obs. Bull., vol. 7, p. 55.
  1923. Earthquake wave in Hawaii. Hawaiian Volc. Obs. Bull., vol. 11, p. 11.
  1931. Hawaiian damage from tidal waves. Volcano Letter, no. 321 (February 19, 1931), pp. 1–3.

JARVES, J. J.
  1843. History of the Hawaiian or Sandwich Islands. Pp. 18–23.

JONES, A. E.
  1931. Earthquake and sea wave of October 3, 1931. Volcano Letter, no. 361 (November 26, 1931), pp. 2–3.

LAMB, SIR HORACE
  1942. Hydrodynamics. 6th ed. Cambridge Univ. Press.

MARIN, DON FRANCISCO
Unpublished journal in the Archives of Hawaii. Translated by R. C. Wiley.

MILNE, J.
Catalogue of destructive earthquakes, A.D. 7 to A.D. 1899. Brit. Assoc. Adv. Sci.

NASU, N.
1934. Papers and reports on the tsunami of 1933 on the Sanriku coast, Japan. Tokyo
Imp. Univ. Earthq. Res. Inst. Bull., suppl. 1, p. 226.

OGAWA, T.
1924. Notes on the volcanic and seismic phenomena in the volcanic district of Shimabara,
with a report on the earthquake of December 8, 1922. Kyoto Imp. Univ., Mem.
Coll. Sci., ser. B, vol. 1, pp. 219–224.
1933. Papers and reports on the tsunami of 1933, Sanriku coast, Japan. Tokyo Imp.
Univ., Earthq. Res. Inst. Bull., suppl. 1.

POWERS, H. A.
1946. The tidal wave of April 1, 1946. Volcano Letter, no. 491 (January-March, 1946).

SHEPARD, F. P.
1948. Submarine geology. Harper & Bros., New York.

STEARNS, H. T., and G. A. MACDONALD
1947. Geology and ground-water resources of the island of Molokai, Hawaii. Hawaii Div.
of Hydrog., Bull. 11, p. 23.

SVERDRUP, H..U., M. W. JOHNSON, and R. H. FLEMING
1942. The Oceans. Prentice-Hall. New York.

WILLIAMS, H.
1941. Calderas and their origin. Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 25, pp.
253–264.

WILLIS, BAILEY
1929. Earthquake conditions in Chile. Carnegie Inst. Wash.

WOOD, H. O.
1914. On the earthquake of 1868 in Hawaii. Seismol. Soc. Am., Bull., vol. 4, pp. 196–199.

ZETLER, B. D.
1947. Travel times of seismic sea waves to Honolulu. Pacific Science, vol. 1, pp. 185–188.

PLATES

PLATE 6

Tsunami crossing the reef and lagoon near Kawela Bay, Oahu. A few seconds after the picture was taken the wave swept across the low ridge in the foreground. Note the turbulence in the normally protected lagoon. Photo by F. P. Shepard.

PLATE 7

a. One of the late, relatively small waves of the tsunami sweeping over Coconut Island, in Hilo Bay.

b. Water draining from shore during the recession of the same wave. Photos by Millard Mundy.

a

b

PLATE 8

a. Bore advancing past the railroad bridge at the mouth of the Wailuku River, Hilo. A previous wave had removed one span of the bridge. Note the steep front, the turbulence of the water behind the bore. and the placidity of the water in front of it. Photo by Shigeru Ushijima.

b. Advance of one of the later waves into the Wailuku River. This photograph was taken from the bridge next upstream from that shown in *a*, above. Photo by Francis Lyman.

a

b

PLATE 9

Later stages in the advance of one of the later waves into the Wailuku River. Photos by Francis Lyman and Warren Flagg.

a

b

PLATE 10

One of the late waves approaching the Wailuku River, Hilo. Part of the ruined Hilo water front is seen to the left. Photo by U. S. Army Transport Command.

PLATE 11

Photo by the U. S. Navy which apparently shows one of the waves of the tsunami spread over the coast near Laupahoehoe. Note raft dropped by Air Force plane to rescue persons swept to sea by waves which crossed Laupahoehoe Peninsula. Part of the turbulence is evidently due to wind waves, but the crest which is apparently moving along the coast is probably due to the tsunami.

PLATE 12

a. An early wave flooding over the sea wall at the Puu Maile Hospital near Hilo. Note the broad, relatively flat crest of the tsunami with smaller storm waves superimposed. Photo by Mrs. Pearl Welsh.

b. Grove of pandanus trees pushed over by the waves, and blocks of coral thrown up on the shore platform near Haena, Kauai. Photo by G. A. Macdonald.

a

b

PLATE 13

a. Scarp cut by the tsunami near Haena, Kauai. Photo by F. P. Shepard.

b. Large block of concrete and limestone carried out to the fringing reef by the tsunami near Haena, Kauai. Photo by G. A. Macdonald.
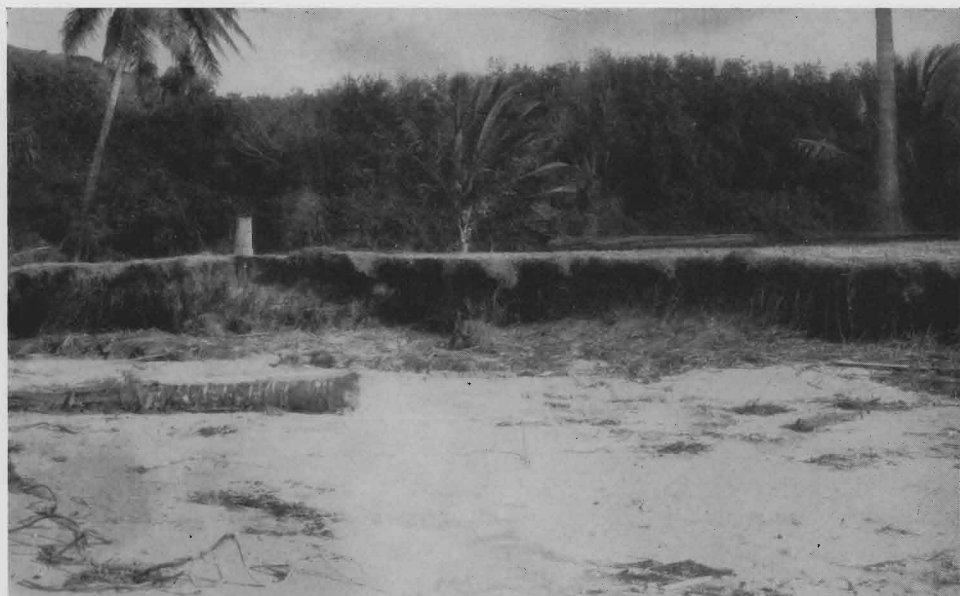
a

b

PLATE 14

a. Scarp 6 feet high cut by the tsunami at the head of the beach at Moloaa, Kauai. Note the roots exposed on the bank. Photo by G. A. Macdonald.

b. Shacks and pier close to sea level in Kaneohe Bay, Oahu, untouched by the tsunami. Photo by G. A. Macdonald.

a

b

PLATE 15

a. Swash marks left by the tsunami 37 feet above sea level in the small embayment just northwest of Makapuu Head, Oahu. Photo by John Isaacs, University of California.

b. Highway east of Koko Crater, Oahu, washed out by the tsunami. Photo by F. P. Shepard.

a

b

PLATE 16

a. Beach cusps 6 feet high and with sharply truncated ends, formed by the tsunami east of Koko Crater, Oahu. Photo by John Isaacs, University of California.

b. House swept seaward near the mouth of Limaloa Gulch, Oahu, by the tsunami. Its former position is marked by the concrete foundation platform. Photo by G. A. Macdonald.

a

b

PLATE 17

a. House at Kawela Bay, Oahu, demolished by the tsunami. Sugar cane in the background was knocked over by the waves. Photo by H. S. Palmer.

b. Coral blocks washed ashore by the tsunami at the head of Kawela Bay, Oahu. The blocks were quarried from the reef on the floor of the bay. Photo by G. A. Macdonald.

a

b

PLATE 18

a. Palmer house at Kawela Bay, Oahu, badly damaged by the tsunami. A glassed-in lanai (porch) along the front of the house was demolished. Note the escarpment which was largely a product of the waves. The ironwood trees served as some protection to the house. Photo by H. S. Palmer.

b. Another view of the Palmer house.

a

b

PLATE 19

Houses shifted and wrecked by the tsunami, at the southeastern side of Kawela Bay, Oahu. In the center foreground two houses have been washed into a sinkhole lake, and the house shown by the arrow was carried 200 feet into the cane field without damage to its furnishings or occupants. Photo by U. S. Navy.

PLATE 20

a. View of Kalaupapa Peninsula, Molokai, from the air. At the end of the peninsula (foreground) the wave rose only 8 feet, whereas it attained 54 feet on the side of the canyon in the left background. Photo by F. P. Shepard.

b. Line of driftwood (at the man's feet) left by the tsunami 8 feet above sea level near the end of Kalaupapa Peninsula, Molokai. A higher line of driftwood left by winter storms can be seen just over the man's head. Photo by G. A. Macdonald.

a

b

PLATE 21

a. Air view of Waikolu Valley, Molokai, where the water rose 54 feet above sea level. Note the small islands which may have helped funnel the water into this valley. Photo by F. P. Shepard.

b. View of Halawa, northeastern Molokai, on April 2. The land was swept so clean that it could serve as an airport. Photo by F. P. Shepard.

a

b

PLATE 22

a. Damaged house and escarpment cut by the tsunami at the head of the beach at Kainalu, Molokai. The beach head was cut back at least 10 feet. Photo by G. A. Macdonald.

b. Kiawe (algaroba) trees pushed over by the tsunami, near Kapuhi on the western end of Molokai. Photo by G. A. Macdonald.

a

b

PLATE 23

An early wave, probably the third of the series, breaking over Pier 1, Hilo, and sweeping away part of the shed. Arrow points to a man facing the approaching torrent of water and subsequently lost. Photo from the deck of a vessel lying at the pier, published by permission of Press Association, Inc.

PLATE 24

View of the next wave at a later stage, indicated by the smaller degree of turbulence. Photo from the deck of a vessel lying at Hilo pier, published by permission of Press Association, Inc.

PLATE 25

a. House floated inland 200 feet by the tsunami and left essentially intact, at Hamoa, Maui. Its former position is indicated by the concrete steps in the foreground. Other houses in the area were destroyed. Photo by G. A. Macdonald.

b. Beach and dune ridge at mouth of Pololu Valley, Hawaii, showing erosion caused by the tsunami on the side and end of the dune ridge. High-water mark of 55 feet indicated by arrow. Photo by G. A. Macdonald.

a

b

PLATE 26

a. Houses swept 500 feet from their foundations by the tsunami at Laupahochoe, Hawaii. The two houses in the central background formerly stood on the concrete footings in the foreground. Other houses swept more to the right were carried into the sea.

b. Closer view of houses shown in *a*, above. Photos by G. A. Macdonald.

a

b

PLATE 27

a. Railroad bridge at Kolekole Stream, Hawaii, showing the girders of the trestle thrown 500 feet inland by the tsunami, and the bridge deck left hanging by the rails. Photo by G. A. Macdonald.

b. Breakwater at Hilo, Hawaii, severely damaged by the tsunami. The rocks were removed to an average depth of 3 feet below sea level. Photo by U. S. Navy.

a

b

PLATE 28

Wreckage left by the tsunami along Kamehameha Avenue, Hilo. Photos by Francis Lyman.

a

PLATE 29

Water front at Hilo, Hawaii, swept almost bare by the tsunami. Photo by U. S. Navy.

PLATE 30

a. The sea wall at the Puu Maile Hospital at Hilo after the tsunami.
See also plate 12, *a.* Photo by Mrs. Pearl Welsh.

b. The same sea wall partly collapsed after the huge wind waves of
January, 1947, which produced more damage than the tsunami at
this locality. Photo by F. P. Shepard.

a

b

PLATE 31

a   Scotch Cap Lighthouse, Unimak Island of the Aleutians, taken before the tsunami. The foundation of the lighthouse is at an elevation of 45 feet, the upper radio mast 103 feet, and the upper plateau 115 feet.

b.   The same place after the tsunami. Note that the lighthouse and the radio masts have gone, the slopes are heavily washed almost to the plateau level, and debris has been deposited on the plateau. Note also the exposure of stratification on the slopes, revealed by removal of the overburden. The radio masts around the upper building are still standing, and, since the waves hit the locality about four hours before Hawaii, it may be supposed that warning of the imminence of disastrous waves could have been transmitted to Hawaii well in advance of their arrival. Photos by courtesy of 17th Coast Guard.

a

b

PLATE 32

a. One of the early waves of the series sweeping by the Hakalau sugar mill, Hawaii. The wreckage of the mill can be seen. Photo by Shigeharu Furusho.

b. Building at Hilo, Hawaii, of which the lower story collapsed, allowing the second story to drop to the ground level. Photo by Francis Lyman.

a

b

PLATE 33

a. Railroad swept inland from its bed, at Waialee, Oahu. Photo by U. S. Navy.

b. A fish (*Myripristis* sp., probably *M. praslinus* Cuvier) washed inland and left by the retreating waves. Photo by John Isaacs, University of California.

a

b