The Tsunami of April 1, 1946, in the Hawaiian Islands

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INTRODUCTION

THE TSUNAMI WHICH STRUCK the shores of the Hawaiian Islands on the morning of April 1, 1946, was the most destructive, and one of the most violent, in the history of the islands. More than 150 persons were killed, principally by drowning, and at least 161 others were injured. Property damage reached about $25,000,000.

The wave attack on Hawaiian shores was far from uniform. The height and violence of the waves at adjacent points varied greatly, and not always in the manner which would have been expected from superficial inspection and a study of the existing literature on tsunamis. Therefore, a detailed study of the effects of the tsunami has been made, in an effort to understand the observed variations, and in the hope that the principles established may help lessen the loss of life and property in future tsunamis. Space is not available in the present short paper to discuss findings in detail, or even to present all the evidence for all the conclusions. These matters will be treated in detail in a longer paper (Shepard, Cox, and Macdonald, in preparation).

Acknowledgments: We wish to thank the many persons who furnished information during the course of the field study. We are also especially grateful to M. H. Carson, H. S. Leak, H. W. Beardin, and W. K. Sproat, who supplied measurements of the high-water level in areas not visited by us; H. W. Iversen and J. D. Isaacs, who supplied additional measurements on Oahu; A. F. Robinson and Dexter Fraser, who furnished descriptions of the wave effects on Niihau and Lanai, respectively; the Hawaii County Engineer's Office, which supplied a map showing the extent of flooding in Hilo; and the U. S. Coast and Geodetic Survey, which supplied data on the earthquake and the record of the Honolulu tide gage, and permitted the use, in advance of publication, of C. K. Green's manuscript on the tsunami along the shores of North and South America. Howard A. Powers, Seismologist of the Volcano Observatory at Hawaii National Park, aided greatly in the investigation on the island of Hawaii. Miss Maude Jones, Archivist of the Territory of Hawaii, and Miss Margaret Titcomb, Librarian of the Bishop Museum, aided in locating records of past waves. C. K. Wentworth and H. S. Palmer aided greatly in discussions. Wentworth and Walter Munk read and criticized the manuscript. J. Y. Nitta prepared the illustrations.

DEFINITION OF "TSUNAMI"

The name "tsunami"[2] is applied to a long-period gravity wave in the ocean caused by a sudden large displacement of the sea bottom or shores. A tsunami is accompanied by a severe earthquake, but the earthquake does not cause the tsunami. Rather, both are caused by the same sudden crustal displacement. The waves of a tsunami have a period

[1] U. S. Geological Survey, Scripps Institution of Oceanography, and Hawaiian Sugar Planters' Association Experiment Station, respectively. This paper is published by permission of the Director, Geological Survey, U. S. Department of the Interior.

[2] Also spelled "tunami," the Japanese equivalent of the letter *t* being pronounced *ts* in English. It appears preferable, however, to use the phonetic spelling in English, avoiding thereby much incorrect pronunciation.

of several minutes to an hour as contrasted with several seconds for ordinary storm waves caused by wind, a wave length of scores of miles as contrasted with less than 500 feet for wind waves, and a speed of hundreds of miles an hour as contrasted with less than 60 miles an hour for wind waves. Tsunamis are also sometimes termed "seismic sea waves," and are popularly known as "tidal waves." The latter term is patently undesirable, as the waves have no connection whatever with the tides. "Tsunami" is used herein in preference to "seismic sea wave" because of its greater brevity, and because the etymological correctness of the term "seismic sea wave" appears open to question.[3]

HISTORY OF TSUNAMIS IN HAWAII

Tsunamis probably reach Hawaiian shores on an average of more than one a year. Most of these are small, however, and generally escape notice except when their record is recognized on tide gages. Earlier tsunamis in Hawaii have been discussed by Jaggar (1931: 1–3) and Powers (1946: 3). The accompanying table lists all the tsunamis noticed on Hawaiian shores, in the period of written history, of which record could be found, together with their sources if known. A total of 27 are listed, or an average of one every 4.7 years since 1819. Most of them, however, did little damage. During the same interval there are listed five severe tsunamis which caused extensive damage, an average of one every 25.6 years.

Other violent waves have been termed "tidal waves" in the newspapers, but were more probably storm waves. Such were the wave which hit Maliko, Maui, on January 28, 1895, and those which struck Kaumalapau on Lanai, and Nawiliwili on Kauai, on May 30, 1924.

It will be noted that only two of the 27 tsunamis listed in the table were of local origin. With the exception of the numerous volcanic earthquakes on the island of Hawaii, which seldom cause tsunamis, the Hawaiian region is only moderately active seismically (Gutenberg and Richter, 1941: 84–85). The great majority of the tsunamis reaching Hawaii originate in the highly seismic border zone of the Pacific. Of the 22 tsunamis from known sources listed in the table, five came from near South America, one from near Central America, one from near California, three from near Alaska and the Aleutian Islands, five from near Kamchatka, three from the Japanese area, and one from near the Solomon Islands. Of the five severe tsunamis, three originated

TABLE 1

HAWAIIAN TSUNAMIS

DATE	SOURCE	DAMAGE IN HAWAII	AVERAGE SPEED OF WAVES
	nearest coast		mi. per hr.
1819 Apr. 12	Unknown	Unknown	—
1837 Nov. 7	South America	Severe	—
1841 May 17	Kamchatka	Small	—
1868 Apr. 2	Hawaii	Severe	—
1868 Aug. 13	South America	Severe	—
1869 July 25	South America (?)	Moderate	—
1872 Aug. 23	Hawaii	Small	—
1877 May 10	South America	Severe	—
1883 Aug. 26	East Indies	Small	—
1896 June 15	Japan	None	478
1901 Aug. 9	Japan (?)	None	—
1906 Jan. 31	Unknown	None	—
1906 Aug. 16	South America	Small	—
1918 Sept. 7	Kamchatka	Small	456
1919 Apr. 30	Unknown (distant)	None	—
1922 Nov. 11	South America	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 Is.	None	492
1931 Oct. 3	Solomon Is.	None	447
1933 Mar. 2	Japan	Small	477
1938 Nov. 10	Alaska	None	496
1944 Dec. 7	Japan	None	425
1946 Apr. 1	Aleutian Is.	Severe	490

[3] The adjective "seismic" is derived from the Greek root *seismos,* meaning earthquake, and is defined as pertaining to, produced by, or characteristic of an earthquake. The waves in question are not, however, characteristic of most earthquakes, even those of submarine origin, and are not produced by earthquakes.

near the coast of South America and one in the Aleutian area, and one was of local origin. One tsunami of moderate intensity came from near Kamchatka, and another probably from South America.

GENERAL FEATURES OF THE APRIL, 1946, TSUNAMI: ORIGIN AND NATURE OF THE WAVES

The tsunami of April 1, 1946, was caused by a movement of the sea bottom on the northern slope of the Aleutian Deep, south of Unimak Island. The same crustal movement gave rise to a violent earthquake, recorded on seismographs all over the world. In Hawaii, it was recorded on the instrument of the U. S. Coast and Geodetic Survey located on the campus of the University of Hawaii in Honolulu, and on those of the Hawaiian Volcano Observatory at Kilauea on Hawaii. The epicenter of the earthquake has been located by the Coast and Geodetic Survey at latitude 53.5° N. and longitude 163° W., and the time established as 1^h 59^m A.M. Hawaiian time (12^h29^m Greenwich time) (Bodle, 1946: 464). It may be assumed that the tsunami originated at the same place and time as the earthquake. The place of origin was thus 2,241 miles N. 8.5° W. of Honolulu, and 2,375 miles N. 12° W. of Hilo (Fig. 1).

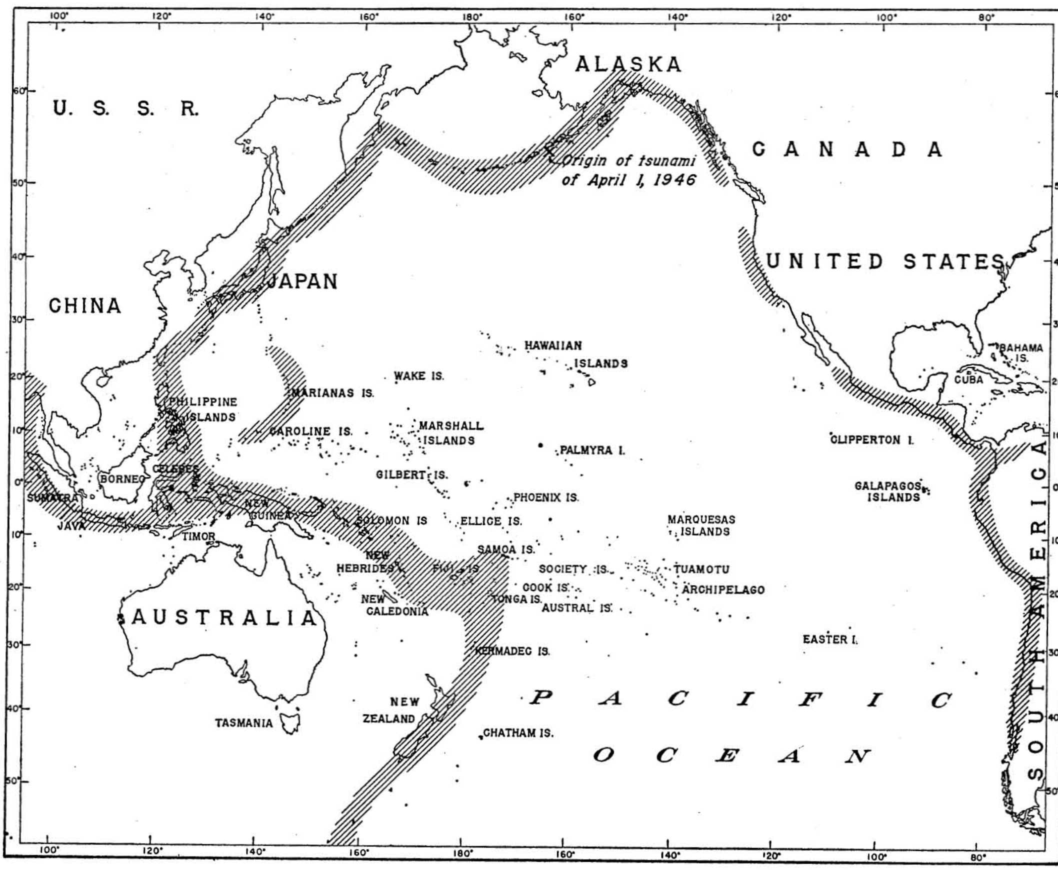

FIG. 1. Map of the Pacific basin, showing the position of the Hawaiian Islands, the place of origin of the tsunami of April 1, 1946, and the distribution of seismically active belts around the Pacific in which tsunamis are likely to originate.

The time of arrival of the waves in the Hawaiian Islands is known with certainty only at Honolulu. The record of the Honolulu tide gage (Fig. 2) shows that the first rise started at about 6:33 A.M. (Green, C. K., 1946: 491), though the exact time cannot be stated closer than 2 or 3 minutes. The drum of the water-stage recorder at the Waimea River, on Kauai, revolves too slowly to give an accurate indication of time, but the first rise appears to have started there at about 5:55. At Hilo, electric clocks were stopped at 7:06, and a brief power failure occurred at 7:18. These have been interpreted by Powers (1946: 2), probably correctly, as the time of arrival of two wave crests at Hilo. From other considerations, discussed briefly elsewhere (Shepard, Macdonald, and Cox, in preparation), it appears probable, however, that the crest at 7:06 was the second wave at Hilo, not the first. If so, allowing for the observed 15-minute interval between later waves, the first rise at Hilo probably started at about 6:45. Computed from these times of arrival, the approximate average speed of the tsunami from its origin to Honolulu and Hilo was, respectively, 490 and 498 miles an hour. On entering shallow water the waves decreased greatly in speed. The waves moving up Kawela Bay, on Oahu, were estimated by Shepard to be moving only about 15 miles an hour. Similar low speeds near shore were reported by other observers, and are comparable to the speed of 20 miles an hour recorded in San Francisco Bay (Green, C. K., 1946: 492).

The interval between the first and third wave crests, as recorded on the Honolulu tide gage (Fig. 2), was about 25 minutes, indi-

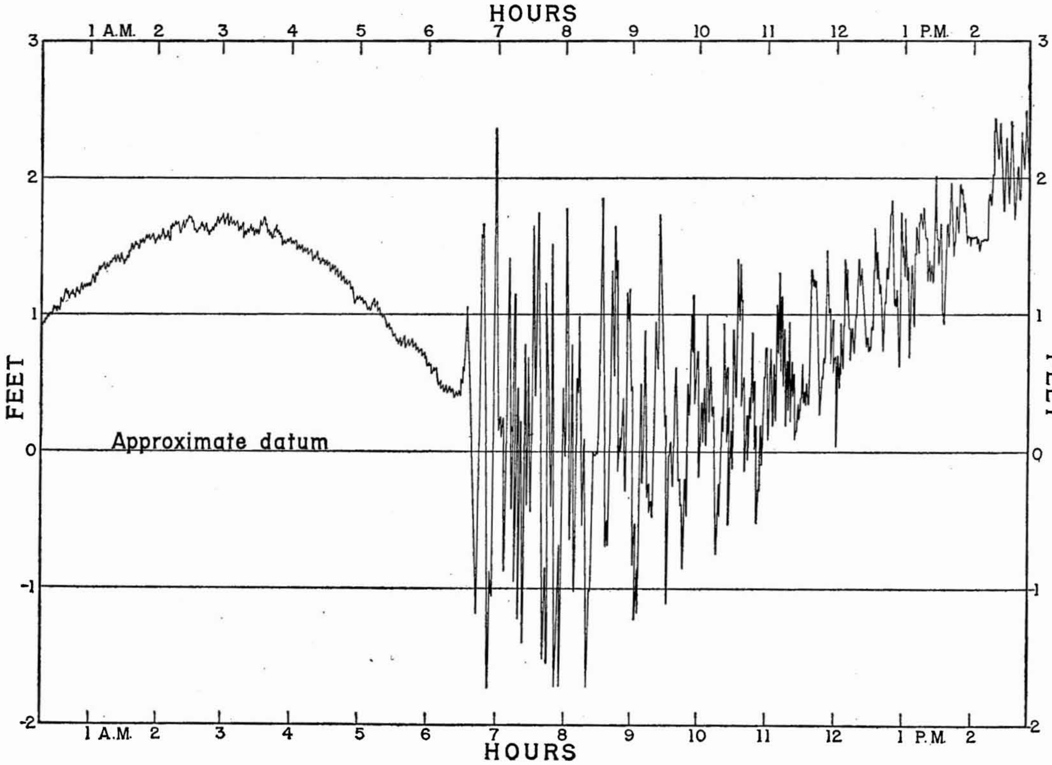

FIG. 2. Record produced on the tide gage in Honolulu Harbor by the tsunami of April 1, 1946.

cating 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 (1946: 499) at Honolulu and eight other stations on the coasts of North and South America. 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 at about 7:45 A.M. Observations elsewhere were poor, but in general indicated an interval not far from 15 minutes between the early waves of the series. The interval between later waves at Honolulu (Fig. 2) and elsewhere was shorter and less regular, probably because of the arrival of chains of waves traveling by somewhat different routes, refracted around different sides of islands, and reflected at various points, as well as traveling by the most direct route. Probably contributing to the irregularity of later waves were wind waves and also the free-period oscillations, in harbors and channels, known as "seiches." If the period of the waves is assumed to be 15 minutes, and the average speed to be about 489 miles an hour, the average wave length from crest to crest was about 122 miles.

Direct observations on the height of the waves in the open sea are lacking, but theoretical considerations indicate that the height probably did not exceed 2 feet from crest to trough.[4] If so, the small height combined with the very great wave length should have made the waves imperceptible to ships at sea. That such was indeed the case is indicated by the fact that the master of a ship lying offshore near Hilo could feel no unusual waves, although he could see the great waves breaking onshore. Crews of fishing boats in the Hawaiian area also reported no unusual conditions at the time of the tsunami, although heavy storm waves were running. The few reports of violent waves of great height from ships at sea were probably occasioned by storm waves, together with the knowledge that a tsunami was taking place.

The nature of the waves sweeping up on to Hawaiian shores varied greatly from place to place. At some places the water rose gently, flooding over the coastal lands without the development of any steep wave front. At such places most of the damage resulted from the violent run-back of the water to the sea. At some localities, although the general water surface rose gently, ordinary storm waves moved in over the top of the broad swells of the tsunami, and there at least part of the damage was caused by the storm waves. At most places, however, the waves of the tsunami swept toward shore with steep fronts and great turbulence, causing a loud roaring and hissing noise. Locally, the wave closely resembled a tidal bore, the steep front rolling in over comparatively quiet water in front of it. Behind the steep front, the wave crest was broad and nearly flat, with smaller storm waves superimposed upon it. Such bores were best developed in bays and estuaries, but waves of closely similar form were observed crossing shallowly submerged reefs upon otherwise open coasts.

At many places the violence of the waves moving shoreward was sufficiently great to tear loose heads of coral and algae, up to 4 feet across, and toss them onto the beach as much as 15 feet above sea level. Locally, blocks of reef rock weighing several tons were quarried at the outer edge of the reef and thrown onto the reef surface.

Between crests, the water withdrew from shore, exposing reefs, coastal mud flats, and

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[4] Based on the assumption of a 10-foot wave in 10 feet of water, and the variation of the wave height inversely as the fourth root of the depth.

harbor bottoms for distances up to 500 feet or more from the normal strand line. The outflow of the water was rapid and turbulent, making a loud hissing, roaring, and rattling noise. At several places houses were carried out to sea, and in some areas even large rocks and blocks of concrete were carried out onto the reefs. Sand beaches were strongly eroded by the outgoing water. People and their belongings were swept to sea, some being rescued hours later by boats and life rafts dropped from planes.

At a few places, generally but not exclusively on the sides of the islands away from the wave origin, the first wave was reported to have been the highest. At those places, the rise was generally of the quiet sort. There are, however, no instrumental records showing the first wave to have been the highest, and it is possible that at places reporting the first wave as the highest, earlier waves may have been overlooked. Much more generally the third or fourth wave was reported to have been the highest and most violent. The third crest was the largest at the Honolulu tide gage (Fig. 2). At other localities the sixth, seventh, or eighth waves were said to have been the highest. At Waimea River, Kauai, the sixth crest was higher than any other, both in absolute level and in its height above the preceding and succeeding troughs.

In general, if not everywhere, the size and violence of the waves increased to a maximum with the third to eighth waves. The oscillations then gradually decreased in amplitude over a period of at least 2 days, but with occasional waves which were larger than those just before and after them. Such temporary increases in wave height probably resulted from mutual reinforcement by the essentially simultaneous arrival, in phase, of waves which had traveled different paths, or from the coincidence of tsunami waves with storm waves or seiche oscillations.

Measures of the height of the waves approaching shore in shallow water, but before they dashed up on shore, are poor. At Kawela Bay, Oahu, Shepard estimated the height of the waves advancing across the reef to have been as much as 18 feet, and observers estimated the height of the waves crossing the reef off Lanikai, on Oahu, to have been about 7 feet. Photographs taken at Hilo show the top of the breakers to have been 25 feet above the normal bay surface where they struck Cocoanut Island, but the waves may have increased considerably in height in crossing the breakwater, and the effect of dashing up on the shore was probably already present, further exaggerating the height. Photographs of some of the late waves at the mouth of the Wailuku River, in Hilo, show them to have been 6 to 8 feet high (Plate 8), and early waves undoubtedly were higher. In general, these heights correspond fairly closely with the measured heights to which the water dashed on the shore at those localities. At any rate it appears clear that the waves not only slowed down, but increased in height on entering shallow water. George Green (1838: 457–462) states that the wave height varies inversely as the fourth root of the depth of the water.

Most observers reported the first movement on Hawaiian shores to have been a withdrawal of the water. However, the only available instrumental records, at Honolulu and Waimea, both indicate the first movement to have been a rise. The instrumental records are probably more reliable than the reports of untrained observers. The initial rise at Honolulu was small (Fig. 2), and a similar small rise at other localities may easily have been overlooked. Certainly it would have been less impressive than the large withdrawal of the water from shore as the succeeding trough approached. It is interesting to note that the records of tide gages along the coasts of North and South America obtained by C. K. Green (1946: 497) all show the initial movement to have been a rise, with amplitude of about one third that of the ensuing trough.

HEIGHTS REACHED BY THE WAVES ON HAWAIIAN SHORES

Measurements of high-water marks have been made around the shores of all five major islands of the Hawaiian group. The measured heights are shown on Fig. 3 to 7. All heights are stated in feet above lower low water. At each point sea level was estimated, the height of the high-water mark above that level was measured by means of hand level or steel tape, and the measurement reduced by means of tide tables to height above lower low water. Some inaccuracy undoubtedly has entered in the estimation of mean sea level, but it is believed that the heights are probably accurate to within 1 foot. The levels measured include: points indicated by eyewitnesses as the upper limit of the water, lines of flotsam or swash marks, the upper limits of soil and vegetation scouring, levels of consistent scratching and barking on trees, and the upper level of staining on the walls of buildings.

The measured heights of high-water marks range from 55 feet at Pololu Valley

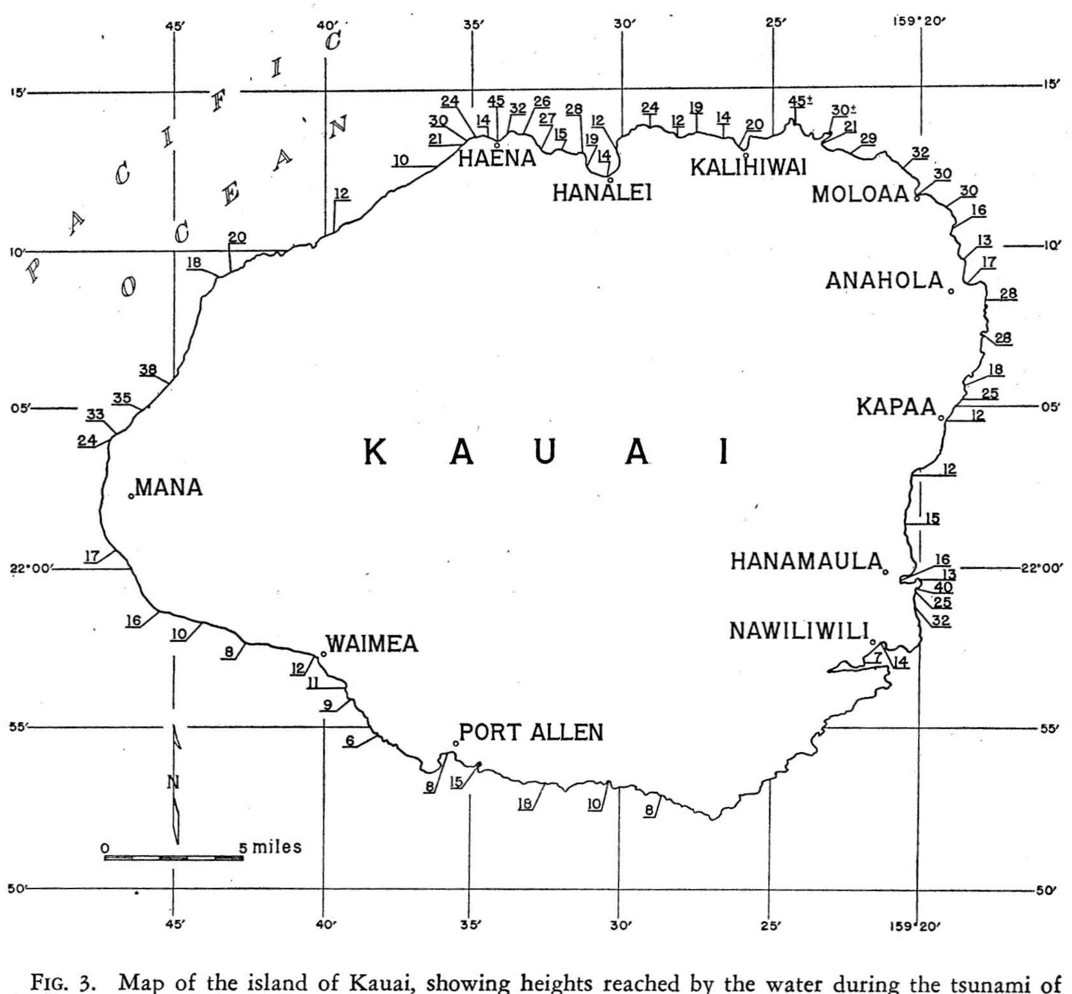

FIG. 3. Map of the island of Kauai, showing heights reached by the water during the tsunami of April 1, 1946. Heights are in feet above lower low water.

on Hawaii, 54 feet at Waikolu Valley on Molokai, and 45 feet at Haena and Kilauea Point on Kauai, to 2 feet at Kaunakakai on Molokai, 2 feet at Milolii and Hoopuloa on Hawaii, and less than 2 feet at the head of Kaneohe Bay on Oahu. Causes of the variations in height will be discussed in a later section.

Most of the heights measured are, of course, not the heights of the actual waves, but rather the heights to which the water was driven on shore. On a vertical cliff directly across the path of the wave, this height may theoretically amount to twice the height of the actual wave. On slopes less than vertical, or on cliffs at an angle to the direction of wave advance, it should be somewhat less than twice the wave height. This measure represents the height of dash of solid water, but very abundant spray may be thrown much higher. Moreover, storm waves riding on the crest of the broader swells of the tsunami undoubtedly added in places to the height to which water dashed on shore. There are places where normal trade-wind waves are flung to a height nearly as great as that reached by the tsunami, and many places, particularly on shores facing away from the origin of the tsunami, where waves of heavy storms reached appreciably higher than did the waves of the tsunami.

It is not possible to make reliable estimates of the magnitudes of these complicating factors, as there are too many unknown elements involved. However, it is probable that most of the water heights recorded for the tsunami on the northern and eastern sides of the islands were appreciably increased by these factors.

FACTORS INFLUENCING THE HEIGHTS AND INTENSITIES OF THE WAVES

It may be assumed that the size and speed of the waves approaching the islands from the open ocean to the north were essentially the same throughout the length of the Hawaiian Archipelago. Differences in height reached by the water and in violence of wave attack along Hawaiian shores must be attributed to local influences modifying the size and behavior of the waves.

The factors found to have affected the height and intensity of the waves during the tsunami of April 1, 1946, are:

1. Orientation of the coast line with respect to the point of origin of the tsunami.
2. Shape of the island.
3. Exposure to storm waves.
4. Submarine topography.
5. Presence or absence of reefs.
6. Configuration of the coast line.
7. Merging of waves from different directions, or of different types.

Orientation of the coast line with respect to the point of origin of the tsunami.—In general, the heights reached by the water were greatest on the sides of the islands facing the origin of the waves, and lowest on the sides away from the wave origin. This is evident from even a cursory inspection of the maps (Fig. 3 to 7). Heights average consistently greater on the northern than on the southern sides of the islands. All the extreme heights were measured on the northern or northeastern sides. Conversely, most of the lowest figures were found on the southern and southwestern sides. It appears almost self-evident that this should be so. Waves striking northern shores retain their full force, whereas the refracted waves striking southern shores suffer a diminution in force and height. This effect is discussed for wind waves in *Breakers and surf* (U. S. Navy Hydrographic Office, 1944: 12–13). No wave can be refracted or reflected without losing some of its force.

Shape of the island.—Waves were refracted around circular or nearly circular islands much more effectively than around angular or elongate islands. This fact had a marked effect on the height and violence of waves on the southern shores. Thus the water reached considerably greater heights along the southern coast of the nearly round island of Kauai (Fig. 3) than along the southern coast of the angular and elongate island of Molokai (Fig. 5), even though the heights along the northern coast of Molokai were on the average perhaps a little greater than those on the northern coast of Kauai. The contrast between the very high average height on the northern coast of Molokai and the very low average height on the southern coast is greater than that between the two sides of any other island, although the difference between the extreme highs and lows is almost exactly the same as on the island of Hawaii (Fig. 7).

Exposure to storm waves.—At the time of the tsunami, large storm waves had been running for several days. As already pointed out, these storm waves riding in on the backs of the broad swells of the tsunami in places undoubtedly increased the height to which the water dashed on shore. Moreover, in other places, where the rise in water level due to the tsunami was gentle, storm waves on top of the tsunami were responsible for much of the damage. The generally greater violence of the waves on the windward (northern and northeastern) coasts as compared to that on the leeward coasts may have been in considerable part the result of the large storm waves which were driving in on the windward coasts. Places on the wind-

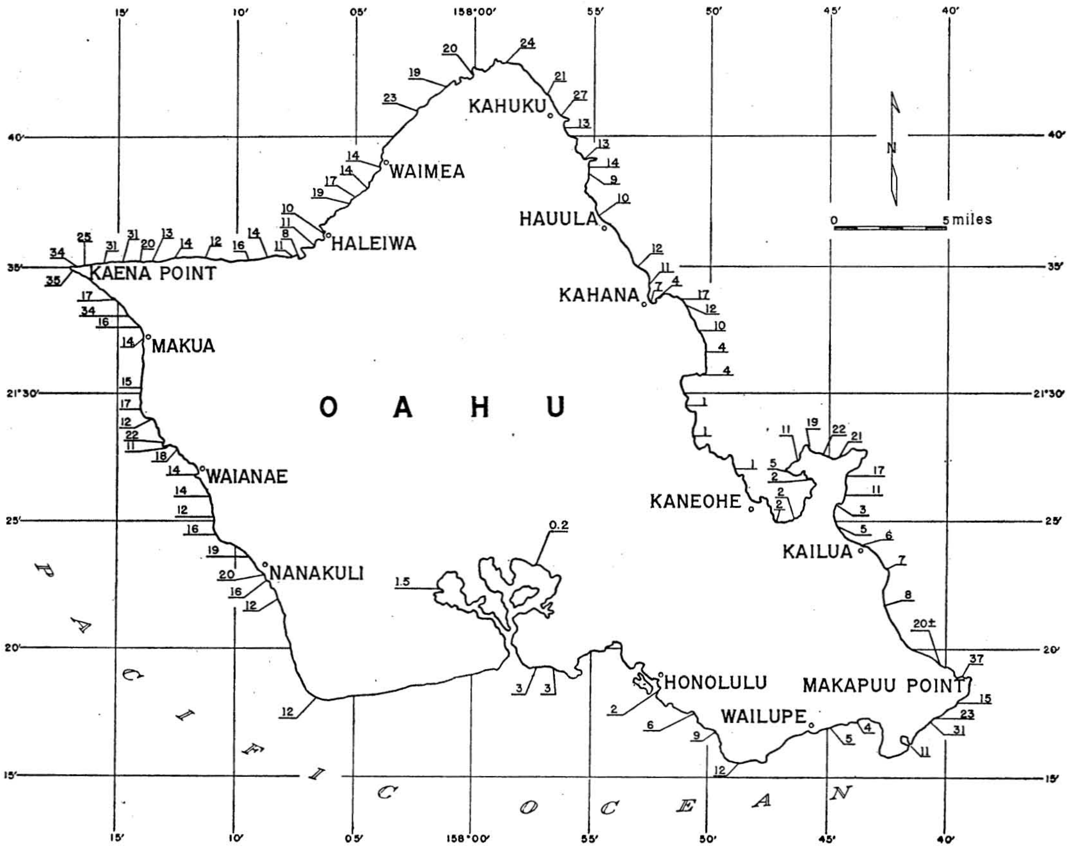

FIG. 4. Map of the island of Oahu, showing the heights reached by the water during the tsunami of April 1, 1946. Heights are in feet above lower low water.

ward coasts which were sheltered from the storm waves also experienced less violent waves. Thus at Kalaupapa, on the sheltered side of the peninsula on the windward side of Molokai, both photographs and the testimony of observers indicate that the rise of 25 feet caused by the tsunami was not violent. On the windward coasts, much of the rapid variation in intensity of wave attack may have resulted from the caprice of storm waves.

Submarine topography. — Owing to their great wave length, the waves were somewhat affected by the ocean bottom throughout their course. However, the effect of the bottom increased greatly as the waves moved into shallow water, and caused a slowing of the wave, an increase in its height, and a steepening of its front. A direct evidence of the increase in height of the waves in shallow water was afforded by the lesser heights reached by the water at the ends of certain peninsulas projecting into deep water and not prolonged seaward by pronounced ridges, as compared with the heights on adjacent shores rising from shoal water. Thus at the end of Kalaupapa Peninsula, on the northern coast of Molokai (Fig. 5), the water dashed only 7 feet above normal sea level, distinctly less than do the waves of ordinary storms; whereas on the coasts rising from shoal water both east and west of the peninsula, the water swept up to heights of 30 to 54 feet. At the end of Keanae Peninsula, on the northern coast of Maui (Fig. 6), the tsunami reached heights only a little greater than large trade-wind waves.

Submarine ridges and valleys, particularly those pointing toward the wave source, were of great importance in their effect on the strength of the waves. The best examples of the effect of ridges are found on the northern coast of Kauai. A long ridge extends in a direction slightly west of north from Haena, to a depth of about 8,000 feet (Plate 2). Another extends northeastward from Kilauea Point, to even greater depths. The greatest heights (45 feet) reached by the water on the shores of Kauai were at the heads of these two ridges (Fig. 3). Another ridge extending northwestward from the western coast of Kauai is probably responsible for heights of 35 to 38 feet at its head. Long ridges projecting from Kaena and Kahuku Points on Oahu similarly caused an increase in wave heights there as compared to the heights on both sides (Fig. 4). The ridges projecting eastward north of Hilo Bay and at Cape Kumukahi on Hawaii had, on the other hand, no such pronounced

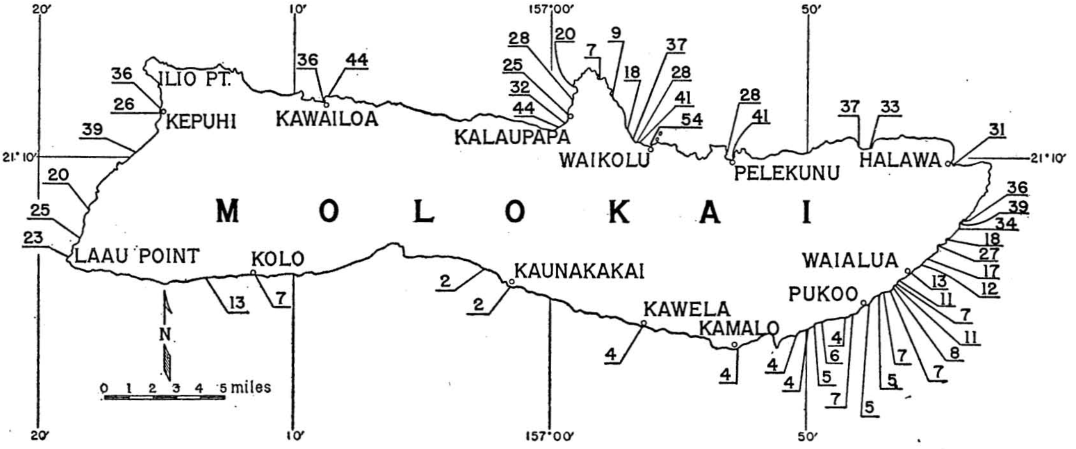

FIG. 5. Map of the island of Molokai, showing heights (in feet above lower low water) reached by the water during the tsunami of April 1, 1946.

effect on the heights at their heads; but it should be noted that they extend across the general direction of wave advance, not toward it.

The greater heights reached by the water at the heads of submarine ridges are not difficult to explain. The ridge has a greater effect in limiting the movement of water particles in the advancing wave than does the deeper water alongside it. Consequently the portion of the wave over the ridge is retarded more than that away from the ridge, and the wave front becomes bent, with its concavity directed toward the ridge head. The result is a focusing of wave force on the shore at the head of the ridge (U. S. Navy Hydrographic Office, 1944: 13).

Similarly, in moving toward shore along the axis of a submarine valley, the part of the wave in the deep water along the valley axis moves faster than that in shallower water on the two sides. In consequence the wave front becomes bent, with its convexity toward the valley head. In the vicinity of the valley head the force lines (orthogonals) of the wave are diffused or spread apart, and over any unit area the force of the waves striking shore is greatly decreased.

An example of the effect of a submarine valley in lessening the force of the waves at its head is found at Kahana Bay, on Oahu (Fig. 4). There the waves dashed to heights of 11 to 17 feet on the coasts north and south of the bay, but reached heights of only 4 to 7 feet in the bay itself. A small submarine valley extends 2 miles northeastward from the bay, to a depth of 150 feet. An example on a much larger scale is af-

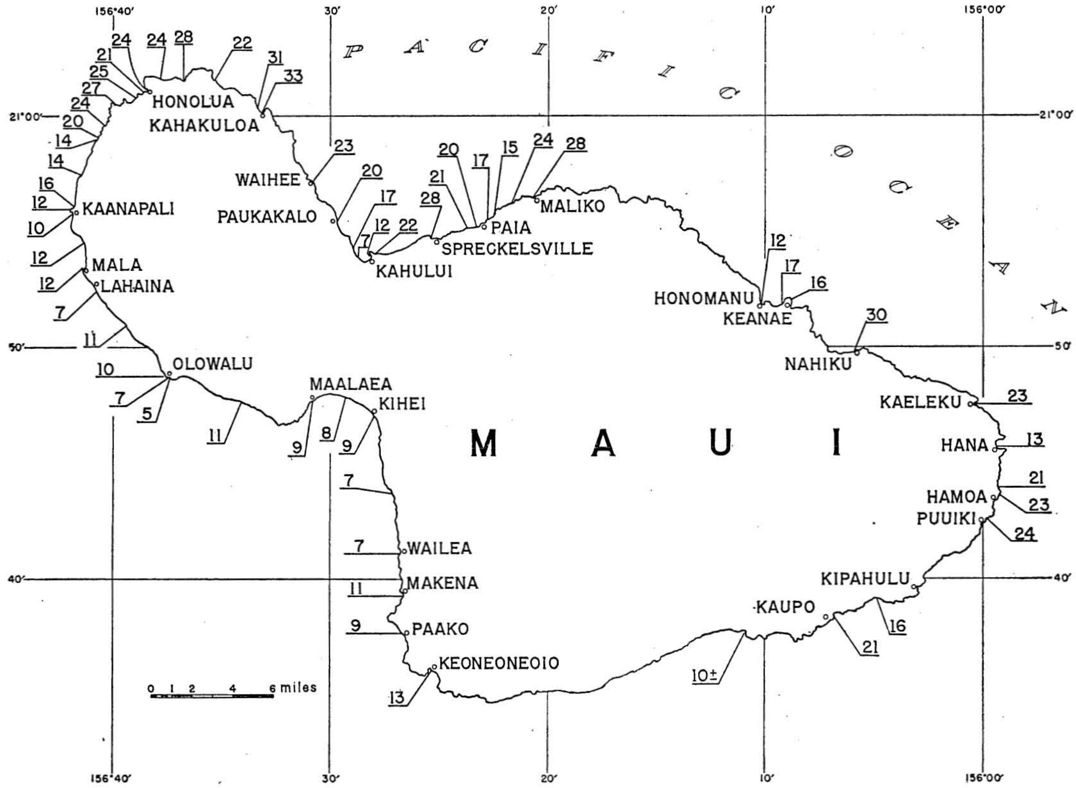

FIG. 6. Map of the island of Maui, showing heights (in feet above lower low water) reached by the water during the tsunami of April 1, 1946.

forded by the zone of small heights along the northwestern shore of Kauai (Fig. 3), at the head of a broad swale extending outward to oceanic depths. The broad valley-like depression off the eastern coast of Hawaii south of Hilo Bay probably also was somewhat effective in reducing the heights reached by the water along that coast. Although fairly great, ranging from 16 to 19 feet, the heights there are not much greater than those reached by ordinary storm waves.

Presence or absence of reefs.—The presence of a well-developed fringing reef appears to have had a decided effect in reducing the intensity of wave onslaught. Along the reef-protected northern coast of Oahu the heights reached on shore by the waves were on the average decidedly less than on the unprotected northern coasts of Molokai and Hawaii, or on the less protected northern coast of Kauai. The best-developed coral reef in the Hawaiian Islands fills Kaneohe Bay on Oahu, where it has a width of about 3 miles. Despite the fact that the broad mouth of Kaneohe Bay is open to the north and northeast, the tsunami produced a rise in water level at the bay head which was so small as to be hardly perceptible to observers, and, so far as could be determined, nowhere exceeded 2 feet. Along the shore north of the bay the heights ranged from 4 to 10 feet, and on the end of Mokapu Peninsula southeast of the bay the heights reached more than 20 feet (Fig. 4).

The lesser heights along the southern shore of Molokai were probably partly due to the wide protecting reef. The effect of the reef in reducing wave violence along that shore is well shown at places where channels cross the reef. There 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, damaging houses, whereas just east and west of this channel the water rose only 7 to 8 feet.

Configuration of the coast line.—It is generally considered that the effects of tsunamis should be intensified near the heads of V-shaped embayments. Such embayments greatly increase tidal fluctuations, as in the Bay of Fundy, and might be expected to act likewise on the similarly long waves of a tsunami. Imamura (1937: 125–127) states that as such a wave rolls up a V-shaped embayment its height increases in inverse ratio to the width and depth of the bay, and cites examples of such increases in height of the waves toward the bay head during Japanese tsunamis. Consequently, special search was made for this phenomenon in funnel-shaped bays on Hawaiian shores. No good examples could be found. Hilo Bay would appear to be an almost ideal site for such funneling, but measurements around its shores show no systematic increase in heights toward its head (Fig. 7 and Plate 1). Similarly there was a lack of increase in heights toward the head of the broad V-shaped embayment on the northern coast of Maui. Possibly the extreme height of 54 feet at Waikolu Valley, on the northern shore of Molokai, may have been partly the result of funneling between Kalaupapa Peninsula and the point and small islands just east of the mouth of the valley. At both Pololu Valley on Hawaii and Pelekunu Valley on Molokai, the water level was higher at the bay head than on the walls of the bay part way out. However, at Pololu Valley, and probably also at Pelekunu, this level was the result of a local upsurge where the waves crossed the beach. Conversely, several bays were found in which the heights reached by the water were less at the bay head than near its mouth.

Several small steep valleys, debouching into small bays, were found in which the water rose to appreciably greater heights along the valley axis than on the sides near the bay mouth or opposite the beach. Thus,

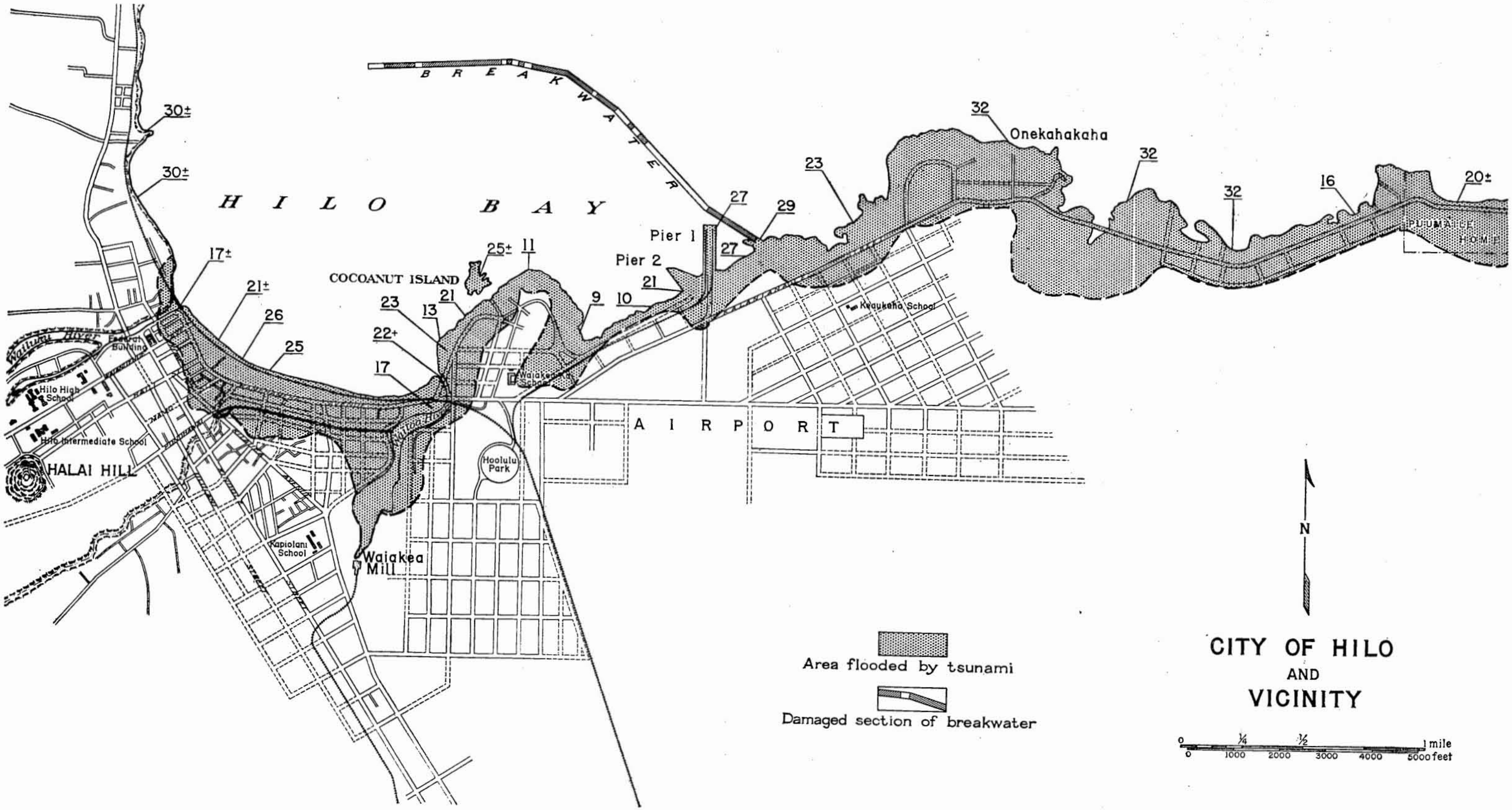

PLATE 1. Map of the Hilo area on the island of Hawaii, showing the heights reached by the water, the area of flooding, and the portion of the breakwater destroyed (shaded portions) during the tsunami of April 1, 1946. Heights are in feet above lower low water.

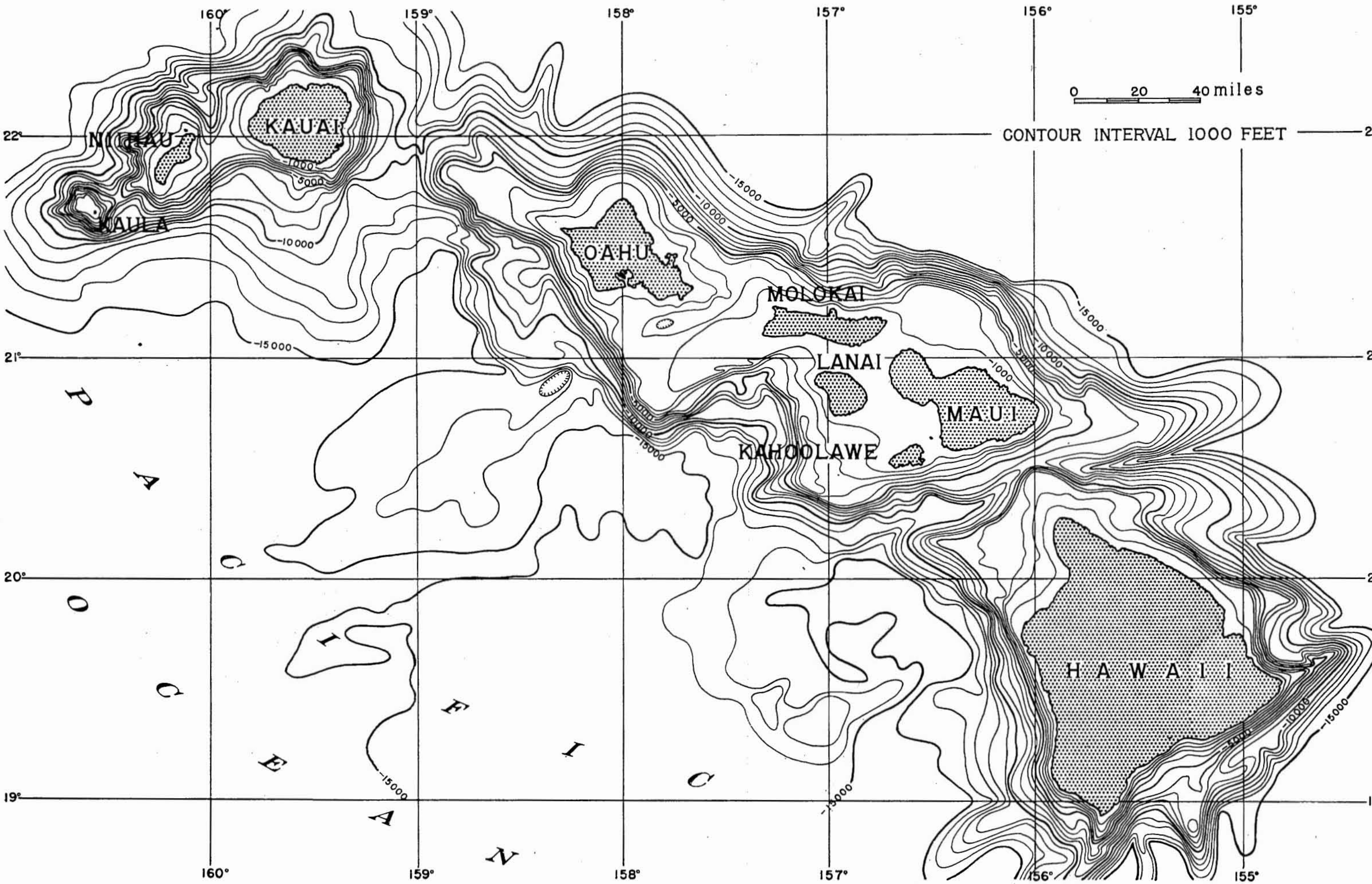

PLATE 2. Map of the Hawaiian Islands, showing submarine topography (after H. T. Stearns).

PLATE 3A. Wreckage left by the tsunami along Kamehameha Avenue, Hilo. Buildings on the left-hand (seaward) side of the street have been pushed into the street, some more or less intact, others as heaps of debris. Photo by Francis Lyman.

PLATE 3B. House in Keaukaha, east of Hilo, carried inland about 100 feet by the waves. The house in the background was above the reach of the water. Photo by G. A. Macdonald.

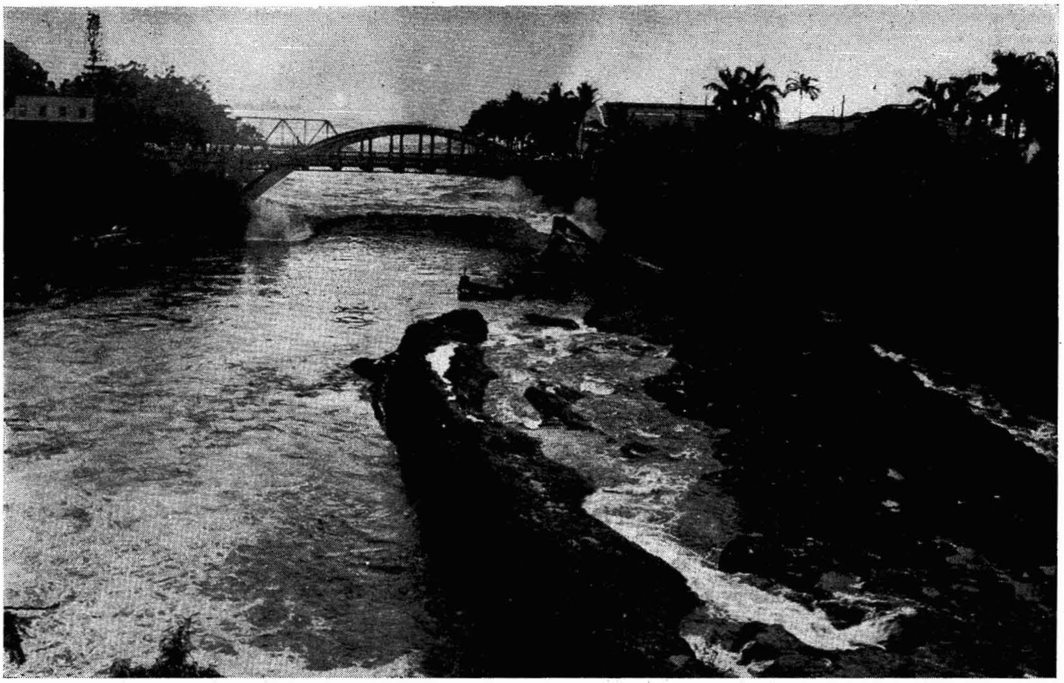

PLATE 4A. Mouth of the Wailuku River at Hilo, showing the advance of one of the later waves into the river mouth. Photo taken near the trough between two waves, showing very low water, and the waves starting up the river as the next crest approaches. The steel span from the distant railroad bridge is visible in the middle distance. Photo by Francis Lyman.

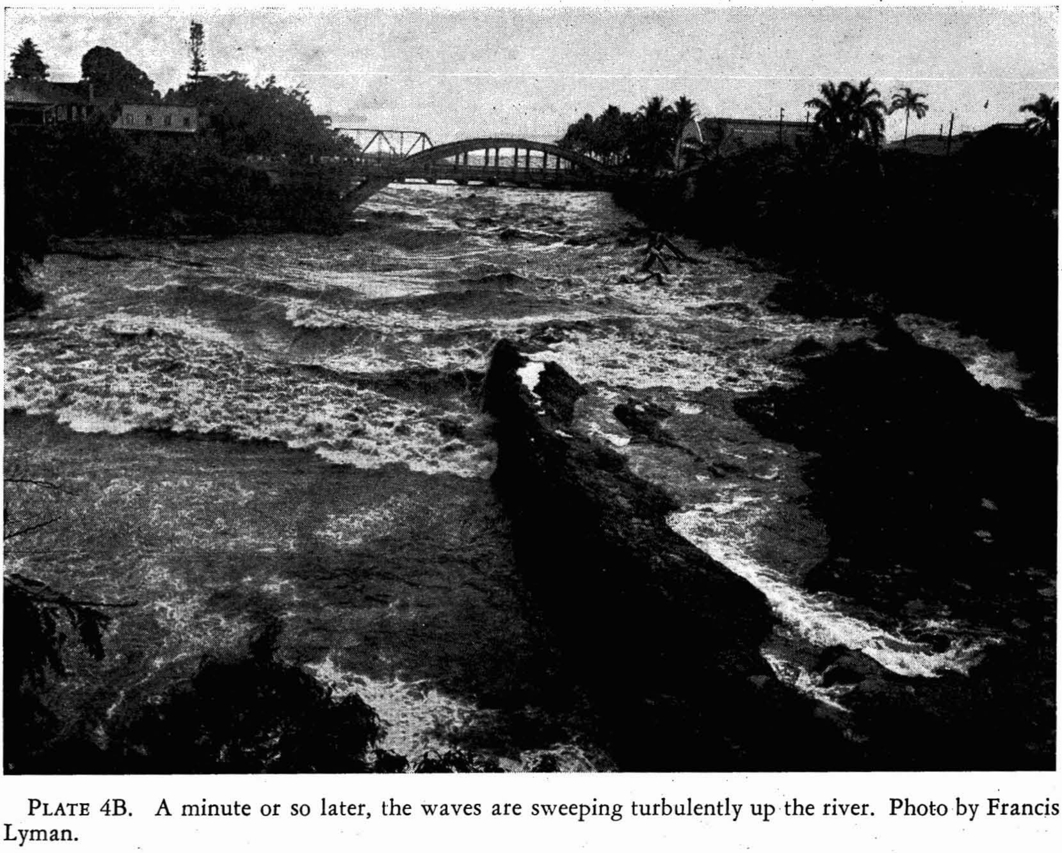

PLATE 4B. A minute or so later, the waves are sweeping turbulently up the river. Photo by Francis Lyman.

PLATE 5A. The very high stage of the water, in Wailuku River at Hilo, reached 3 or 4 minutes later than the stage shown in Plate 4B. Photo by Warren Flagg.

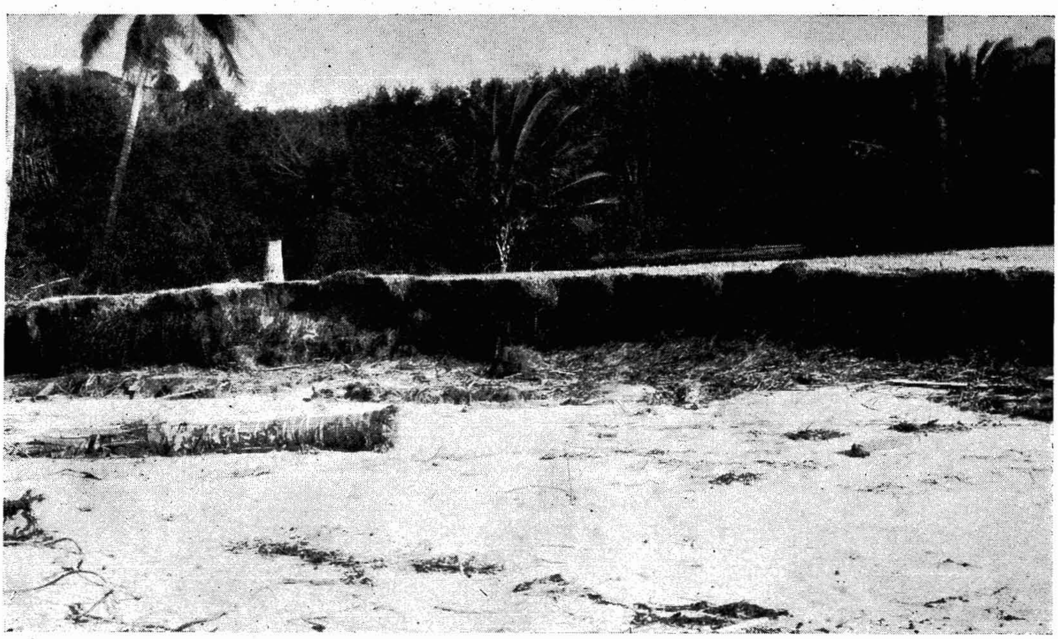

PLATE 5B. Scarp 5 feet high cut by the tsunami at the head of the beach at Moloaa, Kauai. The roots were exposed by removal of the enclosing soil. Photo by G. A. Macdonald.

PLATE 6A. Railroad track swept inland from its bed at Waialee, Oahu. Photo by U. S. Navy.

PLATE 6B. Coral heads thrown up on the beach at Kaaawa, Oahu, by the tsunami. Photo by G. A. Macdonald.

PLATE 7A. Grove of pandanus trees pushed over, and blocks of coral thrown up on the shore platform by the tsunami near Haena, Kauai. Photo by F. P. Shepard.

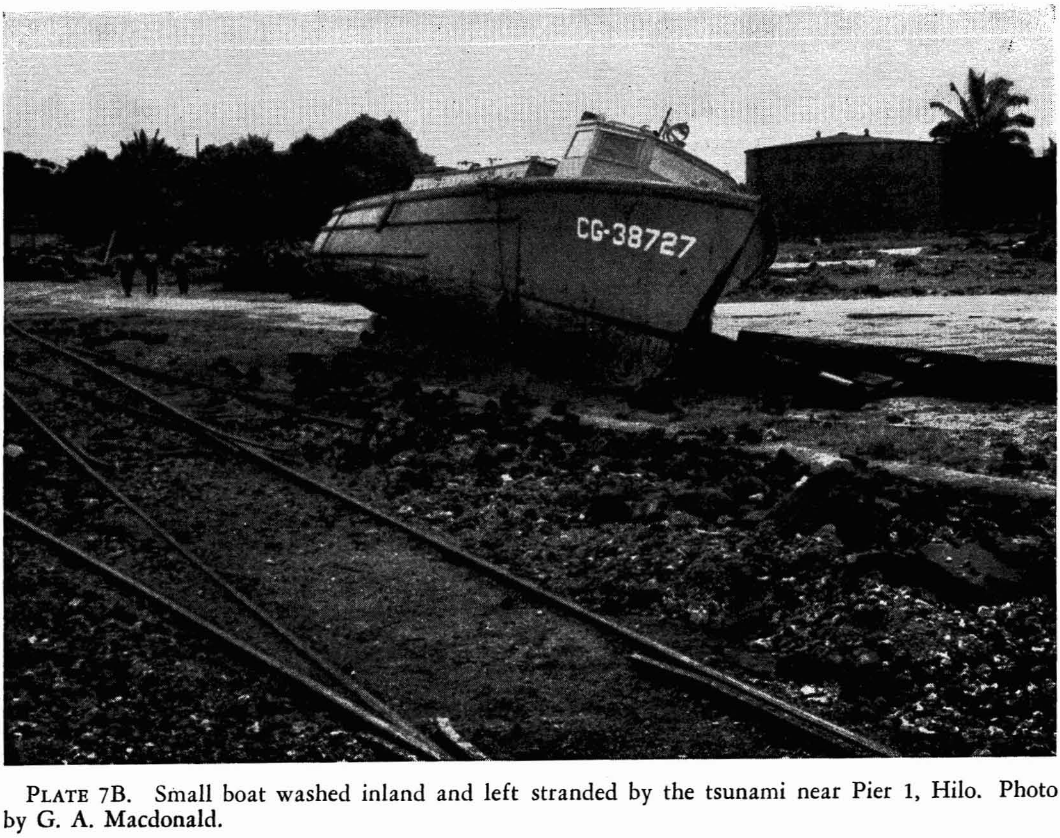

PLATE 7B. Small boat washed inland and left stranded by the tsunami near Pier 1, Hilo. Photo by G. A. Macdonald.

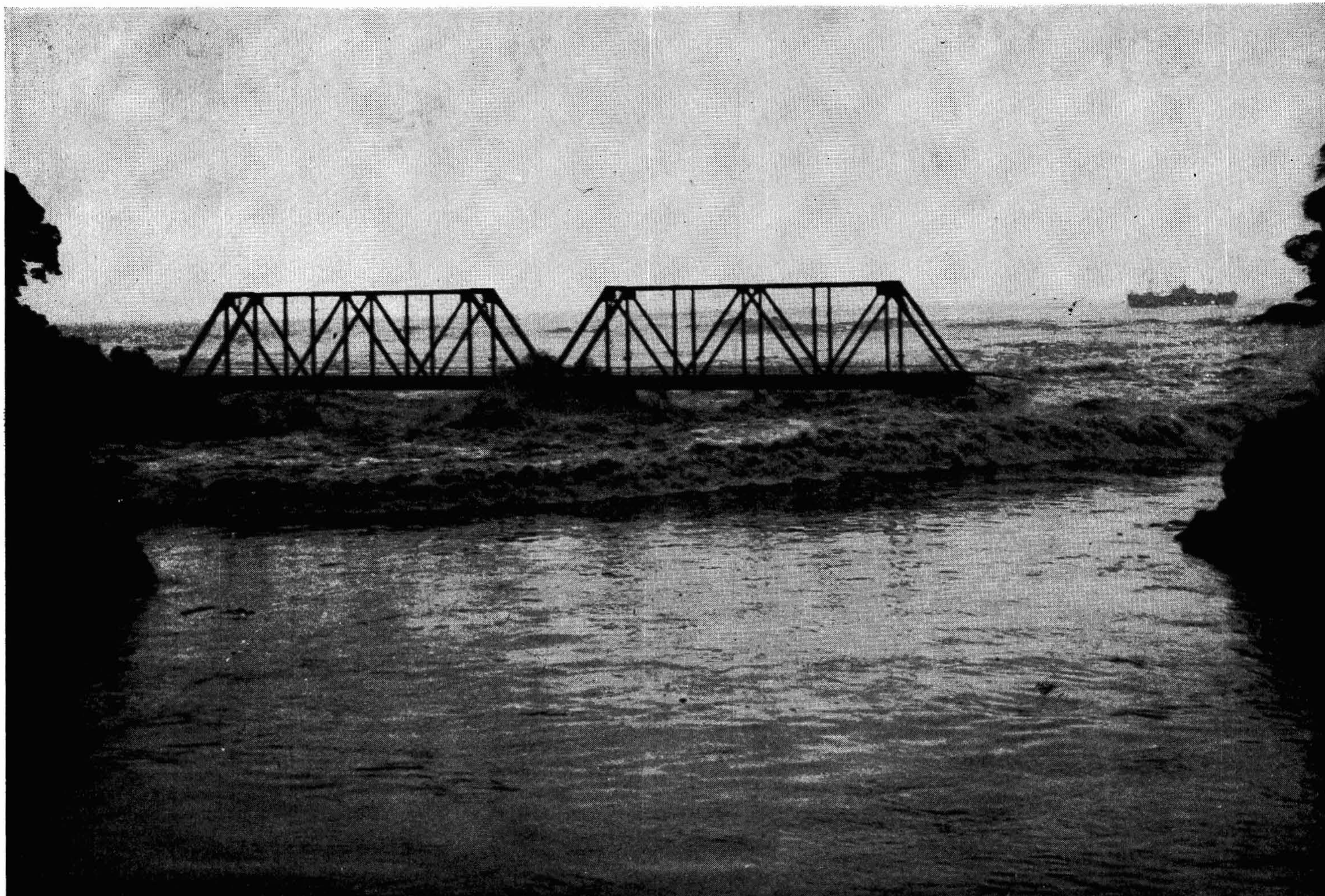

PLATE 8. Bore advancing past the railroad bridge at the mouth of the Wailuku River, Hilo. Note the steep front, the turbulence of the water behind it, and the placidity of the water in front of it. Photo by Shigeru Ushijima.

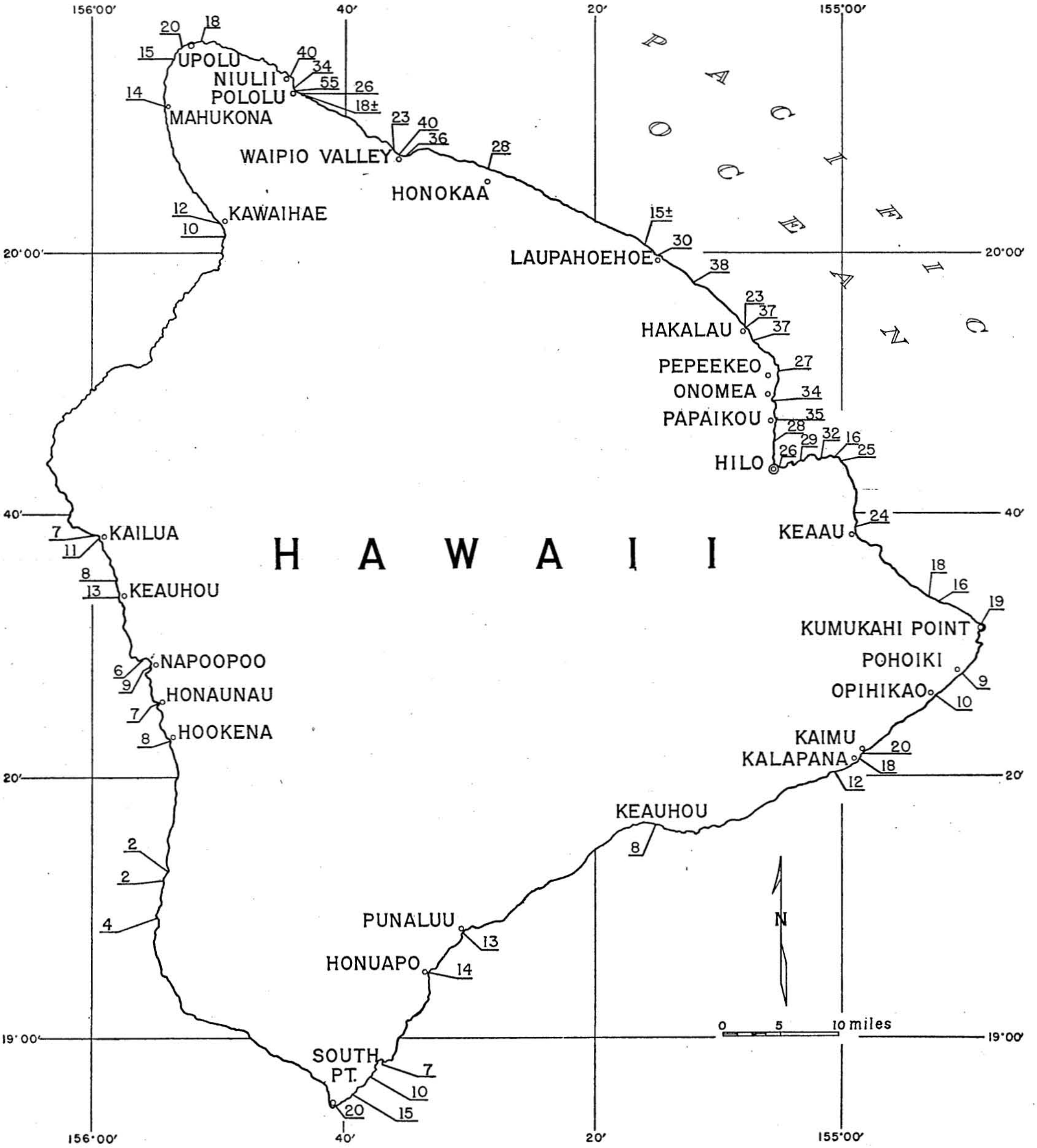

FIG. 7. Map of the island of Hawaii, showing heights (in feet above lower low water) reached by the water during the tsunami of April 1, 1946.

in the small bay just south of Hanamaulu Bay, on the eastern shore of Kauai, the water rose only 25 feet on the bay sides, but swept up the small valley at its head to a height of 40 feet. At Moloaa, on Kauai, the water reached an altitude of 40 feet in the axis of the valley, but only 30 to 35 feet on the bay walls. Again, at Honouliwai, on Molokai, the water reached a height of 27 feet opposite the beach, but went 6 feet higher up the valley. These are merely specialized examples of effect, upon the rush of water up on shore, of a topography above sea level which served to concentrate the inrushing water.

Merging of waves from different directions.—Wave crests traveling by different routes may arrive at a given locality simultaneously, giving rise to a wave of greater size than either. Likewise, the simultaneous arrival by different routes of a wave crest and a wave trough may effectually cancel out both. Thus, variations in the size and intensity of waves, particularly on the sides of the islands away from the wave origin, may result from the arrival, either in or out of phase, of two wave trains. During the tsunami of 1946 several examples of the formation of a large wave by the juncture of two smaller ones were observed. Thus, in the Keaukaha area east of Hilo, witnesses described the arrival of a wave from the north simultaneously with one from the northeast, which built up a very high crest at the place of juncture. At the head of Maunalua Bay, on the southeastern shore of Oahu, two waves were seen to advance up channels across the wide reef, move toward each other parallel with the shore, and meet, throwing water upward like the spray from a geyser. The water dashed up 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.

Progressively southward around the shores of Kauai, the average height of the high-water marks gradually decreases, and along much of the southern shore it is 6 to 12 feet above sea level. However, in a zone 3 or 4 miles wide it ranges from 15 to 18 feet. This zone is almost directly across the island from the direction of wave origin, and probably represents the area in which the waves refracted around opposite sides of the island met and reinforced each other.

DAMAGE BY THE TSUNAMI

Damage by the tsunami can be divided into structural damage, damage by erosion and deposition, and damage by flooding. The total property damage has been estimated by the office of the Governor, Territory of Hawaii, at about $25,000,000. Space permits only a brief review of the types of damage. The numbers of dwellings destroyed and damaged by the tsunami on the major islands are listed in Table 2 on page 36.

Structural damage includes damage to buildings, roads, railroads, bridges, piers, breakwaters, fishpond walls, and ships. Frame buildings at low altitudes along Hawaiian shores suffered extensive damage. Some were knocked over, by the force of the waves, by cutting away of the sand on which they stood, or by destruction of the foundations. Others were bodily washed away from their foundations. Some had walls pushed in by the force of the water, and in a few residences the water went on through the house and took out the opposite wall. As with earthquakes, there was a tendency to reduce the few two-story buildings to a single story, by destruction of the lower story. It is noteworthy that houses which were well built and tied together internally could be moved for considerable distances without suffering severe damage. Even more striking was the fact that houses elevated on stilts a foot to several feet above the ground survived the waves much more effectively than did those built directly on the ground. Apparently the water was able to pass under such houses without greatly disturbing them, unless it was deep enough actually to float the house off the stilts. The few reinforced concrete structures in devastated areas suffered little or no damage except that caused by flooding.

The railroads along the northern coast of Oahu and in Hilo were wrecked, partly through destruction of the roadbed, but largely because the tracks were shifted off the roadbed, either inland or shoreward. Locally rails were torn loose, but more generally the track was moved en masse, a motion probably aided by the buoyancy of the ties. Coastal highways also were partly destroyed, largely by undercutting as the water returned seaward, but partly by the direct force of the waves. Several highway and railway bridges were destroyed. Most appear to have been partly or entirely lifted from their foundations by the rising of the water under them. The head of the pier at Waianae, Oahu, was damaged in the same manner. At the Wailuku River, in Hilo, an entire span of the steel railroad bridge was torn loose and carried 750 feet upstream, passing under but not damaging a highway bridge. At Kolekole Stream, 11 miles farther north, an entire leg of the high steel railroad trestle was removed and carried upstream about 500 feet.

Part of the end and much of the shed of Pier 1 in Hilo was wrecked by the force of the wave. Most of the damage on Pier 2, however, resulted when heavy pontoons, which had been moored near by, were washed across the pier. The wharves at Kahului on Maui were flooded, but sustained little structural damage.

The upper part of the breakwater at Hilo was about 61 per cent destroyed (Plate 1). Blocks of rock weighing more than 8 tons were lifted off the breakwater and dropped both inside and outside it. Destruction was limited, however, to the part above water or that only slightly submerged. The average depth of water over the destroyed sections after the wave was only about 3 feet. The breakwater at Kahului, Maui, also suffered minor damage. At both Hilo and Kahului the breakwaters appear to have reduced materially the height and violence of the waves in the enclosed portions of the harbors.

Many small boats were washed ashore and damaged. Railroad cars were overturned on Oahu, Maui, and Hawaii. Many automobiles were wrecked. The loose stone walls of fishponds along the southern coast of Molokai were partly thrown down. The mill of the Hakalau Sugar Company, situated only about 10 feet above sea level at the mouth of Hakalau Gulch on the island of Hawaii, suffered severe damage.

Erosion by the tsunami resulted in the partial removal of some sand beaches, in some places causing a retreat of the shore line for several tens of feet, cutting of small scarps, and forming of large beach cusps at the heads of beaches; locally, erosion caused stripping away of a small amount of soil. The erosion was largely concentrated high on the beach, several feet above sea level. Some of the sand from the beaches was carried inland and redeposited. At Haena, Kauai, the highway was buried under 4 feet of sand, and thinner layers of sand covered roads on Oahu.

Flooding caused much water damage to house furnishings and personal property.

LOSS OF LIFE AND PERSONAL INJURY

The following table summarizes, by islands, the number of persons killed, injured, or missing as a result of the tsunami. The figures were supplied by the American Red Cross. Most of the deaths were by drowning. By far the heaviest toll was at Hilo, with 83 known dead and 13 missing. Those listed as missing have been missing for more than 2 months, and must be presumed dead, bringing the total number of probable dead to 159. Great as it was, this loss of life was moderate compared to that in some other tsunamis, such as that of 1896 in the Sanriku district in Japan, which took more than 27,000 lives (Byerly, 1942: 72).

TABLE 2

LIST OF CASUALTIES DURING THE TSUNAMI OF APRIL 1, 1946

ISLAND	KNOWN DEAD	MISSING	INJURED*	HOMES DEMOLISHED†	HOMES DAMAGED†
Hawaii	87	34	153	283	313
Maui	9	5	2	65	144
Oahu	9	0	0	67	335
Molokai	0	0	0	13	14
Kauai	10	5	8	60	130
Total	115	44	163	488	936
	159				

* Injury sufficiently serious to require hospitalization.
† Homes only; other buildings not included. Data from Lewers and Cooke, Ltd.

MITIGATION OF DISASTERS RESULTING FROM FUTURE TSUNAMIS

There is no Hawaiian shore which is exempt from tsunamis. The most likely sources of devastating tsunamis are the North Pacific and South America. The areas heavily hit by the 1946 tsunami are probably those most likely to be hit hard again by tsunamis from the North Pacific. Violent tsunamis from Central or South America might, however, cause much more damage than did the 1946 tsunami along eastern and southern coasts. There is also possibility of serious damage on western shores by a tsunami from Japan, particularly if the tsunami occurred during a heavy southwesterly storm. Tsunamis of local origin might do heavy damage on any shore.

It is obviously impractical to consider the removal of all dwellings from Hawaiian shores because of the danger from tsunamis. It might, however, be advisable to prevent or restrict building in certain areas of greatest danger, particularly in centers of heavy population, such as the waterfront at Hilo. Construction of suitable sea walls might also be advisable in places. Sea walls cannot, however, be built high and strong enough to hold the water back completely, and an open zone should be left back of the wall in which the water pouring over the wall can use up its energy in turbulence. Any construction permitted in such areas should be of a wave-resistant type, such as reinforced concrete. These wave-resistant buildings would have the added virtue of serving as a line of defense for frailer structures behind them. Frame structures in rural areas should be built up off the ground, and far enough back from the edge of the beach to reduce the danger of undercutting. They should also be properly reinforced and tied together.

It appears inevitable that future tsunamis will cause loss of property on Hawaiian shores, but loss of life from all except tsunamis of local origin could be largely or entirely avoided. A system of stations could be established around the shores of the Pacific and on mid-Pacific islands, which would observe either visually or instrumentally the arrival of large long waves of the periods characterizing tsunamis. The arrival of these waves should be reported immediately to a central station, whose duty it would be to correlate the reports and issue warnings to places in the path of the waves. It should be possible in this way to give the people of the Hawaiian Islands enough warning of the approach of a tsunami to permit them to reach places of safety. The effectiveness of the warning, however, would depend on education of the public on the necessity for leaving areas of danger, and on the efficiency of the local organization in spreading the warning and evacuating the threatened areas. Eventually it should also be possible to state, at the same time, which areas are likely to suffer the most damage. Before that can be done, however, we need more knowledge of the behavior of tsunamis on Hawaiian shores, particularly tsunamis from sources in the eastern and western Pacific, and a more complete picture of the submarine topography around the Hawaiian Islands.

SUMMARY

The tsunami which reached the shores of the Hawaiian Islands on April 1, 1946, was the most destructive in the history of the islands. Generated by a sudden shifting of the sea bottom on the northern slope of the Aleutian trough, the waves traveled southward to Hawaii with an average speed of 490 miles an hour, an average wave length of about 122 miles, and a height over the deep ocean of about 2 feet. Effects on Hawaiian shores varied greatly. Locally the water dashed more than 50 feet above sea level and swept as much as half a mile inland. Elsewhere the rise in water level was very small, and waves were gentle. Property damage was heavy but loss of life was moderate.

The heights and intensities of the waves at different points were influenced by position on the island toward or away from the source of the waves, offshore submarine topography, presence or absence of coral reefs, shore-line configuration, mutual reinforcement or interference by waves traveling different paths, and the presence or absence of storm waves. Loss of property during future tsunamis can be reduced by proper construction, by erection of sea walls, and by restricting or prohibiting construction in certain especially dangerous areas. Loss of life can be nearly or entirely eliminated by the establishment of a suitable system for warning of the approach of waves.

REFERENCES

BODLE, R. R. Note on the earthquake and seismic sea wave of April 1, 1946. *Amer. Geophys. Union Trans.* 27: 464–465, 1946.

BYERLY, PERRY. *Seismology.* x+256 p., 58 fig. Prentice-Hall, New York, 1942.

GREEN, C. K. Seismic sea wave of April 1, 1946, as recorded on tide gages. *Amer. Geophys. Union Trans.* 27: 490–500, 1946.

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

GUTENBERG, BENO, and CHARLES F. RICHTER. *Seismicity of the earth.* 131 p., 17 fig. Geol. Soc. Amer. Spec. Paper 34. New York, 1941.

IMAMURA, AKITUNE. *Theoretical and applied seismology.* 358 p. Tokyo, 1937.

JAGGAR, THOMAS A., JR. Hawaiian damage from tidal waves. *Volcano Letter* 321: 1–3, 1931.

POWERS, HOWARD A. The tidal wave of April 1, 1946. *Volcano Letter* 491: 1–3, 1946.

SHEPARD, FRANCIS P., GORDON A. MACDONALD, and DOAK C. COX. The tsunami of April 1, 1946. [In preparation.]

UNITED STATES NAVY HYDROGRAPHIC OFFICE. *Breakers and surf.* 52 p., 19 fig., 4 pl. U. S. Navy Hydrog. Off. Pub. 234. Washington, D. C., 1944.