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LOCAL TSUNAMIS IN HAWAII— IMPLICATIONS FOR HAZARD ZONING

By
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HAWAII INSTITUTE OF GEOPHYSICS
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ABSTRACT

Determination of tsunami hazard zones is needed in conjunction with various forms of hazard management. The inland boundaries of the hazard zones are usefully defined as the limits to which tsunami inundation may be expected with certain average frequencies. In the National Flood Insurance Program, for example, the coastal high-hazard zone is defined as the 100-year tsunami inundation zone. In that program, the extent of 100-year tsunami inundation has been, or is being, estimated for any coastal site from the 100-year tsunami runup height near the shore at that site. The 100-year runup height at each site has been estimated through frequency analysis of a partly synthetic, site-specific record of the runups of historic tsunamis. The record to which the frequency analyses have been applied does not take into account all available information concerning tsunamis that, with various degrees of certainty, have been locally generated, and the record contains some erroneous local-tsunami runup data.

The local tsunami study of Cox and Morgan (1977) provides a basis for correction. In that study, 19 possible local-tsunami event dates were identified. Along some Hawaiian coasts, or at least at one or more sites, the runups of 14 of the local tsunamis were higher than the lowest historic runups to which the earlier frequency analyses were applied. Information concerning these 14 tsunamis is, then, significant to a revision of the frequency analyses and of inundation limits derived from them.

The runup record is most extensive in the case of the large tsunami generated off the southeast coast of Hawaii in November 1975 and next most extensive in the case of the similar tsunami of April 1868. Through analysis of these records, criteria for estimating the runup profiles of all of the local tsunamis along Hawaiian coasts were developed in this study.

All available historical data were used in estimating runup heights of each tsunami, or at least the limits within which the runup heights probably lay, at various sites. Rules were developed for the use of uncertain or questionable values. Constant log-runup gradients were assumed in interpolation between, or extrapolation from, the sites of available runup values.

The profiles of the 14 significant local tsunamis, reconstructed in accordance with these criteria, are shown in figures in this report, and means are presented for using runup heights read from the profiles in revising the frequency analyses in the National Flood Insurance Program.

TABLE OF CONTENTS

	Page
Abstract	iii
List of Tables	vii
List of Figures	vii
I. INTRODUCTION	1
II. TSUNAMI HAZARD ZONING	3
Rationale and bases	3
Input data requirements	3
Frequency distributions of runup heights	3
Runup heights for selected recurrence frequencies	4
Inundation limit determinations	4
III. PRESENT AND PROPOSED TSUNAMI HAZARD ZONES IN HAWAII	6
Evacuation zones	6
Coastal high hazard zones in National Flood Insurance Program	6
First proposal for Hawaii	6
First proposal for Oahu	7
Present proposal	7
Discussion	7
IV. WES FREQUENCY DISTRIBUTIONS	9
Methodology	9
Reported results	10
Needs for revision	10
V. PURPOSE AND METHODOLOGY OF THIS STUDY	11
Purpose	11
Data considered	11
Tsunami record	11
Significance criterion	13
Coastal regions	13
Runup heights	13
Reconstruction of runup profiles	13
Guidance from major events of April 1868 and of November 1975	17
Ranges of uncertainty and local variations of runup heights	17
Additional runup estimates	17
Limiting runup values	18
Questionable runup values	19
Effects of subsidence	19
General runup patterns on Hawaii	19
General runup patterns on other islands	21
Interpolation	22
Extrapolation	22
Uncertainties in location	24

		Page
	Profiling criteria adopted	24
	Use of historical information generally	24
	Use of geophysical information generally	24
	Plotting positions and scales	25
	Vertical ranges of uncertainty and local detail	25
	Use of limiting values	25
	Use of questionable values	26
	Interpolation, extrapolation, and use of values of uncertain location	26
	Significant runups	28
	Additional estimates of runups	28
VI.	RECONSTRUCTED RUNUP PROFILES	28
	Southeast coast of Hawaii	29
	West coast of Hawaii	31
	Northeast coast of Hawaii	31
	Maui	34
	Molokai	36
	Oahu	38
	Kauai and other islands	40
VII.	SUMMARY AND CONCLUSIONS	41
	Summary of results	41
	Utilization of results	41
	Final comments	43
	ACKNOWLEDGMENTS	44
	REFERENCES	45

TABLES

		Page
1.	Possible local tsunamis in Hawaii	12
2.	Available measurements and estimates of local-tsunami runup heights	14
3.	Runup profile criteria: Southeast Hawaii	29
4.	Runup profile criteria: West Hawaii	31
5.	Runup profile criteria: Northeast Hawaii	34
6.	Runup profile criteria: Maui	36
7.	Runup profile criteria: Molokai	38
8.	Runup profile criteria: Oahu	40
9.	Significance of local tsunami runups in estimating site-specific runup frequency distributions	42

FIGURES

1.	Alternative reconstructions of 1975 runup profile, Kaimu to Ninole, Hawaii	23
2.	Reconstructed local-tsunami runup profiles, Southeast coast of Hawaii	30
3.	Reconstructed local-tsunami runup profiles, West coast of Hawaii	32
4.	Reconstructed local-tsunami runup profiles, Northeast coast of Hawaii	33
5.	Reconstructed local-tsunami runup profiles, Maui	35
6.	Reconstructed local-tsunami runup profiles, Molokai	37
7.	Reconstructed local-tsunami runup profiles, Oahu	39

I. INTRODUCTION

The history, distribution, and generating mechanisms of tsunamis that were or may have been locally generated in Hawaii were discussed in a previous report (Cox and Morgan, 1977). The study reported here was undertaken to put that information into a form useable in tsunami hazard zoning.

Following a discussion of the information needed for tsunami hazard zoning, this report addresses the present and proposed zoning in Hawaii, and the form in which local tsunami information must be put in order to fit into the procedures used to define the hazard zones, particularly those used in the National Flood Insurance Program. The report then describes the methods used to put the local tsunami information in the required form, and gives the results.

Runup profiles of the possible local tsunamis along Hawaiian coasts were reconstructed as well as seemed possible, with interpolation between and extrapolation from the previously available runup values. Although available historical information and geophysical evaluation were used, considerable judgment also was necessary. The criteria for judgment and their rationale are described in detail to indicate that the methods used, though somewhat arbitrary, were reasonable and not capricious, and also to facilitate the investigation by others of the effects of substituting alternative reasonable criteria.

II. TSUNAMI HAZARD ZONING

Rationale and bases

Determination of a tsunami hazard zone may be necessary: (1) in conjunction with a tsunami warning system to indicate from what coastal areas persons should be evacuated; (2) in conjunction with a land-use control system to indicate in what coastal areas uses should be restricted, construction should be prohibited, or special design criteria should pertain; or (3) in conjunction with an insurance system to determine coastal areas of risk.

Establishment of the zone in which waves of any sort, including tsunamis, present a significant hazard depends upon: (1) definition of the average frequency of flooding that is considered intolerable for the use of the land in the zone, and (2) estimation of the distance inland from the shoreline to which flooding will occur with that average frequency. For example, in the National Flood Insurance Program, which provides for federal participation with respect to insurance in conjunction with state or local land-use control legislation, the coastal high-hazard zone is defined as the 100-year tsunami inundation zone (the zone subject to tsunami inundation, on the average, once in 100 years).

There are few historical records of the horizontal limits of tsunami inundation, and irregularities of terrain would result in considerable irregularity in the relationship between inundation and recurrence frequency even at a single coastal site, and great differences in the relationships at different sites. Hence, direct determination of the distance inland to which tsunami inundation may be expected with any selected average frequency is generally impracticable. The extent of inundation expectable in a 100-year period, however, may be determined from the 100-year runup height at the inundation limit, and may be estimated from the 100-year runup height at any other point between that limit and the shoreline. Hence, the frequency distribution of tsunami runup heights—the relationship between tsunami runup height and average recurrence frequency—is of great importance in tsunami hazard zonation.

Input Data Requirements

Frequency distributions of runup heights

The relationship between tsunami runup height and average recurrence frequency, specific to a coastal site, may be displayed as a graph of tsunami runup heights (or some transformation of the heights) plotted against the average frequencies of recurrence of tsunamis with equal or greater heights (or some transformation of the frequencies).

If, with suitable transformations, the plotted points fall close to straight lines, algebraic equations for the best-fit straight lines may be obtained by least-squares regression.

In an investigation of the frequency distribution of the runup heights of tsunamis that had occurred at Hilo, Hawaii in the 137-year period beginning in 1837, for example, Cox (1964) found a negative linear correlation between the runup heights of the larger tsunamis and the logarithms of their expectable recurrence frequencies, in other words that:

$$H = -B - A \log F \qquad (1)$$

where H = runup height

F = expectable recurrence frequency of tsunamis of height equal to or greater than H

A, B = coefficients determinable by least-squares regression.

The frequency distribution model implied by equation 1 is exponential. Other investigators have found that the exponential model fits elsewhere, for example, at San Francisco and Crescent City, California (Wiegel, 1964, 1965); in Japan (Wiegel, 1970); and on the West Coast of Mexico and elsewhere on the Pacific Coast of North America (Rascón and Villareal, 1975).

The exponential model fits distributions at places in Hawaii other than Hilo. Adams (1970) found it to fit the distribution at Kahuku Point, Oahu, but his finding is not really independent of that pertaining to Hilo because runup values for many of the tsunamis were estimated by reference to the Hilo record.

Wybro (1976) found that if the tsunami runups at Hilo, at Kahului, Maui, and at Honolulu, Oahu were normalized as ratios to the respective maximum runups reported in the period of record common to all three localities, the ratios could be described by a common formula. As observed by Cox (1978b), Wybro's finding implies an exponential distribution in which there is but one site-specific coefficient. However, most of the investigations suggest that there are two site-specific coefficients (the A and B coefficients in equation (1)).

To the runup records at Hilo, Kahului, and Honolulu, Wybro (1976) also applied Gumbel's method of analysis, which assumes a double-exponential distribution. The results were not much different from those of a method assuming a simple exponential distribution, and the theoretical basis for assuming the double-exponential distribution may be questioned. Rascón and Villareal (1975) attempted to improve the means of estimation using Baysian statistics, but the additional sophistication of their technique does not seem pertinent to this study.

Solov'ev (1969, 1972) found that, in regions of tsunami generation, the exponential distribution applies to the intensities of tsunamis rather than to their runup heights, and that the distributions are reasonably well described by a single site-specific coefficient. For general tsunami hazard zoning, however, the concern is with the distribution of runup heights on affected coasts rather than the distribution of intensities of tsunamis in generating regions.

In his analysis of the Hilo record, Cox (1964) found that the smaller tsunamis were distributed in accordance with a power law rather than an exponential one. At Hilo, the transition from the power-law to the exponential-law distribution occurred in the frequency range from 0.10 to 0.12 per year and in the height range from 5 feet to 8 feet above sea level. For tsunami hazard zoning, however, it is the larger tsunamis that are of concern.

The question of the best model for the frequency distributions of tsunami runups is not settled. The model represented by equation (1) has been used in the National Flood Insurance Program. Unless and until some alternative is shown to fit better the large runups of low recurrence frequencies that are of greatest significance, it seems best to continue the use of this model in tsunami hazard zoning in Hawaii.

In the use of this model, the values of the site-specific coefficients must be determined by analysis of either (1) the actual long-term historical record of tsunami runup heights at each site or (2) a synthetic record constructed from the long-term historical record of runup heights elsewhere (or of related geophysical parameters) and from quantitative relationships between the parameters in the historical record and the tsunami runups at the site.

<u>Runup heights for selected recurrence frequencies</u>

Once the frequency distribution of runup heights has been determined for a site, the heights to which tsunamis may be expected to rise with any chosen frequency may readily be calculated. For example, if the frequency units used are per year, the 100-year runup height at the site will be, from equation (1):

$$H_{100} = -B - A \log (1/100) = 2A - B \qquad (2)$$

<u>Inundation limit determinations</u>

To determine rigorously the inland limit of inundation of a tsunami at a site where its runup height was known, even in the absence of horizontal convergence or divergence of energy, it would be necessary to know, in addition:

1) The location of the runup height measurement relative to the shoreline;

2) The velocity of the water in the tsunami wave at that location, so that the total energy of the wave at that location could be calculated; and

3) The rate of loss of energy of the wave inland of that location.

From these the energy profile transverse to the shoreline could be determined. The inundation limit would be established as the intersection of the energy profile and the ground profile.

Various simplifying assumptions are necessary in estimating even the inundation of a historic tsunami from a reported runup, and more assumptions are necessary in estimating the maximum inundation expectable with a certain recurrence interval from the maximum runup expectable with that recurrence interval. Cox (1961) simply assumed a standard maximum tsunami wave energy in shallow water offshore and a standard downward inland slope to the energy profile. However, Bretschneider and Wybro (1976) developed a method for estimating a transverse tsunami runup profile from a known runup height and the locus of that runup height, the ground profile, and the roughness that is provided, for example, by vegetation or structures. Their method gives different results depending on whether or not the tsunami inundation was in the form of a bore.

The slope of the surface of the ground may, of course, be determined in the field or estimated from topographic maps.

The runup heights of some historical tsunamis in Hawaii have been measured at the limits of inundation. Often, however, they were measured closer to the shoreline. At least since 1946, according to Cox (1977), runup heights were ordinarily measured about 200 feet inland from the shoreline and, in the absence of contrary information, not only the runup heights of historic tsunamis at a site but also the runup height associated with a certain recurrence frequency may usually be assumed to apply to this locus. Cox (1978c) has suggested methods for correcting the effects of erroneously assuming that all historic runup measurements applied to this locus.

The method of Bretschneider and Wybro neglects the influence of wave period on inundation, and the influence of the combination of wave period and wave height on bore formation. No method now available takes wave period into account, and in any case the wave periods of many historic tsunamis are not known; hence period-frequency distributions cannot be satisfactorily estimated. The formation of bores by tsunamis is uncommon in Hawaii except at a few identifiable locations, notably Hilo.

III. PRESENT AND PROPOSED TSUNAMI HAZARD ZONES IN HAWAII

Evacuation Zones

For establishing the coastal zones in Hawaii that should be evacuated when warnings are issued by the Seismic Sea Wave Warning System (now the Pacific Tsunami Warning System), Cox (1961) identified potential tsunami inundation limits on the basis of the recorded runup heights of the tsunamis of 1946 (from the eastern Aleutians), 1952 (from Kamchatka), 1957 (from the central Aleutians), and 1960 (from Chile). He found that these runup heights would fall beneath envelopes constructed, in general, by assuming: (1) that the maximum effective tsunami energy would be equivalent to standardized runup heights against a cliff offshore where the water was 10 feet deep, and (2) a loss of height equal to one percent of the distance inland from the minus-10-foot contour. The standard height at the 10-foot contour was assumed to be 50 feet on coasts facing northwest, northeast, and southeast and 30 feet on coasts facing southwest. Adjustments were made, however, for the effects of broad reefs lying at depths between 10 and 20 feet, and for the effects of channels. In a few coastal areas where the standardized construction did not seem to offer sufficient protection, the actual highest runup values were used in determining the potential tsunami inundation limits.

The potential tsunami inundation zones outlined by Cox were on the islands of Kauai, Oahu, Maui, and Hawaii. Using a similar procedure, Adams (1968) outlined zones on the islands of Molokai and Lanai.

At the time, the Pacific Tsunami Warning System was incapable of providing effective warnings of locally generated tsunamis; hence no provision was made for identifying zones of potential inundation by local tsunamis.

As recommended, for administrative and logistic reasons the State and county Civil Defense agencies made some adjustments to the potential tsunami inundation limits in defining the evacuation zones. The evacuation limits have been plotted in numerous maps, for example, maps published annually in Hawaiian telephone directories. The tsunami evacuation zones thus defined represent areas to be evacuated on the occasion of every tsunami warning. Adams (1973) subsequently proposed the adoption of conditional tsunami inundation zones for use with individual warnings, dependent on the direction from which a particular tsunami is expected and on its expected magnitude.

Coastal High Hazard Zones in National Flood Insurance Program

As is appropriate, the provisions of the National Flood Insurance Program have been extended to cover marine flooding hazards in Hawaii and other states in which such hazards are considered significant. Marine flooding may result from storm waves, storm surges, tsunamis, and subsidence. In Hawaii the hazard zone is to be defined primarily on the basis of the potential for flooding by tsunamis.

The base flood in the Federal Flood Insurance Program is the 100-year flood, hence the hazard zones to be defined in Hawaii under the Program are the 100-year tsunami inundation zones.

First proposal for Hawaii

For use in the application of the National Flood Insurance Program in the county of Hawaii (the island of Hawaii), Taniguchi, Ltd. (1973) proposed to define the limit of the coastal hazard zone on the basis of the runups of the 1946 and 1960 tsunamis at intervals along the coastline. They concluded (apparently from consideration of the Hilo tsunami record) that these two tsunamis were the highest in 129 years. They proposed that the shoreline height of the 100-year tsunami above sea level at any site should be estimated as 0.91 times the height of the 1946 or 1960 tsunami, whichever was greater at that site. They assumed that the runup heights thus estimated would pertain to the shoreline, although the historic runup heights had not been measured at the shoreline. From the shoreline runup heights they proposed to estimate the inundation distances by a method similar to that later refined by Bretschneider and Wybro (1976).

First proposal for Oahu

The Towill Corp. (1975) proposed that the coastal hazard zone on Oahu be defined on the basis of runup records compiled by Loomis (1976) for five tsunamis: the four tsunamis used by Cox (1961) plus the 1964 tsunami from Alaska. They proposed to estimate the 100-year tsunami runup at any site from the runups of the five tsunamis assuming that the slope coefficient of the distribution was that determined by analysis of the record of tsunami runups at Honolulu since 1837 (Pararas-Carayannis, 1969). They assumed, as did Cox, that the runup heights would decrease one percent with distance inland, but also assumed erroneously that the historical runup heights had been measured at the shoreline, instead of at points inland (Cox, 1977).

Present proposal

The Federal Insurance Administration now proposes that the coastal hazard zone in each island be established on the basis of tsunami height-frequency distributions estimated by Houston et al. (1977) at the Corps of Engineers Waterways Experiment Station (WES) for sites spaced at intervals of ¼ to 3½ miles along the coasts. These distributions were determined generally from the estimated runups of the tsunamis that were considered the ten highest at each site since 1837. A total of 16 tsunamis was assumed to include the 10 highest at each site. The inundation distances are to be determined by the method of Bretschneider and Wybro (1976), assuming that the runup distributions apply to points 200 feet inland from the shoreline.

Discussion

The primary objective of the tsunami warning system is to reduce the loss of life due to tsunamis, whereas that of the National Flood Insurance Program is to reduce the destruction of property. In spite of these differences in purpose, the establishment of evacuation zones and zones of special land use controls, design criteria, and insurance requirements should be based on considerations of risk. Account should presumably be taken of tsunamis with lower recurrence frequencies in considering risk to persons than to property. Considerations of recurrence frequencies and the means of estimating recurrence frequencies should, however, be common to both the warning-system and evacuation, and the flood insurance programs.

Although intended to permit improvement in the estimation of inundation extent and recurrence frequency in the National Flood Insurance Program, the results of this study should also eventually find use in the revision of evacuation zones.

In all three methods proposed for establishing the coastal hazard zone for the National Flood Insurance Program, the frequency analyses were applied to runup heights. Differences among the methods of analysis are indicated in the following tabulation:

Runup height record used in analysis	Analysis: Taniguchi Ltd. (1973)	Towill Corp. (1975)	Houston et al. (1977)
Nature of heights	Reported	Reported	Reported and synthesized
Period of record, yr.	129	29	140
Number of tsunamis			
i) Considered	2	5	16
ii) Highest actually used in site-specific analysis	1	5	10[a]
Number of site-specific coefficients determined[b]	1	1	2

a) Except 3 on Molokai.
b) Taniguchi, Ltd. and Towill Corp. implicitly assumed uniformed standard values for the coefficient A in equation 1.

Houston et al. noted an abnormally high incidence of large tsunamis since 1946 in the Hilo record. Through the use of partially synthetic records of estimated runup heights for historic tsunamis, they were able to apply their frequency analysis to larger numbers of tsunamis than were analyzed by either Taniguchi, Ltd., or Towill Corp., and to tsunamis occurring over a much longer period than that used by Towill Corp.

If the runup measurements they used were valid, if the means they used for synthesizing other runup values were sound, and if the 16 tsunamis they considered included the 10 that were highest at each site, the Houston et al. methodology for estimating specific frequency distributions of tsunamis is clearly superior. These conditions will be examined subsequently in this report.

IV. WES FREQUENCY DISTRIBUTIONS

Methodology

The methodology used by Houston et al. (1977) in developing the Waterways Experiment Station (WES) distributions of tsunami runups in Hawaii was as follows:

a) They adopted for their analyses the 140-year period beginning with 1837 when the first historical tsunami was reported at Hilo according to Cox (1964) and Pararas-Carayannis (1969).

b) For reported runup heights of tsunamis occurring during this period, they used the following data:

   i) For the following tsunamis, runup measurements compiled by Loomis (1976), more or less well distributed along most Hawaiian coasts: 1946 (E. Aleutians), 1952 (Kamchatka), 1957 (Central Aleutians), 1960 (Chile) and 1964 (Alaska).

   ii) For an important tsunami locally generated in 1975, runup measurements reported by Loomis (1976), well distributed where significant along coasts of the island of Hawaii.

   iii) For other tsunamis occurring during the period, runup heights compiled by Pararas-Carayannis (1969).

c) From the above records they identified 16 tsunamis which, they considered, would include the highest at any Hawaiian coastal site. These included, in addition to the tsunamis identified in b-i) and b-ii), an important local tsunami occurring in 1868 and 10 distant tsunamis. The runup records used in the analyses pertained, then, to 14 distant tsunamis and 2 local tsunamis.

d) They assumed that all tsunamis from a given source region would have similar runup patterns along Hawaiian coasts, and that all significant tsunamis came from the following source regions: Kamchatka, the Aleutian Islands, Alaska, South America, Japan, Tonga, and the Kau-Southeast Puna coast of Hawaii that was the source of the local tsunamis of 1868 and 1975.

e) They synthesized the runup pattern of a historical tsunami or a typical tsunami from each of the first four source regions listed in d), using a hybrid finite-element numerical model. The numerical model had 506 nodal points on coasts of the Hawaiian Islands, spaced generally from ½ to 3½ miles along the coasts: 154 on Hawaii, 81 on Maui, 55 on Molokai, 34 on Lanai, 105 on Oahu, 58 on Kauai, and 19 on Niihau. The results of the numerical analyses were found to agree well with Hawaiian marigrams of the respective tsunamis.

   i) For the 1960 tsunami from Chile and the 1964 tsunami from Alaska, they used as input to the numerical analyses the estimated sea-bottom deformations that caused the tsunamis.

   ii) For typical tsunamis from Kamchatka and the Aleutian Islands they used as input a sinusoidal disturbance of tsunami period.

f) For sites at which to determine the frequency distributions of tsunami runups they used the sites with runup data from b-i) and, where these data were sparse, additional sites representing nodal points of the numerical model in e) (James Houston, personal correspondence).

g) At each of the sites in f), if the runup of any one of the 11 distant tsunamis that was identified in c) and that was generated in one of the source regions in e) (3 tsunamis from Kamchatka, 2 from the Aleutians, 1 from Alaska, and 5 from South America) seemed significant, they estimated its runup from the typical runup for a tsunami from the same source region as in e), interpolating as necessary between nodal points in the numerical analysis and adjusted the estimate by reference to the historical data compiled in b) giving preference to the data as follows:

i) Runup heights reported in the vicinity of each site.

ii) Runup heights reported on the same coast as the site.

iii) Runup heights reported elsewhere in Hawaii.

h) At each of the sites in f) if the runup of any of the five remaining tsunamis in c) seemed likely to be significant, they estimated the runup as follows:

i) For the two local tsunamis, by interpolation as necessary between the points at which the 1975 runups had been measured and by use of the 1975 measurements as a guide to the 1868 runup pattern.

ii) For the two tsunamis from Japan and the tsunami from Tonga presumably by a similar method.

i) By least-squares regression, for each site in f) they fitted the highest runup estimates produced for a site by g) and h) to equation (1).

i) As described in their report, they applied their regression analyses generally to the ten tsunamis that were highest at a site.

ii) However, according to Houston (personal communication), they used only the three highest tsunamis for sites along the coasts of Molokai, on the grounds that the distribution of the runup heights of the lesser tsunamis followed a power law rather than the exponential law represented by equation (1).

Reported Results

The results were reported (Houston et al., 1977) in the form of small-scale maps showing the locations of the nodal points of the numerical model and graphs showing the values of the A and B coefficients at all nodal points and at all intermediate sites for which these were historical runup data.

As pointed out by the University of Hawaii Environmental Center (Cox, 1978a), the typical runup heights estimated from the numerical model were not published except in the form of small-scale maps for Oahu alone, nor were the detailed bases for the adjustments or the adjusted values of the runups for the tsunamis.

Noting, however, that the runups of the smaller and more frequent tsunamis at Hilo were not exponentially distributed (Cox, 1964), Houston et al. tabulated ten-year tsunami runups at all sites estimated as 0.7 times the tenth highest runups at the respective sites. Hence, the tenth highest runups, those marginally significant in the analyses, may be estimated by the inverse process.

Needs for Revision

Comparison of the results of the subsequently reported study of local tsunamis in Hawaii (Cox and Morgan, 1977) with the historical data on which the WES frequency analysis were based indicates that there were some errors in the reported runup heights of the local tsunamis of 2 April 1868 and 29 November 1975 used in the WES study and, further, that some additional certain or possible local tsunamis have occurred whose runups exceeded the runups of minimum significance in the WES study but were not included in it.

The errors and omissions should be corrected, the frequency distributions should be revised where necessary, and the boundaries of the proposed coastal hazard zone redetermined accordingly.

V. PURPOSE AND METHODOLOGY OF THIS STUDY

Purpose

This study was undertaken to put the historical information on possible local tsunamis in Hawaii compiled and analyzed by Cox and Morgan (1977) into a form useable in tsunami hazard zoning and, more specifically, coastal hazard zoning in the National Flood Insurance Program.

Coastal zones in this program are defined as the zones subject to inundation by the 100-year tsunami. The boundaries of these inundation zones have been estimated on the basis of the runups from place to place of the 100-year tsunami which have been determined by site-specific frequency distributions of tsunami runups estimated by the Waterways Experiment Station (WES) (Houston et al. 1977).

It was the immediate purpose of this study, then, to provide estimates of the runup heights of the local tsunamis wherever they would be significant to revisions of the regression analyses used to determine the frequency distributions. In practice, this purpose translated into reconstructing the profile of the runup of each local tsunami along each coastline on which the runup was significant.

Data Considered

Tsunami record

Cox and Morgan (1977, Table 30) identified 21 possible local tsunamis occurring in Hawaii from 1813 or 1814 to the present. The list of these tsunamis, the runup heights associated with them estimated by Cox and Morgan, and certain additional information in their report from which limiting runup heights may be estimated, constitute the principal input data for this study (Table 1).

The identification of the waves as those of local tsunamis is certain for only six of the events. Some of the other 15 may have been storm waves, but many of them may have been distant tsunamis. Eleven were certainly tsunamis of either local or distant origin. The probability that the rest were tsunamis of some sort seems 0.5 or greater in the case of 8 more of the events, and 0.75 or greater in the case of 4.

In determining whether a tabulated event should be considered in determining the coastal hazard zone under the National Flood Insurance Program, the probability of the actual occurrence of high waves and the significance of their runups seem more important than the identification of the waves. As now defined, the zone is to be determined on the basis of tsunami hazard alone. Although on some coasts the hazard of storm waves may be equally or possibly even more significant, the information on storm wave runup is so scattered and incomplete that the judgment was apparently made that the storm wave hazard should be disregarded, at least for the present. However, to the extent that, at the time of any one of the possible local tsunami events, there were actually high waves, it seems more logical to include the event in the determination of the coastal hazard zone than to exclude it. It seems certain that all four of the tabulated events represented high waves, even if not tsunamis.

In the case of the events of 2 April 1868 the uncertainty is merely whether there was a minor local tsunami separately generated on the northeast coast of Hawaii at the same time as the major tsunami of the same date that was generated on the southeast coast. Only at Hilo were runups reported that might represent the minor tsunami. If these runups did not result from such a separately generated tsunami, they resulted from the major tsunami. Hence the two tsunamis may be considered as a single event, although differences in the runup pattern on the northeast coast might be expected depending on whether there were two tsunamis or only one.

The events of 21 August 1951 were similarly interrelated, but as will be shown, the runups of the two possible tsunamis were so small as to be of little significance in tsunami hazard management.

On each of the two other occasions when the occurrence of unusual waves is in doubt (21 February 1871 and 21 November 1935), as will be shown, the runup heights of the waves were also too small to be significant.

Table 1. Possible Local Tsunamis in Hawaii

Date	Probabilities of occurrence[a)] Local tsunami	Tsunami	Unusual waves	Probable coast of generation if local tsunami	Probable maximum runup Height, ft msl	Place
1813-14	0.25	0.60	0.90	W Hawaii	10	Hookena
1848 July ?	0.50	0.85	1.00	N Maui	11	Maliko ?
1854 Jan 28	0.25	1.00	1.00	NE Hawaii	6	Hilo
1860 Dec 1	0.50	0.65	0.85	N Maui	12	Maliko
1862 Jan 28	0.25	0.45	1.00	SE Molokai[b)]	5[b)]	Waialua
1868 Apr 2(a)	1.00	1.00	1.00	SE Hawaii	45[c)]	Keauhou Lndg.
1868 Apr 2(b)	0.25	0.25	0.25	NE Hawaii	9	Hilo
1868 Oct 1	0.50	0.85	0.85	SE Hawaii	20	Opihikao-Pohoiki
1869 Jul 24-25	0.50	0.85	0.85	SE Hawaii	27	Opihikao-Pohoiki
1871 Feb 19	0.25	0.25	0.25	Lanai ?	2	Honolulu, Oahu
1877 Feb 24	0.75	0.85	0.85	W Hawaii	10	Kona (?)
1878 Jan 20	0.25	0.70	1.00	N Molokai	12	Maliko, Maui
1903 Oct 10-11	0.25	0.85	0.85	SE Hawaii	5	Punaluu
1903 Nov 29	0.50	1.00	1.00	N Molokai	30	Honokohau, Maui
1908 Sep 20	1.00	1.00	1.00	NE Hawaii	4	Hilo
1919 Oct 2	1.00	1.00	1.00	W Hawaii	14	Hoopuloa
1935 Nov 21	0.25	0.25	1.00	NE Hawaii	4	Hilo
1951 Aug 21(a)	1.00	1.00	1.00	W Hawaii	2½	Milolii
1951 Aug 21(b)	0.75	0.75	0.75	W Hawaii	1	Napoopoo
1952 Mar 17	1.00	1.00	1.00	SE Hawaii	10	Kalapana
1975 Nov 29	1.00	1.00	1.00	SE Hawaii	47[c)]	Keauhou Lndg.

a) The indicated probabilities of occurrence of local tsunamis were computed on the basis used in Cox and Morgan (1977): certain = 1.00, probable = 0.75, questionable = 0.50, very doubtful = 0.25. The indicated probabilities of occurrence of tsunamis in general (and of unusual waves regardless of origin) were based on the totals of probabilities similarly computed for the local tsunamis and distant tsunamis (and of these plus unusual storm waves) but adjusted so that total probabilities (including probabilities that there were no unusual waves) were 1.0.

b) The probable coast of generation and probable maximum runup height of the 1862 tsunami are as corrected in Cox and Morgan (1978).

c) Runup heights tabulated are above post-subsidence sea level. Probably maximum heights above pre-subsidence sea level are 52 feet for 2 April 1868 tsunami and 57½ feet for 29 November 1975 tsunami.

Significance criterion

The site-specific WES regression analyses were applied to the ten highest of the estimated runups of the historic tsunamis since 1837. Hence the value assumed by WES for the tenth highest runup at a site is the runup of minimum significance at that site.

The runup profile of a local tsunami along a coast, therefore, was considered significant to this study if it was higher than the profile of minimum significance produced by interconnecting the WES tenth highest runups, site to site, along the coast.

Although the WES report did not include the tenth highest site-specific runup values themselves, these could be determined as 1.4 times the ten-year runups tabulated in the report (Houston et al., 1977, Table 1).

Coastal regions

Cox and Morgan (1977) related the distribution of local tsunamis in Hawaii to six coastal regions. The hazard of local tsunamis is clearly greatest in one of these regions, the southeast coast of Hawaii. In another, the coasts of Kauai and the Leeward Islands, the historical record suggests the absence of any significant hazard. The lack or scarcity of nearshore habitations along parts of the coasts and poor communications in the early historical period may have resulted in some gaps in the historical record. However, the record suggests that the hazard of local tsunamis is of much consequence only in certain parts of the remaining four regions.

The runups of the local tsunamis have been addressed in this study as occurring on the following coasts:

Southeast Hawaii	Maui
West Hawaii	Molokai
Northeast Hawaii	Oahu

Other Islands

Runup heights

The runup-height values that were considered in reconstructing the runup profiles of the local tsunamis in this study are summarized in Table 2. Most of these were drawn from Cox and Morgan (1977, Table A-2). The derivation of the other values and the designations of their sites are discussed either in connection with the patterns of the April 1868 and November 1975 tsunamis or in the sections of this report discussing the reconstruction of the runup profiles of the tsunamis coast by coast.

The sites of the runup-height values are identified not only by place name but also by WES numerical site designations. The whole numbers refer to nodal points of the WES numerical model. These nodal points were not uniformly spaced along the coastlines. The locations of runup values that were not at nodal points are indicated by decimals of the distance between the nearest nodal points, measured from the lower-numbered toward the higher-numbered site.

Reconstruction of Runup Profiles

For no local tsunami other than those of April 1868 and November 1975 are there tabulated runup values for more than five sites. Ten of the local tsunamis are represented by runup values at single sites. It would be absurd to consider that a tsunami had no runup except at the site of a tabulated value. It would be equally absurd to assume that, at all sites without tabulated values, the runup of a tsunami was equal to a tabulated value or to the average of tabulated values.

In a few cases as will be shown, historical information indicates some limitations to the possible range of the runup of a tsunami at points other than those for which there are tabulated values. However, some criteria had to be adopted for interpolating between multiple tabulated runup values for a tsunami where the sites to which these apply are reasonably close, and for extrapolating from

Table 2. Available Measurements and Estimates of Local-Tsunami Runup Heights

Site: Name	Site: Number[a]	Runup height, feet[c] — Hawaii: 1813-1814	January 1854	April 1868	October 1868	July 1869	February 1877	October 1903	September 1908	October 1919	November 1935	August 1951	March 1952	November 1975
Milolii	11											2½ ± 1		≲5½
Hoopuloa	11.3									14 ± 2				
Hookena	16	10 ± 7								≲4½[g]		≲4		6 ± 1
Honaunau	18											≲3		
Napoopoo, S	19.4													11 ± 1
Napoopoo	19.5											1 ± ½		12 ± 1
Kealakekua Bay	19.7			4 ± 1½						≲4[g]				6 ± 1
Hookena to Kailua[b]	16 to 25.4						10 ± 5							
Keauhou	24.5									8 ± 2				9½ ± 1[d]
Kahaluu	25													9½ ± 1
Kahaluu, N	25.4													6 ± 1
Kailua	27.4									3 ± 1				5½ ± 1½
Honokohau	30													7 ± 1
Anaehoomalu	42.4													4 ± 1
Puako	45.6													4 ± 1
Kawaihae	48			2 ± 1										2½ ± 1
Mahukona	54.6													≲3
Wailuku River	103.5													8 ± 1
Hilo, old town	103.7		6 ± 2	9 ± 2					4 ± 2		4 ± 2			
Hilo, Waterfront	104													8 ± 1[e]
Wailoa River	105			7 ± 3										8½ ± 1[e]
Coconut Island	105.6													7½ ± 1[e]
Waiakea Pen.	106													4½ ± 1[e]
Reeds Bay	106.3													3½ ± 1[e]
Pier 2, W	106.7													2½ ± 1
Radio Bay	106.9													3 ± 1
Puhi Bay	108													6½ ± 1
Kealoha Park	109.4													4½ ± 1
Leleiwi Park	110.3													5 ± 1
Leleiwi Pt.	111													6½ ± 1
Honolulu Lndg.	120													≲9½
Makaukiu	120.6													20 ± 1
Kumukahi	122													11 ± 1
Kapoho Pt.	122.3													5?
Pohoiki	124.1													7 ± 1
Pohoiki to Opihikao[b]	124.1 125.7			17 ± 5	20 ± 10	27 ± 5								
Opihikao	125.7													11½ ± 1½
Kaimu, NE	128.4													14 ± 1[h]
Kaimu, SW	128.6													10 ± 1[h]
Kalapana	129			≲10[g]									10 ± 1	10 ± 1[h]
Kupapau	129.7													13½ ± 1½[h]
Kamoamoa, E	130.8													20½ ± 2[h]
Kamoamoa	130.9													20½ ± 2[h]
Kamoamoa	131													25 ± 2[h]
Apua Pt.	135													28½ ± 4½[h]
Keauhou Lndg., E	135.8													28½ ± 4[h]
Keauhou Lndg., E	135.9													53 ± 4[h]
Keauhou Lndg.	136			52 ± 6[h]										51 ± 4[h]
Keauhou Lndg., W	136.1													57½ ± 3½[h]
Halape, E	136.9													30 ± 3[e][h]
Halape, W	137													36 ± 3[e][h]
Kalue	138.8													35 ± 2[h]
Kalue, W	139													38½ ± 2[h]
Punaluu, E	145.6													18 ± 1
Punaluu	145.7			20 ± 2										25 ± 1
Ninole	146			20 ± 2				5 ± 3						17 ± 1
Honuapo, E	147.8													6?
Honuapo	148			≲20										21½ ± 2
Kaalualu	151.8			20 ± 5										16 ± 1[d]
Hanalua	153.5													22 ± 1
Kaulana, E	153.7													18½ ± 1
Kaulana, E	153.8													20 ± 2
Kaulana, E	153.9													16½ ± 1
Kaulana	154.2													16 ± 1
KaLae, E	154.3													17 ± 1
KaLae	154.5													13 ± 2

Table 2 (continued)

Maui							
Site: Name	Site: Number	July 1848	December 1860	July 1869	January 1878	November 1903	November 1975
Lahaina	20					$\lesssim 2$ [g]	2 ± 1 [f]
Kaanapali	23.6					$\lesssim 5$ [g]	
Honokohau	30.5					30 ± 2	
Kahakuloa	33					$\lesssim 10$ [g]	
Kahului	39		8 ± 2			$\lesssim 3$ [g]	$2 \pm ½$ [i]
Kahului to Maliko [b]	39 to 44	11 ± 5					
Maliko	44		12 ± 4		12 ± 4		
Halehaku	46.9				10 ± 6		
Honomanu	49.7				10 ± 6		
Keanae	50				$\lesssim 5$ [g]		
Hana	58			$\lesssim 4$ [g]			2 ± 1 [f]
Kaupo	68			15 ± 4			

Oahu						
Site: Name	Site: Number	April 1868	February 1871	January 1878	November 1903	November 1975
Waialua	8			10 ± 2		
Haleiwa	8.7			$\lesssim 8$ [g]		
Mokuoloe	35.7					0 [i]
Honolulu	66.2	$2 \pm 1½$	2 ± 2	$\lesssim 5$	1 [i]	½ [i]

Molokai			
Site: Name	Site: Number	January 1862	November 1903
Kalaupapa	18		13?
Pelekunu	23.8		13 ± 6
Halawa	28.5		$\lesssim 8$ [g]
Waialua	32.7	5 ± 2	$\lesssim 4$ [g]
Pukoo	36	$\lesssim 2$ [g]	$\lesssim 2$ [g]

Kauai		
Site: Name	Site: Number	November 1975
Nawiliwili		$2½ \pm 1$ [i]

Notes:

a) Site number refers to scheme of Houston et al. (1977) based on numerical-model nodes.
b) Location is uncertain within range of locations indicated.
c) Runup heights are from Cox and Morgan (1977), Table A-2 (criterion a(i))* unless otherwise indicated.
d) Maximum value of range indicated in Cox and Morgan (1977) (criterion d(iii))*.
e) Value specific to location from range indicated in Cox and Morgan (1977) (criterion d(ii))*.
f) Value estimated from effects (criterion a(iii))*.
g) Limiting value estimated from lack of report (criterion a(ii))*.
h) Value adjusted for subsidence (criterion b(i))*.
i) Value estimated from marigraphic record (criterion a(ii))*.

*Profiling criteria are summarized later in text.

for a tsunami where the sites to which these apply are reasonably close, and for extrapolating from single tabulated values or beyond the limits of closely spaced multiple values, in the absence of guidance from historical information.

The matter of interpolation and extrapolation was discussed in June 1978 at a meeting at the Hawaii Institute of Geophysics involving tsunami specialists of the Joint Institute of Marine and Atmospheric Research and representatives of the Corps of Engineers Pacific Ocean Division and Waterways Experiment Station, the Federal Insurance Administration, and the State Civil Defense Divison. The importance of the effects of local topography and bathymetry was recognized. However, because the areas of origin of most of the local tsunamis are unknown, and hence their directions of approach to the coastlines, there seemed to be no satisfactory means by which some of these effects could be taken into account. No suggestions were made for improving on the assumptions used in interpolation and extrapolation derived from the runup patterns of the April 1868 and November 1975 tsunamis that are discussed below.

Guidance from Major Events of April 1968 and of November 1975

The most extensive record of the runup height distribution for a local tsunami is that of the major tsunami of 29 November 1975 . Both this tsunami and the major tsunami of 2 April 1868 were clearly of tectonic origin, having accompanied major earthquakes on the southeast coast of Hawaii and subsidence of that coast. The maximum runup heights of both were the highest on record, exceeding 50 feet above mean sea level (pre-subsidence), and the maxima in both cases were at Keauhou Landing. Although the runup record of the 1868 tsunami is much less complete than that of the 1975 tsunami, it is clear that the runup patterns of the two were similar in general but significantly different in detail.

Several uncertainties that were faced in reconstructing the runup profiles of the local tsunamis generally were exemplified in the record of these two tsunamis, and most of the assumptions used generally were derived from their consideration.

Ranges of uncertainty and local variations of runup heights

Cox and Morgan (1977) assigned possible ranges of error to each measured or estimated runup height value that they reported. In the absence of any compelling contrary evidence, it was assumed in this study that the runup height of a local tsunami was that considered most probable rather than some other value within the possible range.

For a few localities such as Keauhou, Kaalualu, Halape, and Hilo, much more detail in the variation of the runup height of the 1975 tsunami is available in original reports than is significant in reconstructing the runup profile of that tsunami in general. The detail was reduced in Cox and Morgan to ranges for Keauhou, for Kaalualu, for Halape, and for three short coastal segments in Hilo.

Only the maxima of the ranges at Kaalualu and Keauhou are indicated in Table 2. Of the runups at Halape, 2 representative values, and of the runups at Hilo, 13 representative values have been indicated in the table.

Additional runup estimates

Cox and Morgan summarized all previously available measurements and estimates of the runups of the 1868 and 1975 tsunamis, and of all other possible local tsunamis in Hawaii, and estimated their runups at most additional points where historical evidence provided a basis for estimation. In discussing the 1975 tsunami, however, they considered the marigraphic heights of the tsunami separately from the runup heights (Cox and Morgan, 1977, Table 12).

Marigraphic heights and runup heights at Hilo may be compared as follows:

Maximum marigraphic crest height above tide level	2.5 feet
Maximum marigraphic range	5.8 feet
Mean of crest height and range	4.1 feet
Crest height X 2.5*	6.2 feet
Runup near tide gage	3 feet
Runups elsewhere in Hilo Harbor	2½ to 8½ feet

*(The factor 2.5 used by Cox, 1964, to estimate runup heights from maximum marigraphic crest heights above tide level was based on correlation between marigraphic records at the tide gage in Hilo and the highest runups in Hilo Bay rather than the runup in the vicinity of the tide gage.)

Although among the marigraphic values the crest height corresponds most closely to the runup near the tide gage, the mean of crest height and range reflect better the average runup height in the eastern part of Hilo Harbor. Hence the mean of crest height and range, plus or minus one foot, was adopted as an estimate of the runup in the vicinity of each of the four other tide gages that recorded the 1975 tsunami as indicated below:

Place	Marigraphic height, feet: Max. crest above tide level	Marigraphic height, feet: Max. range	Estimated runup, feet
Kahului, Maui	1.3	2.8	2 ± 1
Honolulu, Oahu	0.5	2.2	1½ ± 1
Mokuoloe (Kaneohe Bay), Oahu		0.1	0
Nawiliwili, Kauai	1.9	3.6	2½ ± 1

The 1975 tsunami was observed on Maui at Hana and Lahaina as well as recorded at Kahului. Cox and Morgan provided no estimates of the runup at Hana and Kahului. However, from the description of the waves and their effects (Cox and Morgan, 1977, p. 65), it seems reasonable to suppose that the runups at both places were about 2 ± 1 feet. These runups are also included in Table 2.

Limiting runup values

No runup value is available for the 1868 tsunami at Kalapana, Puna. However, there was a mission at Kalapana (Cox and Morgan, 1977), and it is unlikely that the occurrence of the tsunami there would not have been reported if its runup had exceeded that of the 1975 tsunami, 10 feet. Because the runups at the nearest sites of available values in both directions from Kalapana considerably exceeded 10 feet, in reconstructing the runup profile it was assumed that the 1868 runup at Kalapana was 10 feet.

At Honuapo, Kau, the runup of the 1868 tsunami is known only to the extent that it did not exceed 20 feet. Because the available runup values at the nearest sites in both directions from Honuapo were equal to 20 feet it was assumed that the runup at Honuapo was only slightly less than 20 feet.

At Mahukona, Kohala, the runup of the 1975 tsunami is known only to the extent that it did not exceed 3 feet. The runup at the nearest site with an available value to the south, Kawaihae, was only 2½ feet, and there are no available values for sites farther north. Hence the runup at Mahukona was assumed to be not more than 2½ feet, and thus insignificant.

Questionable runup values

Runup values for 1975 are questionable for Kapoho Point, Puna, and for a point east of Honuapo, Kau. In both cases the questionable values are considerably lower than the certain runups at the nearest sites.

Because the distance to the site of an available value nearest Kapoho Point is great, the runup there was assumed equal to the smaller of the values at the nearby sites, considerably less than the value that would be estimated by simple interpolation.

Because the distance from Honuapo to the site of the questionable value nearby was very small, the questionable value was disregarded in reconstructing the profile.

Effects of subsidence

The generation of the 1868 and 1975 tsunamis was accompanied by subsidence of part of the southeast coast of Hawaii. Assuming that a tsunami may be generated similarly in the future, the concern now is with the probable elevation of its runups above the level of the present mean-sea-level shoreline, not the level of the shoreline after the subsidence occurs. Hence, the runup profiles of interest for these tsunamis are those relative to the land before rather than after subsidence, and pre-subsidence rather than post-subsidence values of runup heights are included in Table 2.

The pre-subsidence values for the 1868 tsunami are from Cox and Morgan (1977, Table 3). Those for the 1975 tsunami are taken from the same report (Table 9) except for sites at and near Kamoamoa and Kupapau, for which the corrected values in the supplement (Cox and Morgan, 1978) are given.

General runup patterns on Hawaii

The tsunamis of 1868 and 1975 were both generated off the southeast coast of Puna. Differences in detail in the nature of the generating mechanisms may have resulted in considerable differences in detail in the runup patterns of the two tsunamis along this coast. Indeed even the general resemblance of their runup patterns on these coasts seems remarkable. Between Kaalualu in Kau and the vicinity of Pohoiki and Opihikao in Puna, sites of runup values are spaced so closely that it is not necessary in reconstructing the profile of the 1868 tsunami to rely on the 1975 runup pattern.

Runup profiles of these tsunamis and others generated along this coast were published by Cox and Morgan (1977, Figure 12). Their profiles differ from those produced in this study in three respects:

1) The 1868 and 1975 runups plotted were heights above post-subsidence sea level rather than pre-subsidence sea level.

2) The runups were plotted on linear scales, whereas logarithmic scales were used in this study for reasons presented below.

3) The coastal distances plotted were obtained by projecting the sites of available runup values to a straight line approximating the general alignment of the entire coast. Such projection was satisfactory on the southwest coast of Hawaii, which is reasonably straight; however, coastline curvatures made it unsatisfactory on other coasts. The coastal distances used in the projections in this study represent the cumulated distances between nodal points in the Houston et al. (1977) analysis. Coastal lines in these profiles reflect actual distances along the coast neglecting only coastal configuration details of scale smaller than the spacing of the nodal points.

In estimating the 1868 profile southwest of Kaalualu and on the west coast of Hawaii the following 1868-1975 runup comparisons at identical or nearly identical sites are of interest:

Place	Site	1868	1975
Punaluu-Ninole	145.7 to 146	20	17 to 25
Honuapo	147.8	20	19 to 21½
Kaalualu	151.8	20	9 to 16
Napoopoo-Kealakekua	19.4 to 19.7	4	6 to 12½
Kawaihae	48	2	2½

At points on these coasts where there is no guidance from historical records, the 1868 runup may be estimated as follows:

Coast	1868 runup
Kaalualu to Hanalua	= 1868 runup at Kaalualu
Hanalua to Ka Lae	= 1975 runup disregarding detailed variations
Ka Lae to Milolii	Gradual change in ratio to 1975 runup from 1.00 to 0.75
Milolii to Hookena	0.75 times 1975 runup
Hookena to Kealakekua Bay	Simple interpolation
Kealakekua Bay to Kawaihae	0.75 times 1975 runup

The use of simple interpolation between Hookena and Kealakekua Bay is based on the assumption that if the 1868 tsunami had had runups at Napoopoo as high as the values reported for the 1975 tsunami there, these would have been reported instead of the value reported at Kealakekua Bay.

A similar comparison is useful in estimating the 1868 runup east and north of the Pohoiki-Opihikao vicinity.

Place	Site	Probable runup height, feet 1868	1975
Opihikao-Pohoiki	124.1 to 125.7	17	7 to 11½
Vicinity of Waiakea village (Wailua River to Waiakea Peninsula)	105	7	4½ to 8½
Hilo (old town)	103.7 to 104	9	7½ to 8½

The similarities in the runups in the Hilo vicinity, including Waiakea, suggest that along most of the northeast coast of Hawaii the 1868 runup may be taken as equal to the 1975 runup. The possibility that the 1868 Hilo runup resulted from a northeast-coast tsunami, separately generated at the same time as the major southeast-coast tsunami, suggests more variability to the 1868 runup than the 1975 runup on the northeast coast. There is, however, no direct evidence of such greater variability.

The 1975 tsunami had an anomalously high runup (20 feet) at Makaukiu, on the northeast coast about 2½ miles northwest of Kumukahi. Such anomalies have been observed with other tsunamis moving past sharp points, for example, the April 1946 Aleutian tsunami at Makapuu Point, Oahu. An anomaly of this kind may well have occurred in 1868, but it was assumed in this study that the 1868 tsunami runup was no higher at Kumukahi and Makaukiu than in the Opihikao vicinity, and decreased east of Makaukiu to the runup height of the 1975 tsunami at Honolulu Landing.

General runup patterns on other islands

The 1975 tsunami was not observed or recorded on Molokai, on Oahu except at Honolulu and Mokuoloe, or on Kauai except at Nawiliwili. By simple interpolation between Lahaina or Kahului and Honolulu, its runup on Molokai and eastern Oahu would be estimated between 1½ and 2 feet. By simple interpolation between Lahaina or Kahului and Nawiliwili its runup on Molokai and Oahu would be estimated as somewhat more than 2 feet. Runups of about 2 feet or less could easily have escaped detection. However, in their survey of the effects of the April 1946 Aleutian tsunami Shepard et al. (1950) found that the runups along the south coast of Molokai were greatly reduced by the broad, shallow reef fringing the coast except where there were channels through the reef. The runups of the 1868 and 1975 tsunamis along that coast were assumed to be to be affected similarly. If, except for the reef effect, the runups had been higher than 1½ or 2 feet, estimates would have been made of the runups on the shore opposite the channels, but in the case of the 1868 and 1975 tsunamis it was assumed that even opposite the channels the runups were not significant.

Along most of the rest of the coasts of Molokai and Oahu, runups of only 1½ or 2 feet would be less than the runups of minimum significance. Other than values of 1½ feet estimated for points on the unprotected east end and north coast of Molokai, where the runups of minimum significance were lower, no runups of the 1975 tsunami were considered significant.

The 1868 and 1978 tsunamis might have had observable runups on Kahoolawe, but this island is uninhabited and no runup frequency distributions for sites along its coastline were estimated in the WES study. These tsunamis might have had observable runups on Lanai, but the lack of observations of the 1975 tsunami suggests that its runup at Kaumalapau Harbor did not exceed 2 feet and hence was barely significant.

The runup of the 1868 tsunami at Honolulu was estimated at 2 feet (Cox and Morgan, 1977), slightly higher than the estimate for the 1975 tsunami based on the marigraphic record, and barely significant. If the runup values of the two tsunamis in Pearl Harbor, a few miles to the west, had been equal to the values at Honolulu, they would have been significant. In a large bay with a narrow entrance, such as Pearl Harbor, tsunami runups are much lower than on an open coast; for this reason, the runup profiles were projected across the mouth of Pearl Harbor as if the Harbor did not exist.

Similarly, tsunami runups are subject to great reduction in Kaneohe Bay, which is protected by a wide reef. As expectable, the 1975 tsunami was barely recorded on the tide gage at Mokuoloe in Kaneohe Bay and the oscillations of the 1868 tsunami there were probably similar.

In this study, the 1868 tsunami runups were estimated elsewhere on Maui, Molokai, Lanai, and Oahu as equal to those of the 1975 tsunami.

The runup of the 1975 tsunami at Nawiliwili Harbor, Kauai, estimated on the basis of the marigraphic record, was 2½ feet, higher than the 2-foot runup of minimum significance on the east and south coasts of Kauai. It is doubtful that the runups at the head of Nawiliwili Bay, at places north of Nawiliwili such as Hanamaulu, Waialua, Kapaa, and Kealia, or southwest of Nawiliwili such as at Poipu, could have been as high as 2 feet without being noticed and reported. For this reason, and because the 1975 runup and the probably similar 1868 runups would have been barely significant, the runups of these tsunamis on Kauai have not been considered.

There is no evidence by which to estimate the possible runups of the 1868 or 1975 tsunamis on Niihau. They might have been significant by the WES criterion, but they could not have been of much consequence.

Interpolation

Even in the case of the 1975 tsunami, the available runup values are at discrete sites, closely spaced along some parts of the coast but widely separated elsewhere. It would be absurd to consider that at all other sites the runup was equal to one of the available values. It would also be absurd to consider that there was no runup at other sites. Either consideration would be even more absurd in the case of the tsunami of April 1868, for which fewer runup values are available.

To permit reconstruction of the runup profiles of these and other tsunamis where historical evidence was lacking, it was necessary to make some assumptions, which, although necessarily somewhat arbitrary, should be reasonable, simple, and mutually consistent. The results of testing two such assumptions against the available runup values for the 1975 tsunami along the southeast coast of Hawaii from Ninole to Kaimu are shown in Figure 1. In both cases a constant gradient is assumed between the sites of available values. In one case the constancy applies to the runup gradient itself, in the other, to the gradient of the logarithm of the runup.

The runup decreases less rapidly with distance from the maximum value near Keauhou Landing under the assumption of constancy of runup gradient than under the assumption of constancy of log-runup gradient. Since there are reasons for believing that the high runup values were restricted to the vicinity of Keauhou Landing, the profile constructed under the second assumption is the more reasonable.

The maximum runups for other tsunamis may well have been at sites where no observations were made or at least where no estimates are available. However, for two reasons in addition to the better fit indicated in Figure 1, the assumption of constancy of log-runup gradient was adopted in this study for interpolation of runup heights between the sites of available values:

1) The assumption of constancy of log-runup gradient is consistent with the finding of Van Dorn (1965) that the runups of a tsunami along a particular coast are log-normally distributed;

2) It results in better agreement between the profiles of the 1868 and 1975 tsunamis along the coastline covered by Figure 1.

Under the assumption of constancy of log-runup gradients, linear interpolation is possible if a logarithmic scale is used for plotting runup heights and a linear scale is used for coastal distances. For this reason, semi-log plots were used for reconstruction of all runup profiles in this study.

As indicated earlier, the runup of the 1975 tsunami could be estimated at Hana, at Kahului, and at Lahaina, Maui. The distances along the coast from Hana to Kahului and from Kahului to Lahaina are about 2×10^5 and 1.5×10^5 feet, respectively. The wide reef along the shore west of Kahului may reduce tsunami runups along the coast for a distance of about 3×10^4 feet west of Kahului. Otherwise there is no reason to suppose that the runup of the 1975 tsunami anywhere along the Maui coast was less than the values estimated at Hana, Kahului, and Lahaina. Hence, the estimation of runups by interpolation between sites separated by as much as 2×10^5 feet seemed reasonable in the absence of either historical evidence or special reasons for considering the coast especially vulnerable or especially protected from tsunamis.

Extrapolation

The sites of significant known runup values farthest along the coast of Hawaii clockwise and counterclockwise from the origin of the 1975 tsunami are, respectively, Kawaihae and the Wailuku River in Hilo. The runup at Kawaihae is no higher, and the runup at the Wailuku River is very little higher than the respective runups of minimum significance of the two sites, so the problem of extrapolation beyond the limits of available values is trivial in the case of the 1975 tsunami. In the

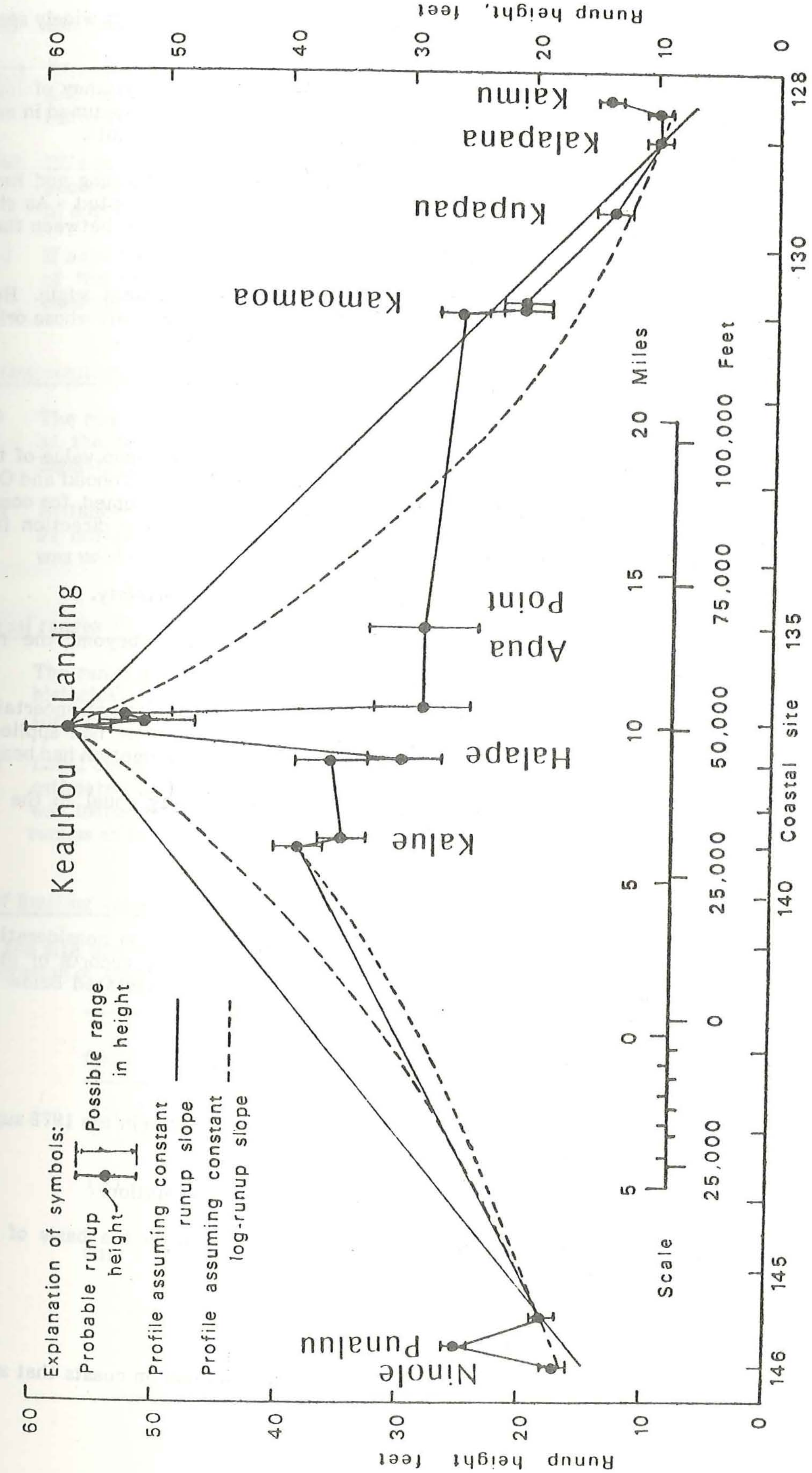


Figure 1. Alternative reconstructions of 1975 runup profile, Kaimu to Ninole, Hawaii.

case of other tsunamis for which only single runup values are available, or values at widely separated sites, some assumptions as to profile gradients had to be made.

For the sake of consistency with the assumption used in interpolation, constancy of log-runup gradients was assumed in extrapolation. A standard, uniform gradient had to be assumed in addition, because in extrapolation the gradient is not determined between pairs of known points.

The average log-runup gradient of the 1975 tsunami between Keauhou Landing and Kalapana, which was about midway in the range of 1975 gradients, was the standard adopted. As shown in Figure 1, the runup decreased by a factor of 5.75 in the distance of 100,000 feet between these two points. This is equivalent to a negative $\log_e$-runup gradient of 1.75×10^{-5} per foot.

A flatter gradient would be more reasonable in the case of tsunamis of distant origin. However, the above standard was applied even in the case of those few significant tsunamis whose origin was possibly local but more probably distant.

Uncertainties in location

On the southeast Puna coast northeast of Kalapana the only available runup value of the 1868 tsunami is a high one at Kahaualea, a place known only to be in the vicinity of Pohoiki and Opihikao. In the use of this value and other single values of uncertain location, it was assumed, for consistency with the assumptions made in interpolation and extrapolation, that, in either direction from the center of the range of uncertainty in location:

1) The log-runup (and hence runup) was constant to the limit of uncertainty.

2) The log-runup gradient was constant for the same distance beyond the range of uncertainty.

3) The area under the log-runup profile, to a distance equal to the range of uncertainty, was the same as that which would have resulted if the available value had applied at the center of the range of uncertainty and the usual extrapolation assumption had been made.

4) Beyond a distance from the center of the range of uncertainty equal to the range of uncertainty, the usual extrapolation assumption would apply.

Profiling Criteria Adopted

Several of the criteria for reconstructing the runup profiles derived from consideration of the April 1868 and November 1975 tsunamis were used in extending the runup records of other local tsunamis and in reconstructing their runup profiles. These criteria are restated below in forms covering their general application:

a. Use of historical information generally

(i) All runup values tabulated by Cox and Morgan (1977) (or corrected in the 1978 supplement) were plotted except as indicated in d(ii).

(ii) Additional runup values were estimated from marigraphic information.

(iii) Additional runup and limiting runup values were estimated on the basis of historical evidences discussed by Cox and Morgan.

b. Use of geophysical information generally

(i) Runup heights were adjusted to pre-subsidence mean sea level on coasts that subsided at the time of tsunami generation.

(ii) Similarities of runup patterns were assumed for tsunamis with similar origins.

(iii) Effects on runups independent of the direction of tsunami approach, such as those of reefs and narrow entrances to bays, were taken into account in reconstructing runup profiles between sites of available values.

(iv) Effects on runups dependent on the direction of tsunami approach were not taken into account in reconstructing profiles between sites of available values unless the directions of approach were known.

(v) If an event may have involved two nearly coincident tsunamis and it is uncertain to which of the two the available runup values pertain, both alternatives tsunami source were considered in deciding the most probable profile.

c. Plotting positions and scales

(i) The runup values plotted were based on mean-sea-level datum. On a coast that subsided at the time of tsunami generation the datum was pre-subsidence mean sea level. A logarithmic scale was used in plotting runup values.

(ii) Distances were measured between WES coastal sites (spaced at intervals of between ½ and 3½ miles) neglecting details of coastal configuration between these sites. A linear scale was used in plotting distances.

d. Vertical ranges of uncertainty and local detail

(i) The runup at each site was assumed to lie within the range of uncertainty indicated by the historical evidence. The value of the middle of the range was considered most probable in the absence of compelling contrary regional evidence.

(ii) Local details of runup-pattern variations on a scale of less than about 1000 feet cannot be estimated if historical evidence is lacking, and hence were neglected even where there was historical evidence. Where the detail was neglected, the maximum of the range of runups at the site was used.

e. Use of limiting values

At the site of a value representing the upper limit of possible runups, the runup was estimated in consideration of adjacent values as follows:

Case	Runup estimated from adjacent values	Assumed runup
(i)	Considerably higher than limiting value	Limiting value
(ii)	Slightly higher than or equal to limiting value	Slightly lower than limiting value
(iii)	Lower than limiting value	As estimated from adjacent values

f. Use of questionable values

At the sites of questionable runup values, the runup was estimated as follows:

Case	Runup estimated from adjacent values	Assumed runup
(i)	In close agreement with questionable value	Questionable value
(ii)	Not in agreement, if site of an adjacent value is close	As estimated from adjacent values
(iii)	Not in agreement, if site of nearest adjacent value is distant	As estimated by compromise

g. Interpolation, extrapolation, and use of runup values of uncertain location

In the absence of historical and geophysical evidence the profiles were constructed assuming:

(i) Constant log-runup gradients for interpolating between sites of previously available runup values separated by not more than about 2×10^5 feet.

$$\frac{d(\log H)}{dx} = \frac{\log H_2 - \log H_1}{x_2 - x_1}$$

$$\text{or} \quad H = H_2^{\left(\frac{x - x_1}{x_2 - x_1}\right)} \cdot H_1^{\left(\frac{x_2 - x}{x_2 - x_1}\right)}$$

(ii) A standard log-runup gradient for extrapolating from a single runup value or a value separated from adjacent values by more than about 2×10^5 feet.

$$\left|\frac{d(\log H)}{dx}\right| = -aM$$

$$\text{or} \quad H = H_1 e^{-a|x - x_1|}$$

(iii) In the vicinity of a value of uncertain location:

For $0 \leq x' \leq \Delta$

$$H = H_o e^{-2a\Delta/3}$$

For $\Delta \leq x' \leq 2\Delta$

$$H = H_o e^{-2a(x' - \Delta)/3}$$

For $x' \geq 2\Delta$

$$H = H_o e^{-2ax'}$$

Where H = runup

H_1 = previously available runup value at site 1

H_2 = " " " " " " 2

H_o = " " " " of uncertain location

x_1 = coastal distance to site 1

x_2 = " " " " 2

x' = |coastal distance from center of range of uncertainty in location|

Δ = 1/2 range of uncertainty in location

e = base of natural logarithm

$M = \log_{10} e$

$a = 1.75 \times 10^{-5}$ if coastal distances are measured in feet

$aM = 7.4 \times 10^{-6}$ if coastal distances are measured in feet

$| \; |$ = indicates absolute value of quantity between vertical bars

h. Significant runups

The runup of a local tsunami at a site is not significant if it is smaller than the tenth highest tsunami runup there as estimated by Houston et al. (1977).

Additional Estimates of Runups

In addition to the runups estimated from marigraphic records for the 1975 tsunami, a runup of about 1 foot at Honolulu was estimated for the November 1903 tsunami on the basis of a report that it was recorded at the tide gage there (criterion a (ii)).

Reported effects of the 1975 tsunami were the basis for estimates of the runup at a few places, and the lack of reported observations was considered to indicate that the 1868 tsunami did not exceed certain values at a few other places (criterion a(iii)).

The lack of a reported observation of a tsunami at any place cannot indicate certainly that it could not have been observed there, or even that it was not observed there. However, if a place were populated at the time of a tsunami, and if communications between that place and Honolulu or other major towns were good, the lack of a report that the tsunami was observed at that place may indicate a probable upper limit to its runup there.

Limiting runups estimated on this basis (criterion a(iii)) that were not drawn from Cox and Morgan (1977) but were found useful in this study have been included in Table 2 as follows:

Island	Place		Year	Limiting runup, feet
	Name	Site no.		
Hawaii	Hookena	16	1919	4½
	Kealakekua	19.7	1919	4
	Kalapana	129	1868	10
			1869	10
Maui	Lahaina	20	1903	2
	Kaanapali	23.6	1903	5
	Kahakuloa	33	1903	10
	Kahului	39	1903	3
	Keanae	50	1878	5
	Hana	58	1869	4
Molokai	Halawa	28.5	1903	8
	Waialua	32.7	1903	4
	Pukoo	36	1862	2
			1903	2
Oahu	Haleiwa	8.7	1878	8

VI. RECONSTRUCTED RUNUP PROFILES

The runup profiles of the possible local tsunamis reconstructed in this study are presented in Figures 2 through 7, each of which relates to a particular coastal region. Each figure includes a map locating the nodal points in the WES numerical model and a composite profile covering the coastal reaches along which the runups of one or more of the possible local tsunamis were significant according to criterion h(ii).

The composite profiles are semi-logarithmic. Sites represented by the nodal points and intermediate sites of available runup values are plotted on a linear scale in accordance with criterion c(ii). Runup heights are plotted on a logarithmic scale in accordance with criterion c(i). Each composite profile includes:

a) The profile of minimum significance constructed in accordance with criterion h.

b) Runup values for the local tsunamis previously available in accordance with criterion a(i) or estimated in accordance with criterion a(ii); and

c) The runup profile of each possible local tsunami of significance.

Special criteria used in reconstructing the runup profiles are indicated in the following sections.

Southeast Coast of Hawaii

Six of the possible local tsunamis were observed on the southeast coast of Hawaii:

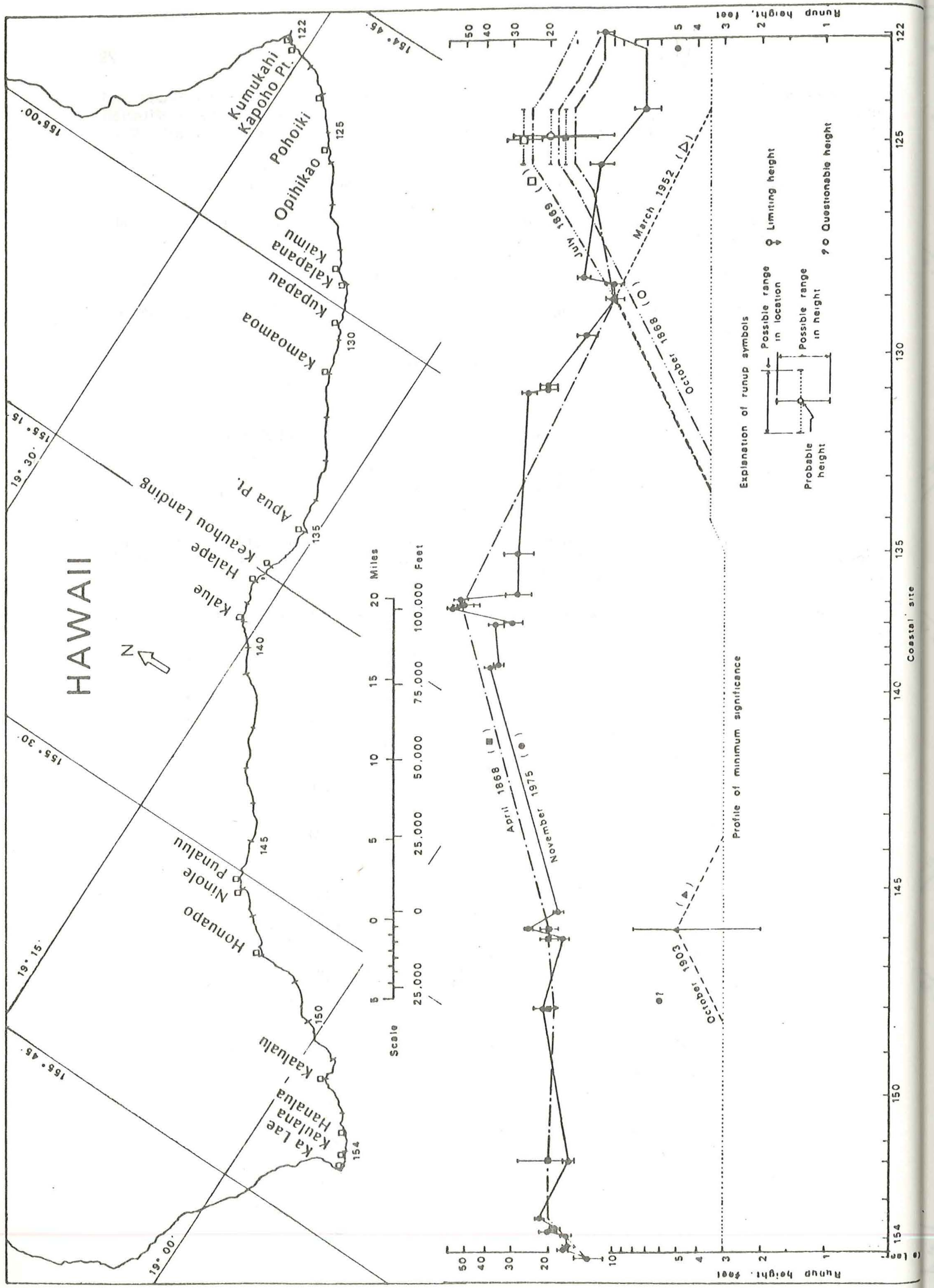
April 1868	October 1903
October 1868	March 1952
July 1869	November 1975

The tsunamis of April 1868, March 1952, and November 1975 originated off this coast. The tsunamis of October 1868 and July 1869 may have been generated off the same coast. If the probable tsunami of October 1903 was a local tsunami its source was probably off the same coast.

The criteria used in reconstructing the profiles of these tsunamis, section by section in Figure 2, were:

Table 3. Runup Profile Criteria: Southeast Hawaii

Events	Sites	Criteria
April 1868	122-123	g(i)
	123-127	g(iii)
	127-129	g(i)
	129	e(i)
	129-148	g(i)
	148	e(ii)
	148-151	g(i)
	151-154.5	b(ii)
October 1868	122-123	g(ii)
	123-127	g(iii)
	127-133	g(ii)
July 1869	122-123	g(ii)
	123-127	g(iii)
	127-129	g(i)
	129	e(ii)
	129-134	g(ii)
October 1903	143-149	g(ii)
March 1952	124-134	g(ii)
November 1975	122-122.3	g(i)
	122.3	f(iii)
	122.3-136.9	g(i)
	136.9	d(ii)
	136.9-147.8	g(i)
	147.8	f(ii)
	147.8-151.8	g(i)
	151.8	d(ii)
	151.8-154.5	g(i)



West Coast of Hawaii

The tsunamis of April 1868 and November 1975, generated off the southeast coast of Hawaii, had significant runup heights on the west coast of Hawaii as well. In addition, five tsunamis possibly generated off the west coast itself were observed there: the very doubtfully local tsunami of 1813-14, the certainly local tsunamis of October 1919 and August 1951, and the probable local tsunami independently generated by a landslide on the same date as the latter tectonic tsunami.

Since the runups of the two 1951 tsunamis cannot be distinguished, they have been lumped, resulting in the consideration of the runups associated with six possible local-tsunami events:

1813-1814	October 1919
April 1868	August 1951
February 1877	November 1975

The criteria used in constructing profiles of these tsunamis, section by section in Figure 3, were:

Table 4. Runup Profile Criteria: West Hawaii

Events	Sites	Criteria
1813-1814	10-26	g(ii)
April 1868	0.5-47.7	b(ii)
February 1877	13-32	g(iii)
October 1919	3-16	g(ii)
	16	e(i)
	16-19.7	g(i)
	19.7	e(i)
	19.7-27.4	g(i)
	27.4-29	g(ii)
August 1951	11	g(ii)
	16	e(iii)
	18	e(iii)
	19.6	b(v), g(ii)
November 1975	0.5-24.5	g(i)
	24.5	d(ii)
	24.5-47.7	g(i)

Northeast Coast of Hawaii

At least five of the possible local tsunamis were observed on the northeast coast of Hawaii and two others probably had significant runups on this coast:

January 1854	September 1908
April 1868	November 1935
October 1868	November 1975
July 1869	

The tsunamis of 1854, 1908, and 1935 were generated off the northeast coast if they were indeed local tsunamis. Each of these was observed only at Hilo. It is uncertain whether the Hilo effects of 2 April 1868 were those of a tsunami independently generated at the same time as that of the major tsunami of the southeast coast. The October 1868 and July 1869 probable tsunamis were those for which high runups were estimated on the southeast coast. The 1975 tsunami was the major tsunami generated off the southeast coast on 29 November 1975.

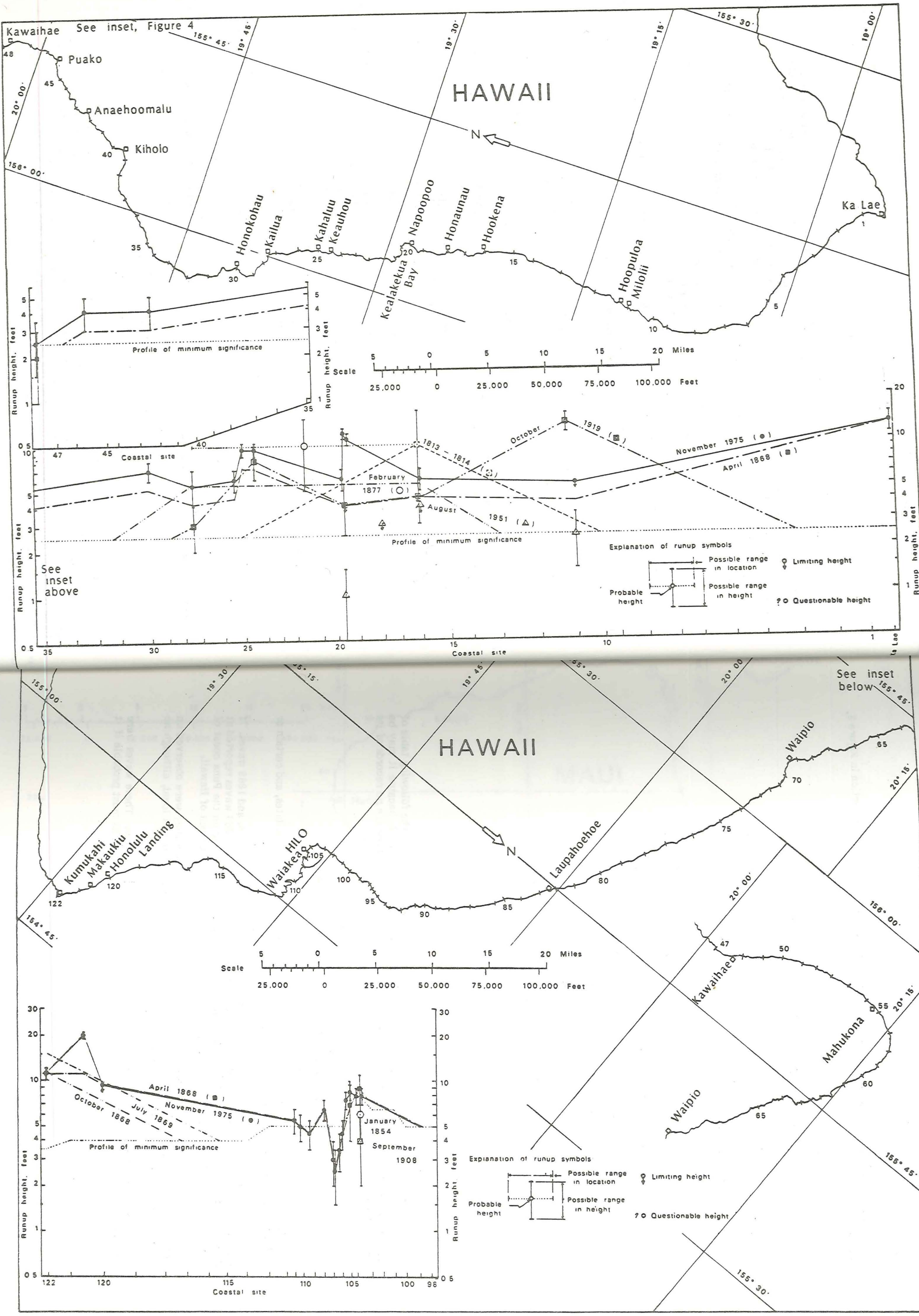


Figure 4. Reconstructed local-tsunami runup profiles, northeast coast of Hawaii.

The criteria used in reconstructing the profile of these tsunamis, section by section in Figure 3, were:

Table 5. Runup Profile Criteria: Northeast Hawaii

Events	Sites	Criteria
January 1854	103.7	g(ii)
April 1868	99-103.71 103.7-105 105-122	b(v), g(ii) b(v), g(i) b(i), b(v)
October 1868	117-122	g(ii)
July 1869	115-122	g(ii)
September 1908	103.7	g(ii)
November 1935	103.7	g(ii)
November 1975	99-103.5 103.5-122	g(ii) g(i)

Maui

Observations of six of the possible local tsunamis were reported on Maui. The following table of events of concern in this study includes a seventh, the tsunami of April 1868, because it may be assumed to have had runups similar to those of November 1975, although there are no records of its observation on Maui:

July 1848	January 1878
December 1860	November 1903
April 1868	November 1975
July 1869	

It seems certain that there were unusually high waves on each of the listed dates, and certain or highly probable that the waves were those of tsunamis.

A local source is as likely as a distant source in the case of the 1848, 1860, and 1869 waves. If the 1848 and 1860 origins were local, they were probably north of Maui. The 1869 waves reported at Kaupo on 24 July 1869 were probably the same as those reported as occurring on the Puna coast of Hawaii on the following day. The waves probably originated off the southeast coast of Hawaii.

The probability of a local source of the 1878 waves is slight. Because they were observed on Oahu as well as Maui, a source north of Molokai seems most probable if it was local, although no reports of waves from Molokai are known.

A local source is as likely as a distant one in the case of the 1903 waves. These waves were observed on the north coast of Molokai, and a source north of that island seems most probable if it was local.

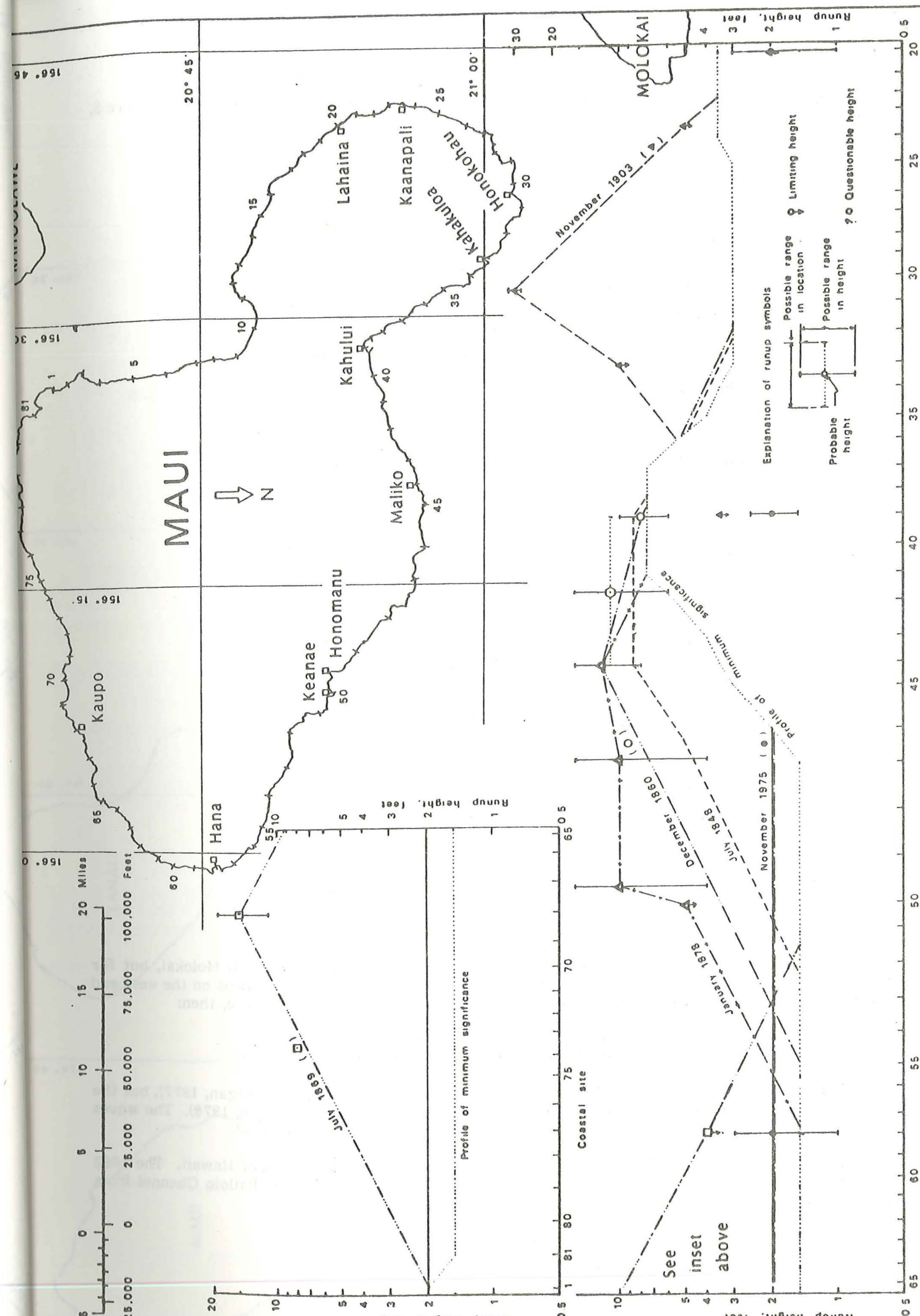


Figure 5. Reconstructed local-tsunami runup profiles, Maui.

The criteria used in reconstructing the profiles of these tsunamis, section by section in Figure 5, were:

Table 6. Runup Profile Criteria: Maui

Events	Sites	Criteria
July 1848	31-36	g(ii)
	36-47	g(iii)
	47-53	g(ii)
December 1860	32-39	g(ii)
	39-44	g(i)
	44-55	g(ii)
July 1869	49-58	g(ii)
	58	e(ii)
	58-67	g(i)
	67-82	g(ii)
January 1878	41-44	g(ii)
	44-50	g(i)
	50	e(i)
	50-58	g(ii)
November 1903	20	e(i)
	22-23.6	g(i)
	23.5	e(i)
	23.5-33	g(i)
	33	e(i)
	33-34	g(i)
	39	e(i)
November 1975		g(i)

Molokai

Only two of the possible local tsunamis listed in Table 1 were observed on Molokai, but for reasons indicated earlier, two others may be assumed to have had significant runups on the east end and north coast of the island. The tsunamis of concern on Molokai in this study were, then:

January 1862	November 1903
April 1868	November 1975

The possible 1862 tsunami was reported to have affected Oahu (Cox and Morgan, 1977), but the effects reported were actually on the southeast coast of Molokai (Cox and Morgan, 1978). The waves were more likely storm waves than those of a tsunami, and a local origin is doubtful.

The 1868 and 1975 tsunamis were those generated on the southeast coast of Hawaii. The 1903 tsunami was that which had a very high runup at Honokohau, Maui, across the Pailolo Channel from Molokai.

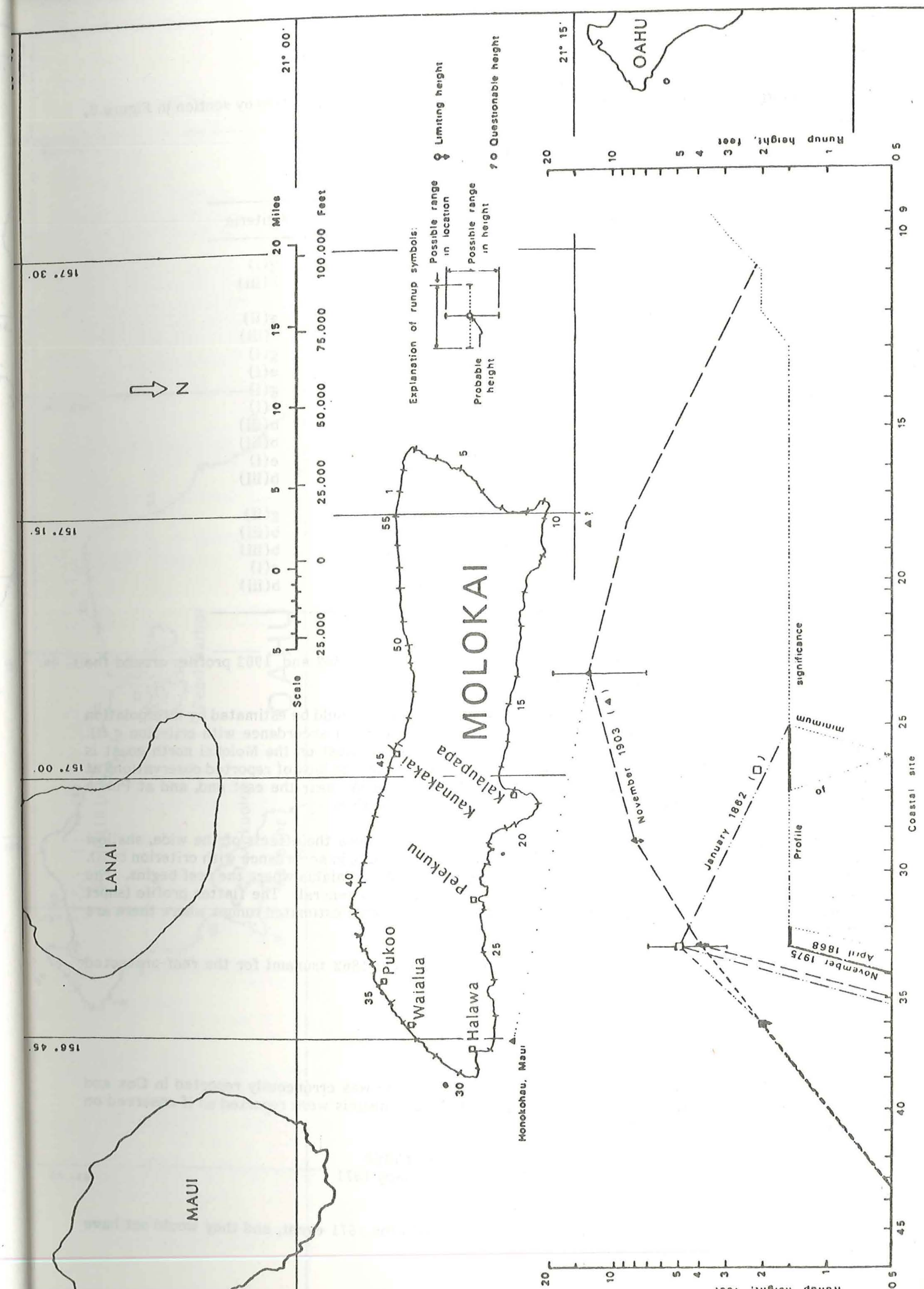


Figure 6. Reconstructed local-tsunami runup profiles, Molokai.

The criteria used in reconstructing the profiles of these tsunamis, section by section in Figure 6, were:

Table 7. Runup Profile Criteria: Molokai

Events	Sites	Criteria
April 1868	25-33	g(i)
	33-34	b(iii)
November 1903	10-18	g(ii)
	18	f(iii)
	18-28.5	g(i)
	28.5	e(i)
	28.5-32.7	g(i)
	32.7	e(i)
	32.7-35 generally	b(iii)
	32.7-36 at channels	b(iii)
	36	e(i)
	36-44 at channels	b(iii)
January 1862	25-32.7	g(ii)
	32.7-35 generally	b(iii)
	32.7-36 at channels	b(iii)
	36	e(i)
	36-44 at channels	b(iii)

The application of the criteria to the reconstruction of the 1862 and 1903 profiles around the east end of Molokai requires special explanation.

High runups of the 1903 tsunami on the east end of Molokai would be estimated by interpolation between the values at Pelekunu, Molokai, and Honokohau, Maui, in accordance with criterion g (i). (The location of Honokohau relative to Halawa and sites to the west on the Molokai north coast is indicated in Fig. 6.) However, limiting runup heights indicated by the lack of reported observations at Halawa, just north of the east end, at Waialua on the south coast near the east end, and at Pukoo farther west, had to be taken into account in constructing the profile.

In the reconstruction of the 1903 profile southwest of Halawa the effects of the wide, shallow reef fringing much of the south coast had to be taken into account in accordance with criterion b(iii). Two profiles are shown in Figure 6 for the coastline southwest of Waialua where the reef begins. The steeper profile (long dashes) represents the estimated runups in general. The flatter profile (short dashes), based on the estimated limiting runup at Pukoo, represents estimated runups where there are channels through the reef.

Two corresponding profiles are shown in Figure 6 for the 1862 tsunami for the reef-protected part of the coast for the same reason.

Oahu

Eliminating the possible tsunami of January 1862, which was erroneously reported in Cox and Morgan (1977) as affecting Oahu, five of the possible local tsunamis were reported as if observed on Oahu:

January 1878	April 1868
November 1903	February 1871
November 1975	

It is doubtful that unusual waves were associated with the 1871 event, and they would not have been significant if they had occurred.

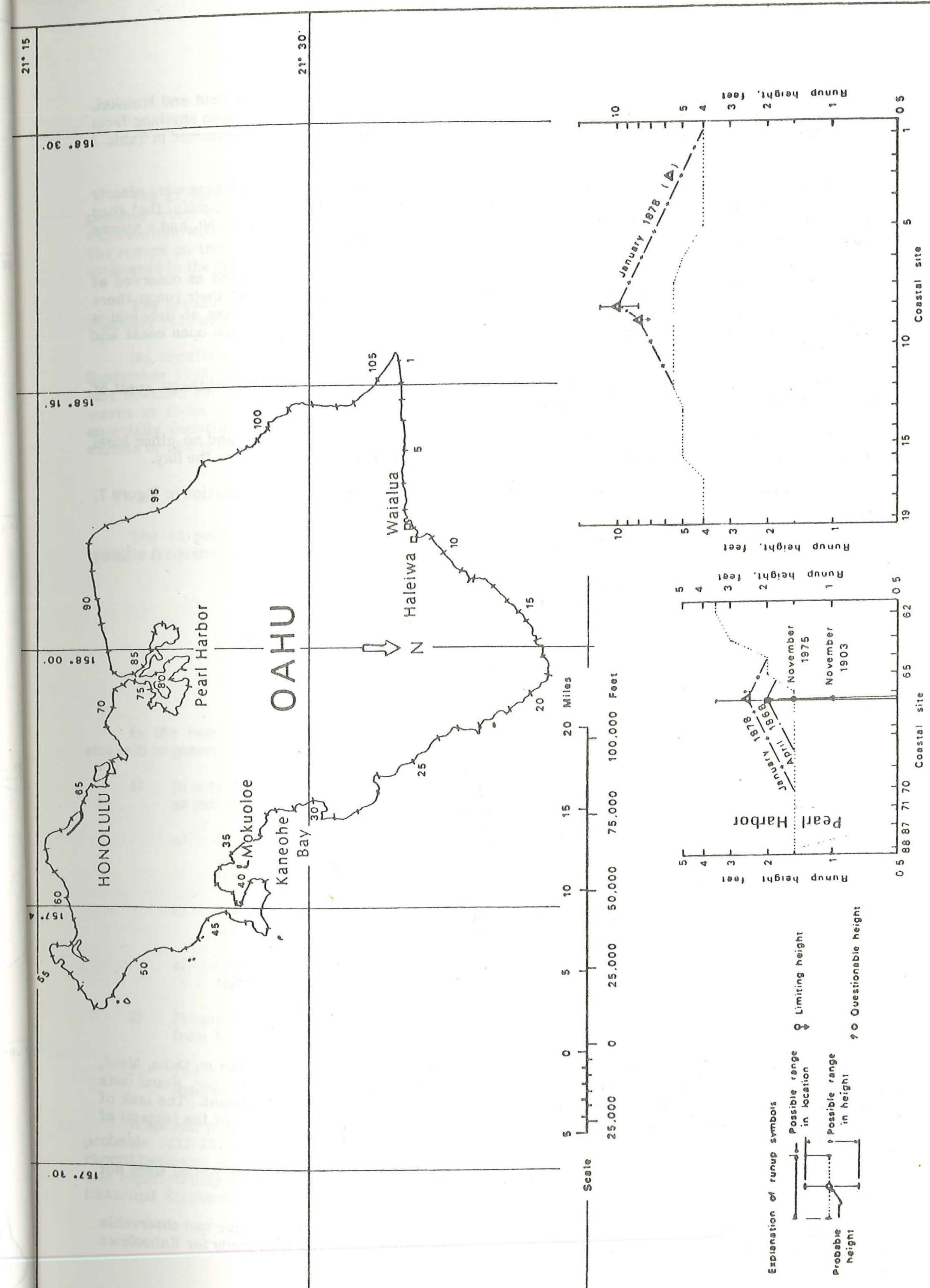


Figure 7. Reconstructed local-tsunami runup profiles, Oahu.

The November 1903 tsunami, which had high runups on the north coasts of Maui and Molokai, was recorded on the Honolulu tide gage. Its runup in Honolulu harbor might have been anything from ½ to 2 feet without resulting in reports of direct observation. The value of 1 foot assumed in Table 2 is not significant.

The event of greatest significance on Oahu was that of January 1878. High waves were clearly observed. They were more likely storm waves than those of a tsunami, and it is doubtful that they represented a local tsunami. The 1878 waves had higher runups on Maui than on Oahu, and a source north of Molokai is most probable if they represented a local tsunami.

The 1878 waves caused damage on Maui, far to the east, and were reported as observed at Honolulu, but the fact that that they caused no damage at Haleiwa suggests that their runup there was not as high there as the 1862 runup. The reported observation of these waves at Honolulu is somewhat doubtful. Their runup there was almost certainly less than 5 feet on the open coast and probably less than 2 feet in the harbor. A value of 2½ feet was assumed in Table 2.

The tsunamis of April 1868 and November 1975 were those generated off the southeast coast of Hawaii. Evidences of their occurrence on Oahu have already been discussed.

Because the runup of the 1975 tsunami was insignificant in Kaneohe Bay, and no other local tsunami probably had a significant runup there, no composite profile was prepared for the Bay.

The criteria used in reconstructing the profiles of these tsunamis, section by section in Figure 7, were:

Table 8. Runup Profile Criteria: Oahu

Events	Sites	Criteria
April 1868	64-66.2	g(ii)
	66.2	f(i)
	66.2-69	g(ii)
	71-88	b(iii)
January 1878	1-8	g(ii)
	8-8.7	g(i)
	8.7	e(i)
	8.7-12	g(ii)
	64-66.2	g(ii)
	66.2	a(ii)
	71-88	b(iii)
November 1903	66.2	a(ii), g(ii)
November 1975	35.7	a(ii), b(iii)
	66.2	a(ii), g(ii)
	71-88	b(iii)

Kauai and Other Islands

The only reported Hawaiian observation of a possible local tsunami other than on Oahu, Maui, Molokai, and Hawaii is the record of the November 1975 tsunami at Nawiliwili Harbor, Kauai (site 37), where its runup, as estimated from the marigraphic record, was barely significant. The lack of observations elsewhere suggested that neither the runups of that tsunami nor those of the tsunami of April 1868 on Kauai be considered consequential in this study.

For similar reasons, also discussed earlier, the April 1868 and November 1975 runups were not considered consequential on Lanai or on Niihau.

The April 1868, November 1975 and possibly the July 1869 tsunamis might have had observable runups on Kahoolawe, but no frequency distributions were estimated in the WES study for Kahoolawe sites.

VII. SUMMARY AND CONCLUSIONS

Summary of Results

The 21 possible local tsunamis listed in Table 1 are related to 19 event dates. The runups of the possible minor local tsunamis of 2 April 1868 and 21 August 1951 were considered in this study in combination with the runups of the certainly local tsunamis of the same dates. The significance of the runups on the 19 dates on various coasts, in relation to the tenth highest historic tsunami runups estimated in the WES study, is indicated in Table 9.

The probability that there were actually unusual waves is small only in the case of the 21 February 1871 event, and no significant possible runup is associated with this event.

No significant runups are known to be associated with the events of 28 January 1854, 20 September 1908, or 21 November 1935, and the maximum runup of the tsunami of 21 August 1951 just equalled the minimum significant runup at the same site. Although the identification of the waves as those of tsunamis is certain only in the case of one of the remaining 14 events, and especially doubtful in the case of the 28 January 1862 event, the occurrence of unusual waves is certain or nearly certain in all 14 cases.

Utilization of Results

The 14 possible local tsunamis that should be taken into account in revising the WES site-specific frequency distributions are:

1813-1814	24 February 1877
July (?) 1848	20 January 1878
1 December 1860	10-11 October 1903
20 January 1862	29 November 1903
2 April 1868	2 October 1919
1 October 1888	17 March 1956
24-25 July 1869	29 November 1975

In the revision, the use of the runup heights read from the reconstructed profiles for any site will in general be simple.

1) In a table listing in order, from highest to lowest, the ten highest runup heights at a site, as estimated in the WES study by Houston et al. (1977) for the historic tsunamis:

   a) For the WES value for any local tsunami disagreeing with the value for that tsunami indicated by its profile, the value read from the profile should be substituted, and the order of the runups should be rearranged if necessary.

   b) For possible local tsunamis not in the original list, runups read from the profiles should be inserted in the list.

   c) Ordinal numbers should be assigned to the ten highest runups in the revised list, $n = 1$ for the highest runup, $n = 2$ for the second highest, etc.

2) Frequency plotting positions for the ten highest runups at the site should be recomputed from $F = n/140$.

3) The A and B coefficients of the revised frequency distribution should be computed by least squares regression of runup height on log frequency.

A special problem arises in connection with the use of the reconstructed runup profile for the probable 1813-1814 tsunami. The WES frequency analyses were based on the 140-year period of record beginning in 1837, 23 or 24 years after the occurrence of that tsunami. The 1813-1814 tsunami was reported only at Hookena (Hawaii site 16) where its runup is estimated at 10 feet. The lack of historical information on the occurrence of other tsunamis at Hookena prior to 1837 has little

Table 9. Significance of Local Tsunami Runups...
in Estimating Site-Specific Runup Frequency Distributions

Tsunami event	Probabilities of occurrences of: Unusual waves	Probabilities of occurrences of: Tsunami	Significance on coastlines of*: SE Hawaii (Fig 2)	W Hawaii (Fig 3)	NE Hawaii (Fig 4)	Maui (Fig 5)	Molokai (Fig 6)	Oahu (Fig 7)	Kauai
1813-14	0.9	0.6		X					
1848 Jul	1.0	0.8				X			
1854 Jan 28	1.0	1.0			0				
1860 Dec 1	0.8	0.6				X			
1862 Jan 28	1.0	0.5					X		
1868 Apr 2	1.0	1.0	XX	X	X	x	x	x	
1868 Oct 1	0.8	0.8	XX		X				
1869 Jul 24-25	0.8	0.8	XX		X	X			
1871 Feb 21	0.2	0.2						0	
1877 Feb 24	0.8	0.8		X					
1878 Jan 20	1.0	0.7				X		X	
1903 Oct 10-11	0.8	0.8	x					0	
1903 Nov 29	1.0	1.0				XX	XX		
1908 Sept 20	1.0	1.0			0				
1919 Oct 2	1.0	1.0		XX					
1935 Nov 21	1.0	0.2			0				
1951 Aug 21	1.0	1.0		?					
1952 Mar 17	1.0	1.0	X						
1975 Nov 29	1.0	1.0	XX	X	X	x	x	?	0

*Significance on a coast is determined by relationship of maximum estimated runup of possible local tsunami at a site on the coast to runup of minimum significance (= 10th highest runup in Houston et al., 1977, analysis) at the same site as follows:

Symbol	Maximum estimated runup
XX	Exceeded runup of minimum significance by more than 10 feet. (In case of 1975 tsunami, exceeded runup assumed by Houston et al. by more than 10 feet.)
X	Exceeded runup of minimum significance by more than a foot at more than one site.
x	Exceeded runup of minimum significance at only one site or by a foot or less.
?	Equalled runup of minimum significance.
0	Was less than runup of minimum significance.

significance, particularly for the period before 1813-1814. However, from the fact that the 1813-1814 occurrence was considered noteworthy, it may be supposed that there had been no other event of similar magnitude for several years. The frequency distribution defined by the regression coefficients tabulated for site 16 by Houston et al. (1977) suggest that a 10 foot runup corresponds at Hookena to a 100-year average recurrence interval, but that in the 140-year period of more complete records there a tsunami whose runup was estimated at something like 12 feet was expectable. The same frequency distribution suggests that in a 23- or 24-year period, two tsunamis with runups equal to or in excess of the level of minimum significance (2 feet) would be expectable (with runups of 2½ feet and 5 feet).

Rather than discard the historical evidence of the 1813-1814 tsunami at Hookena, it would seem preferable to use it in the revision of the frequency distribution by a method suggested by Dalrymple (1960). The frequency plotting positions for all of the runup heights estimated for the period since 1837 that did not exceed 10 feet should be computed as indicated above. In the compilation of the frequency plotting position for the 10-foot runups of 1813-1814 and any higher runup occurring in the period since 1837, however, the denominator should be 160 rather than 140.

Two more problems arise in connection with the use of the reconstructed local tsunami runup profiles for Molokai:

(1) In computing the frequency distributions for sites on this island Houston et al. used only the three highest rather than the ten highest runups on the grounds that the lower runups did not follow the assumed exponential distribution. It would seem that, at least at sites on the north coast and east end of Molokai, where the runup of the November 1903 tsunami considerably exceeded the tenth highest runups estimated by Houston et al., the least squares regression should be applied to the four highest runups, including the November 1903 runups.

(2) Along the southeast coast of Molokai, two profiles have been reconstructed for the January 1862 and November 1903 events, one pertaining generally, the other pertaining to sites on shore opposite channels through the reef. The best use of these profiles depends upon how Houston et al. treated the reef effect in their analyses, which is not clear in their report.

Final Comments

The process of reconstructing the runup profiles of the local tsunamis and waves that might have been those of local tsunamis necessarily involved geophysical and common-sense judgments in the interpretation of historical information more than scientific analysis. Certain somewhat arbitrary assumptions were required; however, every attempt was made to make these rationally and systematically.

The alternative of disregarding all historical evidence of the local tsunamis other than runup measurements reported by scientifically trained observers would be irrational. Even in the case of the November 1975 local tsunami, for which by far the most complete record of such runup measurements is available, Cox and Morgan (1977) found it necessary to apply judgments of the kind described above, and additional judgments of the same kind were found necessary in this study. Without similar judgments, none of the possible local tsunamis would be represented by runup values at more than a very few sites, and most would not be represented at all. Yet in the case of all whose runups were significant in hazard zoning, there were clearly unusual waves, and it would be quite irrational to consider that the significant effects of these waves were restricted to a single locality.

Because judgments were so heavily involved, the criteria used in reconstructing the runup profiles of the local tsunamis have been explicitly described and their application section by section along the coast indicated in the report. Others interested may thus check the bases for the resulting runup heights estimated for any locality, and investigate the effects of making alternative rational assumptions.

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