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REGIONAL TSUNAMI EVACUATIONS FOR THE STATE OF HAWAII: A FEASIBILITY STUDY BASED ON HISTORICAL RUNUP DATA

Daniel A. Walker

Tsunami Memorial Institute

59-530 Pupukea Road

Haleiwa, Hawaii 96712

ABSTRACT

Historical runup data for the Hawaiian Islands indicate that evacuations of only limited coastal areas, rather than statewide evacuations, may be appropriate for some small tsunamis originating along the Kamchatka, Aleutian, and Alaskan portion of the circum-Pacific arc. With such limited evacuations most statewide activities can continue with little or no disruptions, saving millions in lost revenues and overtime costs, and maintaining or enhancing credibility in state and federal agencies. However, such evacuations are contingent upon accurate real-time modeling of the maximum expected runup values. Also, data indicate that such evacuations may not be appropriate for small Chilean tsunamis. Furthermore, data from other regions are thus far too limited for an evaluation of the appropriateness of partial evacuations for small tsunamis from those regions.

Introduction

Historical data indicate that tsunami runups are generally greatest along the northern coastlines of the Hawaiian Islands for earthquake originating in that portion of the circum-Pacific arc from Kamchatka through the Aleutians Islands to Alaska. A critical question is whether a statewide warning should be issued if tide gauge, magnitude, and modeling data predict a maximum runup of only 1 meter for some portions of those northern shores. [A one meter tsunami is generally considered by the scientific community and civil defense agencies to be a potentially life threatening phenomenon requiring a warning, if possible, of its arrival and location.] The answer to the question depends on the accuracy of the prediction and how much smaller the runups might be on those other coastlines. If the predictions are fairly accurate, and the runups are significantly smaller along those other coastlines, successful regional evacuations may be possible. Such evacuations would reduce the unnecessary chaos and business losses associated with statewide evacuations, as well as maintain credibility in the warning system. This report examines the relative runup values along differing shorelines for differing source location throughout the Pacific for which historical data is available. The primary data sources are the runup plots compiled for the State of Hawaii's Tsunami Observation Program (2002; and appended to this report); and the secondary data source is Lander and Lockridge (1989).

Analysis of Data from Source Areas Outside the Kamchatka to Alaska Portion of the Circum-Pacific Arc

<u>Chile</u>. The 1960 Chilean earthquake is the only event outside of the Kamchatka to Alaska region that produced a large number of reported runups on all of the major islands. In examining these data (see Appendix), it is clear that comparable values were measured on many coastlines. For example, on the northern, eastern, southern and western shorelines runups as high as: 13.5, 9, 14, and 8 feet, respectively, were reported on Kauai; 12, 9, 9, and 12 feet, respectively, on Oahu; 17, 10, 12, and 10 feet, respectively, on Maui; and 11, 35, 17, and 16 feet, respectively, on the Big Island. No values are reported for Molokai and Lanai – only damage to fishponds and beach houses, presumably on the southern shorelines. The next largest value to the 35' reading on the Big Island's east coast is 22', also in Hilo Bay. Outside of Hilo Bay the largest value on the east coast is 14 feet.

A Chilean earthquake in 1837 produced a tsunami with runups of 6.0, 2.5, and 2.5 meters in Hilo, Lahaina, and Honolulu, respectively. A Chilean earthquake in 1868 produced a tsunami with runups of 4.5, 1.8, and 1.6 meters in Hilo, Kahului, and Honolulu, respectively. A Chilean earthquake in 1877 produced a tsunami with runups of 3.7, 4.5, 1.5, 3.6, and 1.5 meters in Hilo, Kealakekua Bay, Kahului, Lahaina, and Honolulu, respectively. The 1906 Chilean earthquake produced runups of 1.5 and 3.6 meters in Hilo and Maalaea (Maui), respectively.

Data for the 1960 tsunami support the conclusion that aside from high values in Hilo Bay, the largest values along many differing coastlines throughout the State are fairly comparable. This conclusion is suggested by more limited data from other Chilean tsunamis. Thus, any 1 meter runup predicted anywhere in the State for a Chilean earthquake could be expected to produce 1 meter values along many other coastlines. Therefore, any effort to provide regional warnings, rather than a statewide warning, for an expected 1 meter tsunami from Chile would not be appropriate.

Japan. Another source area outside of the Kamchatka to Alaska portion of the circum-Pacific arc is Japan. The 1933 Sanriku earthquake produced values of around 3 meters along the Kona Coast, 0.5m in Hilo, 1.2m at Nawiliwili, and 0.3m in Honolulu. The 1896 Sanriku earthquake produced values of up to 5.5 meters on the Kona Coast, 2.4m in Hilo, 1.5m at Nawiliwili, and 0.5m in Honolulu. [There are only 10 data points for 1933 with 6 from the Big Island; and only 17 data points for 1896 with 11 from the Big Island.] The area of greatest danger would appear to be the Kona Coast. However, until more data is acquired, especially along other western shores, any effort to provide regional warnings, rather than a statewide warning, for an expected 1 meter tsunami from Japan would not be appropriate.

Other Source Areas. Aside from the Kamchatka to Alaska portion of the circum-Pacific arc, there are no other source areas providing sufficient data to test the possibility of regional evacuations. At best there are only a few data points for these other areas and the values are much less than 1 meter (Lander and Lockridge, 1989). The largest number of data points found is for a Kurils earthquake in 1963 (10 data points with the largest value at 0.4 meters). Runups reported for 1901 (3 values: 1.2, 1.2, and 0.1 meters) are probably for a local tsunami (Walker, 2000) and not as reported in Lander and Lockridge as being generated in Tonga.

Analysis of Data from the Kamchatka to Alaska Region

Analysis is now directed to the large quantities of data from the Kamchatka to Alaska portion of the circum-Pacific arc. Data for each island are examined beginning with the 1946 Aleutian event.

Kauai. For the 1946 tsunami, there are no runups at or in excess of 50 feet, 4 are at or in excess of 40', 13 are at or in excess of 30' (i.e., the same 4 that are more than 40' and an additional 9 that are between 30' and 40'), and 32 are at or in excess of 20'. The 40+'s extend from Haena almost to Nawiliwili with the 3 largest values along the north shore, the 30+'s extend from Barking Sands northward and down the east coast almost to Nawiliwili, and the 20+'s cover the same coastal areas as the 30+'s. Values in other areas of the island (i.e., the south shore) do not exceed 17 feet.

For 1952 (Kamchatka) much damage is reported for the north shore, but there are no reported runup values and there is no other information..

For 1957 (Aleutians) there is 1 runup in excess of 50' (actually meaning at or in excess of 50' here and in subsequent discussions of this and other runup heights, but the "at or" will hereafter be deleted), 1 in excess of 40' (the same one in excess of 50'), 3 in excess of 30', and 11 in excess of 20'. The 30+'s are all in the Haena to Lumahai area. The 20+'s extend from Hanakapiai to Wailua. Values elsewhere do not exceed 16'. Hanakapiai is about 15 to 20 miles northeast of Barking Sands and Wailua is about 7 miles north of Nawiliwili.

For 1964 (Alaska), there are only 8 values – all less than 10 ft. All are between Hanakapiai and Wailua.

For Kauai a large volume of data indicates that the largest values reported along the north shore are at least twice as large as the largest values along the southern shore from the south of Nawiliwili just to the west of Kekaha (approximately from Kawelikoa Point through Kekaha Beach Park). Thus this area could be excluded from an evacuation if modeling accurately determined that the maximum runups in other areas of the island were no more than 2 meters.

Niihau. There is very little data for Niihau. Until sufficient data becomes available, no shorelines should be excluded from any evacuation plans.

Oahu. For 1946 there are no runups in excess of 40’, 6 in excess of 30’, and 19 in excess of 20’. The 30+’s are just to the north and south of Kaena Point, and in the Makapuu and Koko Head area. The 20+’s are from Nanakuli up to Kaena Point along the North Shore through Kahuku, the north shore of the Mokapu Peninsula, and in the Makapuu and Koko Head area. Outside of these areas the only double-digit values are 14’ or less moving down from Kahuku nearly to Chinaman’s Hat, 12’ at Diamond Head, and 12’ at Barbers Point.

For 1952, there are no runups in excess of 30’, 1 in excess of 20’ just to the northeast of Haleiwa, and 16 in excess of 10’ from Nanakuli to Kaena Point to Kahuku down past Hauula, and at Koko Head. The largest values are in the Waialua and Haleiwa areas.

In 1957 there are no runups in excess of 40’, 1 in excess of 30’ at Kaena Point, 8 in excess of 20’ in the Kaena Point to Kahuku Point area, 24 in excess of 10’ from Kahe Point north to Kaena, east to Kahuku, down the east coast almost to Chinaman’s Hat, and in the Hanauma Bay area.

In 1964 values range from 6’ to 16’ along the north shore with the highest value at Waimea Bay, and the only other values being 4’ at Hauula and 3’ at Waiahole.

For Oahu, a large volume of data indicates that the largest values are at least twice as large as values along the Windward Coast from Chinaman’s Hat to Waimanalo, excluding the shorelines of the Marine Corps Air Station, and along the south shore from Hawaii Kai just to the west of Ewa Beach, (through Oneula Beach) excluding Diamond Head. Thus these areas could be excluded from an evacuation if modeling accurately determined that the maximum runups in other areas of the island were no more than 2 meters.

Molokai. For 1946, there is one runup in excess of 50’ and 5 in excess of 40’. These are on the northern shore. There are 16 runups in excess of 30’ and 26 in excess of 20’. These values are on the northern, western, and eastern shores. Values west of Waialua through Kaunakakai are far less than half of the largest values reported. No measurements are available for the Hale o Lono Harbor area. The only other tsunami from the Kamchatka to Alaska area reported on Molokai was a 9’ runup at Halawa Valley for the 1957 Aleutian event.

For Molokai, sufficient data indicates that the largest values are more than twice as large as the values from Waialua through Kaunakakai and Coconut Grove. Thus these areas could be excluded from an evacuation if modeling accurately determined that the maximum runups in other areas of the island were no more than 2 meters.

Maui. For 1946, there are no values in excess of 40’, 3 are in excess of 30’ (2 at Kahakuloa and 1 near Nahiku), and 25 are in excess of 20’ from north of Kapalua around to Kahului to Hana and to Kaupo. All of the values past Malama Bay, west of Kaupo, and through the western shores just past Lahaina are less than half of the largest recordings along the northern shores.

For 1952, the tsunami is reported only as observed with most of the damage in the Kahului area.

For 1957, there are no runups in excess of 20’, and 15 are reported in excess of 10’. One of the 15 is at Napili Bay north of Kapalua and the other 14 are in the Kahului area from the Waihee River to Maliko Bay. With the exception of a single 9’ reading at Kealia Pond, all of the runups past Malama Bay through the western shores to just past Lahaina are less than or equal to half the largest recordings along the northern shores (i.e., 17’, 16’, 16’).

For 1964, there are only single and low double-digit (10’ to 12’) readings in the Waihee River to Kahului area. The only other readings outside of the Waihee River to Kahului area were two 5’ readings midway between Maliko Bay and Hana.

For Maui, a large volume of data indicates that the largest values are twice, or in one instance nearly twice, as large as values from Mamalu Bay, west of Kaupo, westward through Makena, Wailea, and Kihei to north of Lahaina. It should be noted, however, that from Mamalu Bay to La Peruse Bay there is only one reading of 10'. The area north of La Peruse Bay (i.e., Makena, Wailea, and Kihei), west through Maalaea and Olowalu, and on to the north of Lahaina, (Kuunoa Point), could be excluded from an evacuation if modeling accurately determined that the maximum runups in other areas of the island were no more than 2 meters.

Lanai. For 1946, there are only two readings – 7' at Manele Bay and 7' at Kamaulapau Harbor. There are no other readings for tsunamis from the Kamchatka to Alaska region. Tsunamis from the Kamchatka to Alaska region expected to have values no larger than 2 meters elsewhere in the Hawaiian Island should not require an evacuation of the southern shores of Lanai.

Kahoolawe. There is no data for this island. Until sufficient data becomes available, no shorelines should be excluded from any evacuation plans.

Hawaii. For 1946, there is one reading of 50+' and 3 of 40+'. All are in the Waipio and Pololu Valley areas. There are 16 values of 30+' extending from Pololu down to the Hilo Bay area. There are 39 values of 20+' in these same coastal areas and extending further south to Kaimu and west from Pololu to just past Upolu Point. A single value of 20' is at South Point.

For 1952, values from 9' to 11' are reported in the Hilo area. The only other values are 3' at Kaimu, 2' at Kawaihai, and 2' to 4' along the Kona coast.

For 1957, there was one reading in excess of 30', 3 in excess of 20', and 26 in excess of 10'. These had the same distribution as the 1946 values.

For 1964, there were small readings except for three 6' readings near Mahukona, Upolu Point, and near Pololu Valley.

For the Big Island, a large volume of data indicates that the largest values are at least twice as large as values west of Kaimu along the Puna and Kau coastlines, with the exception of South Point, and up through the Kona and Kohala coasts just past Kawaihae. Thus, these areas could be excluded from an evacuation if modeling accurately determined that the maximum runup in other areas of the island were no more than 2 meters.

Tsunami Periods

It is generally believed that the period of the 1960 tsunami was longer than the period of the 1946 tsunami. Therefore, one might speculate that tsunamis from the north Pacific with longer periods could have comparable values on all coasts like the 1960 tsunami; and, conversely, Chilean tsunamis with shorter periods might have much larger values on southern or eastern shores. Table 1 gives historical data on the periods measured for the tsunamis described in this report. Not all of the 1960 tsunami's periods were long, nor were all of the periods from the north Pacific short. Modeling studies could determine the periods from differing regions of the Pacific, the possible variability in periods from differing regions for differing source mechanisms, and whether these differences would substantially alter the relative distribution of runups along differing shorelines in the Hawaiian Islands.

Conclusions

When modeling is capable of accurately predicting maximum runups in the Hawaiian Islands, marginal warnings may be improved to either reduce the number of warnings perceived to be false or the number of small, but potentially destructive tsunamis for which no warning may be issued. Although tsunamis just over one meter may occur only at one location or a small number of locations, existing State Civil Defense procedures require a statewide evacuation of all low lying coastal areas. Such warnings are not only expensive in business and tourism losses, work stoppages, and overtime costs, but are also the type of tsunamis expected to occur most frequently. Because of the small runups of these tsunamis and their personal and economic disruptions, credibility in the warning system and civil defense agencies will rapidly erode with the potential for major loss of life when a large tsunami does occur. One way to reduce the negative effects of warnings for these small ("gray") tsunamis is to eliminate statewide evacuations and evacuate only those areas expected to have runups of 1 meter or more. In this study historical data has been used to determine those areas most likely to be inundated by small tsunamis, thereby identifying those areas of the State that need not be evacuated and can continue with uninterrupted activities.

The results are as follows. Regional evacuations are possible for tsunamis originating in the Kamchatka to Alaska portion of the circum-Pacific Arc. Runups for the 1960 Chilean tsunami are somewhat uniformly distributed along all the coastlines of the Hawaiian Islands. Therefore a one meter runup from Chile type tsunamis on any coast could appear on many other coasts, negating the possibility of regional evacuations. Also, insufficient data prevents conclusions regarding regional evacuations for other source areas in the Pacific including the Japan region. For the Kamchatka to Alaska portion of the circum-Pacific arc, regional evacuations appear to be possible for Kauai, Oahu, Molokai, Maui, Lanai, and the Big Island. Insufficient data prevents any conclusions regarding regional evacuations of Niihau and Kahoolawe. Coastal areas not required to evacuate for marginal tsunamis appear to be the following: Kauai – from west of Nawiliwili through Kekaha; Oahu – along the windward coast from Chinaman's Hat to Waimanalo, exclusive of the Marine Corps Air Station, and from Hawaii Kai through Ewa Beach, exclusive of the Diamond Head area; Molokai – from Waialua west through Kaunakakai; Maui – from the north of La Peruse Bay through Makena, Wailua, and Kihei through Lahaina; Lanai – the south shore; the Big Island – west of Kaimu along the Puna, Kau, Kona, and Kohala coasts through Kawaihae, with the exception of South Point.

With such limited evacuations, major segments of the State's activities can continue with little or no disruptions, saving millions in lost revenues, overtime costs, and maintaining or enhancing credibility in Civil Defenses agencies and the Pacific Tsunami Warning Center. However, such regional evacuations are contingent upon accurate real-time modeling of maximum expected runup values. Finally, since those areas to be evacuated in the event of a small tsunami would be expected to have runups of less than two meters, practical considerations might suggest a reexamination of existing evacuation plans and road closures for some areas.

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Tsunami Technical Review Committee (2002). Field Guide for Measuring Tsunami Runups and Inundations, State of Hawaii, Department of Defense, Civil Defense Division, 23 pp + appendices.

Walker, D.A. (2000). Twentieth Century Ms and Mw values as tsunamigenic indicators for Hawaii, Sci. of Tsunami Hazards, 18-2, 69-76.

Table 1. Periods of Tsunamis Discussed in This Report *

		Period in Minutes				
Year	Origin	Hilo	Honolulu	Kahului	Nawiliwili	Other
1837	Chile	15	28	---	---	---
1868	Chile	10	---	---	---	20 min. for Molokai
1877	Chile	8	20	---	---	---
1896	Japan	6	20	---	---	10 min. for Kailua-Kona
1906	Chile	---	25	---	---	---
1923	Kamchatka	---	23	---	---	---
1933	Japan	15	15	---	---	10 min. for Kawaihae, Kailua-Kona, and Napoopoo
1946	Aleutians	15	15	---	---	15 min. for Waikiki; 10 min. for Waimea Bay, Kauai
1952	Kamchatka	27	38	21	---	20 min. for Pearl Harbor; 15 min. for Port Allen
1957	Aleutians	19	14	22	12	---
1960	Chile	30	33	18	15	27 min. for Coconut Is. (Oahu)
1964	Alaska	19	21	23	13	---

* Taken from Lander and Lockridge (1989).

Appendix: Sources of Historical Data and Documentation of Discrepancy Resolutions

Primary references, if available, were maps found in the tsunami archives at the University of Hawaii at Manoa in the School of Ocean, Earth Science, and Technology (SOEST). Data from field notes were originally put on to these maps that have scales of 1:62,500 (Kauai and the Big Island) and 1:24,000 (Oahu, Maui, and Molokai). These maps will, hereafter, for convenience sake be referred to as "quads". Some of the quads may not be originals. Some may be second or even third generations of the original quads. However, these data are the closest to the original field notes (also missing) that could be found. The data on the available quads have been color coded for the differing major tsunamis of 46, 52, 57, 60, and 64. Although some of the colors are fading, all are still readable. The values on the quads, as well as the values in all of the references cited, have been corrected to mean lower low water. Secondary references, hereafter referred to as A, B, and C, respectively, follow.

(A) Shepard, F. P., G. A. Macdonald, and D. C. Cox (1950). The Tsunami of April 1, 1946, Bull. Scripps Inst. Oceanog., Univ. of Calif. Press, 5 – 6. 391-528.
(B) Macdonald, G. A., F. P. Shepard, and D. C. Cox (1947). The Tsunami of April 1, 1946 in the Hawaiian Islands, Pacific Science, 1, 21-37.
(C) Loomis, H. G. (1976*). Tsunami Wave Runup Heights in Hawaii, Hawaii Institute of Geophysics, HIG-76-5, (*corrected and reissued January 1980), 95 pp.

Additional references follow.

Macdonald, G. A., and C. K. Wentworth (1954). The Tsunami of November 4, 1952, on the Island of Hawaii, Bull. Seismol. Soc. Amer., 44-3, 463 -469.

Fraser, G. D., J. P. Eaton, and C. K. Wentworth (1959). The Tsunami of March 9, 1957, on the Island of Hawaii, Bull. Seismol. Soc. Amer., 49-1. 79 - 90.

Eaton, J. P., D. H. Richter, and W. U. Ault, (1961). The Tsunami of May 23, ,1960, on the Island of Hawaii, Bull. Seismol. Soc. Amer., 51-2, 135 - 157.

Cox, D. C., and J. F. Mink (1963). The Tsunami of 23 May 1960 in the Hawaiian Islands, Bull. Seismol. Soc. Amer., 53 -6. 1191 - 1209.

Loomis, H. G., (1972). "The Major Tsunami in the Hawaiian Islands" in The Great Alaskan Earthquake of 1964 – Oceanography and Coastal Engineering, Nat. Academy of Sciences, Washington, D. C., 181 - 190.

Lander, J. F., and P. A. Lockridge (1989). United States Tsunamis (Including United States Possessions) 1690 – 1988, National Geophysical Data Center, Publication 41-2, Boulder, Colorado, 265 pp.

There are no missing quads for Kauai or Molokai. Four of 14 quads with data are missing for Oahu (Kahana, Kaneohe, Mokapu, and Ewa). Three of 14 quads with data are missing for Maui (Kahakuloa, Kipahulu, and Kaupo). Five of the 16 quads with data are missing for the Big Island (Honokaa, Kukaiau, Papaaloa, Papaikou, and Hilo). The "new" quad names may not be the same as the names of the missing old maps. [The existing old quads do not always have the same names as the new quads.]

Only data for 1946 is available for Molokai and Lanai. The Lanai quads, if they ever existed, are missing; but only two values were reported for this island (7' at Manele Bay and 7' at Kaumalapau Harbor). Niihau quads, if they ever existed, are also missing. Values of about 20' and 10' were reported for the 46 and 57 tsunamis, respectively. The locations for those readings is unknown.

There was much damage reported along the north shore of Kauai for the 52 tsunami. However, the only reported values were 10' at Wahiawa Bay and 1' at Port Allen (Lander and Lockridge, 1989). [Since Wahiawa Bay is on the south shore of Kauai right next to the 1' reading at Port Allen, the 10' value may be a typo, and possibly should be 1'.] There are no values reported for Maui for 52, but the greatest damage was reported in the Kahului – Spreckelsville area where the tide gauge went off scale (Lander and Lockridge, 1989). All of the quads and references were cross-checked for evidence of discrepancies. Greatest weight was given to the quads, then the secondary references, and finally the additional references. The following is a list of discrepancies, considerations and decisions.

General Observations. In the secondary references, a total of 472 locations statewide were found where runup measurements have been made for the 46, 52, 57, 60, and 64 tsunamis. Of these, 356 are for the 1946 tsunamis. Many of the locations for the 52, 57, 60, and 64 tsunamis (in C) are plotted as being the same as for the 1946 tsunami, and many are not. This seems to differ from island to island. For example, Kauai has many (51 out of 126) locations other than 1946 locations for the other tsunamis, while data for Oahu for all of the tsunamis is nearly exclusively plotted at 1946 locations. Only 2 of the 95 locations for Oahu were non-1946 locations. I don't believe it is possible for readings in 52, 57, 60, and 64 to have been taken at the same locations as in 1946 to the extent possibly inferred by anyone looking at the data in C. Some sort of clumping must have occurred, as Doak Cox and George Curtis have suggested (personal communication); and it is logical to do this for plotting and comparison purposes. Also, there is no point in trying to "unclump" the data. It may not be possible, the process would have its own errors, and there is no clear reason why it should be done.

Kauai

- There is a little bit of "clumping" for Hanalei Bay in C. These values have been "unclumped" using values on the quad.
- There is a value of 33' (1946) north of Mana in A. On the quad, in B, and in C it is 34'. [Decision: Change to 34'.]
- On the original quad, in A, and in C there is a single reading of 45'(1946) at Haena, but in B there are 2 distinct readings of 45' at Haena. [Decision: Ignore the 2nd reading.]

- At Haena there are values of 9’ and 14’ (1946) on the quad and in B. These are reversed in C. [Decision: Use the values on the quad.]
- The reading of 21’ (1946) at Kilauea Bay in C is not on the quad. [Decision: Delete.]
- The reading of 29’ (1946) south of Kilauea Bay in C is actually 32’ on the quad. [Decision: Use 32’.]
- At Moloaa there are readings of 30’(1946) in A, 30’ and 40’ in B, and 45’ (inland), 30’ (at shore), and 35’ on the quad and in C. [Decision: Use 45’. The designations “inland” and “at shore” are confusing. Do not use.]
- A value of 30’ (1946) south of Moloaa in A does not appear on the quad or in B or C. [Decision: Do not use.]
- For Kepuhi Point there are readings of 32’ (1946) in B, 32’(at shore) and 38’(inland) on the quad and in C. [Decision: Use 38’ and delete “inland”.]
- At Kalihiwai the value of 21’ (1957) in C was found to be 22’ on the quad. [Decision: Use 22’]
- In map 11 of C the 9 ½’ reading (1960) should be blank as it goes with the 2nd reading in map 1 of C. This is confirmed by the quad. [Decision: Blank it.]
- The 6’ reading (1960) on the north side of Anahola Bay in (C) is not on the quad. [Decision: Delete.]
- Three values south of Kapaa of 7” (1960) are on the quad, but one of these is 8’ in C. [Decision: Use 7’.]
- A value of 14’ (1960) at Hanapepe Bay in C is not on the quad. [Decision: Delete.]
- The value of 6 ½’ (1960) near the middle of map 8 in C is 9’ in Cox and Mink, but 6 ½’ on the original quad. Could have been rounded up to 7’, then a handwritten 7’ was misplotted as 9’. [Decision: Use 6.5’.]
- The value of 8’ (1960) near Kukuiula Bay in map 6 of C also appears on the original quad but shows up as a 7’ reading in Cox and Mink. [Decision: Use 8’.]
- Plotting from the original quad onto figures in C is extremely accurate for Kauai with no corrections for locations required.

Oahu

- Two values (1946) in Pearl Harbor are shown on quads and in A and B, but not in C (maps don’t go there). [Decision: Add these points.]

- A 12’ (1946) value near Maile Point on the quad and in A and B is not in C. [Decision: Add this data point which lies between values of 14’ and 16’.]
- There are 27’ (1946) and 6’ (1952) readings near Kahuku on the quad and in A and B but not in C. [Decision: Add these data points.]
- There is a 2’ (1946) reading on the east side of Kaneohe Bay in A and B but not in C. The quad map is missing. [Decision: Add this data point.]
- There are some duplicate readings in C east of Niu Valley not on the quad nor in other publications. [Decision: Delete these values.]
- There is no 3’ (1946) value for the Ewa Beach area in A or B but is in C. The quad is missing. Scale may be too small for plotting in A and B, or value thought to be too insignificant at the time, or a neighboring value of 3’already plotted may have suggested that plotting not necessary. [Decision: Put in the 3’ value.]

- In C (map 2) the 12’ (1960) north of Punaluu Stream is 7’ in Cox and Mink.The 12’ doesn’t fit with surrounding values. Also, 12’ would be the largest value on the entire eastern and southern coastlines. Perhaps a handwritten comma and a 7 was misplotted as a 12. Quad is missing. [Decision: Use 7’.]
- The 5’ (1960) value next to Koko Head in Cox and Mink is missing in C but is in the original quad but not in a secondary quad. [Decision: Use 5’.]
- A 5’ (1960) reading east of Diamond Head in Cox and Mink is missing in C and in the quad. [Decision: Do not use this 5’ value.]
- A 2’ (1960) reading on the west side of Kaneohe Bay in Cox and Mink is missing in C. Quadrangle map is missing. [Decision: Use 2’ value.]
- All locations in C follow the locations on the available quad maps with the exception of Hanauma Bay. They are on the northern edge in C and more toward the center of the bay on the quad. [Decision: Use the quad location

Molokai

- On the quad the 36’ value north of Kepuhi Bay is about 1 mile further north and the 13’ at Halena is about 1 mile further east than in C. [Decision: Move values to location indicated on quad.]
- There is an additional 9’ reading on the quad on the west side of Kalaupapa Peninsula not found in A, B, or C. [Decision: Add this value.]
- There are 7 additional values in B and C around Kalaupapa and 7 additional values in B and C along the southeastern coast that are not on the quads. These values may not have been plotted on the smaller scale map in A because of a lack of space. [Decision: Include these values.]
- A 36’ reading in B and C at the eastern edge of Molokai is 35’ on the quad. [Decision: use 35’.]
- A 30’ reading in C below the 36’ reading is 39’ on the quad and in A and B. [Decision: Use 39’].

Maui

- On the quad and in A and B, the value for Hana Bay is 13’ (1946). In C the value is 30’ [Decision: Use 13’]
- A and B have 24’ (1946) at Puuiki (South of Hamoa) but this value is not in C and the quad map is missing. [Decision: Add this value.]
- A value of 7’ (1960) is missing in C but is on the quad. [Decision: Add this value.]
- No values at Honokohau Bay or Nakalele Point on the quad, yet are in A, B, and C. Also a quad is missing for Kahakuloa that could have the missing values for Honokohau and Nakalele. This lost quad appears to be an odd one with borders overlapping the existing quads, probably including the Honokohau , Nakalele , and Kahakuloa areas. [Decision: Keep the values that are given in A, B, and C.]

- In addition, quad maps are missing from south of Hamoa south and eastward to La Perouse Bay. Data from C were checked against all original published sources for this area for the 46, 57, 60, and 64 tsunamis (there is little or no data for the 52 tsunami for Maui or Kauai). No discrepancies were found and the data from C were used for these areas of the coast.
- The 7' (1960) for Honolua Bay in Cox and Mink and on the quad is missing in C. [Decision: Add the 7' reading.]
- Plotting from the original quads onto figures in C is extremely accurate for Maui with no corrections for locations required.

Hawaii

- The 25' (1946) reading near Leleiwi Point in A and B is 20' on the quad and in C. Perhaps handwritten 0 was read as 5 in drafting. [Decision: Use 20'.]
- Readings of 7' and 11' (both 1946) for Kailua-Kona on the quad and in A and B are missing in C (no map for this area). [Decision: Use the 7' and 11' readings, and add a map that covers this region.]
- The 11' (1952) for Reeds Bay in Macdonald and Wentworth is missing in C, but is very close to a 9' reading in C consistent with other nearby
- readings. Quadrangle map is missing. [Decision: Not critical to add the 11' reading.]
- Just north of Keaukaha the 13' for 1952 in Loomis should be for 1957 as indicated in Fraser et. al. There is no 13' value in Macdonald and Wentworth for this location. Quad is missing. [Decision: Make 13' for 57 not 52.]
- The 2' (1952) reading for Kailua-Kona in Macdonald and Wentworth is missing in C (no map). [Decision: Add map and value.]
- At Kauhola Point the 10' and 27' (both 1957) readings in C are indicated as values for 1946 on the quad but are not in A or B (the papers for 1946 - on this small map not every data point could be shown, so they may have been deliberately deleted to reduce the visual clutter). They are in Fraser, Eaton, & Wentworth; and Eaton, Richter, and Ault (the papers for 1957 – but the 57,52,46 order may have gotten reversed). [Decision: Consider the primary source as valid, i.e., the 10' and 27' are 1946 values.]
- The 5' (1957) value for Kailua-Kona is on the quad but missing in Loomis (no map). [Decision: Add map and value.]
- For the two 7' (1957) readings in the Hilo map in Fraser et. al., no values can be found in Loomis but there are other larger values for 57 close to the same general area. Quad is missing. [Decision: Use C.]
- A 6' (1960) reading east of Upolu Point near Keawaeli Bay in C is not on the quad or in Cox and Mink. It is the same value and is at the same location as was reported in Loomis for the 1964 tsunami. [Decision: Do not use for 1960 and add for 1964.]
- A 12' (1960) reading at Pololu in Cox and Mink adjacent to values of 10' and 11' also in Cox and Mink, is not in C and does not appear on the quad. [Decision: Do not use.]
- The 8' (1960) reading in C near the fish pond at Waipio is not on the quad and may be carried over from an 8' value already indicated just to the west of the pond. [Decision: Do not use.]
- There is no map for Kailua values in C. There is an 8' (1960) value in Cox and Mink, and on the quad. [Decision: Add maps and value.]

- Values for 1964 are not plotted on any of the quads for the Big Island. Therefore, the primary data sources are the Loomis reports of 72 and 76.]
- In maps 9 and 10 of C, there is duplicate data for 46, 57, and 60. Map 9 has no value for 64, but map 10 has 3' for 64. The 3' value is in Loomis (1972). [Decision: Use the 3' value.]
- A reading of 2' (1964) at Puako Bay is in C but not in Loomis (1972) There is no map for this area in C. [Decision: Add map and 2' value.]
- On the quads, there are no values for Honuapo and only some values down to South Point. However, values are present at Honuapo and at other locations extending to South Point in C and in other publications. All of these addition points are in C. [Decision: Use these additional data points.]
- Plotting from original quads onto figures in Loomis extremely accurate for Hawaii. Only two locations had to be moved slightly (near Limukoko Point and Honomalino Bay).

Other data. The only other values for the above tsunamis in the Hawaiian Islands are for Midway: 6.2' in 1952, 1.6' in 1957, 2.0' in 1960, and 0.3' in 1964 (Lander and Lockridge, 1989). Also, flooding was reported at French Frigate Shoals in 1946 (personal communication, Pacific Tsunami Museum). There are no values from Midway for 1946. Thus far, the only other areas of the Pacific Rim (i.e., other than Kamchatka, the Aleutians, Alaska, and South America) producing double-digit runups in Hawaii were from the Japan earthquakes of 1896 and 1933. Values in excess of 5' were only observed in Hilo in 1896 and along the west coast of the Big Island with a maximum reported value of 18' in Keauhou for the 1896 tsunami (Lander and Lockridge, 1989).

Addendum:

Subsequent to completion of the above, field notes of Mink and Takasaki for the 1952 tsunami on Oahu were found in the SOEST archives, consisting of an 8 ½" X 11" map of Oahu on which 54 runups or water levels are indicated. Six of the values on that map are missing in C; but two values in C are not on Mink and Takasaki's map. However, the two additional values in C are identical to immediately adjacent values that do appear on Mink and Takasaki's map. Since a larger scale map may have been available for Loomis to work with in C, these values are retained in the new maps. Regarding the 6 missing values: (1) an 8' reading east of Kaena Pt. near the site of a 31' reading for 1946 has been added; (2) an 8' value in Waialua Bay immediately adjacent to a 13' value for 1952 was considered superfluous and not added; (3) a 10' value near Waialee and Sunset Beach between 13' and 10' values for 1952 was also considered superfluous and not added; (4) an 11' value just south of Hauula was larger than adjacent values for 1952 and was added; (5) a 1' value in Kaneohe Bay was considered superfluous and not added; and (6) a 5' value east of Diamond Head which was larger than surrounding values for 1952 was added. In C the only single values plotted were for the 1946 tsunami. Apparently, if any other tsunami had a unique location where the reading was taken, that value was either not plotted in C or was clustered at another location with other values for other tsunamis. Items (4) and (6) above are the only known remaining values that were not plotted in C because of their unique location.

Runups in the Hawaiian Islands
for
Large, Pacific-Wide, 20th Century Tsunamis

Runups given are estimated maximum heights in feet of water levels on land relative to sea level, produced by inland flooding of the tsunami's waves. Runups should not be confused with inundation limits (i.e., horizontal measures of the inland penetrations of a tsunami's waves). In low-lying areas, inundation can extend inland for several hundred yards. Source locations for these tsunamis are the Aleutian Islands (1946 and 1957), the Kamchatka Peninsula (1952), Chile (1960), and Alaska (1964). Runup data are not available for all of the islands. Further discussion of runups, data sources, and the sectional runup maps from which these island-wide maps were derived may be found in "Field Guide for Measuring Tsunami Runups and Inundations," State of Hawaii, Department of Defense, Civil Defense Division, Tsunami Technical Review Committee, 2002. Illustrations by Nancy Hulbirt, data compiled by Daniel A. Walker.

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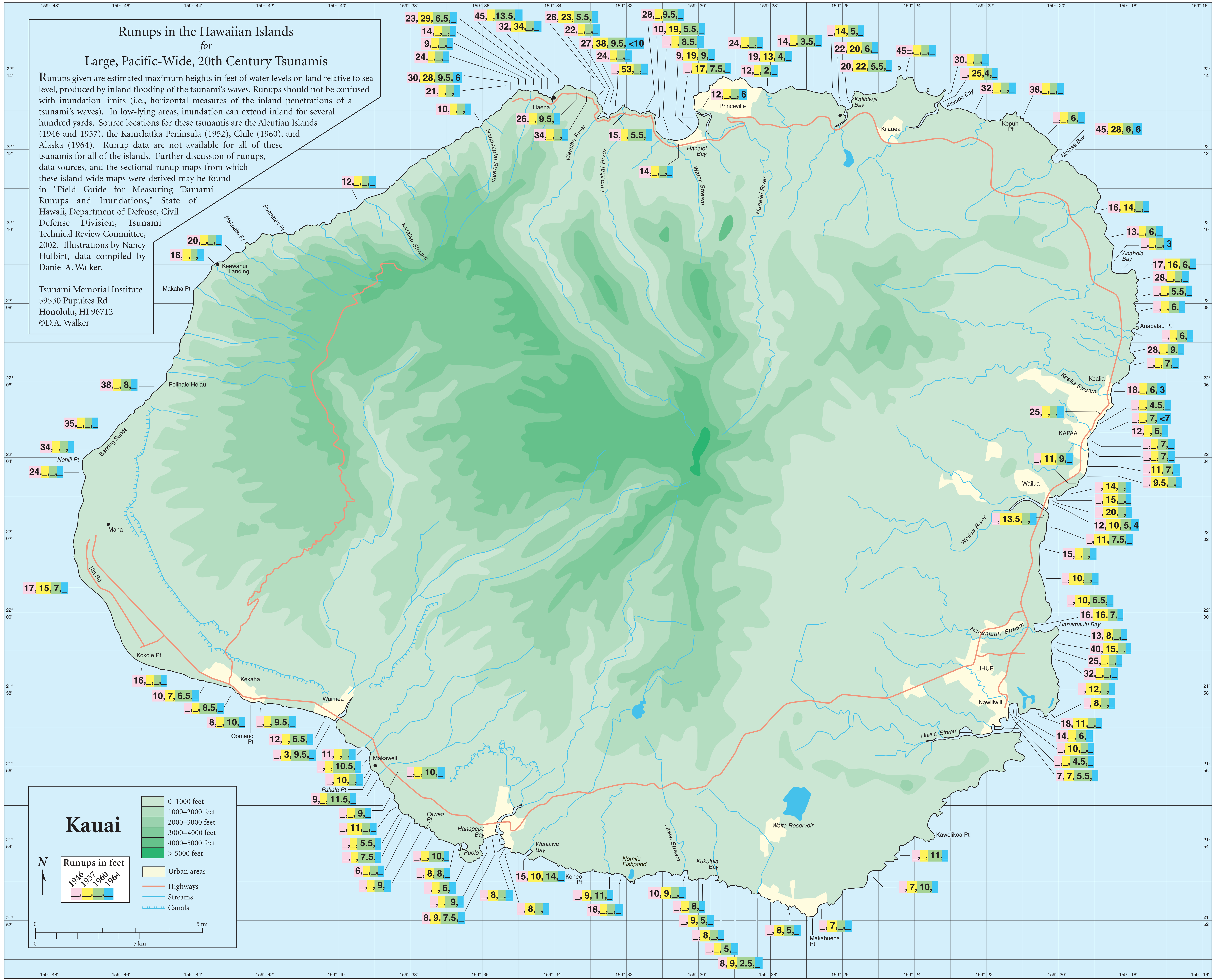

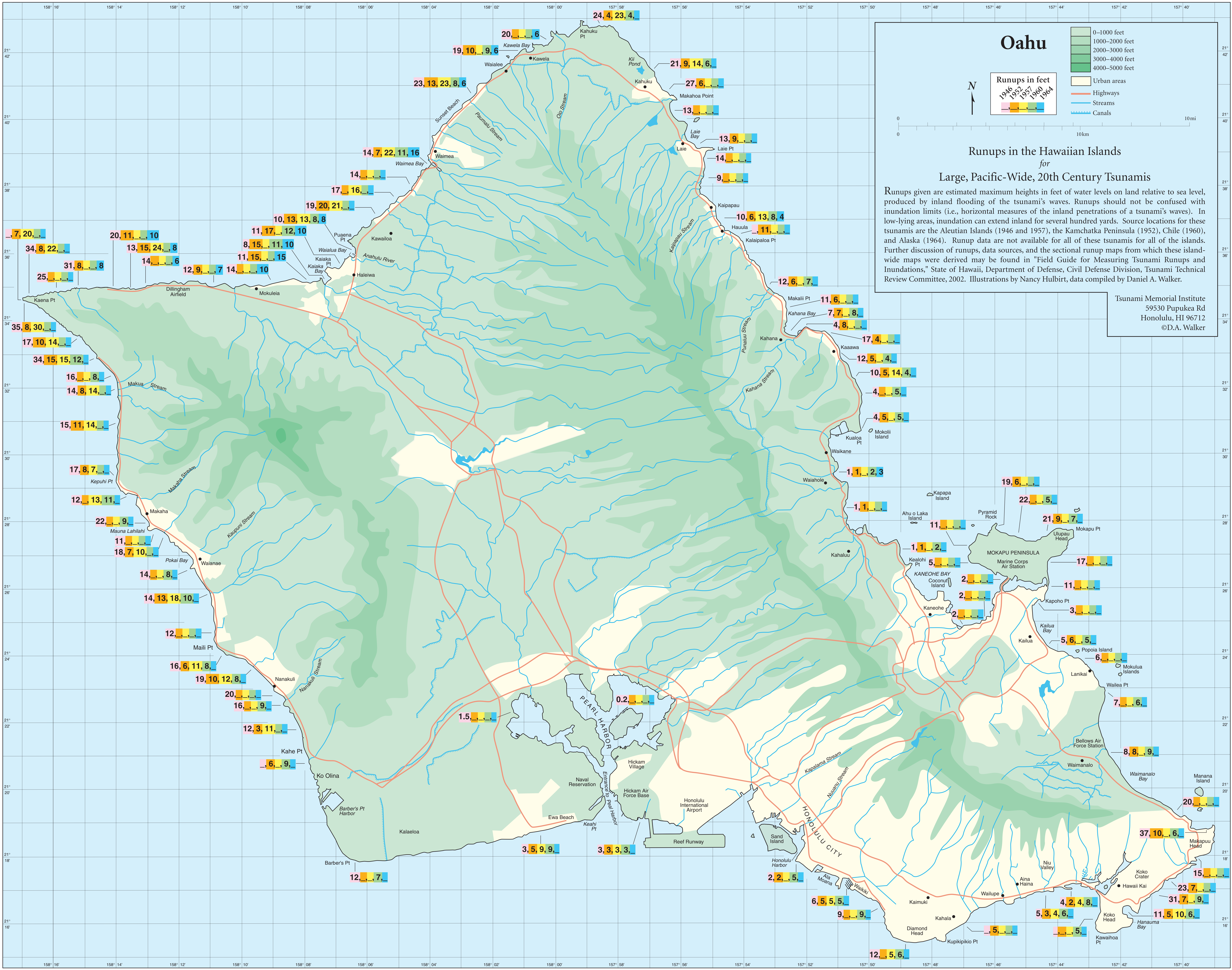

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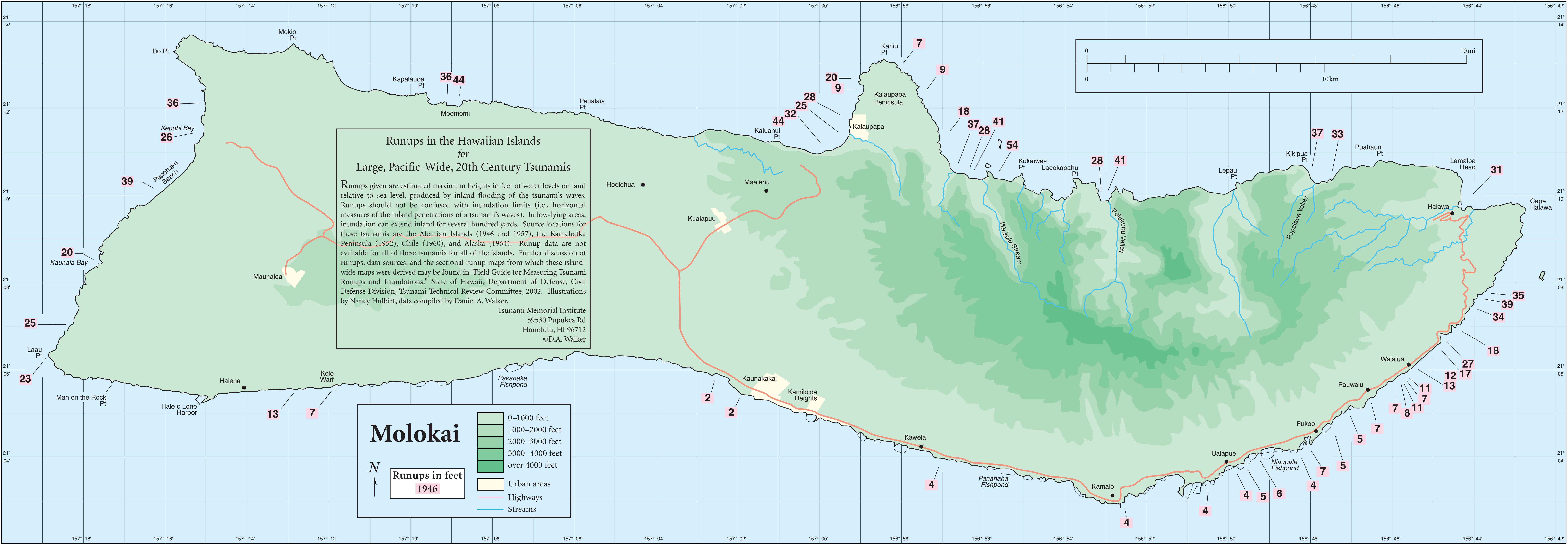

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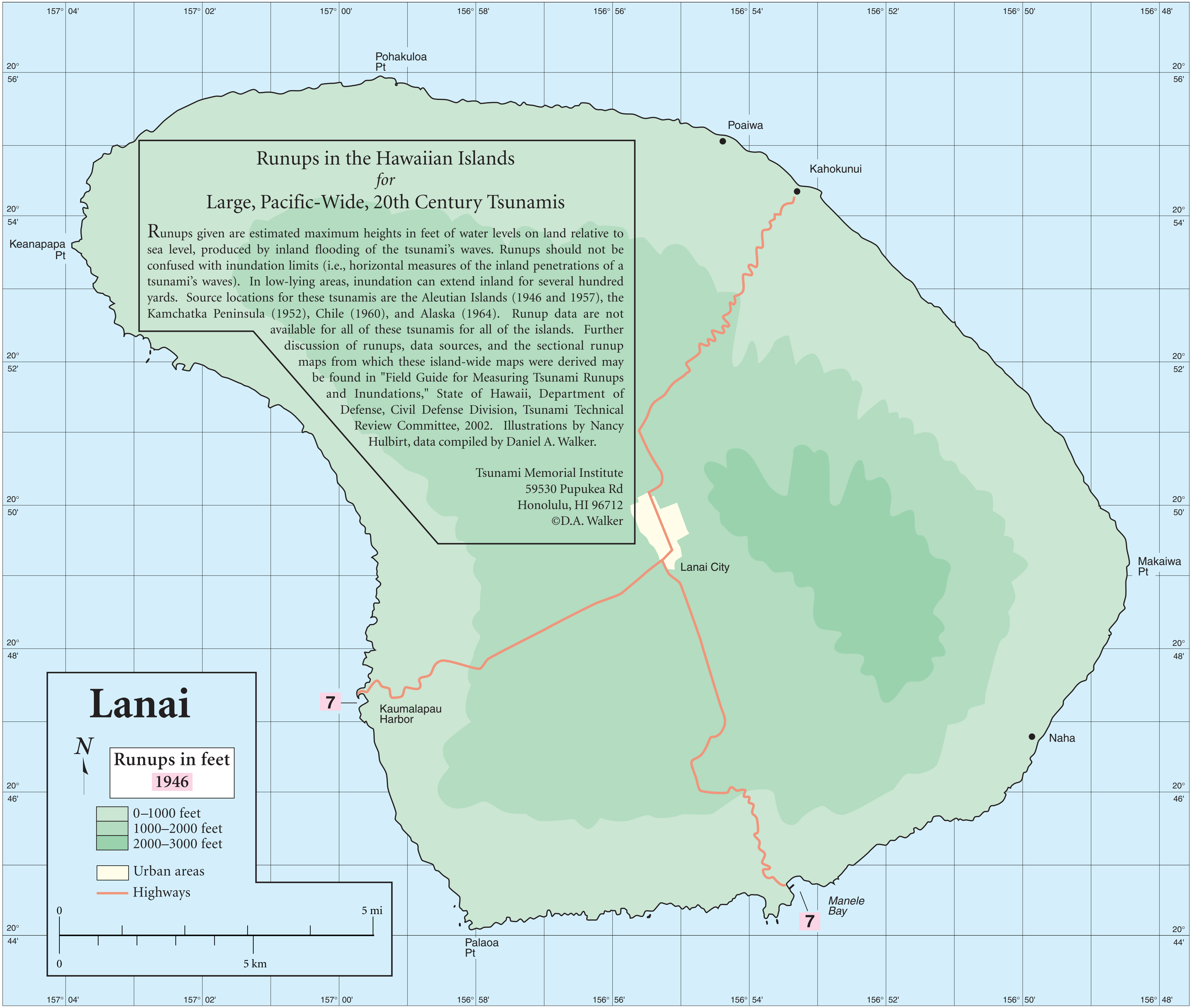

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Lanai

Runups in feet
1946

- 🟩 0–1000 feet
- 🟩 1000–2000 feet
- 🟩 2000–3000 feet
- ▭ Urban areas
- — Highways

Maui

Runups in the Hawaiian Islands
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Large, Pacific-Wide, 20th Century Tsunamis

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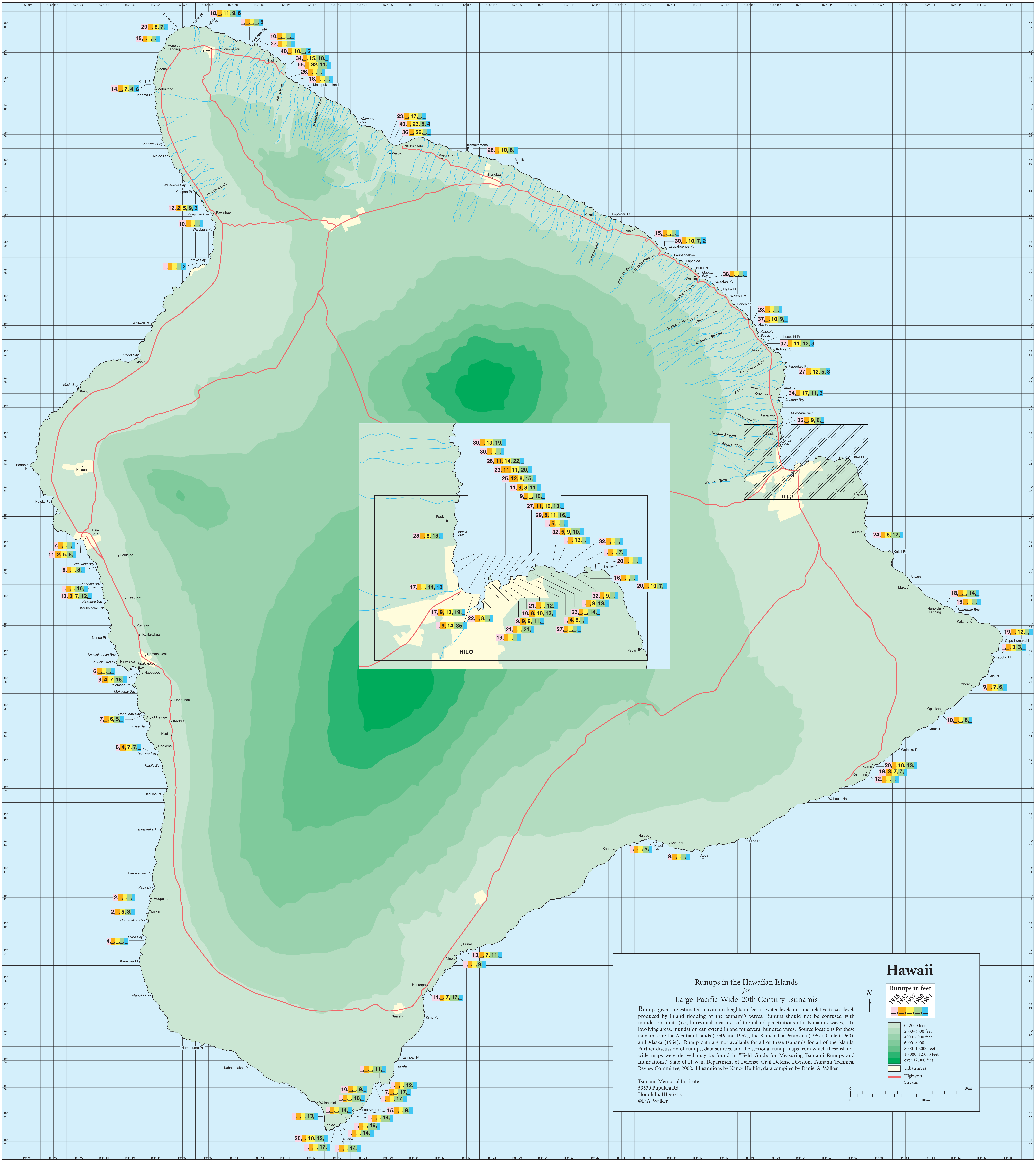

Hawaii

Runups in the Hawaiian Islands
for
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Honolulu, HI 96712

TSUNAMI DEPOSITS AT QUEEN'S BEACH, OAHU, HAWAII – INITIAL RESULTS AND WAVE MODELING

Dr. Barbara Keating
RM 314, Hawaii Institute of Geophysics and Planetology
2525 Correa Rd.
University of Hawaii
Honolulu, HI 96822, USA
bkeating@hawaii.edu

Dr. Franziska Whelan
Department of Physical Geography and Landscape Studies
University of Bamberg
Am Kranen 1, 96045 Bamberg, Germany
franziska.whelan@ggeo.uni-bamberg.de

Dr. Julie Bailey-Brock
Zoology Department
University of Hawaii
Honolulu, HI 96822 USA
jbrock@hawaii.edu

ABSTRACT

Photographs taken immediately after the 1946 Aleutian Tsunami inundated Queen's Beach, southeastern Oahu, show the major highway around the island was inundated and the road bed was destroyed. That road bed remains visible today, in an undeveloped coastline that shows like change in sedimentary deposits between 1946 and today (based on photographic evidence). Tsunami catalog records however indicate that the beach was repeatedly inundated by tsunami in 1946, 1952, 1957, and 1960. Tsunami runup was reported to have reached between 3 and 11 m elevation. Eyewitness accounts however indicate inundations of up to 20 m in Kealakipapa Valley (Makapu'u Lookout) during 1946 and photographic evidence indicated inundation reached 9 m in 1957. The inundation of Kealakipapa Valley has been successfully modeled using a 10-m tsunami wave model.

A comparison of the modern beach deposits to those near the remains of the destroyed highway demonstrate that the sedimentary deposits within the two areas have very different rock characteristics. We conclude the modern beach is dominated by the rounding of rocks (mostly coral) by wave activity. However, in the area that has experienced prior tsunami inundations, the rocks are characterized by fracturing and a high component of basaltic material. We conclude the area near the destroyed highway reflects past tsunami inundations combined with inevitable anthropogenic alteration.

Introduction

The sedimentologic investigation of tsunami deposits is a fairly new field of research (DAWSON 1999). The impact of tsunami waves on coastlines is unlike that of storm waves since tsunami waves have greater wavelengths and wave periods. If there is sufficient sediment supply, tsunami waves are constructive as they move inland, and transport a variety of grain sizes ranging from silt to large boulders. The retreating waves can remobilize and erode sediments.

Literature on tsunami deposits may be organized into three primary categories (WHELAN & KELLETAT 2003): large clasts (e.g. boulders), coarse and fine sediments (e.g. gravel, sand, silt), and other fairly obscure deposits such as wash-over fans. The nature of tsunami deposits is largely determined by sediment supply. The most commonly investigated tsunami deposits are fine sediments that, most frequently, occur as sediment sheets. Large clasts were reported by DAWSON (1994) immediately after 1992 Flores Tsunami in Indonesia. BRYANT et al. (1992) observed anomalous boulder masses, highly bimodal mixtures of sand and boulders, and dump deposits consisting of well-sorted coarse debris along the Australian coast and attributed them to tsunamis. Additional boulder deposits were attributed to tsunamis by PASKOFF (1991) in Chile, by JONES & HUNTER (1992) on the southern shore of Grand Cayman Island, by HEARTY (1997) along the coastline of North Eleuthera Island, Bahamas, by NOTT (1997 and 2000) on the Australian coast, by SCHEFFERS (2002) on Aruba, Curacao, and Bonaire, by WHELAN & KELLETAT (2003) on the southern Spanish Atlantic coast, and others.

Most geomorphic or sedimentologic studies have been carried out on tsunami deposited sediment sheets. Worldwide, the majority of research has been conducted along the coastlines of the Pacific Ocean, especially along the North American Pacific Coastline (e.g. CLAGUE 1997; ATWATER & MOORE 1992; DARIENZO & PETERSON 1990; NICHOL et al. 2002). Other notable studies include the deposition of sediment sheets investigated by SHI et al. (1995) who studied sediment accumulations after the 1992 tsunami of Flores, Indonesia.

Both boulder deposits and coarse tsunami deposits were observed in the Queen's Beach coastal zone located on southeastern coast of the island of Oahu, Hawaii (Figure 1). Queen's Beach was inundated by tsunamis at least four times during the last century, by the Aleutian tsunamis of 1946 and 1957, the 1952 Kamchatka Tsunami, and 1960 Chile Tsunami. This study identifies tsunami deposits that provide new insights into the runup of past tsunamis in the Queen's Beach coastal zone.

The Queen's Beach locality is of interest since it is the site of known historic tsunami activity with deposits photographed during and immediately after the 1946 tsunami. This paper presents initial geological investigations of the Queen's Beach locality, which were undertaken 1.) to document the nature of historic tsunami deposits within the Hawaiian Islands, 2.) in search of a modern analogy to the controversial marine conglomerates on the island of Lanai (MOORE & MOORE 1984, 1988); and 3.) to better understand the nature of the ash-dominated coastal zone of southeastern Oahu.

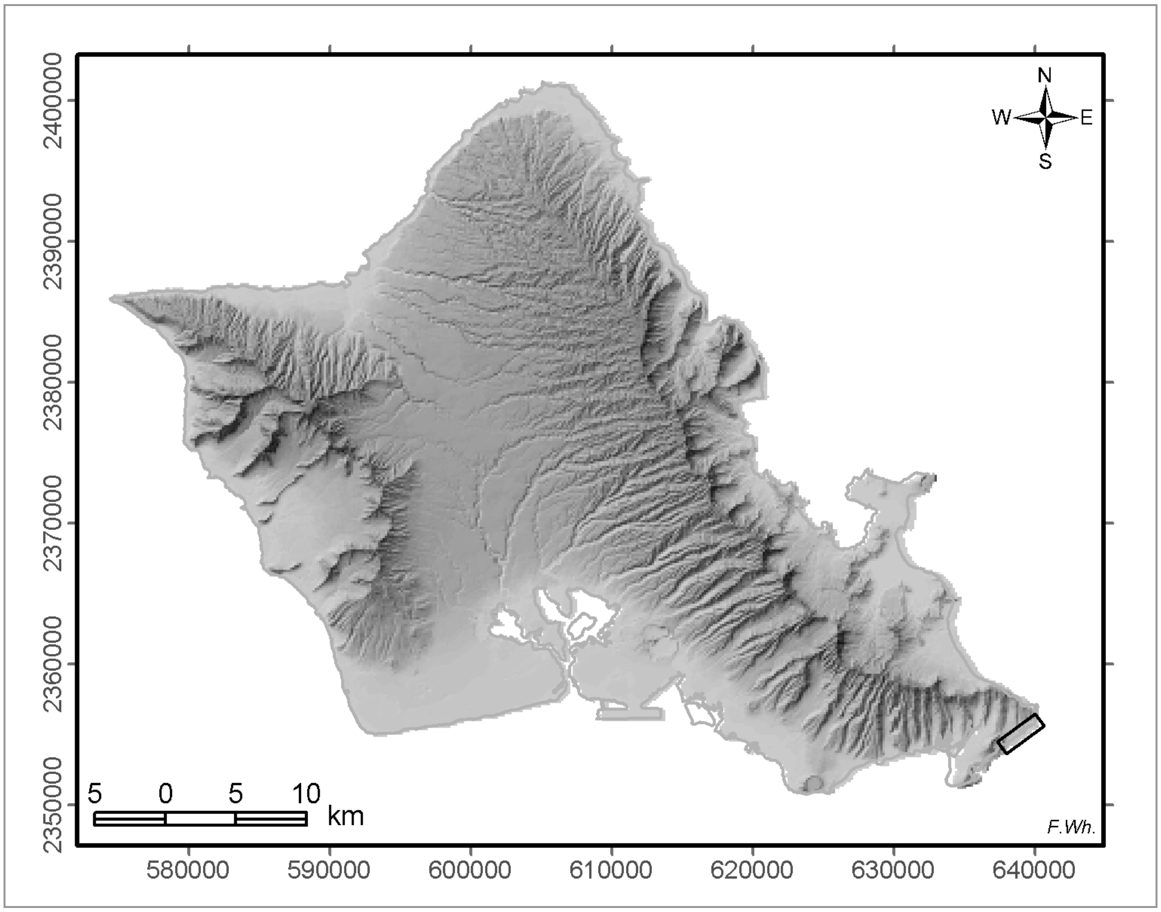

Figure 1: Location of the Queen's Beach coastal zone (small box at lower right) on the Island of Oahu, Hawai'I (UTM, WGS84).

Study Area

The coastal plain between Sandy Beach and Makapu'u Head is referred to as Queen's Beach. Queen's Beach currently displays geomorphic and sedimentologic evidence for tsunami impacts, however the area is destined to become the site of the Ka Iwi Regional Park. Honolulu City and County, as well as state and federal agencies intend to preserve the coastal zone as a park and nature preserve. The proposed park will include shoreline access, a visitor center, paved parking lots, access to Makapu'u Lighthouse, footbridges over high water areas, a system of bike and hiking trails, reforestation, re-vegetation, and interpretative signs.

The study area is located within the Tsunami Inundation Zone (Figure 2), which is defined as an area subject to flooding by the 100-year tsunami (Insurance Rating V22; U.S. DEPT. OF HOUSING AND URBAN DEVELOPMENT 1980; CITY AND COUNTY OF HONOLULU, DEPARTMENT OF PARKS AND RECREATION 1984). The nature of historic tsunami inundation is of particular interest here since the proposed park is likely to greatly alter geomorphic and sedimentologic tsunami evidence due to new construction and increased use.

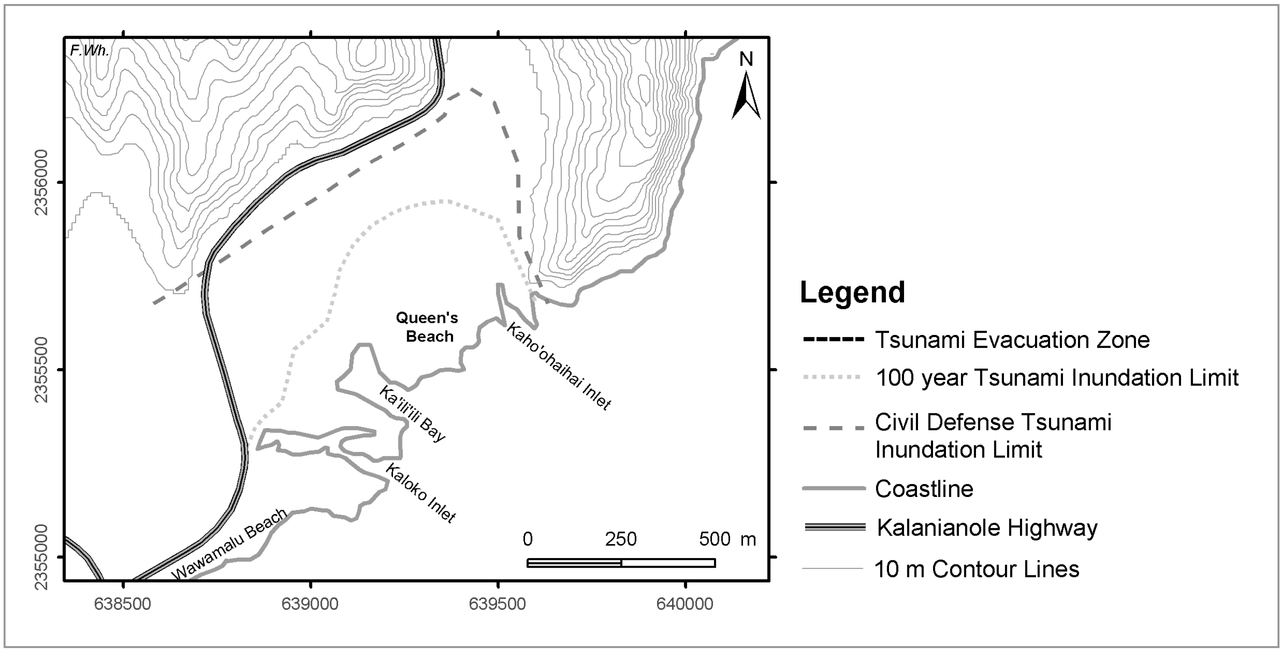

Figure 2: Tsunami inundation limits and tsunami evacuation zones within the Queen's Beach Coastal Zone (UTM, WGS84). (Tsunami Evacuation Zone data were provided by the State of Hawaii Civil Defense and published in County Telephone Directories by GTE in 1991.)

Historic tsunami impacts

As illustrated in Figure 3, the Queen's Beach coastal zone was inundated by tsunamis at least four times during the last century, involving the Aleutian tsunamis of 1946 and 1957, the 1952 Kamchatka Tsunami, and 1960 Chile Tsunami.

The 1946 Aleutian Trough Tsunami originated in the northern slope of the seafloor trough, south of Unimak Island, Alaska. As a consequence of the tsunami, more than 150 people were killed in the Hawaiian Islands, 163 people were injured, and property damage exceeded 25 million dollars (Macdonald et al., 1947). Based on Shepard et al. (1950), who reported on the affects of the April 1, 1946 tsunami at Queen's Beach, the tsunami waves reached 11.1 m (36.4 ft) above sea level (asl) on the north side of Makapu'u Head, 5 m (15 ft) at Kaloko Point located 1.6 km (one mile) southwest of Makapu'u Point, and 9.3 m (31 ft) asl at Koko Head. Since the tsunami originated north of the Hawaiian Islands, both Kaloko Point and Koko Head were affected by tsunami waves that wrapped around the island (Figure 3 and Shepard et al. 1950). Based on eyewitness testimony from Alan Davis, the waves inundated the coastal plain and ran northward up the slope of Kealakipapa Valley (Clark 1997). The tsunami destroyed all of the recorded archaeological sites within the coastal plain.

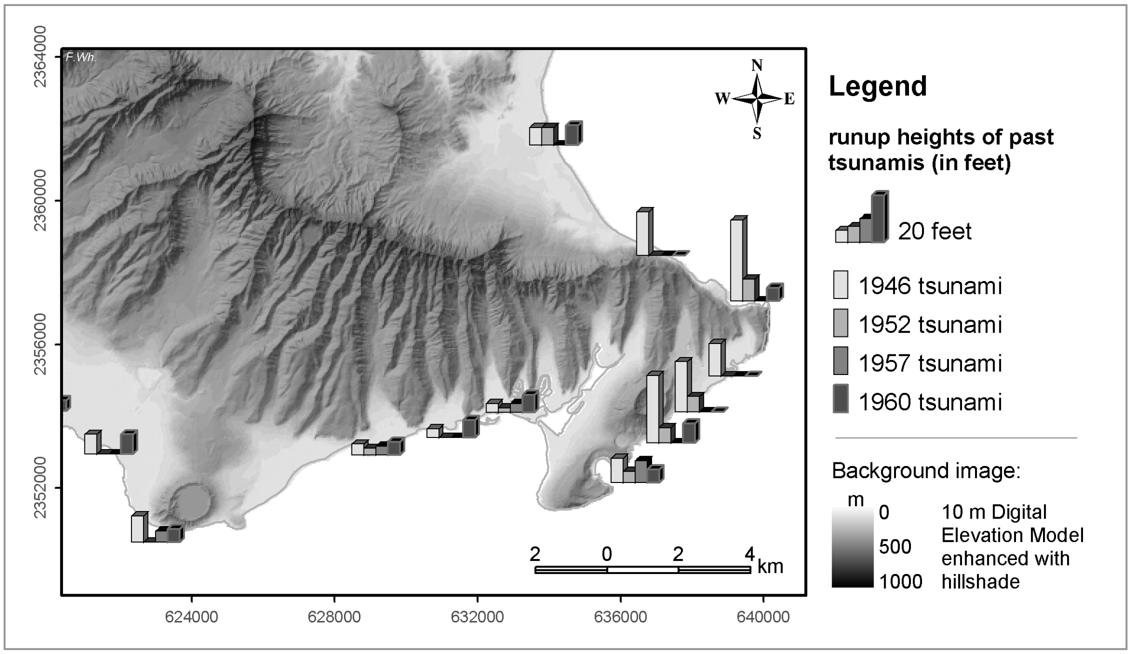

Figure 3: Tsunami wave runup heights in the vicinity of Queen’s Beach (UTM, WGS84). (Data based on Harold G. Loomis 1976, digitized by Office of Planning Staff in 1999.)

SHEPARD et al. (1950) published photographs of tsunami debris on the coastal highway along Queen’s Beach and the bay northwest of Makapu’u Head (Plates 15 a and b in SHEPARD et al. 1950, respectively). The appearance of the remnant of the coastal highway immediately after the 1946 tsunami was hardly different from the present (Figure 4). Blocks of basalt, coral, and pavement are clearly visible on the surface despite repeated tsunami inundation and continued use of the coastal zone by hikers, fishermen, and swimmers.

The 1946 tsunami demolished a group of houses just inland of Queen’s Beach. One of the owners, Alan Davis, waded through water up to his armpits escaping the advancing wave. While most of the houses were swept inland and deposited in form of debris piles against trees roughly 150 m (500 ft) inland, at least one house was swept out to sea. Arriving at Makapu’u Gap (modern day parking area and lookout) Mr. Davis and his family watched as the following wave completely destroyed their home. The next wave rolled up almost the entire length of Kealakipapa Valley. Fearing the next wave would wash up the valley and top the gap, the family drove up to the lighthouse near the top of Makapu’u Ridge (Clark 1997). Jagger (1946) reported that the Honolulu tide gauge recorded 20 fluctuations in four hours.

The 1946 tsunami seemed to have considerably affected the geomorphology of the Queens Beach coastal zone. Based on a photograph published by Shephard et al. (1950, Plate 15a), much of the asphalt highway, constructed in 1932, was washed out by the tsunami. Steep beach faces were left, and large sand dunes were truncated, leaving steep seaward cusps. Recorded runup was extremely high for the coastal zone immediately to the southwest of Queens Beach. In between Queen Beach and

Hanauma Bay, runup was recorded at 9.3 m (31 ft) and (6.9 m) 23 ft for the 1946 tsunami (WALKER 1994 and 2003).

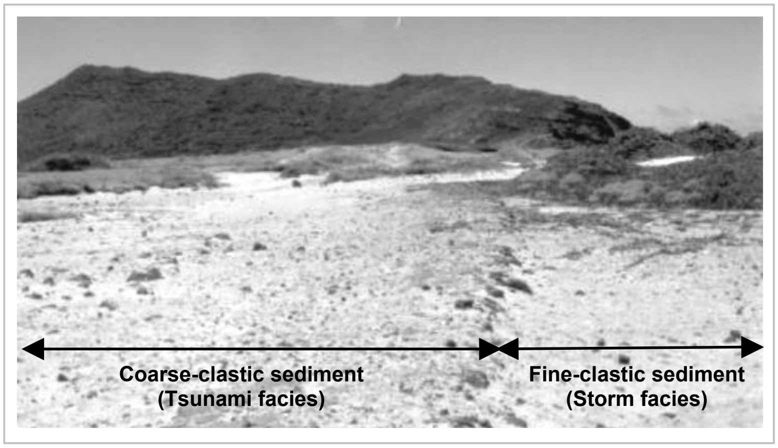

Figure 4. A modern photograph of the tsunami deposits and the destruction of the old highway that occurred as a result of the April 1, 1946 tsunami.

Subsequent tsunamis also inundated the Queen's Beach coastal zone. For example, WALKER (1994) reported a runup of 3.3 m (10 ft) asl at Makapu'u Point from the 1952 tsunami. The U.S. ARMY CORPS OF ENGINEERS (1978) studied the historical recurrence of tsunami around the Hawaiian Islands and suggests that Queen's Beach is likely to be inundated every 25 years by tsunami waves of 2.4 m (8 ft) asl and every 100 years by a tsunami with wave heights of 6.6 m (22 ft) asl.

Geology of the coastal zone

The Queen's Beach coastal plain extends from Koko Head to Makapu'u Ridge (the eastern-most extent of the Koolau Mountain Range. The Koolau mountain ridge consists of volcanic lava flows, vent breccias, and dyke intrusions associated with the caldera complex. The Koolau volcano is of late Pliocene or early Pleistocene age (activity ceased one to two million years ago, MACDONALD et al. 1983). Volcanic activity resumed in the eastern end of the Koolau Range after a roughly 1-2 million-year-long period of post-volcanic erosion, during which the Nuuanu Pali (cliff) was formed, and the Honolulu Volcanic Series became active. This Series consists of cinder, spatter, and ash cones, and lava flows (see Figure 5-8 in STEARNS 1985). Koko Head, Hanauma Bay Crater, Kahauloa Crater, and Kalama Cinder Cone belong to the Honolulu Volcanic Series (MACDONALD et al. 1983). MACDONALD et al. (1983) reported that Honolulu Series lavas have ages ranging from 500,000 (Black Point) to 32,000 yrs (Kaupo Lava Flow near Makapu'u Point). There is a great deal of difficulty in dating these young volcanic rocks so the ages are subject to large errors. OZAWA, et al. (2003, abstract) carried out new K-Ar age determinations on Honolulu Volcanic Series rocks in the Queen's Beach coastal plain, that indicated the age of the volcanic rocks should be close to 100,000 yrs.

Immediately southeast of Makapu'u Ridge, the coastal plain associated with the Honolulu Volcanic Series is underlain by Kalama lava flows and Honolulu Volcanic series ash deposits that extended the shoreline of the island between up to 1 to 3 km to the south and east. Because this coastal zone is constructed largely of soft ash deposits, coastal erosion processes and repeated sea level changes have eroded the rock formations leaving wave-cut notches, sea stacks, beach deposits, and wave-cut platforms in the coastal plain.

Geomorphology of the Queen's Beach coastal zone: field investigations

The Queen's Beach coastal zone displays several distinct morphological units (Figure 5):

1.) The lowest unit, an alternating rocky and sandy beach, as well as a near-shore storm ridge consisting of coral boulders and sand dunes, is associated with modern sea level. There, sands and coral rubble display a bleached white color.

2.) Along the rocky shoreline, beach sands cemented together with basalt and coral clasts and abundant sea shells form isolated and limited inliers (a group of rocks surrounded by rocks of younger age). These inliers of cemented beach sands occur where fresh water is discharged at sea level, facilitating the diagenesis (chemical alteration) and cementation of sand-dominated deposits into beach rock.

3.) A platform truncated at a level of roughly 5.7 to 6 m (19 to 20 feet, based on 1999 USGS topographic map) is located inland of the modern beach. The terrace consists of volcanic outcrops, yellowish-orange clay (altered ash deposits), basalt boulders, and abundant fossils. The pronounced platform at Queen's Beach roughly corresponds to a sea level stand associated with a 6.6 m high wave-cut notch described by STEARNS (1978). STEARNS (1978) identified marine notches at 6.6 and 8.1 m asl (22 and 27 feet, respectively, as illustrated in Figure 14 in STEARNS 1978) that were cut into aeolianite (wind-blown sands) near Kailua on the eastern coast of Oahu, approx. 10 km northeast of Queen's Beach. A third ancient shoreline at the same location occurs at 3.6 m (12 ft) asl and was assigned a similar age by STEARNS (1978).

Uranium series dates from those deposits yielded ages ranging from 120,000 to 125,000 yr (KU et al. 1974; STEARNS 1974). Fossils cover the platform in the form of a thin, spotty veneer of weathered gray color coral clasts and mollusk shells. At the seaward slope and foot of this platform, an assemblage of marine organisms (Table 1) typical of sub-surf zone depths was identified (BAILEY-BROCK 2002, pers. comm.). The gray color of coral and shell deposits, as well as the yellowish-orange color of sands on top of this terrace stand in marked contrast to modern shoreline deposits (Figure 5) and is interpreted as resulting from longer exposure to weathering.

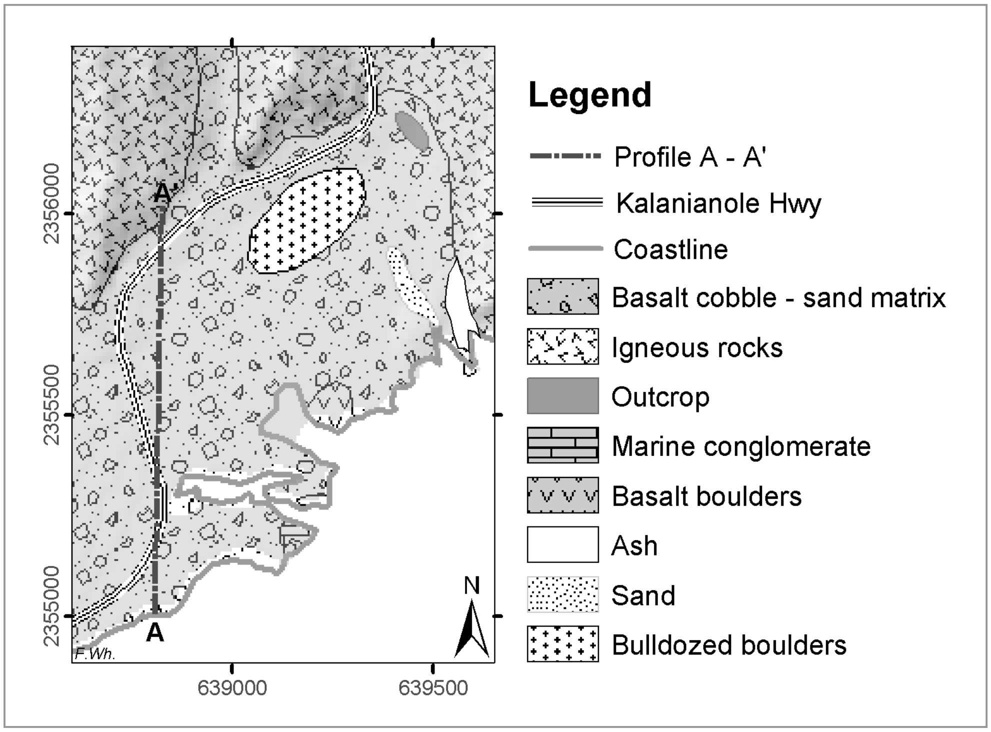

Figure 5. Sketch map (UTM, WGS84) of the geologic units exposed at Queen's Beach. The location of the transect A-A' is displayed on the left. The location of the construction debris (volcanic boulders) is shown southeast of Kalanianole Highway.

Identified Species
Spirorbid tubeworms- Polychaeta, Serpulidae. Dextral species, most likely *Neodexiospira steueri* and sinistral species (operculum full of developing embryos), most likely *Pileolaria militaris.* (for polychaete worms see BAILEY-BROCK 1987)
Sepulid species - *Protula atypha*.
Gastropoda-Vermetidae
Foraminifera – *Gypsina* sp. (PHILIPS 1977)
Coral - *Pocillopora meandrina*
Bryozoan - single zooids of a species of bryozoan nestled in a depression in a piece of basalt.
Coralline algae crust (Rhodophyta)

Table 1: Species identified at Queens Beach (by Julie Bailey-Brock, University of Hawaii, Dept. of Zoology). *All of the surface fossils are species currently alive in Hawaiian waters.

Figure 6: Marine deposits on the shoreline of the Queen’s Beach coastal zone. Note the difference in color between older deposits (associated with the platform in the background) and modern deposits in the foreground.

4.) The forth morphologic unit is of anthropogenic origin and consists of debris bulldozed from the Hawaii Kai subdivision and golf course lands by the Kaiser-Aetna Corporation between 1972 and 1975 (BISHOP MUSEUM FEASIBILITY REPORT 1984) and boulders from the construction of a well near Makapu’u lookout. The debris was stockpiled in the coastal plain adjacent to the realigned and rebuilt Kalanianaole Highway. The pile of boulder debris is roughly 3 to 4 m high, and contains Kalama Flow basalt boulders that range from 1 to 3 m in diameter. Instead of limiting future studies of tsunami impact on the coastal zone, this debris pile might present a natural laboratory for determining what grain size and boulder volume is moved by any future tsunamis.

The debris is restricted to the near-vicinity of the highway and is readily identified and distinct from the underlying platform. Brown soils that are highly expansive form a stratigraphic horizon directly above 6.6 m, at the toe and lower elevations of Kealakipapa Valley.

5.) Other morphologic features include cemented beach sands that occur in a bath-tub ring type distribution at roughly 21 m above sea level on the east side of Kealakipapa Valley. The beach sands are exposed below the paved Makapu’u lighthouse access road on the west side of Makapu’u ridge. Additional fossils were observed in the center of Kealakipapa Valley below the lighthouse access road. Marine fossils were also identified on the eastern flank of Makapu’u Ridge adjacent to the access road.

At the edge of the coastal zone, notches have been cut by wave activity into the lava flows of the eastern and western sides of Kealakipapa Valley. The notches are roughly

17 m (59 ft) high and are evident elsewhere around the periphery of the valley. The notches are best visible north of Hawaii Kai Golf Course entrance and at the foot of Makapu'u Ridge (i.e., the east and west sides of Kealakipapa Valley). The knob at the base of Makapu'u Ridge would have been a sea stack when sea level carved the notches and terraces surrounding the knob (Figure 7).

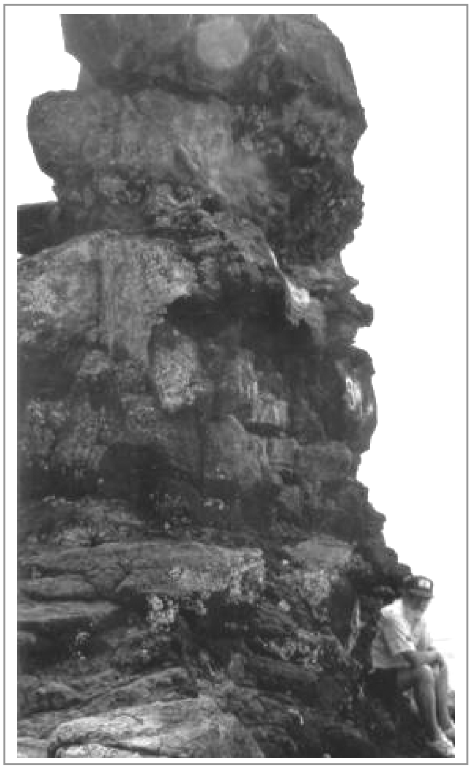

Figure 7. Fossil Sea Stack. The knob at the base of Makapu'u Ridge would have been a sea stack when sea level carved the notches and terraces surrounding the knob. The base of the sea stack is 19 m (63 ft) above sea level.

The coastal zone contains four drainages (from south to north) including Kaloko Inlet, Ka'ili'ili Bay, an unnamed inland basin, and Kaho'ohaihai Inlet (see Figure 2 for site locations). Two additional drainage canals were cut to Kaloko Inlet and Ka'ili'ili Bay during the construction of the Hawaii Kai golf course.

Records of anthropogenic alterations in the Queen's Beach coastal zone

As summarized in the *Queen's Beach Park Feasibility Study* (CITY AND COUNTY OF HONOLULU, DEPARTMENT OF PARKS AND RECREATION 1984), the Queen's Beach coastal zone has been subject to several anthropogenic alterations. In the 1800's, vegetation, including Naio and perhaps beach sandalwood was removed from the area and was replaced by Kiawe (mesquite) and Wiliwili for cattle feed. Between 1930 and 1949, the

Davis family leased a ranch from Bishop Estate at Queens Beach. During this period three homes and a pool were built along the coast. Between 1959 and 1964, the Hawaii Kai Development Corporation and its successors began removing large trees from the site and began land modification. After the death of Henry Kaiser, this development corporation was reorganized several times and changed names, without completing the land modifications underway. While feasibility studies for a community park date back to 1984, development activities for Kaiser Aluminum and Chemical Corporation including an Environmental Impact Statement for a golf course were prepared and considered as late as 1997. Queens Beach was proposed to Congress as the “Ka Iwi National Scenic Shoreline” (KA IWI NATIONAL SCENIC SHORELINE PROPOSAL 1992) and a reconnaissance survey was later carried out by the U.S. NATIONAL PARK SERVICE (1992). The land was eventually purchased by local government in order to stop development and provide for preservation of the land as a park.

In order to survey the Queen’s Beach coastal zone, aerial photographs and maps were examined. Neither the aerial photographs taken in 1952 and 1959 nor a military topographic map (DEPARTMENT OF ENGINEERING TOPOGRAPHIC MAP 1943) showed that any inlet existed immediately south of Makapu’u Head (Pu’u o Kipahulu). However, an aerial photograph of 1-14-1963 (month-day-year) shows a newly created inlet and groins extending out into the sea, as well as the enlarged bay. Based on the *Queen’s Beach Park Feasibility Study* (CITY AND COUNTY OF HONOLULU, DEPARTMENT OF PARKS AND RECREATION 1984), the three inlets were artificially enlarged and a massive groin and a smaller groin were constructed on the north and south sides of Kaho’ohaihai Inlet, respectively. The mauka (mountain-side) portions of Kaloko Inlet and Ka’ili’ili Bay were dredged to form mud flats. Additionally, a 5 m wide dirt drainage channel and a parallel overflow ditch were excavated from the Hawaii Kai golf course to Ka’ili’ili Bay. A sand beach was artificially deposited at the mountain edge of Kaho’ohaihai Inlet and a coral and lava cobble beach was deposited behind the jagged shoreline at Ka’ili’ili Point and northeast of Ka’ili’ili Bay. The basalt boulders forming the groin are 1-2 m in diameter. Wave erosion of the last 40 years has rounded the rocks of the northern groin within the active surf zone.

A rock outcrop at the toe of Makapu’u Ridge was removed to create a flat spot for a proposed restaurant. Kaho’ohahai Inlet and Ka’ili’ili Bay were bulldozed inland at depths of 0.3 to 0.6 m (1 to 2 ft). The beginning of a proposed curved moat to connect Kai’ili’ili Bay to Kaha’ohaihai Inlet was bulldozed, but not completed.

Offshore sand was taken from the location of the groin and inlets and stockpiled on the south side of Kaho’ohaihai Inlet and west of Ka’ili’ili Bay. Kaloko Inlet was deepened and extended with shaped charges and dragline. Dredge spoils were stockpiled around Kaloko Inlet (CITY AND COUNTY OF HONOLULU, DEPARTMENT OF PARKS AND RECREATION 1984).

Vehicle access to the area was restricted in 1975 when large boulders were strategically placed around the periphery finally limiting access to the area by 4-wheel drive vehicles. Since the anthropogenic alterations at Queens Beach have been recorded and reconstructed, there is no doubt that the coral bearing conglomerates observed on the margins of Ka’ili’ili Bay and Kaho’ohalai Inlet are dredge spoils unrelated to tsunami activity.

Observations of surficial tsunami deposits

The Queen's Beach coastal zone displayed three distinct units of deposits that were interpreted as tsunami-genic, including 1.) gravel to cobble-size clasts of coral and basalt, 2.) gravel-size coral deposits mixed with man-made items, and 3.) isolated conglomerate layers. Two additional units have been identified that were associated with development activity, the stockpiled boulders, and the dredge spoils.

The first rock unit is a semi-continuous sheet of gravel to cobble-size clasts that are generally sub-rounded to rounded. The sediment sheet is one clast size thick, extends approx. 200 m inland, and consists of basalt and coral clasts (broken fragments and rounded fragments), both are clearly from the ocean environment. The majority of the basalt pores are filled with coralline algae. Several clasts display worm tubes and are burrowed. The individual clasts are larger than those of the present storm beach. NICHOL et al. (2002) described similar deposits on a coastal barrier on the Great Barrier Island, New Zealand. Both there and at Queens Beach, the deposits' elevations reach well beyond the extent of storm surges. This was verified in November 2003, when a storm generated 30-foot surf on the east side of Oahu. The elevation of the deposits therefore suggests tsunami as the likely transport mechanism.

A survey of the sedimentary deposits was carried out in form of several line transects perpendicular to the coastline. All transects stretched from the present coastline and modern beach to Kaloko Inlet or to the new highway. The initial transect (A-A') presented in this study intersected the modern beach, remnants of the old highway washed out by the 1946 tsunami, and the area seaward of the new highway. Clast size, angularity and rock type were analyzed (Figure 8). Subsequently, additional profiles were sampled and the rocks were analyzed using three different sampling methods. The comparison of sampling methods, details of the clast distribution, as well as GIS analysis (including aerial photography) will follow in a separate publication.

This study focuses on initial results of the field investigations and presents one preliminary transect (A-A'). The starting point for the beach profile was 20º45.453' N; 156º53.677' E (Garmin Etrex GPS barometer elevation 0 - 1.5 m or 0 - 5 ft) and the starting point for the back beach profile (adjacent to destroyed highway) was 20º44.87' N; 156º54.892' E (GPS barometer elevation 2.4 m or 5 ft). The angularity of the clasts was determined by visual comparison to the FOLK (1968) scale.

Transect A-A' extends from south to north across the Queen's Beach coastal zone. The beginning of the transect (A) is characterized by modern beach and storm deposits. The clasts within the modern beach were dominantly coral, having a very white, bleached appearance. A berm at the top of the modern beach largely consist of beach sand and sub-rounded to rounded coral fragments embedded in a sandy matrix that range in size from approx. 2 to 7 cm in diameter. The structure is interpreted as a storm berm and was roughly 2 m in width.

Tsunami deposits were identified inland beyond the storm berm, where both grain size and rock type change considerably (Figure 8). Sedimentary deposits reach diameters of 0.5 m, but generally range between 2 to 4 cm. These rock types are dominated by basalt, coral, and shells within an unconsolidated sand matrix (of a few cm thickness). The clast-rich deposit is generally only one clast thick in several cm of unconsolidated sand. The deposit overlays a well-cemented orange-red clay (interpreted as altered ash). The tsunami deposit ends on the west side of the highway (in the vicinity of the golf course clubhouse), where expansive soils have modified the deposits.

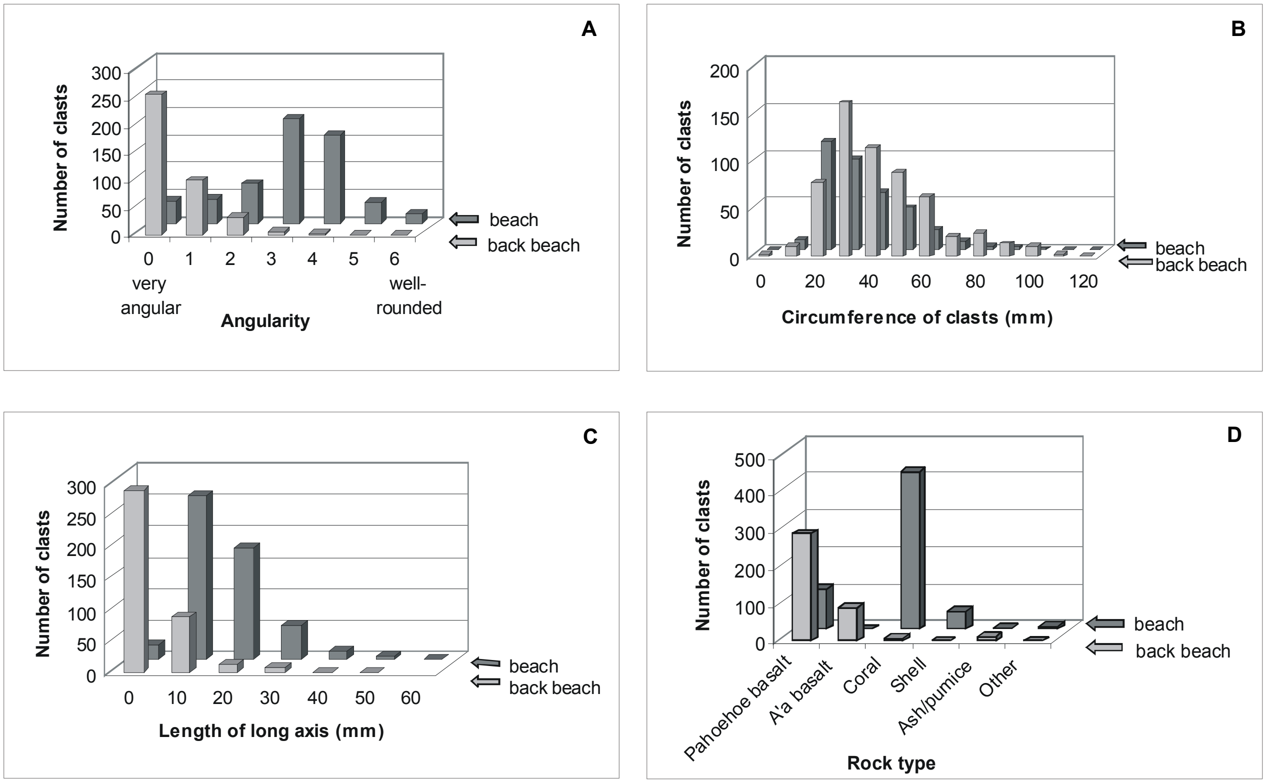

Figure 8. Comparison of rock characteristics between the modern beach deposits and the back beach deposits interpreted as resulting from tsunami activity. The comparisons include A) angularity determined on a 0 to 6 scale after Folk (1968), with increments including very angular, angular, sub-angular, sub-rounded, rounded and well-rounded; B) circumference of clasts (mm); C) length of long axis (mm); and D) rock type, including Pahoehoe basalt, A’a basalt, coral, shells, ash or pumice, and other (e.g. glass).

The investigations indicate that the surface deposits in the vicinity of the remnant of the 1932 roadway destroyed by the 1946 tsunami, Kalolo Point, and the toe of Makapu’u ridge represent tsunami deposits correlating with historic tsunami records. The surface deposits observed in the vicinity of Kaloko Point are rich in coralline algae. Dr. J. Bailey-Brock (Zoology Dept., University of Hawaii) identified several clasts within the deposit and determined that all species were current species indicating that these deposits to an elevation of roughly 3 m (9 ft) are likely to be associated with historic tsunami.

The histograms in Figure 8 above demonstrate that the rock characteristic of the two deposits are very different. While the modern beach deposits are well-rounded by abrasion associated by wave activity, the rocks in the back beach are angular, reflecting breakage. The back beach clasts are darker in color interpreted as increased weathering, smaller in size, more fractured, and dominated by lava fragments rather than coral. These result indicate that the rock groups were produced by different processes. The beach deposits are dominated by modern wave activity, while the back beach deposits appear to preserve the influence of historical tsunamis.

The distribution of clasts along this preliminary transect represents the composite distribution of multiple tsunami and anthropogenic activities. The area of the A-A' transect is the area most accessible to the public and, therefore, most anthropogenically influenced. However, few beaches have ever been left undisturbed after a tsunami event and some degree of anthropogenic activity is common almost to the point of being inevitable. However, the initial observations along A-A' served as a valuable starting point for characterizing historic Hawaiian tsunami deposits and as a baseline for a time series of observations associated with further tsunami and storm events.

Coral fragments are intermixed with material of anthropogenic origin at Ka'ili'ili Bay. There, a series of five graded beds are exposed in the banks of the inlet on the southwest side of Ka'ili'ili Bay (Figure 9) and are dominated by calcium carbonate sediments ranging in size from gravel-size coral clasts through shell hash, to fine grain carbonate sediments. Two layers contain rounded coral boulder beds comparable to those forming the base of the storm berm at the back of the modern beach. The lowest layer contains ceramic tile, blocks, and aged glass fragments, including a Coca Cola bottle fragment, which are likely remnants of the Davis family's home destroyed by the 1946 tsunami deposits.

Figure 9. Photograph of an outcrop on the southwest side of Ka'ili'ili Bay (see Figure 2 for site location) containing a stratigraphic sequence of five graded beds showing gradations from gravel size clasts at the base of the bed, shell hash in the interior of the bed, and fine mud carbonate at the top of each bed.

At the toe of Makapu'u Ridge, there are two thin (0.5 m) isolated horizons of marine conglomerate (Figure 10). These 2 horizons give the appearance of additional cemented inliers of beach-rock present on the modern beach but they outcrop at 1.5 and 2 m asl. Alternately, these conglomerate units could be paleo-tsunami deposits. These rock units will be the subject of further study. Radiometric dating of the coral may provide further evidence of their origin.

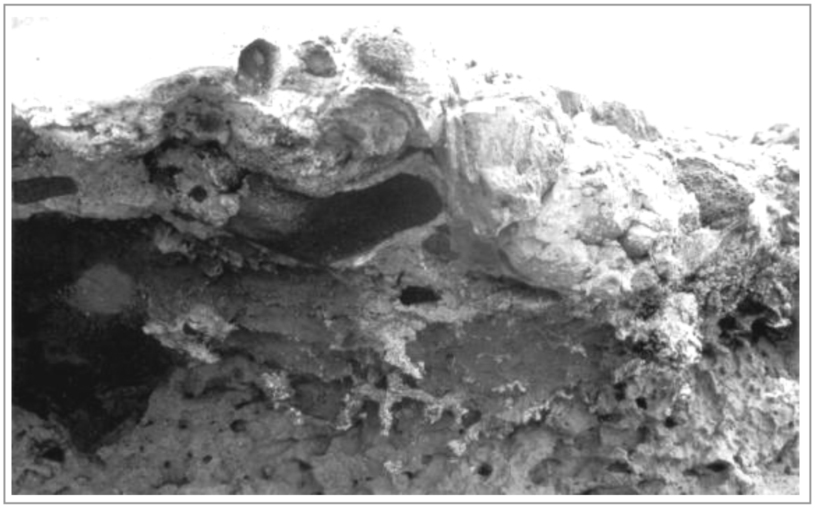

Figure 10. Photograph of one of two well-cemented marine conglomerate horizons at the base and south side of Makapu'u Ridge (Pu'u o Kipahula). The conglomerate rests on Honolulu Series ash deposits. The conglomerate contains basalt and coral clasts and shells cemented in a sandy matrix. The base of the unit does not appear to be erosional but instead appears to be transitional to finer-grain clasts.

The Queen's Beach coastal zone displayed two rock units that were interpreted as not related to tsunami deposits. These included: a unit of relatively small area that consists of large basalt boulders deposited east of the highway at the foot of the Kealakipapa Valley. The boulders are covered with grassland. The aerial photographs of the Queens Beach coastal plain established that the boulders located there were deposited during construction projects (golf course and the water shaft at Makapu'u Lookout) and are not the result of tsunami activity. The remaining unit, consitsting of abundant basalt clasts, coral calsts, and sea shells, is confied to the margins of Kaloko Inlet (Figures 11a and 11b) and Kaho'ohaihai Inlet within the Tsunami Inundation Zone. The deposits on the inlet banks on the north side of Kaloko Inlet and on the south side of Kaho'ohaihai Inlet display irregular layering and teepee layering, and are the products of dredging. A species of mollusk, currently extinct in the Hawaiian Islands, was found at the base of the slope on the north side of Kaloko Inlet (Figure 11b; were identified by Dr. R. Grigg of the Oceanography Department, University of Hawaii). The record of development activities show that this unit represents dredge spoils, not tsunami activity.

Figure 11: A) Coral-bearing conglomerate with coral and basalt clasts exposed in the northeast bank of Kaloko Inlet (center of the photograph above). B) Close-up photograph of the outcrop. Historical records (University of Hawaii library, Hawaiian collection) prove materials are the dredge spoils associated with deepening the bay.

Tsunami modeling

MADER (2002; Science of Tsunami Hazards CD distributed at the Tsunami Society's second Symposium) published tsunami models for the 1946 Aleutian Tsunami inundation of Queen's Beach or Sandy Beach (Figure 12). The tsunami animations were performed using SWAN code (MADER 1988). The analyses show that when a 3 m high tsunami wave is modeled, the runup does not reach Kealakipapa Valley (behind Makapu'u Ridge). However, based on eyewitness reports by the Davis family, waves ran up almost the entire length of the valley. Davis reported that he feared the waves would overrun the gap (Makapu'u Overlook) and flood down onto Makapu'u beach below. The 10 m tsunami wave model (MADER 1988 and 2004; see animation sandy.zip on web site http://t14web.lanl.gov/Staff/clm/tsunami.mve/tsunami.htm) shows the runup in Kealakipapa Valley and accurately fits the eyewitness reports.

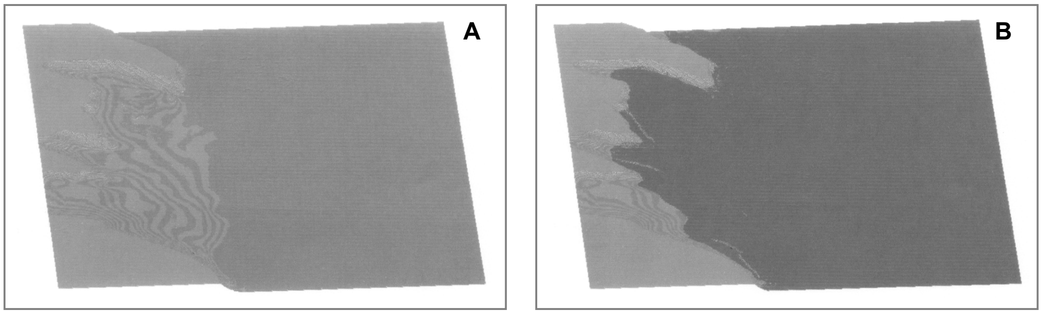

Figure 12: Animation of the 1946 Aleutian tsunami inundation at Queens Beach/Sandy Beach, Oahu, HI. A) Inundation by a typical offshore 3-m-high wave. B) Inundation by a maximum expectable offshore 10 meter high, 2000 second tsunami wave (MADER 1988 and 2004).

Summary

The Queens Beach coastal zone was subject to significant tsunami inundation during the 20th century. This study presents initial investigations of geomorphic and sedimentologic tsunami evidence preserved in the Queen's Beach coastal zone. The deposits consist of coarse clasts and gravel deposits. Based on the presence of glass, ceramics, etc. and surrounding geomorphic cues, the surface deposits appear to originate from the inundations of the 20th century. Comparing the relatively high frequency of tsunami inundation of Hawaiian shorelines with the minimal amount of preserved tsunami deposits, the Queens Beach coastal zone provides a valuable record of the nature of deposits due to tsunami inundation and runup.

Marine conglomerates are identified in the modern beach setting that appears to result from cementation of clasts associated with the discharge of fresh water at the shoreline. Two additional horizons at 1.5 and 2 m asl may represent ancient deposits of the same origin or paleo-tsunami records. Additional studies of these units are required.

The lava flows and ash units at Queen's Beach preserve abundant evidence of fossil sea level stands (e.g., platforms, wave cut notches, sea stacks) above modern sea level. This is due in part to the young age of the Honolulu Series and to the soft nature of the volcanic ash. Elsewhere on Oahu, coastal outcrops occur in volcanic rocks millions of years old, or they are faulted coastlines where much of the volcanic structure has been down-dropped below sea level.

The catalog of tsunami activity for the Hawaiian Islands (WALKER 1994) indicates the Queen's Beach coastal zone was inundated by 4 recent tsunamis: the Aleutian Tsunamis of 1946 and 1957, the 1952 Kamchatka Tsunami, and the 1960 Chile Tsunami. The catalog reports a maximum runup of 3 m (9.8 ft) at Makapu'u Point from the 1952 Kamchatka Tsunami and a 4 m runup for an unspecified location, possibly Kuliouou at the SE corner of Oahu for the 1960 Chile Tsunami. A photograph of a man escaping the 1957 Aleutian tsunami (see Figure 4.7 in DUDLEY AND LEE 1998) shows that the tsunami runup reached the ridge behind the Queen's Beach coastal plain at an elevation of roughly 9 m (or 30 ft based upon comparison of landforms in the photograph and the topographic map).

The 1946 tsunami waves reached 11.1 m (36.4 ft) asl on the north side of Makapu'u Head, 5 m (15 ft) at Kaloko Point located 1.6 km (one mile) southwest of Makapu'u Point, and 9.3 m (31 ft) asl at Koko Head. However the eyewitness accounts from the Davis family indicate the runup in Kealakipapa Valley approached the gap behind Makapu'u Point where the elevation reaches 45 m (150 ft) but apparently did not effect the access road to the lighthouse at roughly 24 m (or approximately 80 ft), which would be consistent with a runup of perhaps 20 m within Kealakipapa Valley. Tsunami modeling indicates that 10 m tsunami waves were sufficient to replicate the eyewitness observations.

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Corresponding author: Dr. Barbara Keating, RM 314 HIGP, University of Hawaii, Honolulu, HI 96822, USA, Telephone (808) 956-8143, Fax (808) 956-3189, email: keating@soest.hawaii.edu

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TSUNAMI GENERATED BY THE VOLCANO ERUPTION ON JULY 12-13, 2003 AT MONTSERRAT, LESSER ANTILLES

Efim Pelinovsky1), **Narcisse Zahibo**2), **Peter Dunkley**3), **Marie Edmonds**4),
Richard Herd4), **Tatiana Talipova**1), **Andrey Kozelkov**5), **Irina Nikolkina**5)

1) Laboratory of Hydrophysics and Nonlinear Acoustics, Institute of Applied Physics, Nizhny Novgorod, Russia (E-mail: enpeli@hydro.appl.sci-nnov.ru)
2) Laboratoire de Physique Atmosphérique et Tropicale, Département de Physique , Université Antilles Guyane, Pointe-à-Pitre, France (E-mail: narcisse.zahibo@univ-ag.fr)
3) Montserrat Volcano Observatory, Montserrat (Email: pnd@bgs.ac.uk)
4) Montserrat Volcano Observatory, Montserrat; currently USGS-Hawaiian Volcano Observatory, Hawaii USA (Email: medmonds@usgs.gov)
5) Applied Mathematics Department, State Technical University, Nizhny Novgorod, Russia (E-mail: ask@land.ru)

ABSTRACT

A major collapse of a lava dome occurred at the Soufrière Hills Volcano (Montserrat, Lesser Antilles), culminating late in the evening (11:35 PM local time) on July 12, 2003 (03:35 GMT on 13 July). This generated a tsunami, which was recorded on Montserrat 2-4 km from the generating area and Guadeloupe, 50 km from Montserrat. Results of field surveys are presented. Tsunami wave height on Montserrat may have been about 4 m according to the location of a strandline of charred trees and other floating objects at Spanish Point on the east coast of the island. The wave height on Guadeloupe according to “direct” witnesses was about 0.5-1 m at Deshaies and near Plage de la Perle. The tsunami at Deshaies caused the scattering of boats as confirmed by fishermen and local authorities. Data from the field survey are in agreement with the predicted tsunami scenario obtained by numerical simulation.

1. Introduction

Soufrière Hills Volcano is located on Montserrat, Lesser Antilles (16.72°N, 62.18°W); see Figure 1. The volcano is currently undergoing a prolonged eruption, which began in July 1995 and has caused widespread devastation to the southern part of the island, including the destruction of the airport and the capital of Plymouth. There have also been a number of fatalities. The island's population fell from about 11,000 to 3,500 during the early part of the eruption, but has increased slightly in recent years to about 4,600. Buffonge in series of books (1996 – 1998) provides a chronicle of Montserrat's society experience with the volcano; see also, Pattullo, 2000.

Figure 1. Chart of Montserrat, Lesser Antilles

The first phase of the eruption lasted from July 1995 until March 1998 and is described in a series of short papers published in Geophysical Research Letters (Young et al. 1998) and in a comprehensive collection of papers in a Geological Society of London memoir (Druitt and Kokelaar, 2002). The largest single event of the first phase of the eruption occurred on 26 December 1997, when the southern wall of the old summit crater failed due to loading by the lava dome. This generated a debris avalanche and resulted in the rapid collapse of the active lava dome, unleashing a powerful pyroclastic density current and a volcanic blast, as well as generating a small tsunami.

A period of stagnation in the eruption began in March 1998 and continued until November 1999 when extrusion of lava recommenced and marked the onset of the second phase of dome growth. During this second phase the dome grew and collapsed several times.

By mid-2003 the lava dome had grown to an unprecedented size, having a volume of about 200 million m^3 and a general summit elevation of around 1100 m. On 12-13 July the dome underwent the largest collapse of the entire eruption to date. This was a prolonged event. Continuous pyroclastic flows (composed of hot rocks, ash and gas) began in the Tar River Valley on the eastern side of the volcano at 09:30 local time (13:30 GMT) on 12 July (Herd et al., 2004). From 10:45 onwards these reached the sea and at 18:30 the flows became larger and more energetic as the collapse progressively cut back into the hotter interior of the dome. The collapse reached its most energetic phase between 21:50 12 July and 0:50 13 July when a sequence of very large pyroclastic flows entered the sea and pyroclastic surges traveled up to 3 km across the surface of the sea. The climax of the collapse occurred at 23:35 when a very large pyroclastic flow impacted the sea and pyroclastic surges devastated 7 km^2 on the NE flank of the volcano (Edmonds et al., 2004). A tsunami appears to have been generated at this stage. A number of explosive events also took place, with the largest occurring during the climax of the collapse, producing ash clouds to an altitude of 15 km. In total over 120 million m^3 of material was removed during the collapse, leaving a large amphitheatre-shaped scar in the dome, which is open to the east above the Tar River Valley. The valley itself was also extensively modified with a deep canyon eroded by the pyroclastic flows. Various photos of this event can be found in the website of the Montserrat Volcano Observatory (http://www.mvo.ms). One of the photos of the pyroclastic flow entering sea is shown in Figure 2.

Figure 2. Pyroclastic flow down the Tar River valley on 12th July 2003 Photograph M Edmonds © NERC

Large dome collapses on Montserrat have produced tsunami waves on two occasions during the current eruption. The earlier dome collapse of December 26, 1997 (Boxing Day Collapse) produced an avalanche in the White River Valley (for location, see Figure 1). This resulted in a large amount of debris entering the sea and the generation of a tsunami. Heinrich et al (2001) presented numerical simulations of this debris avalanche. The wave rolled northwards parallel to the coast, ending up at Old Road Bay, 10 km from the landslide site (see Figure 1), where it pushed boats and trailers some distance up on to the shore (Buffonge, 1998). Lander et al (2002) gives the following description of the tsunami: "The wave was estimated to have been about 1 m higher than the road which lies 2-m above water level, and to have moved inland a maximum distance of 80 m. A variety of objects, including a small wooden boat, a roof to a shelter, and a stone table were displaced several meters inland and a large log was carried even farther by the wave. Impact marks up to 1 m were also reported on the side of palm trees facing the sea. The grass was oriented in such a way as to indicate the retreat of the wave. An observer reported seeing the sea move out and then back in, which is typical of a landslide-generated tsunami. The focusing of the wave at Old Road Bay may be attributed to the peculiarities of wave behavior along a coastline and the abrupt change of coast direction at Old Road Bay. The wave moved inland here, because the coast abruptly changes its direction, and the wave moving parallel to the coast would have met the shore head-on. Also, the shallow offshore bathymetry and onshore topography in the area aided extended wave runup." There is no record of this tsunami on the neighboring islands of Antigua, Guadeloupe, and St Kitts.

The main goal of this paper is to present the data of a field survey conducted on the islands of Montserrat, Guadeloupe and Antigua following the very large collapse of the dome of 12-13 July 2003. The results of numerical simulations of tsunami propagation related to this event are also discussed.

2. Numerical simulation of tsunami waves generated at volcano eruption in Montserrat

A hypothetical tsunami event due to collapse of the lava dome in the Tar River Valley and to a sudden entry of a debris avalanche into sea was in fact modelled numerically by Heinrich et al (1998, 1999). Considering a debris avalanche volume of $40 \cdot 10^6$ m^3 (the same volume is estimated for the debris avalanche of 26 December 1997) entering the sea at speed of 40 m/s, their modelling suggested that most of the wave energy propagates in the open sea in the slide direction, i.e. towards Guadeloupe and Antigua. The distribution of the maximum water surface elevation is presented in Figure 3 taken from Heinrich et al (1998). Along the coast of Montserrat (in fact, near the coast at a depth of 10 m), the computed wave heights are maximal in the epicentral zone (6-10 meters), and 1-2 m at distances of about 10 km from the generation area (Heinrich et al, 1998). According to the modelling, tsunami waves of 2–3 m could reach Guadeloupe and Antigua (50 km from Montserrat) in 10 minutes; see Figure 4 (Heinrich et al, 1999).

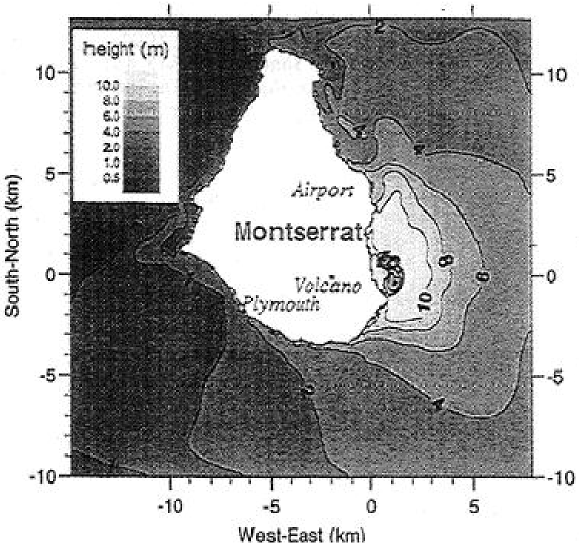

Figure 3. Maximum water surface elevation on Montserrat coast during the tsunami propagation (Heinrich et al, 1998)

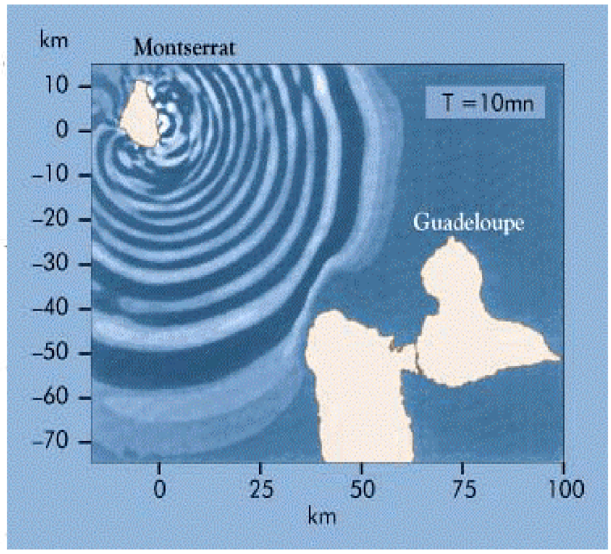

Figure 4. Tsunami wave propagation from Montserrat (Heinrich et al, 1999)

We estimate roughly a comparable distribution of the tsunami wave amplitude along the coasts of Guadeloupe, Antigua and St Kitts. In our simulations the nonlinear shallow water equations are applied based on the numerical code TUNAMI, recently used to study the 1867 Virgin Island tsunami in the Lesser Antilles (see, Zahibo et al., 2003a). The bathymetry of the Eastern Caribbean is taken from the GEBCO Digital Atlas (British Oceanographic Data Centre) with mesh size 1.5 km. As in the modelling of Heinrich et al (1998), the runup stage is not simulated and complete reflection is calculated for the last sea points. The tsunami source is modeled by the initial upward water displacement (up to 10 m) in the "sea" part of the circle of diameter 2 km located at the mouth of the Tar River (16.71N, 62.14W). Such a source was chosen to demonstrate wave propagation along the coasts of neighboring islands far from the source. Figure 5 shows the directivity of the tsunami propagation. It is clearly seen that the tsunami waves mainly propagate towards Antigua and Guadeloupe and relative weakly towards Nevis and Barbuda, as was predicted in the more exact computing by Heinrich et al (1998, 1999). According to our calculations, the maximum wave amplitudes are 1.6 m at Guadeloupe, 1.9 m at Antigua (1.9 m), 1.2 m at Nevis and 0.9 m at Barbuda. We should stress that these results are very sensitive to the properties of the tsunami source (water displacement and directivity). Although the tsunami source model is only approximate, the comparable wave amplitudes in various coastal locations can be used to select zones where the tsunami effect may be expected to be large. Therefore, from our computing we may conclude that wave heights of the 12-13 July 2003 Montserrat tsunami at Guadeloupe and Antigua were approximately the same, and by comparison were at least twice as small at Nevis and Barbuda. We have calculated the relative wave height distributions along the coast of neighboring islands (Figure 6), normalized on its maximum value for each island. This demonstrates that the 12 July 2003 tsunami should have been manifested on the northern capes and western coast of Guadeloupe, western coast of Antigua, and, perhaps, south-eastern coast of Nevis and west-southern coast of Barbuda.

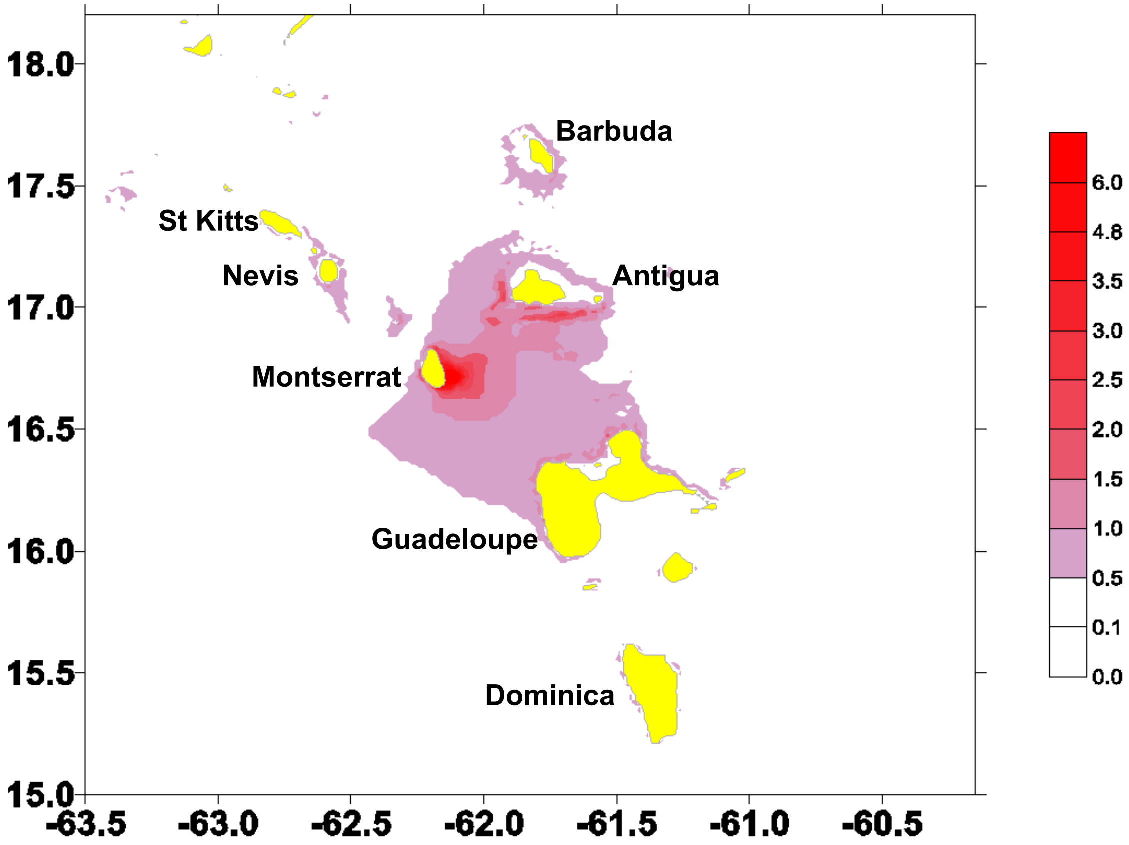

Figure 5. Directivity diagram at the isotropic source

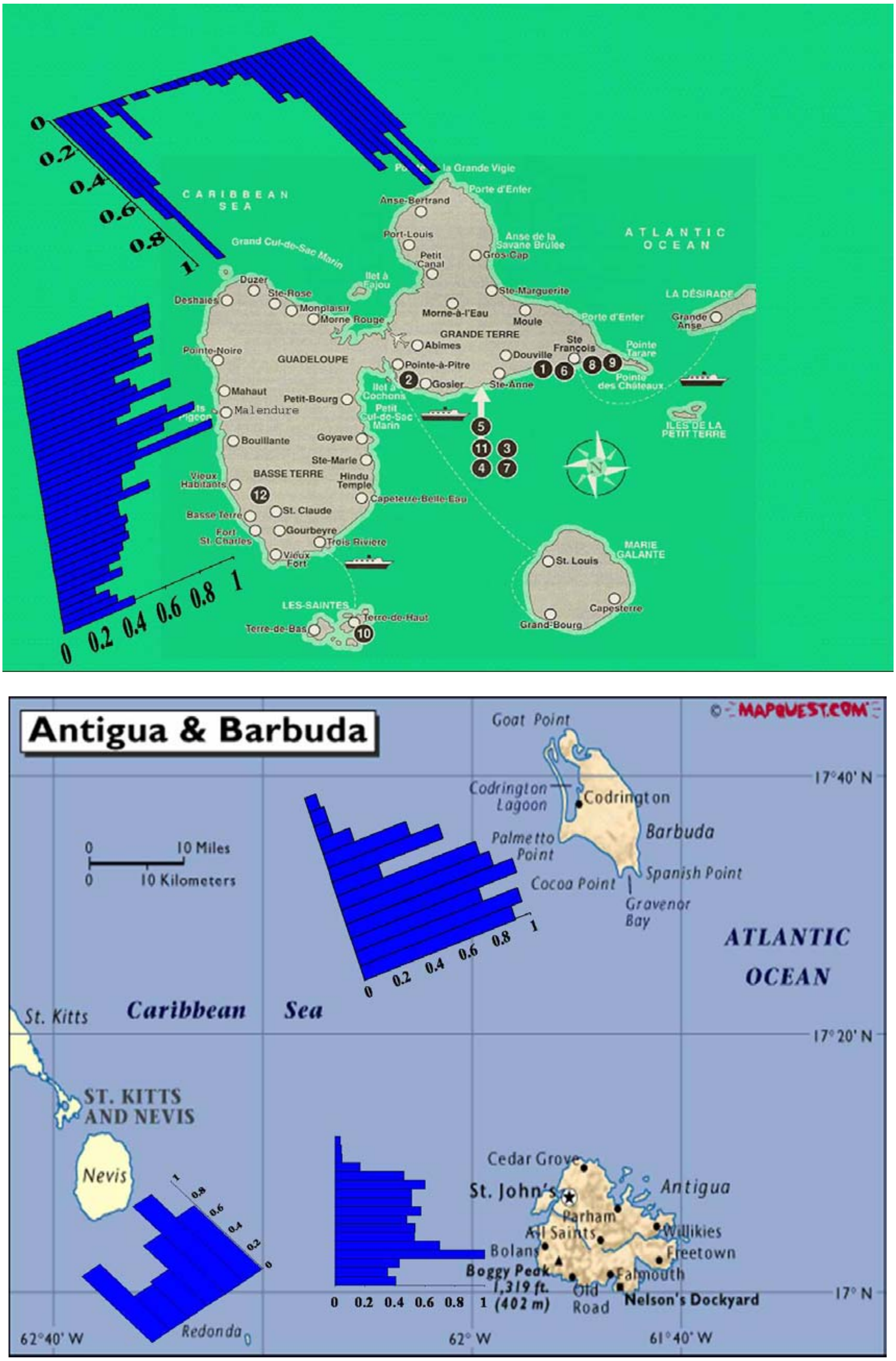

Figure 6. Distribution of the relative wave height along the coasts of Guadeloupe, Antigua, Barbuda and Nevis

3. Field survey data

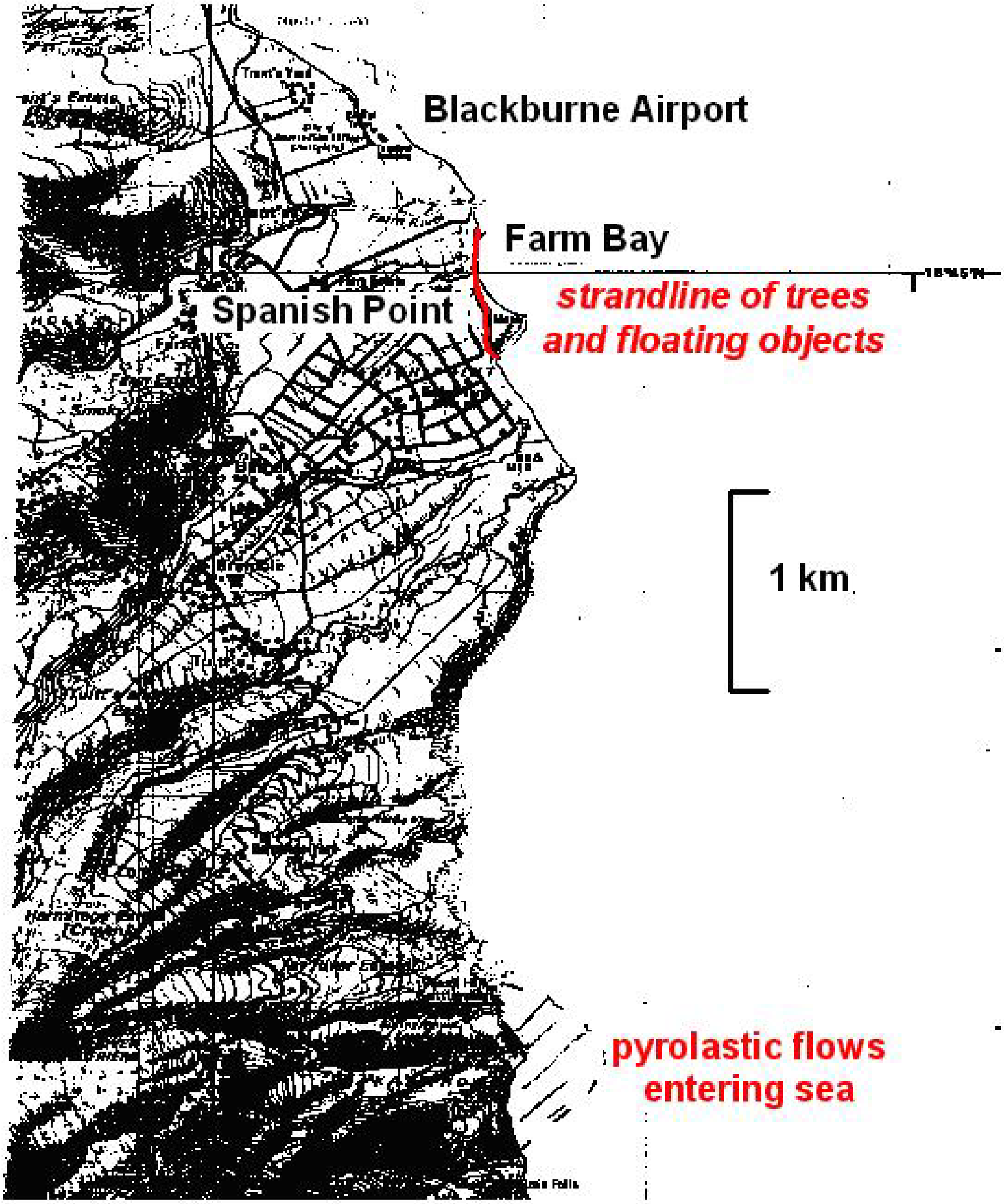

Figure 7. Chart of the area where strandline of trees and floating objects have been found

The first field survey of the coastal area at ***Montserrat*** was conducted in the middle of September 2003 by staff of the Montserrat Volcano Observatory. A strandline of charred trees and other floating objects was found at Spanish Point on the coast at Farm Bay (16.737N, 62.153W) approximately 3-4 km north of the mouth of the Tar River Valley where the pyroclastic flows impacted the sea on 12-13 July; see Figure 7 for the detailed chart of this area. The strandline is located between about 100-150 m from the shoreline at a height of 4 m above sea level (eye estimates). Cyclone activity was high in September 2003 when two hurricanes passed near Montserrat to the north. These were: "Fabian", category 4, September

3; and "Isabel", category 4-5, September 13. Their tracks taken from the *NOAA Tropical Prediction Center* (UNISYS), are shown in Figure 8. It is possible therefore that the strandline of charred trees may have resulted from a tsunami related to the dome-collapse, as well as from a storm surge. Taking into account the local character of this phenomenon near Tar River Valley, the tsunami origin is preferable. A second field survey around Spanish Point was conducted by the writers in January 2004, at which time the strandline was still apparent (Figure 9).

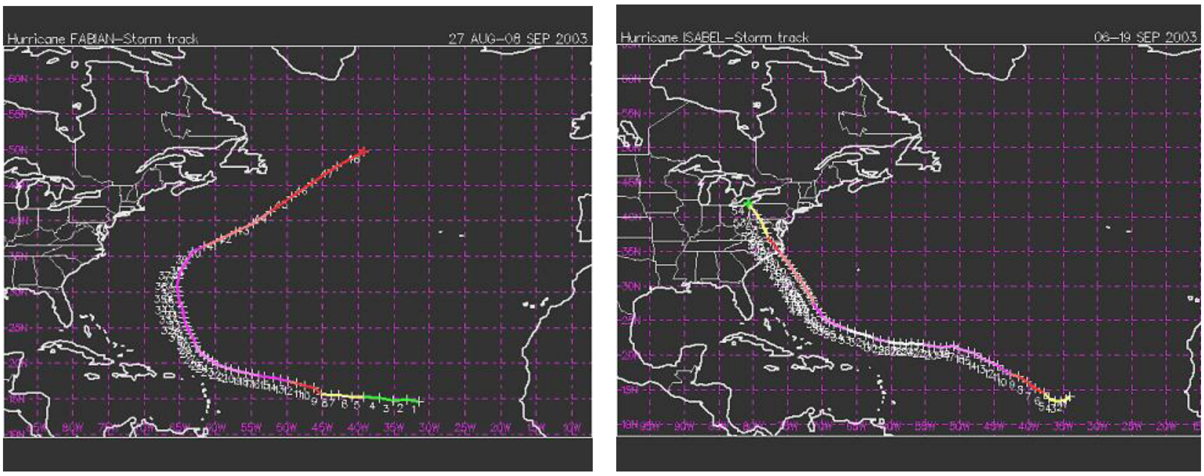

Figure 8. Tracks of hurricanes: “Fabian” (left) and “Isabel” (right)

Figure 9. Strandline of charred trees and other floating objects on the coast at Farm Bay (Spanish Point)

The field survey in ***Guadeloupe*** was conducted in November 2003. First of all, we should mention that there is no tide gauge in Guadeloupe now to provide quantitative information. Also there was no information on the tsunami in the local newspaper "France - Antilles", except for a report from Montserrat concerning the eruption on the night of July 12-13, 2003. We could not find direct traces of tsunami manifestation, but obtained witness reports. These were obtained from three locations on the western coast of Guadeloupe at Deshaies, Malendure, and Vieux Habitans (for locations see Figure 6). The distance between Deshaies and Vieux Habitans is about 27 km. At the port of ***Deshaies*** (Figure 10a), and in the mouth of the river Deshaies (Figure 10b) fishermen on the next morning (13 July) found that approximately 10 boats were scattered in the port and river and had been moved onto the land (up to 15 m). Some of these were slightly damaged. The height of the wall in the place of the boat mooring in the port is 40 cm. One small boat, moored in the mouth of the river Deshaies, was carried for more than 60 meters up the river to the bridge (Figure 10c). The customers of the restaurant "Note Bleue", who were celebrating a wedding, were surprised by an abrupt rise of water in the mouth of the river of Deshaies during the night of the 12-13 July, which occurred sometime between 23.00 and 01.00 (local time). The appearance of the tsunami corresponds approximately to the climax of the dome collapse on Montserrat between 11-12 PM. Water overflowed the coast of the river mouth (60 cm); see Figure 10d. No noise of a wave or wind accompanied this phenomenon. The Police investigated the area at 02.00 (July 13). Some people, referred to as “direct” witnesses, reported that the water rose 1.5 m near the entry to the port and surged 25 m inland. The duration of the wave, which broke on the beach, was about 1 min, and is reported to have arrived at 23:30, although this information is not from first hand reports.

Figure 10. Deshaies, a) port, b) the river mouth, c) 60 m upstream, where the boat was found near the bridge, d) restaurant in the river mouth, where the beach was overflowed

On the ***Plage de la Perle***, a few kilometers to the north of Deshaies, a shopkeeper told us that on the next morning he found that the sand level on the beach had increased by up to 50 cm. We should add that this beach is protected by a coral reef near the shoreline. At ***Malendure*** (14.5 km to the south of Deshaies), where according to our simulations wave height should have been at a maximum, the tide that night rose several meters at certain places along the coast where it penetrated for 20 m inland. The sea rose 46 centimeters on the foot of the pontoon of Malendure (Figure 11). ***At Vieux Habitans*** (13 km to the south of Malendure and 27 km from Deshaies**)**, the water rose up to 60 cm. Unfortunately, we were not able to find “direct” witnesses of the tsunami at Malendure and Vieux Habitans. According to the information collected at these localities on Guadeloupe, we may conclude that the water rise at Deshaies was due to a real tsunami with a confirmed wave height of about 0.5-1 m. The reliability of the information on the tsunami in other places (Malendure and Vieux Habitants) is not quite clear. The water rise in these places was probably not recorded due to it being nighttime and also because of the low amplitude of the wave.

Figure 11. Pontoon of Malendure (46 cm above sea level)

We visited ***Antigua*** (St John's and Jolly Harbour (near Bolans) in January 2004 (see Figure 6 for locations, but were not able to find any reports of the tsunami in these places.

4. Conclusion

The climax of the large dome collapse at the Soufrière Hills Volcano, Montserrat occurred late in the evening (23:35 local time) on 12 July, 2003 (03:35 GMT on 13 July). The impact of a large pyroclastic flow on the sea generated a tsunami, which was recorded on **Montserrat**, 2-4 km from generating area and **Guadeloupe**, 50 km from Montserrat. The results of the field surveys are presented. The wave height on Montserrat may have been about 4 m according to the location of the strandline of charred trees and other floating objects at Spanish Point. The wave height on Guadeloupe according to "direct" witnesses was about 0.5-1 m at Deshaies and near Plage de la Perle. The tsunami at Deshaies scattered boats, as confirmed by fishermen and local authorities. Data from the field survey are in agreement with the predicted tsunami scenario of Heinrich et al (1998, 1999) and our simulations.

It is important to point out that the 2003 tsunami is the third event recorded on Guadeloupe during the last 150 years. The two other events include: the catastrophic 1867 tsunami, when waves generated on the Virgin Islands approached Guadeloupe with heights of about 10 m at Deshaies and St Rose; and the weak 1985 tsunami, when a wave several centimeters high was recorded by the tide gauge at Basse-Terra (Zahibo et al., 2001, 2003; Lander et al., 2002). The tsunami risk for the Lesser Antilles should therefore not be ignored and should be evaluated. Such work is now in progress (Zahibo & Pelinovsky, 2001; Zahibo et al, 2003b)

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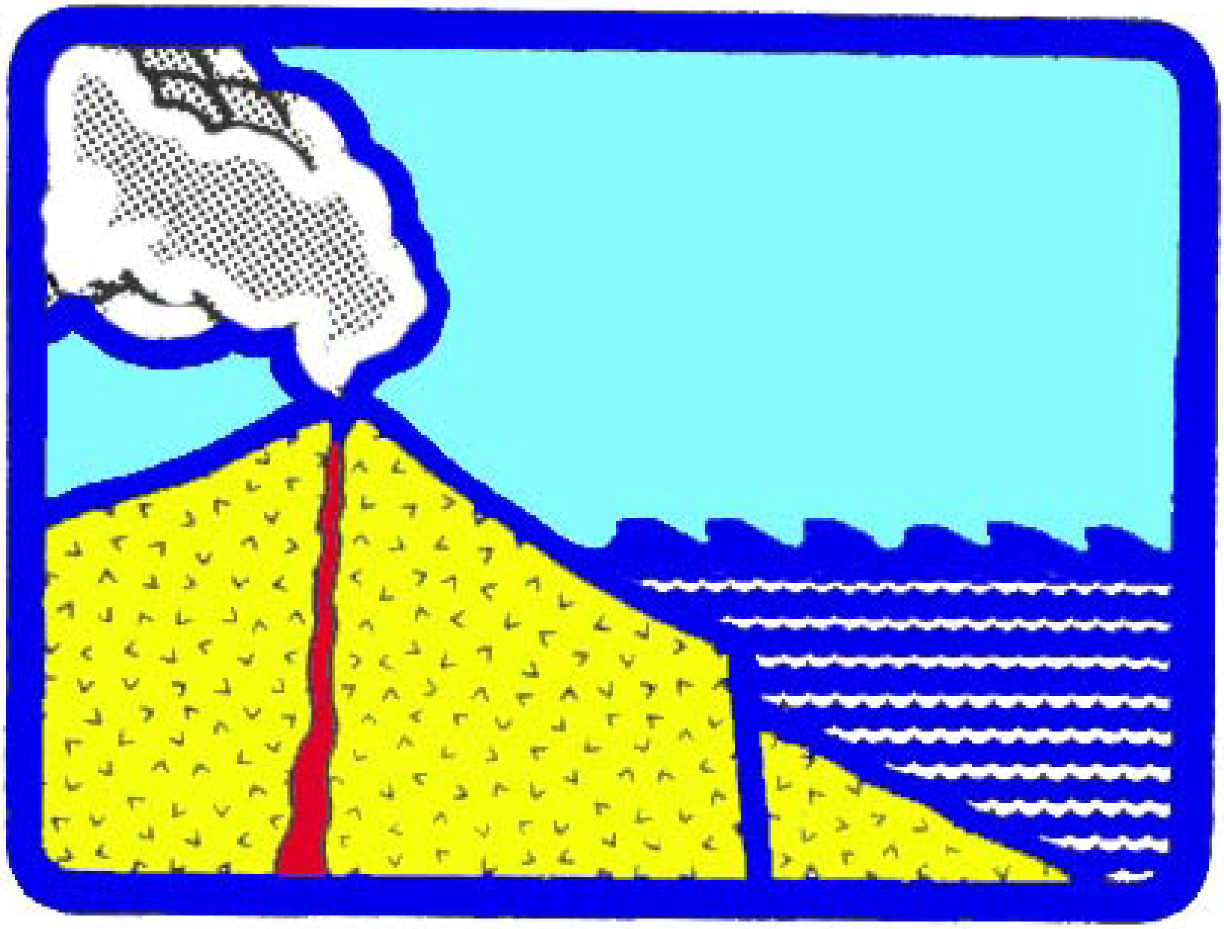

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