A Field Survey of the 1946 Aleutian Tsunami in the Far Field

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INTRODUCTION AND BACKGROUND

This paper reports the interviews of 48 elderly witnesses to the Aleutian tsunami of 1 April 1946, which resulted in the measurement of a database of 54 values of runup and inundation in 31 valleys of the Marquesas, Easter, and Juan Fernández Islands. The 1946 Aleutian tsunami remains one of the most enigmatic such events of the past century. It resulted in catastrophic destruction both locally (with the annihilation of the Scotch Cap lighthouse on Unimak Island, where runup reached 42 m) and in the far field, where it claimed a total of 162 lives in California, the Marquesas, and Hawaii (where runup reached 16 m) and wrought destruction as far away as Winter Island, Antarctica, 15,000 km from its epicenter (Fuchs, 1982). Yet the parent earthquake featured a relatively low conventional magnitude of only $M = 7.4$ as assigned at Pasadena by Gutenberg and Richter (1954).

Kanamori (1972) defined the 1946 Aleutian shock as a "tsunami earthquake", a class of events whose tsunamis have much greater amplitude than would be predicted from their seismic magnitudes. Later work by Fukao (1979), Newman and Okal (1998), Pelayo and Wiens (1992), and Polet and Kanamori (2000) has shown that several tsunami earthquakes feature a slow moment release (most probably involving rupture in sedimentary material), which leads to the underestimation of the earthquake's size if measured at the relatively short periods characteristic of conventional magnitudes.

In the case of the 1946 Aleutian event, a number of studies have suggested that the seismic moment does indeed increase at longer periods, to values as high as 3.7×10^{28} dyne-cm (Kanamori, 1972) or even 7.6×10^{28} dyne-cm (Okal, 1992). Pelayo (1990) suggested 8.5×10^{28} dyne-cm and speculated that the moment could be even ten times larger. In very general terms, a moment of a few times 10^{28} dyne-cm is also compatible with the amplitude of the few existing tidal gauge records of the tsunami in the far field (Johnson and Satake, 1997). However, the interpretation of a seismic source of such a size in terms of fault parameters is difficult due to the relatively small extent (10^4 km^2) reported for the aftershock area of the 1946 earthquake (Pelayo, 1990; Sykes, 1971). The larger source (8.5×10^{29} dyne-cm) proposed by Pelayo (1990) is even more difficult to interpret in terms of source parameters and at any rate remains improbable in view of the general absence of detectable multiple surface-wave passages on such instruments as the Uppsala Wiechert (Okal, 1992).

In addition, the dislocation source remains too small to adequately explain the extreme runup at Scotch Cap, where the radio station located above the lighthouse was flooded at an altitude of 42 m (Plafker *et al.*, 2002). In this framework, Kanamori (1985) proposed that the source of the 1946 Aleutian tsunami may have involved a significant underwater landslide, a suggestion supported by the recent identification of geologically fresh slides along the shelf edge to the west (Dobson *et al.*, 1996).

Modern developments in tsunami simulation techniques make it possible to propose models of runup and inundation for a variety of source scenarios. For example, Titov and Synolakis (1997) have modeled the extreme runup of 29 m observed locally at Okushiri Island during the 1993 tsunami. Regarding the 1946 Aleutian event, Fryer and Watts (2000) have modeled the local runup at Unimak as due to a possible failure of the Ugamak slide; in the far field, Titov and Gonzalez (2001) have simulated the response of Hilo Bay using the dislocation source of Johnson and Satake (1997). The identification of the exact source mechanism of the 1946 tsunami is a very important challenge in the evaluation of tsunami hazards on the Pacific coast of the United States and elsewhere along the Pacific rim, as inundation maps to be used for emergency preparedness are presently being developed (Borrero *et al.*, 2001).

Whereas the inundation of the Hawaiian Islands (with a maximum reported runup of 16 m) has been well described in the literature (*e.g.*, Macdonald *et al.*, 1947), it is clear that further work aiming at the resolution of the source of the 1946 tsunami—dislocation, landslide, or both—will require

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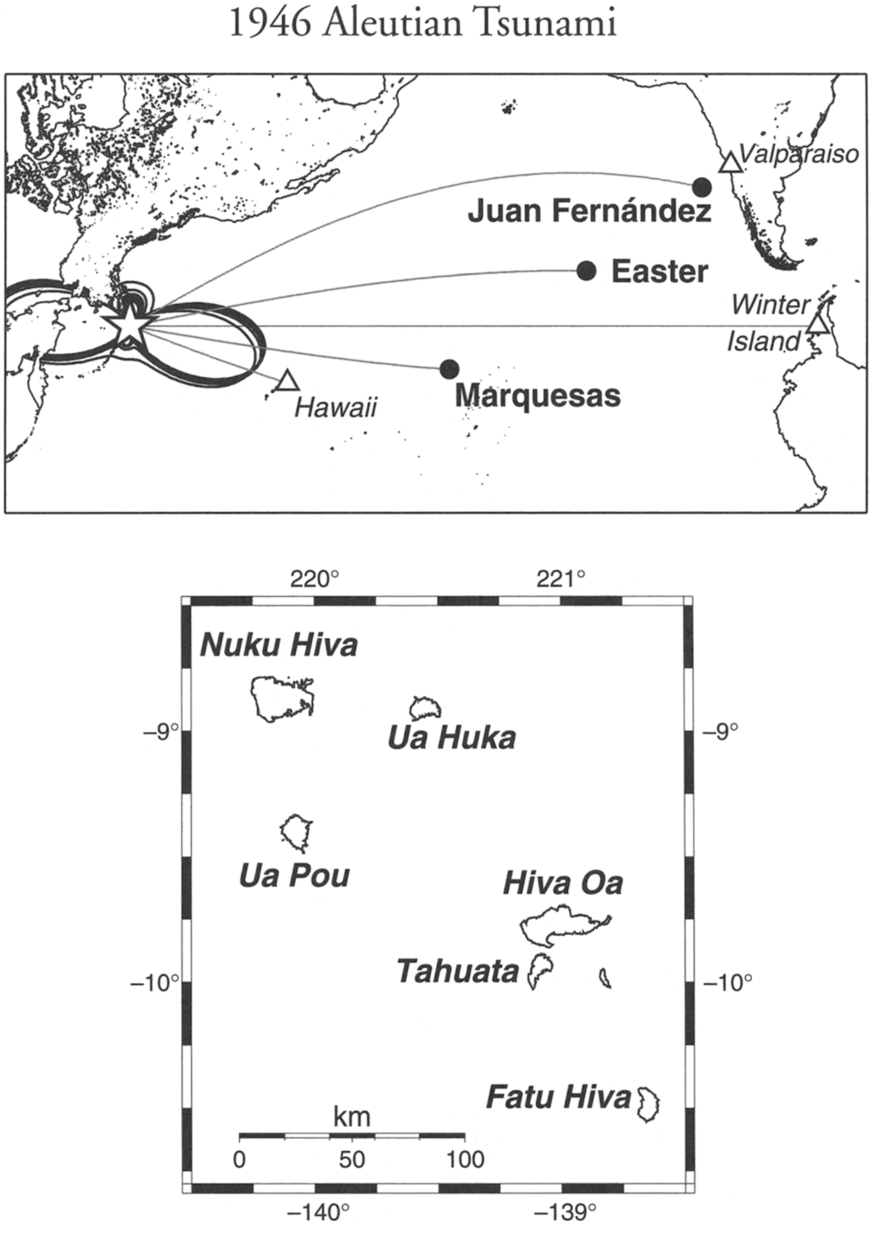
the analysis and modeling of a larger data set, notably with regard to the decay of the far-field tsunami amplitude with distance and to the azimuthal pattern of the far-field amplitude, both properties being potential discriminants between the two possible sources (Okal and Synolakis, 2001; Okal and Talandier, 1991). In this general context, this paper reports the compilation of a new data set of 54 runup and inundation values, obtained in the Marquesas, Easter, and Juan Fernández Islands through the systematic interviews of elderly residents who were eyewitnesses to the 1946 tsunami.

METHODS

As summarized in Figure 1, the eight islands targeted for study were the six inhabited islands in the Marquesas; Easter Island; and Robinson Crusoe Island, part of the Juan Fernández group. We concentrated in this study on high volcanic islands and eliminated those fringed by a coral reef, which can act as a barrier and break the wave's energy. For example, reports from Mangareva in the Gambier group indicate that the 1946 wave reached an amplitude of only 40 cm (J. Talandier, pers.



▲ **Figure 1.** Top: Map of the eastern Pacific showing the epicenter of the 1946 earthquake (star) and the three groups of islands surveyed in the present study (solid dots). The open triangles show other locations discussed in the text where the tsunami was either observed or recorded. This is an oblique Mercator projection, using the great circle to Winter Island as its equator. As such, the projection is conformal and the range of take-off azimuths for the great circle paths is plotted accurately. Directivity diagrams for far-field tsunami waves (Ben-Menahem and Rosenman, 1972) are shown centered on the epicenter for a 200 km bilateral rupture; the curves correspond to rupture velocities varying between 0.6 and 3.5 km/s. Bottom: Close-up map of the Central and Southern Marquesas Islands showing the islands visited in our survey. The Northern group, not shown, is uninhabited.

comm., 2000). In contrast, the presence of deep valleys and the lack of protective reefs make the Marquesas particularly vulnerable to tsunamis (Hébert *et al.*, 2001). In this context, and with the exception of islands with extremely difficult access (Pitcairn) and of a few uninhabited rocks (Sala y Gomez, Peter I, Henderson), our data set includes all non-reefed high islands in the central and South Pacific.

In the Marquesas, Fatu Hiva was visited by a subset of the present authors in October 1999, in the aftermath of the landslide and local tsunami at Omoa on 13 September 1999 (Okal *et al.*, 2002). The other five Marquesan islands (Hiva Oa, Tahuata, Ua Pou, Nuku Hiva, and Ua Huka) were visited in July–August 2000. Robinson Crusoe and Easter Islands were visited in November 2000.

The surveying methods used in this study are based on the previous experience of the International Tsunami Survey Teams (*e.g.*, Abe *et al.*, 1993; Synolakis *et al.*, 1995; Borrero *et al.*, 1997; Bourgeois *et al.*, 1999). They consist of measuring both runup, *i.e.*, the vertical extent, and inundation, *i.e.*, the horizontal extent, of the maximum penetration of the wave. In the particular case of a historical event such as the 1946 tsunami, we obviously could not measure watermarks and had to rely on human memory. On each island visited, we systematically sought out elderly residents having witnessed the 1946 tsunami and recorded their testimony, which we then interpreted quantitatively in terms of runup and inundation. A few interviews in the Marquesan or Pascuan languages were interpreted in real time into French or Spanish by younger-generation residents of the islands; otherwise, interviews were conducted either in French or Spanish by a native-speaking member of the survey team. All original interviews were fully recorded on videotape after obtaining informed consent, for permanent archiving.

In all cases for which data were extracted, the eyewitnesses provided coherent descriptions of the extent of the wave's penetration and in most instances physically accompanied us to the sites. Runup measurements were taken by traditional surveying methods, using a leveling rod, and inundation by measuring the distance to the shoreline, either with a surveyor's tape or through GPS fixes. A record was kept of universal time to effect a tidal correction necessary to refer runup to the high water line. The precision of our measurements is estimated at ±0.1 m for runup and ±3% (3 to 30 m) for inundation.

A major question regarding the recollections of our witnesses is the accuracy of their association with the 1946 event; in other words, we must eliminate the possibility of witnesses mixing their memories of several tsunamis. In the past 60 years, the only tsunami with a Pacific-wide impact comparable to the 1946 event is the 1960 Chilean tsunami. Fortunately, the timing of the two parent earthquakes predicts fundamentally different tsunami arrival times at most of our sites: Epicentral data confirmed by witness reports timed precisely in Hawaii predict that the 1946 tsunami (origin time 12:29 GMT) should have reached the Marquesas in daylight (around noon local solar time), Easter Island in the early evening (6:50 PM solar time, or 02:10 GMT on 2 April), and Juan Fernández at night (around 1 AM solar time, or 06:15 GMT on 2 April 1946). In contrast, the 1960 Chilean tsunami (origin time 19:11 GMT) should have reached Juan Fernández in the afternoon (3 PM solar time, or 20:15 GMT), Easter Island in late afternoon (5 PM solar time, or 00:15 GMT on 23 May), and the Marquesas at night (around 8:30 PM solar time, or 05:50 GMT on 23 May). While it would be unreasonable to expect witnesses (many of whom lived at the time a mostly rural life and may not have worn watches) to have kept a precise memory of time 54 years after the event, their recollection of the general time of day (*e.g.*, midday as opposed to evening or dawn), corroborated by a description of their activity during the arrival of the wave, was beyond doubt in all retained testimonies. Note that the only possible conflict in this respect would be the timings at Easter Island, where the 1960 tsunami would hit within a few minutes of sunset, as opposed to 45 minutes after sunset for the 1946 event, arguably similar times of the day. However, the 14-year span separating the two candidate tsunamis means that they would have occurred at very different periods in the life of our witnesses—typically adolescence as opposed to adulthood, thus providing an additional means of cross-examination based on the activity of the witness at the time of the event remembered (*e.g.*, attending school as opposed to tending to one's children). Any testimony leaving any doubt as to the exact event described by the witness was, of course, deleted from our data set. Finally, note that the above estimates of arrival times are given in local solar time, rather than in official standard time. In these isolated islands, standard time was often adjusted in recent history (*e.g.*, Hawaii went from GMT – 10:30 in 1946 to GMT – 10 presently), and we could not determine beyond doubt if any such variations had taken place in the Marquesas, Easter Island, and Juan Fernández.

We were able to retain a total of 48 interviews, which resulted in 54 measurements in 31 valleys located on eight islands, at distances of 7,183 to 12,577 km from the epicenter of the earthquake. The age of our witnesses in 2000 ranged from 59 to 89 years (average value: 72 years), the testimony of the youngest one (who was only 5 years old at the time of the event) having been confirmed by an older relative. In interpreting runup and inundation values, we note the enhanced penetration at sites located inside the beds of rivers, due to the channeling of the tsunami wave by the river. For this reason we treat separately the data sets of sites located inside and outside riverbeds, noting that the amplification of runup at the former can reach a factor of two relative to the latter.

RESULTS

In the following sections we discuss the principal results obtained on each individual island. Table 1 is a complete roster of our full data set of 54 surveyed locations. Figures 2–4 summarize these results in a common format.

TABLE 1
Inundation and Runup Values Obtained in This Study

No.	Island	Location	Date and Time Surveyed (GMT)	Shoreline Coordinates		Inundation (m)	Runup (m)	Remarks
				Long. E	Lat. N			
Marquesas								
1	Fatu Hiva	Omoa	6 October 1999 18:00	–138.68630°	–10.51400°	270	2.5	
2	Fatu Hiva	Hanavave	6 October 1999 19:53	–138.66400°	–10.46700°	140	6.0	
3	Hiva Oa	Hanamenu	3 October 1999 20:51	–139.14200°	–9.76900°	162	3.9	12-ton coral boulder deposited in 1946
4	Hiva Oa	Hanamenu	3 October 1999 21:31	–139.14200°	–9.76900°	716	7.5	
5	Hiva Oa	Hanaiapa	30 July 2000 20:52	–139.01625°	–9.71719°	0	5.9	Rock at water edge covered by third wave
6	Hiva Oa	Hanaiapa	30 July 2000 20:32	–139.01327°	–9.71780°	486	8.5	Near valley center; not in streambed
7	Hiva Oa	Hanaiapa	31 July 2000 01:02	–139.01293°	–9.71726°	274	10.4	Overland; crossroad
8	Hiva Oa	Hanatekuua	30 July 2000 23:44	–138.99063°	–9.70583°	294	6.6	Overland
9	Hiva Oa	Nahoe	31 July 2000 21:52	–138.92167°	–9.73868°	328	6.7	Overland
10	Hiva Oa	Puamau	31 July 2000 23:48	–138.88185°	–9.76501°	54	5.1	Overland
11	Hiva Oa	Puamau	1 August 2000 00:05	–138.88350°	–9.76387°	73	6.5	Overland
12	Hiva Oa	Hanapaaoa	2 August 2000 21:57	–138.96012°	–9.73980°	319	8.1	Riverbed
13	Hiva Oa	Hanapaaoa	2 August 2000 21:57	–138.96012°	–9.73980°	151	5.3	
14	Hiva Oa	Taaoa	3 August 2000 21:05	–139.06216°	–9.83547°	64	5.6	Overland
15	Hiva Oa	Tahauku	4 August 2000 01:23	–139.02590°	–9.79524°	831	14.6	Overland
16	Tahuata	Vaitahu	1 August 2000 18:32	–139.10945°	–9.93723°	50	4.3	Overland; north of river
17	Tahuata	Vaitahu	1 August 2000 18:32	–139.10945°	–9.93723°	60	4.1	Overland; south of river
18	Tahuata	Vaitahu	1 August 2000 19:57	–139.10949°	–9.93691°	195	9.7	Riverbed
19	Tahuata	Vaitahu	1 August 2000 19:57	–139.10949°	–9.93691°	145	7.3	Overland
20	Tahuata	Hapatoni	2 August 2000 01:11	–139.12198°	–9.96926°	12	4.0	Overland
21	Tahuata	Hapatoni	2 August 2000 01:26	–139.12625°	–9.97047°	19	3.0	Overland
22	Tahuata	Motopu	2 August 2000	–139.0671°	–9.9042°	257		Overland
23	Ua Pou	Hakahetau	5 August 2000 21:02	–140.10394°	–9.35911°	199	6.1	Overland
24	Ua Pou	Hakahetau	5 August 2000 21:02	–140.10394°	–9.35911°	290	8.6	Riverbed
25	Ua Pou	Hakamaii	5 August 2000 23:17	–140.11224°	–9.41467°	280	13.0	Riverbed
26	Ua Pou	Haakuti	6 August 2000 02:13	–140.12026°	–9.37871°	212	20.0	Riverbed (ravine)
27	Ua Pou	Hohoi	6 August 2000 21:05	–140.04552°	–9.43632°	24	6.0	Destroyed hut; inundation probably greater (100 m?)
28	Ua Pou	Hakahau	7 August 2000 21:52	–140.04805°	–9.35993°	259	7.2	Overland
29	Ua Pou	Hakahau	7 August 2000 21:52	–140.04805°	–9.35993°	736	18.9	Riverbed
30	Ua Pou	Hakatao	8 August 2000 22:49	–140.08563°	–9.45077°	69	5.8	Overland
31	Ua Pou	Hakatao	8 August 2000 22:49	–140.08563°	–9.45077°	119	9.0	Riverbed
32	Ua Huka	Vaipaee	10 August 2000 19:51	–139.57333°	–8.93722°	559	10.0	Near river, narrow valley
33	Ua Huka	Hane	10 August 2000 21:18	–139.53403°	–8.92461°	296	10.7	Riverbed
34	Ua Huka	Hokatu	10 August 2000 22:45	–139.52674°	–8.93068°	170	3.2	Overland
35	Ua Huka	Hokatu	10 August 2000 22:45	–139.52674°	–8.93068°	206	4.6	Riverbed
36	Nuku Hiva	Hatiheu	9 August 2000 20:34	–140.08383°	–8.82860°	126	8.2	Overland (cemetery)

TABLE 1 (Continued)
Inundation and Runup Values Obtained in This Study

No.	Island	Location	Date and Time Surveyed (GMT)	Shoreline Coordinates		Inundation (m)	Runup (m)	Remarks
				Long. E	Lat. N			
37	Nuku Hiva	Hatiheu	9 August 2000 21:05	−140.08414°	−8.82868°	303	11.3	Riverbed
38	Nuku Hiva	Hatiheu	9 August 2000 21:15	−140.08210°	−8.82804°	55	7.4	Overland
39	Nuku Hiva	Aakapa	9 August 2000 23:33	−140.13064°	−8.81404°	381	9.3	Riverbed
40	Nuku Hiva	Aakapa	9 August 2000 23:55	−140.12962°	−8.81525°	146	12.8	Overland
41	Nuku Hiva	Anahou	10 August 2000 01:53	−140.06656°	−8.82508°	57	4.5	Offshore coral reef
42	Nuku Hiva	Hooumi	11 August 2000 22:39	−140.02777°	−8.88920°	267	0.7	12-ton coral boulder deposited in 1946
43	Nuku Hiva	Hooumi	11 August 2000 22:39	−140.02777°	−8.88920°	466	1.6	5-ton coral boulder deposited in 1946
44	Nuku Hiva	Hooumi	11 August 2000 22:39	−140.02777°	−8.88920°	657	2.5	Riverbed
45	Nuku Hiva	Taipivai	12 August 2000 00:31	−140.05322°	−8.87667°	522	2.5	Overland
46	Nuku Hiva	Taipivai	12 August 2000 00:31	−140.05322°	−8.87667°	1,250	3.5	Riverbed
47	Nuku Hiva	Hakaui	12 August 2000	−140.17050°	−8.94300°	~300	3.6	Riverbed
48	Nuku Hiva	Taiohae East	12 August 2000 18:13	−140.09707°	−8.91258°	218	8.5	Overland
49	Nuku Hiva	Taiohae East	12 August 2000 18:46	−140.09507°	−8.91423°	172	10.1	Overland
50	Nuku Hiva	Taiohae West	12 August 2000 19:20	−140.10352°	−8.91233°	394	8.3	Riverbed
51	Nuku Hiva	Taiohae West	12 August 2000 19:20	−140.10252°	−8.91233°	218	5.2	Overland (inundation approximate)
Juan Fernández								
52	Robinson Crusoe	San Juan Bautista	21 November 2000 21:37	−78.83108°	−33.63598°	50	2.7	Overland
Easter Island								
53	Rapa Nui	Hanga Roa	29 November 2000 01:05	−109.43053°	−27.14707°	184	7.1	Overland
54	Rapa Nui	Hanga Roa	29 November 2000 01:26	−109.43131°	−27.14834°	118	8.6	Overland

Fatu Hiva

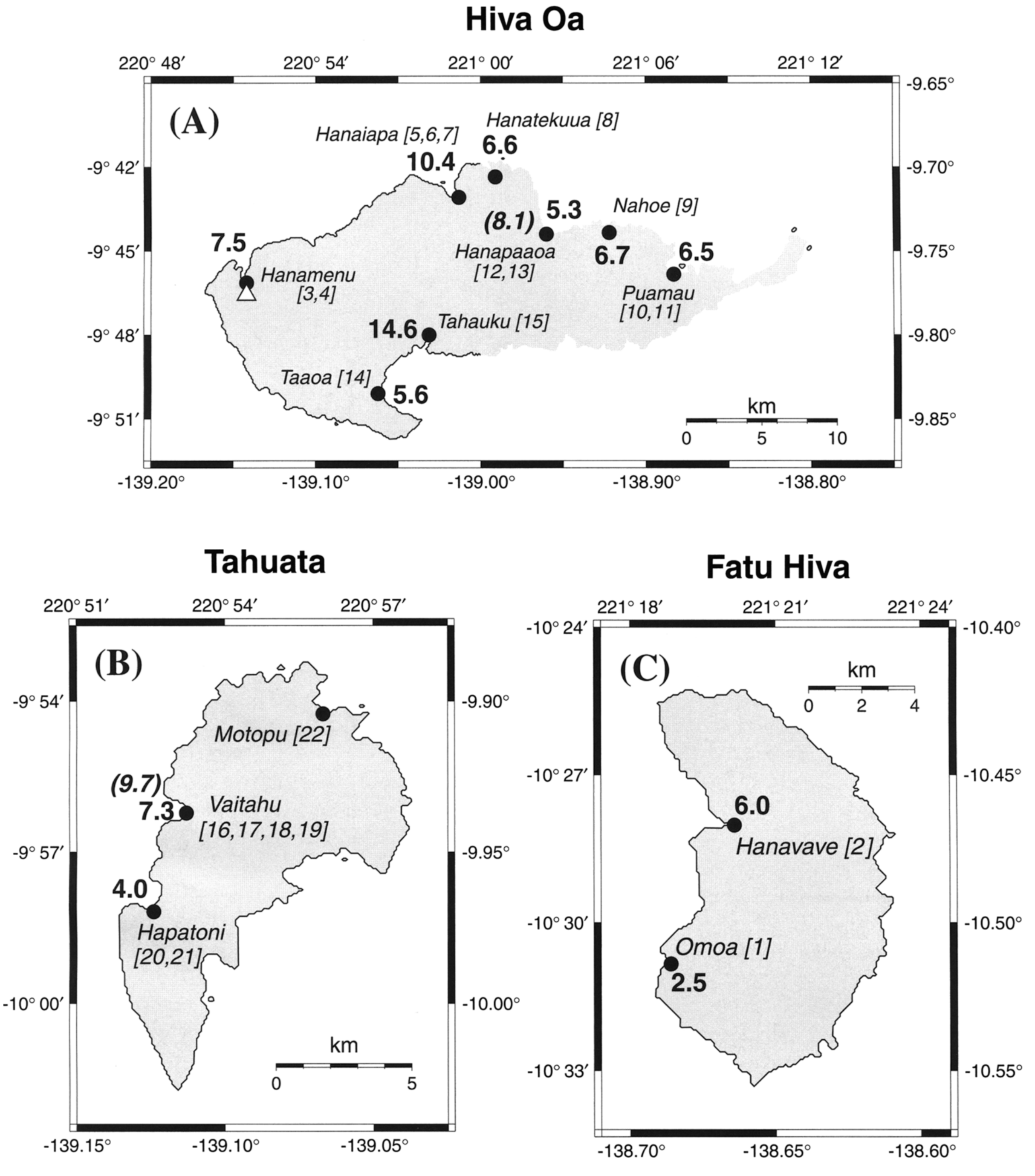
Fatu Hiva (1.18 Ma; Figure 2C) is the youngest of the Marquesas Islands (Desonie *et al.*, 1993). It is kidney-shaped with a maximum elevation of 1,125 m; its population is concentrated in two villages, Omoa and Hanavave.

As described in detail in Okal *et al.* (2002), the floor of the valley at Omoa (present population ~400) is relatively flat, allowing long inundation distances but comparatively low runup. Based on witness reports, we estimate a maximum overland runup in 1946 of 2.5 m, 270 m away from the waterfront, at the present location of the village store. The old church, built on stilts roughly at the center of the present soccer field, 100 m from the shoreline, was destroyed by the 1946 waves and swept back toward the ocean. In the riverbed, sand was transported up to 800 m inland.

By contrast, in the village of Hanavave (population ~200), at the head of the Baie des Vierges, the much steeper valley floor resulted in a combination of higher runup and shorter inundation distances. The wave reached the church door, 105 m inland at an altitude of 6 m, with inundation reaching 400 m in the riverbed.

Hiva Oa

Hiva Oa (present population 1,840; Figure 2A) is the largest island in the Marquesas chain. It consists of the remnants of two shield volcanoes, one centered on Bay Taaoa and rising to an elevation of 1,213 m, the other around Bay Puamau. It has been dated at between 1.6 and 2.7 Ma (Duncan and McDougall, 1974; Katao *et al.*, 1988). An interesting geomorphological feature on Hiva Oa is the long, flat valley of the Faakua River, which empties into Tahauku Bay. The 1946 tsunami penetrated this bay to a considerable inundation distance (830 m) with a very large vertical runup (14.6 m). The village of Tahauku suffered the only two casualties reported in the

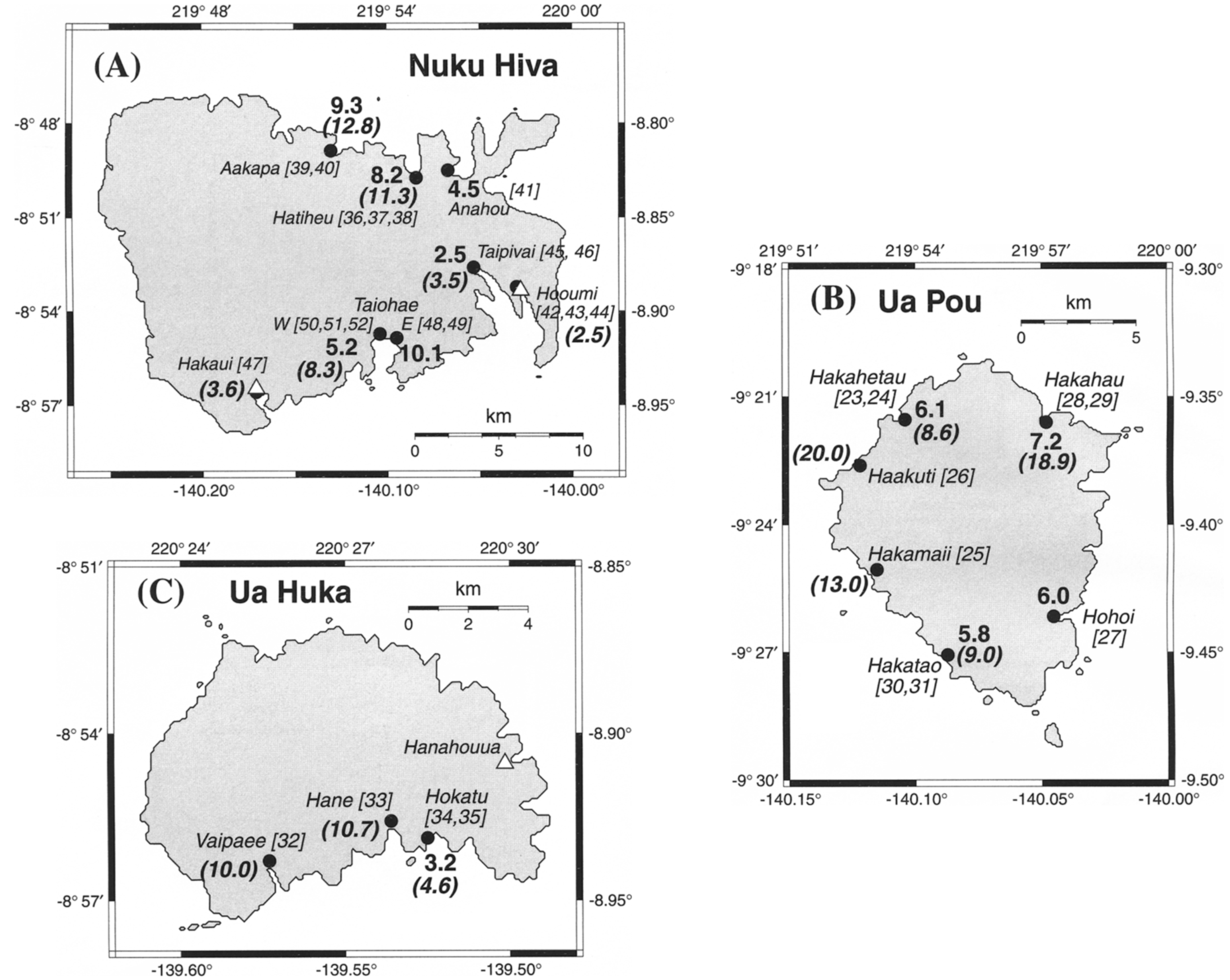


▲ **Figure 2.** Map of sites surveyed on Hiva Oa (A), Tahuata (B), and Fatu Hiva (C). The full dots show the locations of our measurements, with the value of runup (in meters) given in bold. In addition, runup values plotted in bold Italics (with parentheses) refer to measurements taken in riverbeds. The names of the sites are shown in Italics, and the numbers in brackets refer to the sequential number of the data points (left column in Table 1). Open triangles indicate the sites of coral blocks deposited by the 1946 tsunami.

Marquesas, when a mother and her infant were washed away by the tsunami. By contrast, the valleys on the northern coast of the island are somewhat steeper, which limited the inundation distance while preserving runup in the 5 to 10 m range, sufficient to have destroyed many buildings. However, the valleys remain wide, resulting in only modest amplification of runup in the riverbeds.

Tahuata

Tahuata (Figure 2B) is the crescent-shaped remnant of a caldera, culminating at 1,050 m, which was probably formed concurrently with Hiva Oa (Brousse *et al.*, 1990). We visited three settlements (total present population 640) at Vaitahu, Hapatoni, and Motopu, although we did not obtain a runup measurement at the latter. The measurement at Hapatoni (runup 4.0 m, inundation 12 m) is remarkably low.



▲ **Figure 3.** Same as Figure 2 for Nuku Hiva (A), Ua Pou (B), and Ua Huka (C).

Ua Pou

Ua Pou (present population 2,130; Figure 3B) is singular among the Marquesas for the absence of any caldera remnants and for its spectacular phonolithic pinnacles rising to 1,203 m elevation (Brousse *et al.*, 1990). Its tholeitic basalts were emplaced mostly around 4.5 Ma. As a result of its distinctive morphology, the island features steep, narrow valleys, which channeled the energy of the tsunami and greatly amplified its runup. While overland values were in the range of 5 to 7 m, they reached up to 20 m in riverbeds, where many houses were destroyed. These were the largest measured in our survey, casting an ominous shadow on the potential risk to the valley communities during future tsunamis.

Ua Huka

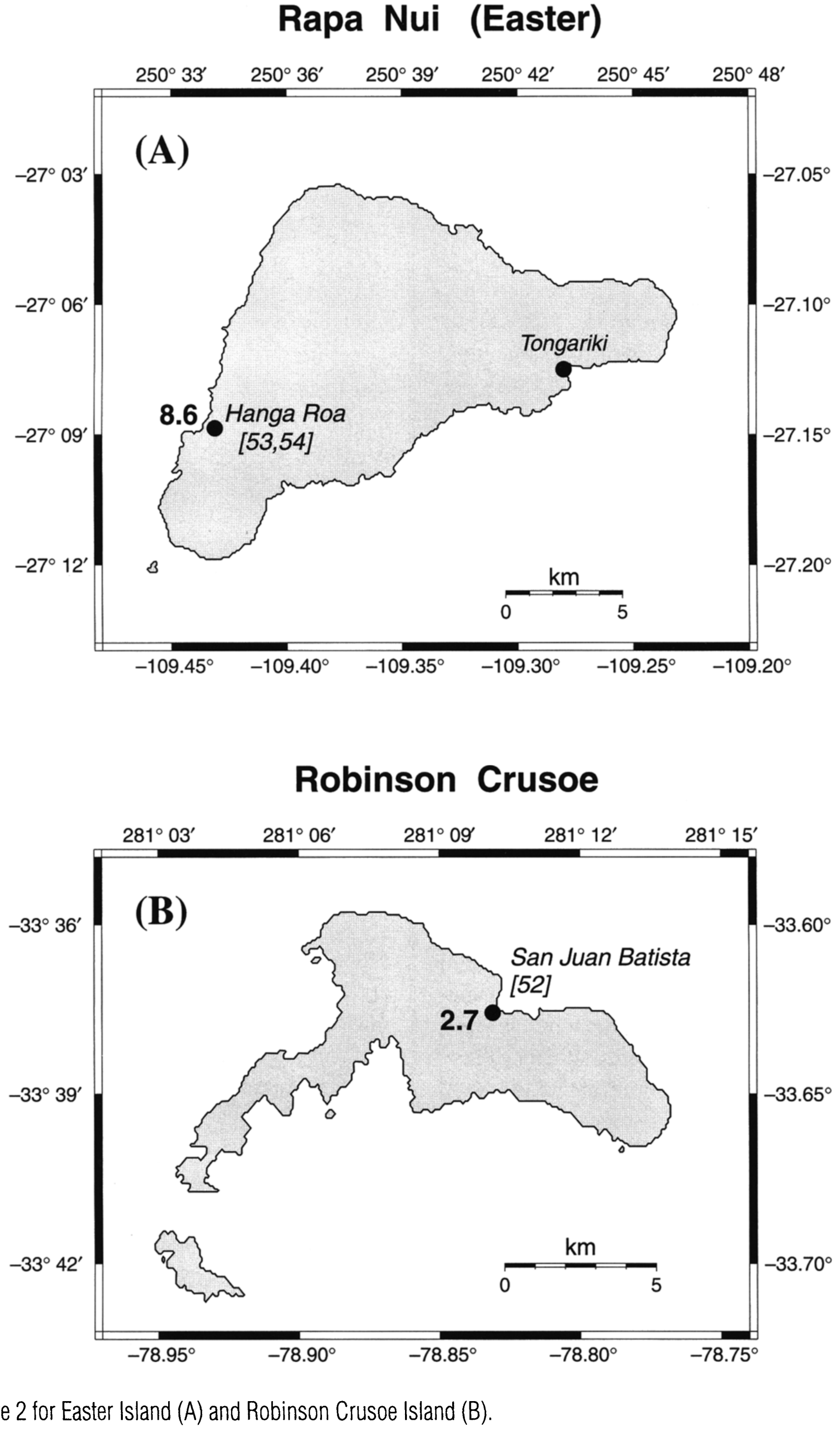
Ua Huka (Figure 3C) is a small island located 50 km east of Nuku Hiva, culminating at 884 m. It consists of the eroded remnants of the northern part of one (possibly two) caldera(s). Its main activity is dated between 3.64 and 2.42 Ma, with a final burst between 1.98 and 0.68 Ma in the southwest part of the island. There are three villages on the south coast, with a present total population of 570. Runup was consistently high (10 m) along the riverbeds of the narrow valleys of Vaipaee and Hane and was more moderate at Hokatu.

Nuku Hiva

Nuku Hiva (present population 2,380; Figure 3A), the second-largest island in the Marquesas, is the administrative and economic center of the chain. It consists of the remnants of two imbricated calderas dated between 3.1 and 4.8 Ma (Brousse *et al.*, 1990) and rising to an elevation of 1,227 m. The valleys are essentially of three kinds. (1) On the north coast, they consist of bays moderately indented into the island and rising at a gentle slope. At these locations we found in general an inundation of 50 to 100 m, increasing to 300 to 400 m in riverbeds. Runups consistently ranged from 8 to 9 m, only moderately amplified inside riverbeds, which resulted in the destruction of many buildings. (2) The bays located on the flank of the inside caldera, principally on the southeastern coast (Hooumi, Taipivai) but also to some extent at Hakaui in the southwest, are characterized by very flat valleys extending several kilometers inland (a total of 9 km from the high seas at Taipivai). In this geometry, we measured extreme values of inundation (1.25 km at Taipivai) but moderate runup heights, not exceeding 3.6 m, even in riverbeds. (3) Finally, the large bay at Taiohae rises faster than the northern ones, with irregular runup values.

Easter Island

Easter Island (Rapa Nui in Pascuan; Figure 4A) is generally considered the youngest member of the Sala y Gomez chain, with ages ranging from 0.2 to 2.5 Ma, although the chain fits only poorly the model of a linear hotspot (Bonatti *et al.*, 1977; Clark and Dymond, 1977; Woods and Okal, 1994). The only settlement on the island is the village of Hanga Roa (present population 2,800), at its western tip. We were able to interview five elderly residents and to measure two inundation points. There are no rivers, and consequently no valleys,



▲ **Figure 4.** Same as Figure 2 for Easter Island (A) and Robinson Crusoe Island (B).

on the island, whose coastline is exceptionally rocky and deprived of beaches. The bay at Hanga Roa is broad and its slope moderate. The runup values reached 7 to 8 m.

Regarding any possible confusion between the 1946 and 1960 tsunamis, expected at Easter Island because of the similar time of the day, we were able to obtain definitive testimony from witnesses remembering both events and describing the former as more powerful in Hanga Roa, while the brunt of the 1960 event was felt on the southeastern coast of the island, where it toppled the famous *moai* (statues) at Tongariki. This, and the fourteen-year time span between the two events, leave no doubt in our mind as to the correct association of our witnesses' reports with the 1946 tsunami.

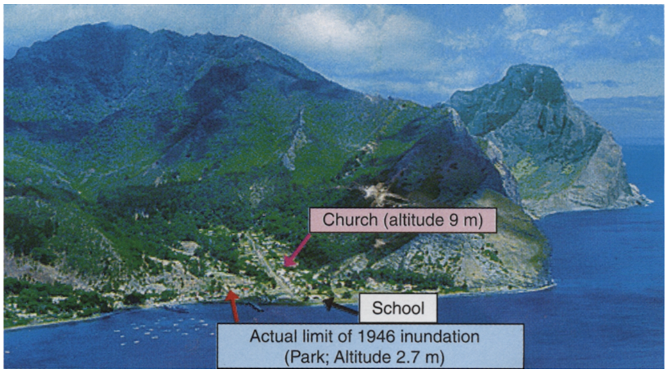
Robinson Crusoe

The Juan Fernández Islands are a young volcanic archipelago (Stuessy *et al.*, 1984). The island of Robinson Crusoe (Figure 4B), ~4 Ma old, is located 750 km due west of Valparaiso, Chile. There is only one settlement on the chain, the village of San Juan Bautista on Robinson Crusoe Island (present population 500). Despite the presence of a riverbed to the east, the bay at San Juan Bautista is broad and the slope of the valley moderate. We were particularly eager to verify the report of a 9 m runup given by Solov'ev and Go (1984); we must conclude that it is erroneous.

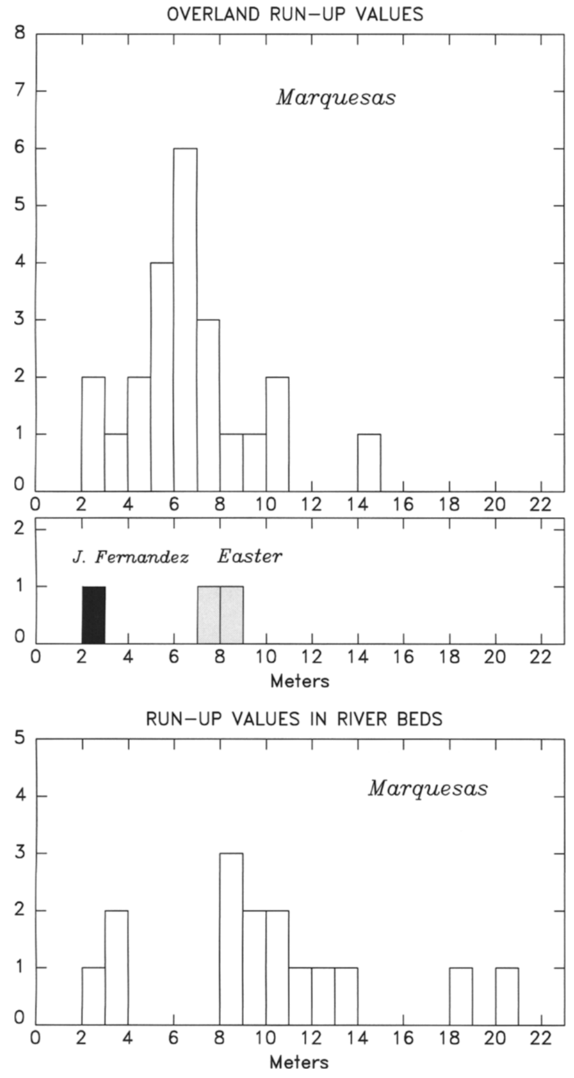
We identified one reliable witness and recorded another, less certain, testimony. Based on both accounts, we measured a runup of only 2.7 m and an inundation of only 50 m, which resulted in the flooding of only a seafront park next to the shore.

The question of the timing of the tsunami is particularly complex at Juan Fernández, since the waves are expected to reach the island in the middle of the night. Our witness, who was at the time the manager of a fishing company, reported to us that the park was flooded when he was awakened at dawn by the night watchman, who told him that the flooding had been going on for approximately two hours. This would suggest that the wave was first noticed in Juan Fernández around 4:00 AM solar time, or 09:15 GMT on 2 April. The expected time of arrival of the first sea-level disturbance is best estimated by using the tidal gauge record at Valparaiso, Chile, as published by Green (1946). The first disturbance on the record takes place at 06:45 GMT, which would suggest an arrival time of 06:15 GMT at Robinson Crusoe, where propagation times are expected to be 30 minutes shorter. This three-hour discrepancy in time deserves some critical discussion. Further examination of the Valparaiso record (Green, 1946) shows (1) that the first oscillations of the waves were of low amplitude with the maximum amplitude (approx 1 m) recorded 45 minutes later around 07:30 GMT; and (2) that successive peaks of comparable amplitude were recorded for at least three hours (the published record ends at 10:10 GMT). Assuming that the wave shapes at Juan Fernández and Valparaiso were reasonably similar, the evidence reported directly by our witness, namely that the park was flooded at dawn (~11:15 GMT), is consistent with the expected timing and history of the waves. The indirect testimony, that the flooding had been going on for some time (approximately two hours) could not be verified (and above all quantified more precisely), the night watchman being now deceased. But a realistic scenario would have him miss the first oscillations of the water, which were of lower amplitude and took place in darkness (a new moon occurred on 2 April 1946 at 04:38 GMT) and notice only subsequent and larger arrivals. This would easily account for a delay of one to two hours between the computed first arrival of the tsunami and the time reported by the watchman. We therefore consider that the apparent time discrepancy can be reasonably resolved and that it should not constitute a redhibitory argument against the testimony of our witness. We also note other details which clearly associate his account with the Aleutian tsunami, including time of year (April), period of the waves (15 minutes), and total duration of the phenomenon (the whole day). Also, the size of the bay at San Juan Bautista is small enough that bay oscillations triggered by the tsunami and lasting for several hours were probably unlikely, and the observed wave motions at the shoreline were probably individual arrivals from the tsunami wave train.

The most important and inescapable conclusion of this testimony is that it is inconsistent with the report of a 9 m runup by Solov'ev and Go (1984). To reach such an elevation, the water would have overrun the shipping office built only 20 m from the shoreline; drowned the watchman and his manager, our witness, who was living at the time in a house nearby; completely flooded the main village street; and reached 250 m inland to the village church (see Figure 5). Elderly residents confirmed to us that no such flooding had ever taken place in their lifetimes. We retain a runup of 2.7 m and can only speculate as to the origin of the inaccurate report in Solov'ev and Go (1984), which may be the result of a simple confusion with Easter Island.



▲ **Figure 5.** View of the village of San Juan Bautista, Robinson Crusoe Island. This picture illustrates the weak penetration of the 1946 wave, which did not inundate beyond the waterfront park (solid red arrow). By contrast, the report of a 9 m runup (Solov'ev and Go, 1984) would have the wave reach up to the church (purple arrow), thus flooding most of the village. Finally, note the hazardous location of the school (black arrow), built too close to the waterfront.

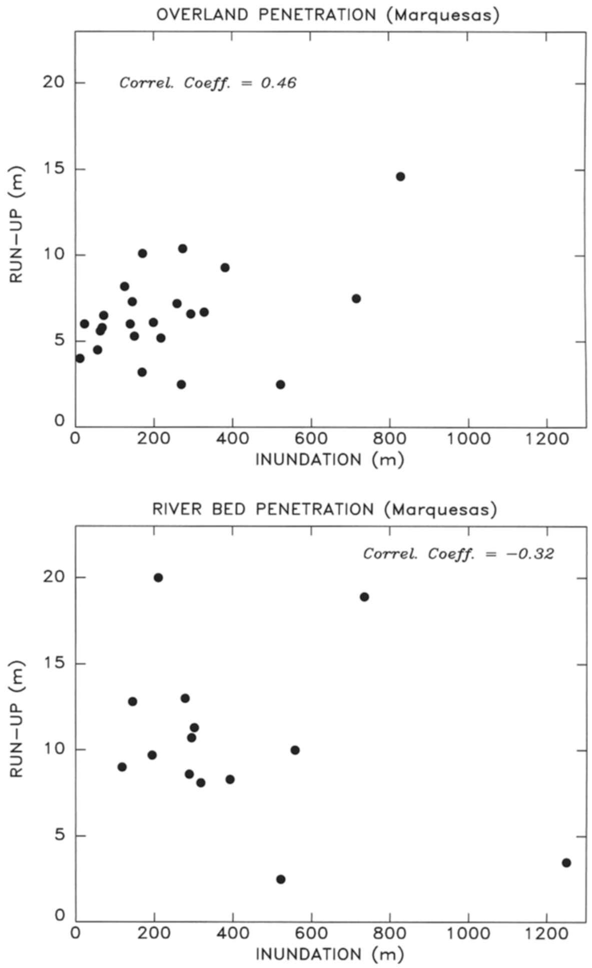


▲ **Figure 6.** Histograms of runup values measured in the present study, binned at 1 m intervals. Top: Overland runup values in the Marquesas (histogram bars shown as open blocks). Note the preponderance of values in the 5–8 m range; the largest value (14.6 m) was obtained in Tahauku Valley, Hiva Oa. Center: Overland values measured at Juan Fernández (solid bar) and Easter Island (stippled bars). Bottom: Runup values measured in riverbeds (Marquesas only). Note the predominance of values in the 8–14 m range. The lower values (2–4 m) were obtained in the flat, deep valleys of southern Nuku Hiva, the highest ones (18–20 m) in the steep narrow valleys of Ua Pou.

DISCUSSION

Runup and Inundation Values

Figure 6 shows histograms of runup values obtained in this study. For each valley, we keep only the largest measured runup, either overland (binned in the top and center frames) or in the riverbed (bottom frame). The average overland runup value in the Marquesas is 6.6 m, the standard deviation 2.7 m; by contrast, the average riverbed value is 10.0 m, with a standard deviation of 4.8 m. As mentioned above, the isolated large value (14.6 m) was obtained at Tahauku Bay, Hiva Oa, where both runup and inundation were found to be exceptionally large.



▲ **Figure 7.** Correlation between inundation and runup for overland penetration (top) and riverbed sites (bottom). Note the mediocre correlation coefficients.

Figure 7 further explores the possible correlation between runup and inundation. In both the overland and riverbed data sets the correlation is poor. In the former case, the data sets are perhaps weakly correlated, suggesting that individual bay response may be a factor. On the other hand, for riverbeds the data sets are weakly anticorrelated, a probable expression of the importance of the slope and narrowness of the valley, both parameters resulting in a strong amplification of runup in the riverbeds but in a shortening of inundation. The extreme inundation in Taipivai Valley (522 m overland and 1.25 km in the riverbed) is clearly an outlying data point, obtained in the singular morphology of a very flat and long bay, where it is likely that the tsunami evolves more like a long wave in a channel than as a long wave in the kind of steep and narrow valleys found, for example, on Ua Pou.

In very gross terms, and based on what remains a limited data set, we find penetration characteristics (runup and inundation) at Easter Island similar to those in the Marquesas; if combined to the Marquesas histogram, the Easter Island data would only slightly broaden its right shoulder. By contrast, the Juan Fernández runup datum is of much lower amplitude and is comparable only to Marquesan values measured in the long, flat estuaries of the southern coast of Nuku Hiva, a morphology totally different from that of Robinson Crusoe Island.

Interpretation of Directivity

We regard as a very important result of our study the disparity of penetration of the 1946 tsunami at Juan Fernández on the one hand and at Hawaii, the Marquesas, Easter Island, and possibly the Antarctic Peninsula on the other. This confirms the concentration of the wave along a narrow azimuthal beam from the epicenter, as noted earlier (*e.g.*, Fryer and Watts, 2000). Significantly, our new data set was obtained in a portion of the Pacific Ocean where propagation is unimpeded by island chains and ridges, in contrast to the situation in the southwest Pacific, where the Hawaiian island and seamount chain may act as a barrier against efficient propagation of the tsunami. Thus, our results confirm that the 1946 Aleutian tsunami featured a significant far-field directivity, with the bulk of its energy directed in the azimuths 133°–165° and amplitudes falling off quickly to the east.

This observed pattern in the far field is characteristic of the directivity induced by finiteness in a dislocation source (Ben-Menahem and Rosenman, 1972). In Figure 1, we show that it is easily explained by propagation of a seismic rupture along a 200 km bilateral fault. This geometry is favored by the results of a new systematic relocation of all aftershocks that occurred in 1946 (Okal and Lopez, 2002). Because of the slow phase velocity of tsunami waves (C) as compared to any acceptable value of the rupture velocity (V) for a dislocation (velocities as low as 1 km/s have been proposed for tsunami earthquakes [Polet and Kanamori, 2000]), the fault rupture is always hypersonic relative to the tsunami, which results in a strong lobe of radiation in a direction essentially perpendicular to the fault propagation. This result is also robust with respect to fault length (unilateral or bilateral) for all lengths greater than 100 km.

This contrasts fundamentally with the case of a submarine landslide for which propagation velocities V at the source always remain much lower than C (even in the case of turbidity currents, where V can reach 50 m/s). For landslides shorter than the tsunami's wavelength this results in essentially no directivity, while for slides comparable in size to the wavelength interference becomes destructive in all azimuths. In both situations, there are no pronounced lobes of far-field radiation. We therefore conclude that the strong directivity of the 1946 Aleutian tsunami requires generation of the far-field wave by a seismic dislocation.

Other Parameters of the Tsunami

In addition to identifying landmarks to allow us to measure the penetration of the tsunami, we asked our witnesses specific questions regarding the number of waves within the tsunami and their amplitude sequence. Notwithstanding the expected imprecision inherent in the recollection of events dating back 54 years, a broad consensus was obtained, describing the tsunami as involving three main waves. The first wave was almost always described as of minor amplitude, and the third one most often given the highest amplitude. This description is in general agreement with witness reports in Hawaii (Powers, 1946) and with the published maregram waveforms (Green, 1946), although the latter would generally favor a larger number of waves. It also explains the very low number of casualties (only two on Hiva Oa), the population having largely fled to the hills following the first, relatively benign wave. On the other hand, it was not possible to decide beyond doubt whether the tsunami was preceded by a significant withdrawal of the sea or if the reported regression took place only after the first crest of the wave. In physical terms, we are unable to determine if the tsunami involved a leading depression.

We then asked the witnesses to give us estimates of the interval of time separating the waves. Answers to such questions must of course be regarded as inherently imprecise, being given 54 years after a frightening event when our witnesses were often running for their lives. Nevertheless, we believe it worthwhile to report that the most frequently quoted interval between two cresting waves was 15 minutes, which again agrees with tidal gauge data and witness reports elsewhere in the Pacific (Green, 1946; Powers, 1946).

Finally, the witnesses indicated that the phenomenon lasted "the whole day", which we interpret as meaning that the sea took anywhere from 8 to 18 hours (the remainder of daylight on that day) following the onset of the tsunami to return to oscillations not exceeding the high-water mark. This would argue for an occurrence of wave trapping around the Marquesas, Easter Island, and Juan Fernández Islands, as modeled in the case of Hawaii by Vastano and Bernard (1974) and Bernard and Vastano (1977).

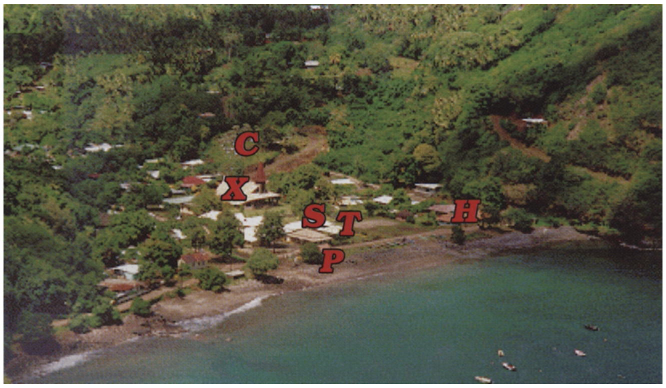
Prior Tsunamis

We systematically asked all our witnesses if they had known about tsunamis before the 1946 event. In the Marquesas, a consensus emerged that the general concept of the occurrence of an inundation by the sea was indeed known to the population (to the extent that a special word for tsunami, *taitoko*, exists in the Marquesan language) and had been transmitted through ancestral tradition to our witnesses (regular, compulsory public schooling came to many valleys of the Marquesas only in the 1960's). On the other hand, none of them had actually lived through a tsunami prior to 1946, and their parents had not described to them any event similar to the 1946 tsunami. Nevertheless, the ancestral tradition was strong enough for the residents to self-evacuate to high elevations upon noticing the first wave (whose low amplitude estimated at 2 m kept it relatively benign) and the subsequent (and possibly precursory) retreat of the sea.

Only one witness (aged 73 in 2000) reported that, during the flooding of Taiohae by the 1946 wave, his grandfather had told him of having witnessed a similar event "about 70 years earlier." In attempting to interpret this testimony in the framework of known large tsunamis of the Pacific Basin, we note that previous catastrophic trans-Pacific tsunamis include the 1868 Arica, 1877 Iquique, 1906 Valparaiso, and reportedly 1922 Chilean and 1923 Kamchatka events. We must come to the conclusion that neither of the latter two (1922 and 1923) could have had any serious impact on the Marquesas, especially since some of our more senior witnesses (aged 11 to 12 at the time of these events) would have been old enough to remember them. This is surprising, given the Pacific-wide character of the 1922 event, which wrought significant destruction as far as Japan. On the other hand, and although we cannot fully dismiss the possibility of an association with the 1906 event, the 1877 earthquake fits the report of our witness in Taiohae, and we speculate that it may have constituted the previous episode of significant tsunami damage in the Marquesas.

Coral Deposits

In the Marquesas Islands, our witnesses reported a number of instances where large coral boulders were deposited on beaches or inland during the 1946 tsunami. Similar instances have been reported during many tsunamis (*e.g.*, Shepard *et al.*, 1950), and it has been suggested that cyclopean blocks of dekametric size standing on the coral platter of Rangiroa (Tuamotu Islands) and on Australia's Great Barrier Reef may have been deposited by tsunamis (Bourrouilh-Le Jan and Talandier, 1985; Nott, 1997). The Marquesas are presently not fringed by coral, but submerged reefs are documented offshore (Rougerie *et al.*, 1992), as witnessed by several beaches of white coral sand (*e.g.*, Tanaeka on Hiva Oa). We were able to observe large coral boulders at four locations and to survey them at three sites: Hanamenu (Hiva Oa) and Hakaui and Hooumi (Nuku Hiva). We also confirmed their presence at Hanahouua (Ua Huka) during a helicopter flyover. The timing of the deposition of the coral blocks was confirmed to us by witnesses whose families used to farm coprah in the relevant valleys in 1946.



▲ **Figure 8.** View of the village of Vaitahu on Tahuata Island (Marquesas), illustrating hazardous waterfront development. The 1946 wave penetrated inland to a location along the back wall of the present church (X; built in the 1980's), 145 m from the shoreline. Note the hazardous location of the post office (P), town hall (T), elementary school (S), and hospital (H). Ironically, only the cemetery (C) is safely located on a hill.

At Hanamenu (Hiva Oa) we surveyed two large coral blocks of 7 m^3 and 4 m^3 volume, respectively. The former (site 3 in Table 1) is 162 m from the shoreline at an altitude of 3.9 m, the latter 249 m from the shore and 3.5 m above it. Allowing for the porosity of coral, their masses are estimated at 12 and 7 tons, respectively. At Taipivai (Nuku Hiva) we surveyed two boulders of 7 m^3 and 3 m^3 volume (sites 42 and 43 in Table 1) which were carried inland a distance of 267 and 466 m, respectively.

Social Aspects

Motivated by the recent inundation of the school building at Omoa, Fatu Hiva during a local tsunami triggered by an aerial landslide (Okal *et al.*, 2002), we examined the positions of critical buildings, such as schools and hospitals, in every village we visited. Unfortunately, we observed repeatedly the overdevelopment of waterfront property, in particular within the zone described to us as having been severely inundated during the 1946 tsunami (and often also in 1960), a practice which must be considered hazardous. This is a relatively recent trend in the history of the islands. Archaeological sites are always located at least several hundred meters inland. Figure 8, a general view of Vaitahu on the island of Tahuata, shows a majority of critical public buildings (school, hospital, town hall, post office) built directly on the waterfront, in the most hazardous location. A similar hazard exists in many villages in the Marquesas, as a consequence of the royal claim of a 62-m-wide strip of land along the shore (known as "les 50 pas du Roi"), upon annexation of the islands by France in 1842, with the real estate eventually becoming public land, presently under ownership of the Territory. Out of 25 schools visited in the Marquesas, 13 are built in hazardous areas and would be exposed to inundation and/or destruction during a future tsunami. The school on Robinson Crusoe Island (Figure 5) is similarly built on the immediate waterfront, within the inundation zone of the 1946 tsunami.

It is particularly important to stress that, while some level of advanced warning should be available to the population prior to the next major transoceanic tsunami, isolated islands can also face the danger of locally generated tsunamis, for which there exist at present no practical means of warning. The 1999 tsunami at Fatu Hiva served as a chilling reminder of the vulnerability of the Marquesas to aerial landslides (Okal *et al.*, 2002). The regular occurrence of felt earthquakes in the Juan Fernández Islands (Wysession *et al.*, 1991) also points to a focus of seismic activity, probably related to the magmatic center responsible for the islands' young volcanism. Such offshore earthquakes could trigger underwater slumps resulting in locally lethal tsunamis, along the mechanism of the 1998 Papua New Guinea disaster (Synolakis *et al.*, 2002).

We therefore recommend that the relocation of school buildings to safe ground, or at the very least their protection by reinforced walls and other mitigation efforts such as the establishment of landside emergency exits, be made an absolute and immediate priority on all oceanic islands in order to avoid horrible tragedy during future tsunamis.

FINAL PERSPECTIVE

Our field survey of the 1946 Aleutian tsunami in the Marquesas and other isolated islands of the Pacific has resulted in a data set of 54 runup and inundation values. This number far exceeded our best hopes before embarking on the survey. In this respect, we have established the feasibility of recording valuable information from elderly witnesses and of transforming it into a homogeneous, quantitative database, comparable to those obtained by survey teams following modern-day tsunamis, which can be used in modeling efforts aimed at unraveling the mechanism of generation of the oceanic wave. Perhaps the most critical aspect of our success at recording testimonies on the 1946 event was the relative lack of tsunamis competing (in amplitude and date) with the Aleutian one, thus reducing the possibility of confusion in the mind of our witnesses. In this respect, a note of caution might be warranted regarding the extension of our method to the interview of witnesses along continental shores, which could be the site of more frequent, local tsunamis. However, given the right conditions, we believe that our approach could be successfully repeated for other historical events. It remains an obvious limitation that such surveys are pressing; our study of the 1946 tsunami would certainly not be possible ten years from now.

ACKNOWLEDGMENTS

First and foremost, we thank the wonderful people of the islands who willingly shared their precious memories with us; they are, unfortunately, too numerous to list individually. We are particularly grateful to Mayors Lucien Kemitete (Nuku Hiva), René Kohumeitini (Ua Pou), Tehivetope Kamia (Fatu Hiva), and Governor Enrique Ximena (Easter Island), who helped identify witnesses and put many resources of their communities at our disposal. Jacques Talandier, Dominique Reymond, and Olivier Hyvernaud are thanked for many conversations on tsunamis in Polynesia, as well as for supporting the logistical aspects of the project. Emilio Lorca also helped our logistics in Santiago. Jean-Louis Candelot shared his personal experience of, and insight into, tsunamis in the Marquesas. Sue Hough provided helpful comments on the original manuscript. Our work in Polynesia was authorized by the Haut-Commissariat de la République en Polynésie française. We acknowledge support from the National Science Foundation, the Federal Emergency Management Agency, the Joint Institute for Marine and Atmospheric Research (United States); and the Commissariat à l'Énergie Atomique (France). Maps were drawn using the *GMT* software (Wessel and Smith, 1991).

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