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REVIEW ARTICLE

A qualitative review of tsunamis in Hawaiʻi

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Abstract

The Hawaiian Islands have a long history of destructive and deadly tsunamis from both distant and local sources. Gaining a more detailed understanding of the historical record of tsunami impacts is a key step in reducing the vulnerability of coastal communities to tsunami inundation. This paper explores the history and prehistory of tsunamis in the Hawaiian archipelago, while proposing methods to narrow the gaps in our current understanding of their impacts. Future strategies to reduce risk and improve resilience to tsunami flooding are also discussed and evaluated.

Keywords Tsunamis · Hawaiʻi · Mitigation · Bioshields

1 Introduction

At approximately 7:00 p.m. on December 21, 1812 CE, Hawaiian historian John Papa Īʻī recorded an account of an unusual wave hitting the Hawaiian Islands. Papa Īʻī, who was visiting his sick uncle at Hoʻokena on Hawaiʻi Island (Fig. 1), reported “a strange rising of the sea” that “brought water into the house and wet the patient.” (Papa Īʻī 1995: 115). Papa Īʻī‘s mention of this event, which seems to have originated from an earthquake off California, marks Hawaiʻi’s first historically recorded tsunami, which appears to have caused

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minimal damage (Lander and Lockridge 1989). Between 1812 and 2022 CE, at least 175 additional tsunamis have struck Hawaiian shores, although only a small number of these (18) were destructive (Lander and Lockridge 1989).

This paper examines the following research question (with particular emphasis on the Hawaiian archipelago, but which may have broader relevance to tsunami-impacted coasts worldwide): how can communities reduce the destructive impacts and loss of lives due to tsunamis, while improving their resilience to such events, by understanding the historic and paleo-tsunami record? It does so by first reviewing the reasons why tsunami research remains necessary for successful hazard risk reduction, tsunami impact mitigation, and natural resource management in Hawaiʻi (Sect. 2). This is followed by a review of the historical and pre-historic records of tsunamis in Hawaiʻi with due recognition that the passage of time increases epistemic uncertainty about the nature of these events (Sect. 3). Section 4 introduces a number of gaps in our knowledge of the impacts and hazards of tsunamis in Hawaiʻi that coastal land managers can address by using multi-proxy approaches, including scientific, ethnographic, and archaeological data. Finally, Sect. 5 explores some of the specific strategies coastal managers can employ to mitigate tsunami impacts. Many of these are derived from tsunami research conducted in the aftermath of recent tsunamis, including the 2004 Indian Ocean, the 2009 Samoan, the 2011 Tōhoku-oki and the 2022 Hunga-Tonga Hunga-Haʻapai tsunamis (Gelfenbaum et al. 2006; Morton et al. 2008; Sugawara et al. 2012; Terry et al. 2022).

Since 1946, the Japanese term ʻtsunami’ (literally ʻharbor wave’) has worked its way into the English lexicon (Goff and Dudley 2021). Recent research has expanded this lexicon to include such descriptors as ʻ*yoda*’ and ʻ*souteigai*’ tsunamis (a small tsunami and an unexpectedly large tsunami, respectively; [Goff et al. 2016]). The use of such terms signals a degree of semantic narrowing that facilitates a more precise description of these events. In the Hawaiian language, the most commonly used term for tsunami is *kai eʻe* (literally ʻmounting seaʻ), which reveals both an awareness of the visual appearance and the destructive power of tsunamis. Throughout this work, we refer to all such events as tsunamis, unless they have been described otherwise in the historical or the research literature.

2 Why study tsunamis in Hawaiʻi?

Studying paleo- and historical tsunamis is important for two reasons. First, given the destructive power of tsunamis, as illustrated by a number of twenty-first century events, coastal land managers and residents need to better understand such events to reduce future tsunami risk. The 2004 Indian Ocean tsunami, which caused over 200,000 deaths, and the 2011 Tōhoku-oki tsunami, which claimed the lives of over 16,000 individuals, should serve as reminders that, as coastal populations grow, seismic and geological instabilities pose a threat to both human and natural resources (including in Hawaiʻi). Hawaiʻi’s (Fig. 1) geographical position at the center of the Pacific Basin makes it particularly vulnerable to tsunamis generated from numerous local, regional, and distal circum-Pacific sources, an important concern for coastal land managers and disaster preparedness agencies (Butler et al. 2017b; La Selle et al. 2020). As with many Pacific Island archipelagos, coastal areas are culturally and ecologically sensitive, plus they have significant economic value.

Second, discerning the tsunami source, whether local, regional, or distant, remains an important dimension of emergency preparedness. Hawaiʻi’s current warning system, housed at the Pacific Tsunami Warning Center on the island of Oʻahu, has proven

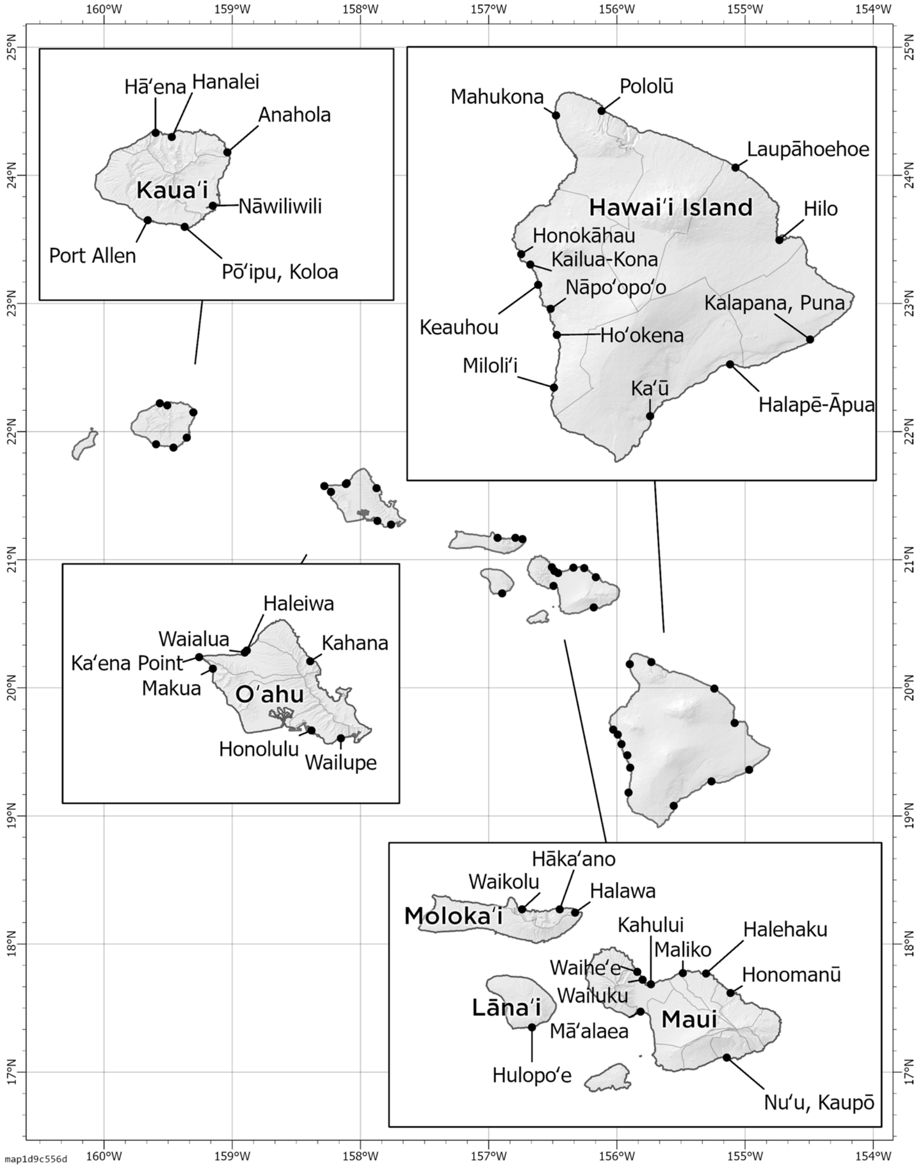

Fig. 1 Map of the Hawaiian Islands showing locations mentioned in the text

remarkably effective in providing ample notice to coastal residents of distant-source (megathrust earthquake generated) tsunamis (Walker 1999). However, local-source tsunamis, with very little warning, have claimed the lives of Hawaiʻi residents in both the nineteenth and twentieth centuries (Anon. 1868; Goff et al. 2006; Richmond et al. 2011).

In addition, the January 2022 Hunga-Tonga Hunga-Haʻapai volcanic eruption near Tonga has raised questions about Hawaiʻi's vulnerability to tsunamis generated by submarine volcanic eruptions (Terry et al. 2022). Gaining a better understanding of such infrequent, but potentially damaging, events and their impacts will contribute to reducing the risk of hazards that the Hawaiian Islands face.

3 An overview of Hawaiʻi's tsunami history

This section examines both the chronology and destructive capacity of tsunamis in the Hawaiian Islands. Doing so provides a link in understanding steps toward building resilience to such events and reducing their impacts. Figure 1 depicts the locations mentioned in the text. Section 3.1 starts with the first historical accounts of tsunamis beginning in 1812 CE and runs through the nineteenth century, while Sects. 3.2 and 3.3 cover twentieth and twenty-first century tsunamis, respectively (cf. Table 1). The primary sources of data for these tsunamis include newspaper reports, missionary accounts and published documents. Field data from the historic period primarily include geochronological, microfossil and sedimentary, and geochemical analyses. Sections 3.4 and 3.5 examine the Holocene (prior to the historic period) and Pleistocene records of tsunami impacts, respectively. The pre-historic evidence of tsunami impacts derives from ethnographic accounts and archaeological data as well as geochronological, microfossil, sedimentary, and geochemical evidence from field analyses (see Table 2).

3.1 Regionally and locally generated historic tsunamis: 1812–1900 CE

The written record in Hawaiʻi, which starts in the 1820s, ushered in an era of historical documentation of tsunamis and other natural phenomenon. As noted above, the first record of a tsunami dates to December 21, 1812 CE, by Hawaiian historian John Papa Īʻī, although he wrote his account as much as five decades after the event (Papa Īʻī 1995). Historical analysis indicates that this wave originated from the California coast, providing important insights into assessing the source of tsunami threats. For example, Atwater et al. (2015) ability to link the 1700 CE Cascadian subduction zone earthquake with an 'orphan' tsunami (an event not preceded by local seismic activity) on the east coast of Japan demonstrates the potential vulnerability of the Hawaiian islands to tsunamis from this source (Goff et al. 2022).

Hawaiʻi's first historically recorded deadly tsunami was generated by an earthquake off the coast of Valdivia, Chile. This wave struck the Hawaiian Islands at approximately 7:00 p.m. on November 7, 1837 CE. Historical reconstructions of this event have estimated current velocities in the town of Hilo, which received the bulk of the damaging impacts of the wave, of between 15 and 18 km/hour (Lander and Lockridge 1989). Missionary accounts of the tsunami have proven especially helpful in reconstructing the physical and social impacts of the event. Two documented historical accounts come from American Congregational missionaries, one stationed at Hilo, Hawaiʻi, and the other at Wailuku, Maui (Fig. 1). Sarah Joiner Lyman's account from Hilo, begins:

> "As we were about to kneel for prayers in the evening we heard a great outcry among the natives on the beach [and] concluded that there was trouble among the sailors of an English ship now in port. As soon as the prayer was over Mr. L. [David Lyman, the author's husband] went out to ascertain the cause of such confusion, when to our great surprise we found that the water in the bay had risen so as to go many rods beyond its usual bonds. A number of houses had been in an

Table 1 Chronology of all known historic Hawaiian tsunamis (1812–2022 CE)

Tsunami: date and source location	Location of tsunami impacts	Methodology	Results of study	Source
Possibly meteorite impact/submarine volcanic explosion, or a submarine landslide—approximately 100 k years BP	Lana‘i	Field investigation of the Hulopo‘e Gravel and mapping around Hulopo‘e Bay, Lana‘i	A single event, occurring approximately 100 k years BP deposited the Hulopo‘e Gravel to several hundred meters	Moore and Moore (1984)
Likely a submarine landslide 105 k years BP, the landslide occurred at a distance of 50 km from Lana‘i	Lana‘i	Field investigation of the Hulopo‘e Gravel and mapping around Hulopo‘e Bay, Lana‘i	Marine sedimentary deposits from 105 k BP a found up to 375 m on the island of Lana‘i from a large wave evidence includes basalt boulders, coral clasts, slabs of calcareous beach rock, and sand and shell fragments	Moore and Moore (1988)
Lana‘i Flank Collapse, 240 k-200 k years BP	Moloka‘i	Distribution, deposition and chronological analysis of marine conglomerates of material found in central and west Moloka’I, use of U-Th dating of marine material	A giant wave impacted Moloka‘i in the Pleistocene, poor taphonomic constraints limited the recovery of material on the eastern end of Moloka‘i	Moore et al. (1994)
Lana‘i Flank Collapse, 135 k BP-240 k years BP	N/A	Field investigation and collection of Coral deposits, geochronology established using Electron Spin Resonance (ESR)	The likelihood of Lana‘i mega-tsunami cast in doubt, marine sediments deposited through lithospheric flexure, eustatic sea level change and possibly anthropgenic movement of coral clasts at elevations above 100 m, tsunami deposits possible below 100 m	Grigg and Jones (1997)
Lana‘i Flank Collapse, 135 k BP-240 k years BP	N/A	Analysis of sedimentary material, including coral clasts, and geochronological dating using U-Th sequences	Late Quaterary uplift, not a tsunami, caused deposition on Lana’I, uplift may have been caused by lithospheric flexure or isostatic rebound, casts doubt on the likelihood of a Lana‘i mega-tsunami	Rubin et al. (2000)

Table 1 (continued)

Tsunami: date and source location	Location of tsunami impacts	Methodology	Results of study	Source
Lana‘i Flank Collapse, 135 k BP-240 k years BP	N/A	Field investigation on Lana‘i, west of Mānele Bay, GPS mapping of coral and basalt deposits in dry gulches from 800 feet, to 30 m above mean sea level	Casts doubt on the likelihood of Lana‘i mega-tsunami, normal coastal processes, including island uplift and glacial eustatic sea level variations account for the presence of carbonate material in the study area	Helsley and Helsley (2012)
Alika Slide I and II, 127-112 k years BP, 110 K years before present	Kohala Coast, Hawai‘i Island	Sedimentary deposit analysis including fossiliferous material along the Kohala Coast, U-series dating	Alika Landslides from the submarine slopes of Mauna Kea deposited the material found on the Kohala Coast	McMurtry et al. (2004)
Alika Slide, 120 k years BP	Kohala Coast, Hawai‘i Island	Microfossil analysis, particularly the foraminefera *Amphistegina lessoni*	The geologic setting, combined with the abundance of microfossils provide evidence for a megatsunami impacting the Kohala Coast	Williams et al. (2006)
Possible Lana‘i flank collapse, 100 k-200 k years BP	Moloka‘i	Particle size analysis at 34 sites to determine the cumulative grain-size curve	Landward fining for carbonate clasts, suggesting deposition by a single tsunami	Moore (2000)
Submarine landslide, 240 k years BP	Moloka‘i	Grain size analysis of carbonate material branching coral and coralline algae deposited approximately 240 ky BP found on the island of Moloka‘i	Landward fining of carbonate material, suggest a single depositional event on Moloka’i likely by a submarine landslide off the Hawaiian Islands	Moore (2008)
Source unclear, 102 k-134 k years BP	Lana‘i and Moloka‘i	Analysis of geophysical and observational information, numerical modeling and tide gauge data	Rates of uplift over the past 30 k years indicate limited vertical movement on Lāna‘i, indirectly supporting the Giant Wave hypothesis	Webster et al. (2006)

Table 1 (continued)

Tsunami: date and source location	Location of tsunami impacts	Methodology	Results of study	Source
Submarine landslide near Lāna‘i, 105 years BP;	Lana‘i	Modeling using the SWAN code	The Alika 2 landslide is the most likely source of the tsunami deposits of this date on Lana’i, but the data remains inconclusive	Johnson and Mader (1995)
Aleutian Islands, 1425–1665 CE, 1946 and 1957	Makauwahi Cave, Kaua‘i	Numerical modeling and examination of palaeotsunami sedimentary evidence	Tsunami deposited material in the Makauwahi cave occurred between 350 and 575 years BP, geometry of the Hawaiian Islands in relation to the eastern Aleutian Islands makes Hawai‘i particularly vulnerable to tsunamis originating there	Butler et al. (2014)
South Pacific, source unclear fifteenth century	Regional, South Pacific, including Hawai‘i	Review of anthropological evidence related to Pacific-wide societal disruptions in the mid-14th to fifteenth century	Societal changes throughout the Pacific in the 14th and/or fifteenth century, likely by either a large wave tsunami or changes in sea-level, data supporting these societal changes can be derived from cultural proxies	Goff and Nunn (2016)
Aleutian Islands, 1586 CE	Makauwahi Cave, Kaua‘i	Analyisis of coral debris from Makauwahi cave using U-Th dating, historical review of possible source locations using chronological constraints provided by these dates, which fall around the mid- to late-sixteenth century	The Aleutian Islands are the most likely source of the tsunami—purported to have done extensive damage to the Sanriku coast, Japan in 1586 CE, BUT this event proven erroneous (Satake et al. (2020)	Butler et al. (2017a)

Table 1 (continued)

Tsunami: date and source location	Location of tsunami impacts	Methodology	Results of study	Source
Primarily Aleutian Islands, 1300–1500 CE, 1946 and 1957	Anahola, Kaua‘i, Kahana, O‘ahu, Pōlolu, Hawai‘i Island	Documentation of stratigraphy using gouge, russian and Vibracores, grain size analysis, tomographic scans, geochronology using ^{137}C and AMS ^{14}C	Identification of previously unidentified tsunami deposits at Anahola, Kaua’I, Kahana, O’ahu and Pōlolu, Hawai‘i, deposits in these areas record one, and possibly two, distant-source tsunamis ranging in age from 1246 to 1460 CE	La Selle et al. (2020)
Local Tsunamis, 1812–1999	Across the Hawaiian archipelago, with primary focus along the Kona coast, Hawai’i	Review of Historical Data, in particular tsunamigenic earthquake magnitudes, tide gauge readings and numerical modeling	Destructive local tsunamis suggest the need for a more effective warning system	Walker (1999)
1946 Aleutian and 1960 Chilean Tsunamis	Pōlolu Valley, Hawai‘i Island	Multi-Proxy: including sedimentary analysis from gouge cores and trenches; geochemistry analysis using Neutron Activation Analysis, core chronologies established using ^{210}Pb and ^{137}Cs; diatom, foraminifera and palynological analysis	Analysis of depositional evidence in Pōlolu Valley, Hawai‘i of the 1946 and 1957 Aleutian Islands tsunamis, publication of the first conclusive sedimentary evidence of distant-source tsunamis in the Hawaiian Islands	Chague-Goff et al. (2012)
Aleutian Tsunamis of 1946 and 1957, Kamchatka Tsunami of 1952 and the Chilean tsunami of 1960	Shinmachi, Hilo, Hawai‘i Island	Multi-proxy analysis of known tsunami impact sites, including geochemical ITRAX and XRF, stratigraphy, grain size analysis, and AMS ^{14}C dating Numerical modeling of sediment source and transport processes	Study indicates that geochemical signatures, dating, and grain size analysis provides useful information on sediment source, analysis assists the distinction between storm and tsunami deposits	Chague et al. (2018)

Table 1 (continued)

Tsunami: date and source location	Location of tsunami impacts	Methodology	Results of study	Source
Aleutian Tsunamis of 1946 and 1957, Kamchatka Tsunami of 1952 and the Chilean tsunami of 1960	Throughout the Island of O‘ahu, study sites included Queen’s Beach and Shark’s Cove, O’ahu	Field investigations of boulders and sediments, Queen’s Beach and Shark’s Cove, O’ahu	Susceptibility of O’ahu to tsunamis from a number of locations, importance of O‘ahu for the study of tsunami impacts on coastal geomorphology	Whelan and Keating (2004)
Aleutian Tsunamis of 1946 and1957, Kamchatka tsunami of 1952 and the Chilean tsunami of 1960	Queen‘s Beach, O‘ahu	Surficial depositional investigation, Queen‘s Beach, O‘ahu, tsunami modelling, Review of historic eyewitness accounts	4 tsunamis inundated Queen‘s Beach in the twentieth century, consistency with post-tsunami runup evaluations, eyewitness accounts and modeling data	Keating and Whelan (2004)
Various tsunami sources and storm deposits, 19th and 20th Centuries	Southeast coast of Hawai‘i Island	Field investigation documenting the sedimentary characteristics and depositional morphology of the area between Apua Point and Keauhou Landing, Hawai‘i Volcanoes national Park	The authors identified tsunami deposits from at least two events 1868 and 1975, study distinguishes between storm inundation distances 50–100 m and tsunami inundation > 300 m	Richmond et al. (2011)
Local Submarine landslide	Halape-Apua Point, Hawai‘i Island	Analysis of depositional material at the site, including basalt and coral boulders, carbonate sands and anthropogenic material	Detailed understanding of the 1975 locally generated tsunami and the transport of sediment related to that event, including deposition patterns of boulders and sand as both suspended and bed-load	Goff et al. (2006)
Kuril Islands Tsunami, 1946	Archipelago wide, with special focus on Penguin Bank	Reconstruction of oscillation and amplification patterns of the 2006 Kuril Islands tsunami impacts on Hawai‘i using non-linear shallow-water models	Resonance amplification is strongly correlated with bathymetric features as well as frequency and direction of tsunami waves, Penguin Bank dominates tsunami wave oscillations, and influences standing waves impacting Kahului and Ma‘alaea, Maui	Munger and Cheung (2008)

Table 1 (continued)

Tsunami: date and source location	Location of tsunami impacts	Methodology	Results of study	Source
Tohoku-ōki Tsunami,2011	Arhipelago wide	Use of NEOWAVE and bathymetric and topographic data from Lidar, Etopoi and multi-beam data sources at 1 arc min–1800 m	Collection of Non-linear shallow-water data using high precision resonance amplification and runup modeling from across the Hawaiian archipelago	Cheung et al. (2013)
Aleutian Islands, possible inundation	Archipelago wide	Probabilistic analysis and forecasting of tsunamigenic Aleutian Islands earthquakes, using NOAA operational code, SIFT, and NEOWAVE, Analysis was done on 15 coastal locations across the Hawaiian Islands	Forecast modeling of Mw earthquakes in the Aleutian Islands, hazards exceed current tsunami evacuation map recommendations in 14 of the 15 coastal locations, modeling suggests that Hilo is at the greatest risk of destructive tsunami impacts	Butler et al. (2017b)

Table 2 Geological tsunami research in the Hawaiian Islands

Day	Month	Year	Age range (CE)	Location (Island)							Source	Runup/wave height/impacts	References
				Hawai'i	Kaua'i	Lana'i	Maui	Moloka'i	O'ahu	Ni'ihau			
21	December	1812		■							S California?	3–4 m at Ho‘okena Hawai‘i Island	Lander and Lockridge (1989)
			1813–1814	■							Unknown	No reports of damage	Lander and Lockridge (1989)
12	April	1819		■			■	■	■		N Central Chile	3 homes damaged at Hāka‘ano, Moloka‘i	Lander and Lockridge (1989)
20	February	1835			■						Central Chile	Moderate damage on the Island of Kaua‘i	Lander and Lockridge (1989)
7	November	1837		■			■	■	■		S Central Chile	66 houses washed away, 14 lives lost at Hilo; on Maui 2 lives lost & 26 homes destroyed	Lander and Lockridge (1989); R. Armstrong, 1878
	March	1839		■							Hawaii	No reports of damage	Lander and Lockridge (1989)
		1840		■							Hawaii	Report made by Samuel Clemens (Mark Twain) in 1872 CE, questionable veracity	Lander and Lockridge (1989)
17	May	1841		■			■	■	■		Kamchatka Peninsula, Russia	4.6 m at Hilo Harbor	Lander and Lockridge (1989)
12	July	1848					■				Tahiti?	No reports of damage	Lander and Lockridge (1989)
27	January	1854		■							Kodiak Is, Alaska	No reports of damage	Lander and Lockridge (1989)
23	December	1854		■							Enshunada, Japan	Unclear	Lander and Lockridge (1989)
24	December	1854		■							Nankaido, Japan	Unclear	Lander and Lockridge (1989)
1	December	1860					■	■			N Pacific? Local?	3 homes & a wharf destroyed at Māliko Maui	Lander and Lockridge (1989), Anon (1860)
23	November	1867					■				Local?	A destructive wave reported at Nu‘u, Kaupō, Maui. No additional information available	Anon (1867)
3	April	1868		■					■		SE Hawaii flank collapse/EQ	47 fatalities, 108 homes destrOyed along the Ka‘ū coast, Hawai‘i Island	Lander and Lockridge (1989)
13	August	1868		■	■		■	■	■		N Chile	4.5 m at Hilo, 3.6 m at Kahului, Maui & 1.2 m on Moloka‘i, US store ship Fredonia sunk on Kaua‘i	Lander and Lockridge (1989)
2	October	1868		■							Hawaii (or remote?)	Flooding on Hawai‘i Island	Lander and Lockridge (1989)
24	July	1869		■		■	■				Hawaii (possibly remote?)	Damage reported on the Puna coast of Hawai‘i Island, inundation at Kaupō, Maui between 180 & 270 m inland over a 4.5 m embankment	Lander and Lockridge (1989); Anon (1869)
20	February	1871							■		Hawaii—Earthquake	No reports of damage	Lander and Lockridge (1989)
23	August	1872		■	■				■		Fox Islands, Alaska?	1.3 m waves at Hilo	Lander and Lockridge (1989)
24	February	1877		■							Hawaii—eruption	No reports of damage	Lander and Lockridge (1989)
4	May	1877		■							Hawaii—eruption	No reports of damage, possibly an	Lander and Lockridge (1989)

Table 2 (continued)

				■								erroneous report of a tsunami	
10	May	1877		■	■		■		■		N Chile	12 m at Hilo, five fatalities & 37 homes destroyed	Lander and Lockridge (1989); Anon(1877)
20	January	1878					■		■		Aleutian Is?	3 m at Waialua, O'ahu, & Halehaku, Maui; 8 homes destroyed at Māliko, Maui	Lander and Lockridge (1989); Anon (1878)
27	August	1883							■		Krakatau, Indonesia	0.2 m at Honolulu Harbor	Lander and Lockridge (1989)
14	November	1883							■		Oahu, offshore Punaluu?	No reports of damage	Lander and Lockridge (1989); Anon (1884)
5	February		1887–1909	■							Unknown—poss landslide	A song recorded at Miloli'i, Hawai'i Island describes this event	Lander and Lockridge (1989)
6	August	1888			■						Unknown—poss landslide	3 m wave hit Koloa, Kaua'i, boulders weighing 22 kg-31 kg carried inland	Anon (1888)
29	December	1888						■			Molokai, submarine landslide?	One house washed away	Anon (1889)
15	June	1896		■	■		■		■		Sanriku, Japan	5.5 m wave reported at Keauhou, nine homes lost	Lander and Lockridge (1989)
	April/May	1900		■							Hawaii—poss landslide	10.6 m at Keauhou, no reports of damage	Anon (1900)
9	August	1901		■					■		Tonga	1.2 m wave at Kailua-Kona, Hawai'i Island, two homes damaged on Hawai'i Island	Lander and Lockridge (1989)
22	September	1901		■							Hawaii, submarine landslide	Damage to a home reported at Mahukona	Anon (1901)
2	September	1902		■							Hawaii, submarine landslide Puna coast?	No reports of damage	Anon (1902)
29	November	1903		■				■			N Pacific? Local? (meteo?)	No reports of damage	Lander and Lockridge (1989)
19	December	1903		■							Hawaii	Facilities damaged on Hawai'i Island & Maui	Anon (1904)
31	January	1906		■			■		■		Colombia/Ecuador	3.6 m wave at Hilo, Hawai'i	Lander and Lockridge (1989); Anon (1906)
16	August	1906		■			■		■		Central Chile (reported 17th in error)	3.5 m on Maui, destroyed piers at Ma'alaea, Maui	Lander and Lockridge (1989); Anon (1906)
21	September	1908		■							Hawaii—EQ	1.2 m wave reported at Hilo	Lander and Lockridge (1989)
11	October	1913							■		Papua New Guinea	Report of a wave at Honolulu	Lander and Lockridge (1989)
26	May	1914							■		Papua, Indonesia	No information	Lander and Lockridge (1989)
1	May	1917							■		Kermadec Is, New Zealand	0.3 m wave at Honolulu	Lander and Lockridge (1989)
26	June	1917							■		Samoa	0.1 m wave at Honolulu	Lander and Lockridge (1989)
15	August	1918							■		Celebes Sea, Indonesia	Recorded at Honolulu; no additional data	Lander and Lockridge (1989)
7	September	1918		■					■		Kuril Islands	1.5 m wave reported at Hilo	Lander and Lockridge (1989)

Table 2 (continued)

4	December	1918							■		Northern Chile	No reports of damage	Lander and Lockridge (1989)
9	April	1919		■							Hawaii, submarine landslide	No reports of damage	Lander and Lockridge (1989)
30	April	1919		■					■		Tonga	0.6 m wave at Hilo Harbor	Lander and Lockridge (1989)
2	October	1919		■							Hawaii, submarine landslide, Alika Bay	4.3 m wave at Kailua, Kona, some damage to facilities & infrastructure	Lander and Lockridge (1989)
11	November	1922		■					■		N Central Chile	2.1 m wave at Hilo, 'many' boats were damaged	Lander and Lockridge (1989)
3	February	1923		■			■		■		Kamchatka Peninsula, Russia	3.5 m wave at Kahului, Maui, 6.0 m wave & one fatality at Hilo, Hawai'i	Lander and Lockridge (1989)
13	April	1923		■					■		Kamchatka Peninsula, Russia	0.3 m wave Hilo, no damage reported	Lander and Lockridge (1989)
1	September	1923							■		Kanto, Japan	0.03 m wave at Honolulu, No damage reported	Lander and Lockridge (1989)
25	January	1926		■							Solomon Is	No reports of damage	Lander and Lockridge (1989)
20	March	1926							■		Hawaii	1.5 m wave at Wailupe, O'ahu, slight damage;	Lander and Lockridge (1989)
24	October	1927							■		S Alaska	Impacts at Honolulu, no additional information	Lander and Lockridge (1989)
4	November	1927		■					■		N to S California	0.1 m wave at Hilo	Lander and Lockridge (1989)
28	December	1927		■					■		Kamchatka Peninsula, Russia	0.1 m wave at Hilo	Lander and Lockridge (1989)
17	June	1928		■					■		S Mexico	0.2 m wave at Hilo	Lander and Lockridge (1989)
7	March	1929		■	■				■		E Aleutian Is	0.2 m wave at Hilo	Lander and Lockridge (1989)
3	October	1931		■					■		Solomon Is	0.05 m wave reported at Hilo	Lander and Lockridge (1989)
3	June	1932		■					■		Central Mexico	0.4 m wave at Hilo	Lander and Lockridge (1989)
18	June	1932		■							Central Mexico	0.10 m wave at Hilo	Lander and Lockridge (1989)
22	June	1932		■							Central Mexico	< 0.10 m wave reported at Hilo	Lander and Lockridge (1989)
2	March	1933		■	■		■		■		Sanriku, Japan	5.3 m at Nāpoʻopoʻo, Hawaiʻi, damage to boats in this area	Lander and Lockridge (1989)
21	November	1935		■							Hawaii	Report is unreliable	Lander and Lockridge (1989)
6	March	1938							■		New Britain, PNG	No reports of damage	Lander and Lockridge (1989)
10	November	1938		■					■		Alaska Peninsula	0.3 m wave at Hilo	Lander and Lockridge (1989)
6	April	1943							■		N Central Chile	0.01 m wave at Honolulu	Lander and Lockridge (1989)
7	December	1944							■		Ryuku Trench, Japan	0.1 m wave at Honolulu	Lander and Lockridge (1989)
1	April	1946		■	■	■	■	■	■	■	E Aleutian Is	8.1 m wave reported at Hilo; 159 lives lost, & $26 million dollars in damages	Lander and Lockridge (1989)

Table 2 (continued)

1	November	1946							■		Aleutian Is	No damage reported	Lander and Lockridge (1989)
20	December	1946		■					■		Nankaido, Japan	0.1 m wave at Hilo & Honolulu	Lander and Lockridge (1989)
9	August	1948		■	■				■		Tonga	0.1 m wave at Port Allen, Kauaʻi, Honolulu	Lander and Lockridge (1989)
22	August	1949		■	■				■		British Columbia, Canada	0.1 m wave at several Hawai'i locations	Lander and Lockridge (1989)
19	October	1949		■	■				■		Solomon Sea	0.1 m waves across the archipelago	Lander and Lockridge (1989)
5	October	1950		■	■				■		Costa Rica	0.1 m waves were reported at Port Allen, Kauaʻi, Honolulu & Hilo	Lander and Lockridge (1989)
23	October	1950		■	■				■		Guatemala	0.1 m waves reported at Hilo & Honolulu	Lander and Lockridge (1989)
14	December	1950			■						S Mexico	0.1 m waves were recorded at Port Allen, Kauaʻi	Lander and Lockridge (1989)
21	August	1951		■	■				■		Hawaii, nr Keauhou	1.0 m waves along the Kona coast	Lander and Lockridge (1989)
4	March	1952		■	■		■		■		SE Hokkaido, Japan	0.3 m at Kahului, Maui	Lander and Lockridge (1989)
17	March	1952		■					■		Hawaii, EQ/submarine landslide, Halape	3.0 m at Kalapana, 180 m inland	Lander and Lockridge (1989)
26	September	1952		■							Chichi Jima, Japan	0.1 m wave at Hilo	Lander and Lockridge (1989)
4	November	1952		■	■		■		■		Kamchatka Peninsula, Russia	9.1 m wave at Kaʻena Point, Oʻahu, damage between $800,000 & $1,000,000 across archipelago	Lander and Lockridge (1989)
14	September	1953		■	■		■		■		Fiji	0.06 m to 0.10 m waves reported at Port Allen, Kauaʻi, Hilo, & Honolulu	Lander and Lockridge (1989)
25	November	1953		■							Kashima, Japan	Waves reported at Hilo	Lander and Lockridge (1989)
19	April	1955		■			■		■		N Central Chile	0.1 m or less waves recorded at various locations	Lander and Lockridge (1989)
30	March	1956		■	■		■		■		Kamchatka Peninsula, Russia	0.3 m at Kahului, Maui	Lander and Lockridge (1989)
9	March	1957		■	■		■	■	■	■	Central Aleutian Is	2.7 m waves on the north shore of Kauaʻi, at least 57 homes were damaged on Oʻahu & Kauaʻi	Lander and Lockridge (1989)
10	July	1958		■	■		■		■		S Alaska	<0.1 m waves across Hawaiʻi	Lander and Lockridge (1989)
6	November	1958		■	■		■		■		S Kuril Is, Russia	0.3 m wave at Kahului, Maui	Lander and Lockridge (1989)
12	November	1958		■			■		■		S Kuril Is, Russia	< 0.1 m waves reported across archipelago	Lander and Lockridge (1989)
4	May	1959		■	■		■		■		N Kuril Is, Russia	0.2 m waves at Kahului	Lander and Lockridge (1989)
21	May	1960		■							S Central Chile	0.1 m wave at Hilo	Lander and Lockridge (1989)
22	May	1960		■	■	■	■	■	■		S Central Chile	6.0 m at Hilo; 61 fatalities; damage estimates range from $20-$75 million	Lander and Lockridge (1989)

Table 2 (continued)

20	November	1960		■							Peru	<0.1 m waves at Hilo	Lander and Lockridge (1989)
21	December	1962							■		Fox Is, Aleutian Is?	No report of any damage, questionably a tsunami	Lander and Lockridge (1989)
13	October	1963		■	■		■		■		Kuril Is, Russia	0.4 m reported at Hilo, Hawai'i & Kahului, Maui	Lander and Lockridge (1989)
20	October	1963		■	■		■		■		Kuril Is, Russia	0.4 m wave at Kahului, Maui	Lander and Lockridge (1989)
28	March	1964		■	■		■		■		Gulf of Alaska	3 m wave at Hilo, Hawaiʻi, total damage of $15,000; 3.6 m wave at Kahului & damage to railroad	Lander and Lockridge (1989)
4	February	1965		■	■				■		W Aleutian Is	1.1 m wave on Kauaʻiʻs north coast	Lander and Lockridge (1989)
30	March	1965		■							W Aleutian Is	0.10 m wave at Hilo, Hawaiʻi	Lander and Lockridge (1989)
2	July	1965		■							E Aleutian Is	0.10 m wave at Hilo, Hawaiʻi; questionably of tsunami origin	Lander and Lockridge (1989)
17	October	1966		■	■		■		■		Peru	0.20 m, 0.13 m, 0.05 m & 0.06 m waves at Kahului, Maui, Hilo, Hawaiʻi, Nawiliwili, Kauaʻi, & Honolulu, Oʻahu respectively	Lander and Lockridge (1989)
28	December	1966		■			■				N Chile	0.14 m wave at Kahului, Maui; 0.15 m wave at Hilo, Hawaiʻi	Lander and Lockridge (1989)
16	May	1968		■	■		■		■		Honshu, Japan	0.5 m wave at Kahului, Maui	Lander and Lockridge (1989)
1	August	1968			■				■		E Luzon Is, Philippines	0.05 m & 0.02 m waves at Nawiliwili, Kauaʻi, & Honolulu Oʻahu, respectively	Lander and Lockridge (1989)
11	August	1969		■	■		■		■		Hokkaido, Japan-Kuril Is	0.22 m wave at Kahului, Maui	Lander and Lockridge (1989)
22	November	1969		■	■		■		■		Kamchatka, Russia	0.1 m wave at Kahului, Maui	Lander and Lockridge (1989)
14	July	1971		■	■		■		■		Bismarck Sea, PNG	0.12 m wave at Kahului, Maui	Lander and Lockridge (1989)
26	July	1971		■	■		■		■		Bismarck Sea, PNG	0.15 m wave at Kahului, Maui	Lander and Lockridge (1989)
15	December	1971		■	■		■		■		Kamchatka, Russia	0.09 m wave at Hilo, Hawaiʻi	Lander and Lockridge (1989)
30	January	1973		■	■		■		■		S Mexico	0.1 m wave at Hilo, Hawaiʻi & Kahului	Lander and Lockridge (1989)
17	June	1973		■	■		■				Hokkaido, Japan-Kuril Is	0.15 m wave at Kahului	Lander and Lockridge (1989)
3	October	1974		■	■		■		■		Peru	0.19 m wave at Hilo & Kahului	Lander and Lockridge (1989)
10	June	1975					■				Hokkaido, Japan-Kuril Is	0.06 m wave at Kahului	Lander and Lockridge (1989)
29	November	1975		■	■		■		■		Hawaii, flank collapse/EQ	6.1 m to 7.9 m waves at Halapē, two fatalities; damage on Hawai`i Island exceeded $1 million	Lander and Lockridge (1989)
14	January	1976					■		■		Kermadec Is, New Zealand	0.15 m & 0.03 m waves at Kahului, Maui & Honolulu, Oʻahu, respectively	Lander and Lockridge (1989)
22	June	1977		■	■		■		■		Tonga Trench	0.13 m waves at Kahului	Lander and Lockridge (1989)

Table 2 (continued)

12	December	1979		■	■		■		■		Ecuador	0.19 m wave at Hilo, Hawai'i & Kahului, Maui	Lander and Lockridge (1989)
17	July	1980		■			■		■		Santa Cruz Is, Solomon Is	0.14 m waves at both Kahului, Maui & Kona, Hawai'I	Lander and Lockridge (1989)
19	December	1982		■					■		Kermadec Is, New Zealand	0.02 m wave at Honolulu	Lander and Lockridge (1989)
3	March	1985		■			■		■		Valparaiso, Chile	0.24 m wave at Hilo	Lander and Lockridge (1989)
19	September	1985		■			■				Mexico	0.12 m wave at Kahului, Maui	Lander and Lockridge (1989)
7	May	1986		■	■		■		■		W Aleutian Is	0.6 m wave reported at Kapa'a, Kaua'i	Lander and Lockridge (1989)
20	October	1986		■			■		■		Kermadec Is, New Zealand	0.1 m wave at Hilo, Hawai'i	Lander and Lockridge (1989)
5	March	1987		■							N Chile	0.1 m wave at Hilo	Lander and Lockridge (1989)
30	November	1987		■	■				■		Gulf of Alaska	0.07 m wave at Hilo, Hawai'i	Lander and Lockridge (1989)
26	June	1989		■							Hawaii	0.29 m on Hawai'i Island	NGDC (2022)
5	April	1990		■							Mariana Islands	Runup of 0.12 m at Kailua, Hawai'i	NGDC (2022)
25	April	1992		■			■				N California	Runup of 0.04 m at Hilo, Hawai'i;	NGDC (2022)
2	September	1992		■			■				Nicaragua	Runup of 0.06 m at Kawaihae, Hawai'i	NGDC (2022)
8	June	1993		■					■		Kamchatka, Russia	Runup of 0.03 m at Haleiwa, O'ahu	NGDC (2022)
8	August	1993		■	■		■		■		Mariana Islands	Runup of 0.04 m on Puna Coast, Hawai'i	NGDC (2022)
4	October	1994		■	■		■		■		Kuril Is, Russia	Runup of 0.48 m at various locations in the Hawaiian Islands	NGDC (2022), Walker (1999)
30	July	1995		■	■		■		■		N Chile	Runup of 0.38 m at Hilo	NGDC (2022)
9	October	1995		■	■		■				Mexico	Runup of 0.06 m at Kawaihae, Hawai'i	NGDC (2022)
3	December	1995		■			■				Kuril Is, Russia	Runup of 0.06 m at Hilo, Hawai'i	NGDC (2022)
21	February	1996		■			■				N Peru	Runup of 0.15 m at Kahului, Maui	NGDC (2022)
10	June	1996		■	■		■		■		W Aleutian Is	Runup of 0.54 m in the Hawaiian Islands	NGDC (2022), Walker (1999)
5	December	1997		■	■		■		■		Kamchatka, Russia	Runup of 0.07 m at Nawiliwili, Kaua'i	NGDC (2022)
26	November	1999		■	■		■		■		Vanuatu	Runup of 0.1 m at Nawiliwili, Kaua'i	NGDC (2022)
23	June	2001		■	■		■		■		S Peru	Runup of 0.35 m at Hilo, Hawai'i	NGDC (2022)
25	September	2003		■			■	■	■		Hokkaido, Japan	Runup of 0.2 m at Kahului, Maui	NGDC (2022)
17	November	2003		■	■		■		■		Aleutian Is, Alaska	Runup of 0.33 m at Kahului, Maui	NGDC (2022)
26	December	2004		■			■		■		Sumatra, Indonesia	Runup of 0.05 m at Honolulu, O'ahu, & Kawaihae	NGDC (2022)
3	May	2006		■	■		■		■		Tonga	Runup of 0.14 m at Honolulu, O'ahu	NGDC (2022)
15	October	2006		■							Hawaii, EQ	Runup of 0.1 m at Kawaihae, Hawai'i	NGDC (2022)
15	November	2006		■	■		■	■	■		S. Kuril Is, Russia	Runup of 0.76 m at Kahului, Maui	NGDC (2022)

Table 2 (continued)

13	January	2007		■	■		■		■		S. Kuril Is, Russia	Runup of 0.1 m at Nawiliwili, Kaua'i	NGDC (2022)
1	April	2007		■			■		■		Santa Cruz Is, Solomon Is	Runup of 0.07 m at Hilo, Hawai'i	NGDC (2022)
15	August	2007		■	■		■		■		S. Peru	Runup of 0.04 m at Honolulu, O'ahu	NGDC (2022)
19	March	2009		■	■		■		■		Tonga	Runup of 0.06 m at Honolulu, O'ahu,	NGDC (2022)
15	July	2009		■							W. Coast, New Zealand	Wave of indeterminate size observed at Hilo, Hawai'i	NGDC (2022)
29	September	2009		■	■		■		■		Samoa (Tonga Trench)	Runup of 0.36 m at Kahului, Maui	NGDC (2022)
7	October	2009		■	■		■		■		Vanuatu	Runup of 0.19 m at Kahului, Maui	NGDC (2022)
27	February	2010		■	■	■	■		■		Central Chile	Runup of 0.86 m at Hilo, Hawai'i	NGDC (2022)
11	March	2011		■	■	■	■		■		Honshu, Japan	Runup of 3.05 m at Mākua, O'ahu Extensive damage in Kona, Hawai'i	NGDC (2022)
24	June	2011		■	■						Aleutian Is, Alaska	Runup of 0.06 m at Hilo, Hawai'i	NGDC (2022)
6	July	2011		■	■				■		Kermadec Is, New Zealand	Runup of 0.09 m at Nawiliwili, Kaua'i	NGDC (2022)
28	October	2012		■	■	■	■		■		BC, Canada	Runup of 0.29 m at Hilo, Hawai'I	NGDC (2022)
7	November	2012		■			■				Guatemala	Runup of 0.07 m at Kahului, Maui	NGDC (2022)
6	February	2013		■	■	■	■		■		Santa Cruz Is, Solomon Is	Runup of 0.07 m at Honokohau, Hawai'i	NGDC (2022)
1	April	2014		■	■		■		■		N. Chile	Runup of 0.11 m at Waimanalo, O'ahu	NGDC (2022)
23	June	2014			■		■		■		Aleutian Is, Alaska	Runup of 0.04 m at Haleiwa, O'ahu	NGDC (2022)
16	September	2015		■	■		■	■	■		Central Chile	Runup of 0.27 m at Kawaiahae, Hawai'i	NGDC (2022)
8	September	2017		■			■		■		Mexico	Runup of 0.18 m at Kahului, Maui	NGDC (2022)
23	January	2018		■	■		■	■	■		Kodiak Is, Alaska	Runup of 0.18 at Hilo, Hawai'i	NGDC (2022)
4	May	2018		■	■		■		■		Hawai'i, EQ	Runup of 0.4 m at Kapoho, Hawai'i Island	NGDC (2022)
5	December	2018							■		New Caledonia	Runup of 0.4 m at Honolulu, O'ahu	NGDC (2022)
25	March	2020		■			■		■		Kuril Is., Russia	Runup of 0.08 m at Kahului, Maui	NGDC (2022)
19	October	2020		■	■		■		■		Shumagin Is., Alaska	Runup of 0.26 m at Hanalei, Kaua'i	NGDC (2022)
4	March	2021		■	■		■		■		Kermadec Is, New Zealand	Runup of 0.18 m at Kahului, Maui	NGDC (2022)
29	July	2021		■			■				Kodiak Is, Alaska	Runup of 0.13 m at Kahului, Maui	NGDC (2022)
12	August	2021		■			■		■		South Sandwich Islands	Runup of 0.17 m at Kahului, Maui, & Hilo, Hawai'i	NGDC (2022)
15	January	2022		■		■	■		■		Tonga	Runup of 0.83 m at Kahului, Maui	NGDC (2022)

The black-marked areas indicate the islands affected by the particular tsunami on the left

> instant swept away and the inmates carried no one knew where... Some members of a family were carried in one direction and some in another. Some individuals were carried out so far in to the bay that they must have drowned, but for the aid of the ship's crew now in port. They took 13 out of the water some of whom were much exhausted. Eight dead bodies have been found and others are missing…This is a solemn visitation and I believe the people feel it so…the prevailing impression seems to be among the people, that it is a judgement from God, on account of their disregarding his word" (reported in Lyman 1990: 98).

The wave at Hilo took the lives of fourteen individuals and destroyed 66 homes. However, Lyman's (1990) reported observation that residents understood the tsunami as both judgement and wrath suggest an important social dimension to this event. Tsunamis are often linked with profound social change, in this case by fostering a heightened sense of piety intended to avoid divine wrath (Goff and Nunn 2016). As discussed below, Hawaiian myths and legends also suggest an association between cataclysmic events (presumably a tsunami) and profound social change.

The Rev. Richard Armstrong on Maui recorded his recollections of the 1837 CE event by noting its unexpectedness:[1]

> "At about seven o'clock in the evening, the waves … gradually receded from the shore to a distance of some fifteen or twenty rods, leaving multitudes of fishes bare upon the ground, so that the children observing it ran and picked some of them up. The rush of the wave was so sudden and unexpected, that the inhabitants of the village… had no warning whatever, except a few who seeing the sea receding from the shore suspected a corresponding reflux, fled inland in season…Some swam single-handed with the waves. Others took their children in their arms. Others the sick on their backs, and bore them up until the water ceased from the earth…one man found the water coming into his house, seized his child and ran so as to escape the inundation entirely; but arriving on the summit of a small sand bank, he looked back and saw the whole village, inhabitants and all, moving towards him, some riding on the tops of their houses, some swimming, and all screaming most frightfully" (Armstrong 1838: 251).

Armstrong's account highlights the danger of tsunamis of unknown origin not associated with any local seismic activity (Atwater et al. 2015). On this occasion, the recession of the sea, which modern studies estimate at 36 m (Lander and Lockridge 1989), elicited two opposing responses. Unsurprisingly, children who witnessed the exposed ocean bottom took the opportunity to gather marine resources. However, those who were aware of the dangers of a rapidly receding ocean fled the scene, presumably an act that saved their lives and one that speaks of a sensitivity to the abnormal behavior of the sea. The impact on Maui included the destruction of 26 homes and the loss of two lives. Inundation distances were estimated to be around 240 m, and while actual wave heights on Maui and Hawai'i Island remain unclear, observers on O'ahu recorded waves of 2.4 m (Lander and Lockridge 1989).

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[1] It should be noted that there is possible discrepancy in the location described in this narrative. Specifically, Lander and Lockridge (1989) indicate the tsunami-impacted the north coast bay of Kahului. However, a scholar of nineteenth century Maui history, Dr. Andrew Walmisley, believes the events took place at Ma'alaea on Maui's south coast.

On December 1, 1860 CE, another tsunami of unknown origin struck the island of Maui. Although it did not produce any fatalities, it destroyed several homes and a wharf at the north shore valley of Māliko (Fig. 1). Observers estimated wave heights at Kahului, approximately 7 km to the west of Māliko, to be about 2.5 m (Anon 1860; Lander and Lockridge 1989). Interestingly, by the late nineteenth century, the community at Māliko had abandoned this site, though it remains unclear to what degree this, and subsequent tsunamis, contributed to the abandonment. However, coastal village abandonment after tsunami inundation did occur at four other locations on Maui in the nineteenth and twentieth century, as described below.

Hawaiʻi's second deadly tsunami in this period struck on April 3, 1868 CE, when a magnitude 7.5 tsunamigenic earthquake on the south east coast of the island of Hawaiʻi, in the district of Kaʻū (Fig. 1), generated the most destructive tsunami to strike the Hawaiian Islands in the nineteenth century. As reported by the Pacific Commercial Advertiser "*the tidal wave swept over the tops of the cocoanut [sic] trees along the whole line of the coast*" (Anon 1868: 619 6 m). Measurements taken in the aftermath of the tsunami indicated wave heights of approximately 6 m. The waves destroyed 108 homes and caused 47 deaths (an additional 34 individuals died because of earthquake-generated landslides) (Lander and Lockridge 1989). In the aftermath of the tsunami, the village of ʻĀpua was abandoned, as visitors to the site noted that the original location lay under approximately 2 m of water due to subsidence (Ladefoged et al. 1987).

A feature of local-source tsunamigenic earthquakes includes the amplification of wave inundation due to coastal subsidence. For example, in the aftermath of a 1975 CE local-source earthquake and tsunami on Hawai'i's Kaʻū coast researchers documented subsidence of 1.5 m on an 8-hectare shelf (Lander and Lockridge 1989) (Fig. 1). Tsunami damage also extended to other parts of Hawaiʻi Island, including Keauhou Bay on the south-east coast (Walker 1999) (Fig. 1).

On July 24, 1869 CE, a tsunami of unknown origin struck the coastal village of Nuʻu in Kaupō (Fig. 1).[2] Although reports do not specify the number of homes (if any) damaged or destroyed in this incident, waves inundated up to 270 m inland in certain areas, and at least one wave overtopped a 4.5 m embankment (Anon 1869; Lander and Lockridge 1989). Once a thriving and vibrant community, Nuʻu experienced tsunami impacts in both the nineteenth and twentieth century, and after a 1946 CE tsunami it was abandoned. Like Māliko, the decline and demise of Nuʻu was closely linked to destructive tsunami waves.

Hawaiʻi's third and final (known) deadly nineteenth century tsunami occurred on May 10, 1877 CE, when a tsunamigenic earthquake occurred off the coast of Chile in the same general location as the 1837 CE event (Lander and Lockridge 1989). Again, the island of Hawaiʻi, and Hilo in particular, suffered the greatest damage. This tsunami, which was reported at 4:45 a.m., took the lives of 5 individuals and destroyed 37 dwellings (Anon 1877). Records revealed wave oscillations of 12 m, with an inundation distance of 92 m (Lander and Lockridge 1989). This incident highlights a reality of Hawaiian tsunamis: that Hilo typically experiences the greatest damage and loss of life from distant-source tsunamis. While the geometry of the bay and the offshore coastal shelf contributes to the destructive potential of tsunami waves in Hilo, the coastal location of dwellings and development along Hilo Bay substantially exacerbates this problem (Chagué et al. 2018).

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[2] Although the historic record only indicates that the tsunami took place in the district of Kaupō, Nuʻu is the only location that fits the description as it is marked by numerous cliffs of this approximate height. This fact, combined with the authors familiarity with the Kaupō coast, suggests Nuʻu as the location of this event.

Fig. 2 Hilo in the aftermath of the April 1, 1946, tsunami in the approximate area of Bayfront Drive. Note the boulders in the foreground and the flow direction from right (seaward) to left (landward) as shown by the debris field. Photograph by Kazuo Takayama, Robynn Takayama Family Archives

The last reported destructive tsunami in the nineteenth century occurred on January 20, 1878 CE, and seems to have been generated from the Aleutian Islands (although its source remains somewhat unclear). O‘ahu’s north shore town of Wailua (Fig. 1) recorded a 3 m wave, yet Maui seems to have experienced the most significant damage (Lander and Lockridge 1989). In Māliko, on Maui’s north shore, 8 homes and one scow were destroyed and two canoes were damaged. Halehaku, approximately 3 miles north-east of Māliko, reported two homes lost and two others damaged. At Honomanū, approximately 10 miles from Halehaku, agricultural fields (taro patches) were substantially inundated (Anon 1878).

As noted above, Māliko had suffered damage 18 years previously during the 1860 CE tsunami. Perhaps more importantly, all three of the communities affected by the 1878 CE tsunami, Māliko, Halehaku and Honomanū, remain unpopulated to this day, although the precise causes and timing of their abandonment remain unclear. While archaeological research has uncovered evidence of village abandonment in other parts of Maui not associated with tsunami impacts (e.g., Waihe‘e on Maui’s north west coast, Fig. 1), the coincidental timing of the abandonment of Māliko, Halehaku and Honomanū after the 1860 CE tsunami suggests a causative link.

The study of Hawaiian tsunamis in the nineteenth century reveals several interesting patterns. First, three out of 30 tsunamis (11 of which were destructive) claimed the lives of 68 individuals. Second, three locations on Maui that experienced tsunami impacts during the nineteenth century (Honomanū, Māliko and Halehaku) remain largely depopulated. Third, although most of the historically recorded tsunamis arrived with little or no warning, they produced surprisingly few fatalities. The low death rate may be explained by three factors: Hawai‘i’s rapid population decline in the nineteenth century; the rural nature of the population (which concealed actual tsunami deaths due to a lack of accurate reporting); and, perhaps, inherited traditional knowledge of the signs of approaching tsunamis, which has been seen recently in other tsunami-impacted areas (Stannard 1989; Goff and Dudley 2021).

3.2 Twentieth century tsunamis in the Hawaiian islands

During the twentieth century, a number of destructive and deadly tsunamis impacted coastal areas of the Hawaiian archipelago. More precise records of economic loss and fatalities, combined with demographic shifts toward population centers (where fatalities would not go unreported), provide a portrait of tsunami impacts in Hawai‘i that is more detailed than that available for the previous century. The twentieth century also saw the development of a life-saving advanced tsunami warning system (Walker 1999).

Hawai‘i‘s first significantly destructive twentieth-century tsunami arrived on February 3, 1923 CE, shortly after 4:00 p.m., and originated from a tsunamigenic earthquake off the coast of the Kamchatka Peninsula, Russia. Hilo recorded seven waves, with heights reaching up to 3.6 m, and one fatality. At Kahului, observers reported wave heights of 3.5 m and substantial damage. Although observers recorded waves at Haleiwa, O‘ahu (Fig. 1) of 3.7 m, residents did not report any damage or loss of life. The 1923 CE Kamchatka tsunami took only one life, but economic losses totalled nearly $1.5 million dollars (over $26 million in 2023 dollars; Lander and Lockridge 1989; Shepard et al. 1950).

Scientists at the newly developed Hawai‘i Volcano Observatory (HVO), who learned of the possibility of a destructive tsunami well in advance of its arrival, notified harbor masters at key port facilities across Hawai‘i, but, tragically, their warnings were dismissed. Hawaii at the time lacked a formal system to broadcast tsunami warnings (Goff and Dudley 2021), but the 1923 CE Kamchatka tsunami demonstrated the potential for a warning system, and one was developed in the aftermath.

In the early morning hours of April 1, 1946 CE, Hawai‘i experienced its most destructive historical tsunami when a Mw 8.6 earthquake occurred at 2:00 a.m. Hawai‘i time in the Aleutian trough south of Unimak Island (López and Okal 2006; Keating et al. 2004; Chagué et al. 2018). The first wave struck the island of Kaua‘i at 6:00 a.m., Honolulu at 6:33 a.m., and Hilo at 7:06 a.m. (Shepard et al. 1950). Fortunately, the small size of the first wave alerted the community and caused limited damage. By the time the 3rd, and largest, of the 9 waves recorded at Hilo (where the most severe damage occurred; Fig. 2), came ashore, many people had escaped, no doubt preventing a larger loss of life (Chagué et al. 2018: 320). Nonetheless, the 1946 CE Aleutian tsunami killed 159 Hawai‘i residents, most of them on Maui and Hawai‘i Island, particularly in and around Laupāhoehoe and Hilo (Goff and Dudley 2021; Chagué et al. 2018). Estimates of economic damage to the archipelago exceed $25 million dollars ($370 million in 2023 dollars) (Shepard et al. 1950).

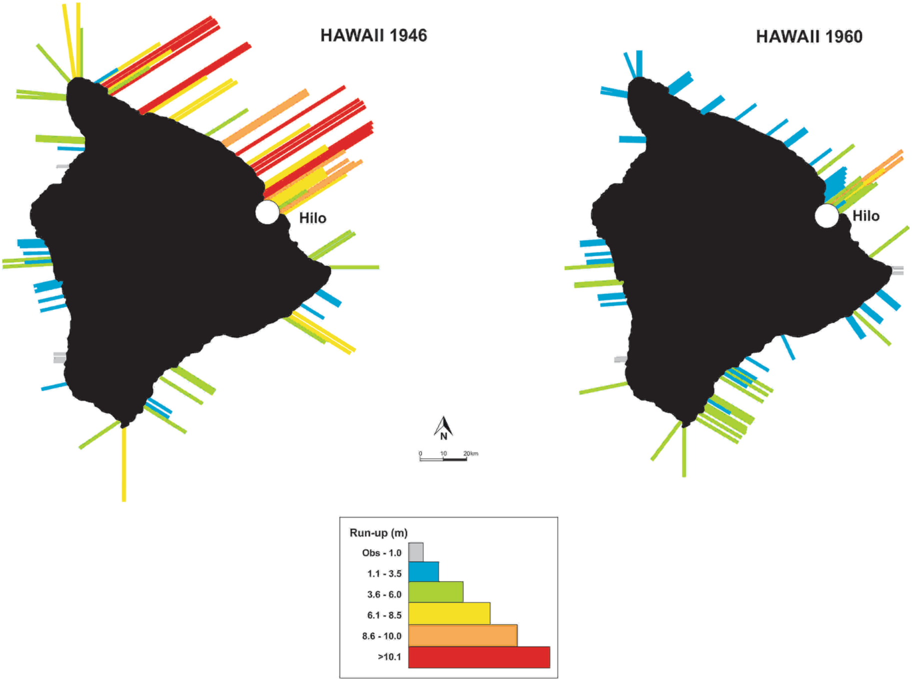

Fig. 3 Tsunami run-up heights on Hawai’i Island, 1946 and 1960. Run-up data derived from Fletcher et al. (2002), Lander and Lockridge (1989), and NGDC/WDS (2023)

The 1946 tsunami provided an opportunity for scientists in Hawai‘i to study details of impacts on various parts of the archipelago. For example, F.W. Shepard, who at the time was vacationing with his wife on O‘ahu, and who narrowly escaped the tsunami, recorded a number of important features of this tsunami (Shepard et al. 1950; Goff and Dudley 2021). He recorded wave heights of 13.7 m at Hā‘ena on Kaua‘i’s north coast and noted that a coral block approximately 4 m in diameter had been transported 152 m inland (Shepard et al. 1950). Perhaps more importantly, he linked wave runups in certain areas to topographical and geomorphological features, recognizing that where fringing coral reefs were present, wave heights were up to 5 m lower than in areas that lacking such features. The wave heights he recorded at Waikolu, Moloka‘i (Fig. 1), exceeding 16 m, were perhaps the largest in the archipelago during this event, and he provided important observations about the relationship between topography, geomorphology, wave runup and destructive potential. Subsequent researchers have followed suit by studying the relationship between these variables and tsunami impacts along other Hawaiian coasts (Whelan and Keating 2004).

With a relatively large geographical area to cover, and relatively few resources to undertake such a monumental task, Shepard et al. (1950) findings include some that are inaccurate or cursory. This should not be seen as an indictment of the quality of their work but as a reminder of the need for additional tsunami and paleotsunami research. For example, at Waihe‘e, on Maui’s north west coast, Shepard et al. (1950) recorded the wave height as 7 m but noted no additional damage to any homes or the dairy facility located there. Ethnographic work from 2004 to 2008 in Waihe’e revealed the loss of at least three homes in this area (H. Shimoda, M. Molina, and J. Ka’ili’ehu, pers. comm. 2004–2008).

At Nu’u, on Maui’s south east coast, a recent ethnographic study of the impacts of the 1946 CE tsunami has provided substantive insights beyond those recorded by Shepard et al. (1950). While Shepard et al. (1950) noted a 3 m wave at Nu’u, survivor testimony reveals changes to patterns of shoreline accretion and the abandonment of this village after the 1946 CE tsunami (H. Starr, and S. Ka’ai, pers. comm. 2009). Site visits to tsunami-impacted areas, such as those studied by Shepard et al. (1950), remain a vitally important resource for coastal land managers. But multi-proxy approaches, including the capture of survivor testimony, contribute to a clearer understanding of wave intensity and general tsunami destructiveness.

As at Nu‘u, the 1946 CE tsunami also prompted the abandonment of the village of Shinmachi, located along the coast of Hilo Bay (Fig. 1). A 2018 study of the now-abandoned Shinmachi village, where many of the fatalities occurred, reported 1946 CE tsunami sediments up to 12 cm thick (Chagué et. al. 2018). Out of the tragedy of the 1946 CE tsunami, the Pacific Tsunami Warning Center (PTWC), which employs a complex network of detectors combined with sirens across the archipelago, emerged. This advanced warning system, the first of its kind, has saved countless lives across Hawai‘i and the North American west coast.[3]

Eleven years later, on March 9, 1957 CE, a Mw 8.3 tsunamigenic earthquake, also from the Aleutian islands, struck the Hawaiian Islands. Observers reported wave heights on Kaua‘i of 16 m; the other islands recorded smaller waves (Lander and Lockridge 1989; Keating et al. 2004). Pololū Valley, on Hawai‘i Island, for example, measured runups of 9.8 m above mean sea level (Chagué-Goff et al. 2012: 84). Despite the destruction of at least 54 homes across the archipelago, and over $300,000 in damage to coastal infrastructure (equivalent to over $3 million today), the evacuation of coastal residents during the 1957 CE Aleutian tsunami, which prevented any loss of lives, testifies to the efficacy of the PTWC (Lander and Lockridge 1989: 44; Keating et al. 2004).[4]

On May 22, 1960 CE, a Mw 9.4–9.6 tsunamigenic earthquake hits the Hawaiian Islands from Valdivia, Chile, the approximate location of the 1837 CE tsunami described above. Hilo suffered substantial damage. The largest wave, the third in the set, arrived at 1:04 a.m. as a 6.1 m bore, which rose to 10.7 m as it arrived on shore. Interestingly, studies that have compared sedimentary deposition in Hilo could not distinguish between the 1946 CE and 1960 CE tsunamis because of the similarity of the depositional area and the behavior of the waves on land, despite the fact that the two tsunamis came from nearly opposite directions (Chagué et al. 2018: 331). This was largely the result of wave resonance inside Hilo harbor (Fig. 3).

While other parts of the archipelago suffered damage, Hilo once again bore the brunt of the destruction (Lander and Lockridge 1989; Whelan and Keating 2004: 77). This tsunami’s high casualty count suggests that implementation of the early warning system was flawed. Tsunami researchers noted two possible reasons for this failure. First, false alarms had become common in the early years of the tsunami warning system, leading

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[3] The imperfection of this system primarily stems from public disregard of the warning system. On several occasions during tsunami warnings, the author has witnessed members of the public willfully ignoring prohibitions to keep away from potential inundation areas.

[4] The inundation of the coast by the tsunami did not produce any fatalities, but two indirect fatalities occurred when a local news plane reporting on the incoming waves crashed on O‘ahu.

Fig. 4 Tsunami Impacts at Waihe‘e, Maui, March 11, 2011. Note the large cobbles in the background and the finer sediment in the foreground forming a lobe pointing inland. The direction of the vegetation suggests wave backflow from a point of lower elevation. Photograph by Scott Fisher, Hawai‘i Land Trust

to a sense of complacency (Walker 1999). Second, the tsunami's arrival early in the morning could have exacerbated this sense of complacency (Chagué et al. 2018).

The last fatal tsunami of the twentieth century occurred on November 29, 1975 CE, in the Halapē-Apuā area, approximately 39 miles south of Hilo. The 1975 CE Halapē-Āpua tsunami was produced by two local earthquakes, a M 5.7 foreshock at 3:55 a.m. followed by a M 7.7 earthquake at 4:48 a.m. (Goff et al. 2006; Richmond et al. 2011; Nettles and Ekström 2004). A Boy Scout troop, camping near the base of a cliff and concerned about the possibility of a rock slide, moved to a location closer to the coast. Shortly after the earthquake, a wave estimated at 5 m above sea level inundated their new camping area to a distance of 250 m inland, transporting debris and boulders and killing one Boy Scout and the troop's leader. Nineteen other Boy Scouts were also injured (Lander and Lockridge 1989). Although locally sourced, the Halapē-Āpua earthquake and tsunami-impacted large areas of the Ka‘ū, or the south-east coast of Hawai‘i Island. Extensive areas were affected by coastal subsidence, which caused approximately $1 million dollars in damages (over $5.2 million in 2023 dollars).

Two recent studies, which included both field surveys and detailed ethnographic research, provide a clear picture of this tsunami and clarify previously unknown dimensions of this event. For example, several waves transported substantial quantities of material as both suspended and bed load, and survivors recounted three powerful waves (Goff et al. 2006; Richmond et al. 2011). Both studies highlight the value of multi-proxy approaches that include the collection and analysis of field data and the incorporation of survivor narratives.

In summary, the twentieth century witnessed a dramatic increase in the number of tsunami-related fatalities, from 68 known tsunami deaths in the nineteenth century to 222 in the twentieth century. Economic losses from tsunamis in the twentieth century were also substantial, exceeding $580 million (adjusted for inflation). Although recorded fatalities have increased (likely due to population growth along the coast), the development of an advanced warning system has no doubt saved many lives, and Hawai‘i has not experienced a direct tsunami-related death in nearly 50 years. However, the tsunamis that have struck the Hawaiian Islands since 1975 CE have been notably smaller than those of previous eras.

3.3 Hawaiian tsunamis in the twenty-first century

During the twenty-first century, four measurable tsunamis have impacted the Hawaiian Islands. All caused only minor damage and produced no direct fatalities. The first of these involved an 8.3 Mw tsunamigenic earthquake on November 15, 2006 CE, which originated in the Kuril Islands. In Hawai’i, the tsunami waves measured only 76 cm at Kahului and 49 cm at Hilo (Munger and Cheung 2008).

The next tsunami to strike the Hawaiian Islands, on February 27, 2010, was produced by a 8.8 Mw tsunamigenic earthquake off the coast of Chile (Roessler and Lipton 2010). The Pacific Tsunami Warning Center anticipated waves in the range of 1.8 m to 3.0 m and issued an evacuation order for the City of Honolulu, the first in 16 years. At Honolulu Harbor, wave heights measured only 45 cm, which led to public skepticism about the efficacy of the tsunami warning system (Dwyer 2010).

In the early morning hours of March 11, 2011 CE, Hawai‘i experienced its largest tsunami to date of the new century. Generated by a Mw 9.0 earthquake off the Tōhoku-oki region of Japan, this tsunami took the lives of over 16,000 people in Japan. The first waves reported in Hawai‘i arrived in the early morning hours, beginning around 3:00 a.m., with the largest wave measuring 1.8 m at Nāwiliwili (Cheung et al. 2013). The fourth and largest wave of this tsunami measured 2.07 m and ripped up trees while flooding low-lying areas in the town of Kahului, with an inundation distance measured at 614 m (Osher 2011). At Waihe‘e on Maui, the tsunami inundated up to 150 m inland depositing a discontinuous layer of sand and cobbles some 12 m inland from the coastal berm ridge (Fig. 4). On Hawai‘i Island, four hotels and a historic structure, the Hulihe‘e Palace in Kailua-Kona, were damaged, with financial losses across the archipelago estimated at $7.5 million ($8.7 million in 2023 dollars; Sakahara 2011).

Modelled data for the 2011 CE tsunami have shed additional light on the nature of Hawaiian tsunamis. Cheung et al. (2013) research demonstrated that the complex wave patterns seen in the Hawaiian archipelago generate relatively long-lasting resonance wave arrays, potentially amplifying tsunami impacts and complicating mitigation strategies. This research demonstrates the need for both field data collection and modelling to better understand, constrain and (for future tsunami) predict the impacts of tsunamis on Hawaiian coastlines.

Hawai‘i’s most recent (at the time of publication) tsunami came in the early morning hours of January 15, 2022 CE, after the submarine volcanic eruption of the Hunga-Tonga Hunga-Ha’apai Volcano, Tonga. Across the archipelago, observations revealed wave heights around 1.0 m, including Hanalei on Kaua‘i and Mānele Harbor on Lāna‘i (Sakahara 2022). Runups of 4.0 m and a 20 m inundation distance were recorded at Nu‘u, on Maui’s south east coast (Terry et al. 2022). The largest wave recorded occurred in the Kailua-Kona area of Hawai‘i Island, where a 1.3 m wave inundated Kai Opua Canoe club and destroyed approximately 80% of the inventory of one local business, causing approximately $75,000 in damages (Sakahara 2022). Although South Pacific tsunami sources are somewhat rare in the historical record, studies of the 2022 Tongan tsunami might prove particularly helpful in gaining a clearer understanding of the fifteenth century Kuwae, Vanuatu, volcanic eruption and tsunami discussed below (Goff et al. 2012).

3.4 Pre-historic holocene tsunamis in Hawai’i

Perhaps the most surprising aspect of Hawaiian Holocene tsunamis is the small number of events discovered by researchers in the ethnographic or sedimentary records, suggesting a substantive knowledge gap for the Hawaiian archipelago. The most extensively studied Holocene deposits come from a sinkhole on Kaua‘i’s south shore, the Makauwahi Cave system near Po‘ipū, which lies 100 m from the coast at 7.2 m above sea level (Butler et al. 2014). In their study of the paleoecological dynamics of the Makauwahi cave system, Burney and others discovered tsunami deposits 80 cm thick initially dated to between 1425 and 1660 CE (Burney et al. 2001). Butler et al. (2014) subsequent Uranium–Thorium (U–Th) dating analyses indicated that the Makauwahi Cave tsunami probably dated to the second half of the sixteenth century (later updated to 1551–1593 CE; Butler et al. 2017a), which the authors linked to an earthquake source near Sedanka Island in the Aleutian Islands. While Butler et al. (2014) research leaned heavily toward an Aleutian Islands source, they point out that a local submarine landslide could have generated a wave of sufficient magnitude to generate these deposits.

Perhaps most importantly, the research conducted by Butler et al. (2014, 2017b) led to a re-examination of the tsunami threat to Hawai‘i posed by the Aleutian Islands. Through modelling, Butler et al. (2017b) concluded that offshore faults in the Aleutian Islands, combined with the proximity of Hawai‘i to the Aleutian Islands and the geometric focusing that occurs during large seismic events, poses a triple threat to the Hawaiian archipelago. Although future research at the Makauwahi Cave site may demonstrate a local, as opposed to an Aleutian Islands, source for the sixteenth-century event, Butler et al. (2017b) have clarified our understanding of the threat presented by Aleutian Island tsunamigenic earthquakes.

Following the work of Butler et al. (2014), the US Geological Survey began additional paleotsunami research at multiple locations across Hawai‘i (LaSelle, pers. comm. 2015). This research, which began with a reconnaissance of 13 sites across the archipelago, conducted extensive research at Anahola on Kaua‘i, Kahana on O‘ahu, and Pololū on Hawai‘i Island. This research yielded sedimentary evidence of one, or possibly two, distant source tsunamis that probably originated in the eastern Aleutian Islands. Evidence included sand beds with normal grading that thinned inland and with sharp lower contacts (La Selle et al. 2020). Each site contained tsunami deposit(s) that could be traced significant distances inland, specifically 650 m at Anahola, 450 m at Kahana, and 500 m at Pololū (La Selle et al. 2020). Conclusive evidence of tsunami inundation, like that found at these various sites across the Hawaiian archipelago, provides a foundation upon which coastal land managers can better understand mitigation options.

While sedimentary evidence of tsunamis in the Hawaiian archipelago during the Holocene is limited, ethnographic and archaeological research can potentially shed light on events which have occurred in the past 1000 years, since the beginning of human settlement of the archipelago. The account recorded by the ethnographer Martha Beckwith (Beckwith 1982) provides one of the most detailed legends about a significant marine inundation event. According to this account, the chief Nuʻu, sometimes known as Kahinaliʻi, lived during the kaiakahinaliʻi or, literally, the time of the bringing down of the chiefs.[5] According to legend, Nuʻu survived this catastrophic event on a double-hulled canoe equipped with living quarters (*Waʻahalaualiʻiokamoku*). When the great wave receded, Nuʻu's canoe came to rest on the summit of Mauna Kea on Hawaiʻi Island, whereupon he made offerings to the deities. Although there exist clear similarities with the biblical story of Noah (perhaps reflecting later missionary influences), the clear use of the term '*kai,*' or ocean water, in the description of the event (as opposed to '*wai*' or freshwater), indicates that the inundation came from the ocean, not rainfall.

This legend seems to suggest an event that dramatically restructured the Hawaiian social hierarchy, particularly the ruling *aliʻi* class (Beckwith 1982). Research throughout the South Pacific has demonstrated the historical validity of legends of a powerful tsunami that occurred in the fifteenth century and is linked to contemporaneous sedimentary evidence (Cain et al. 2019; Goff et al. 2012; Lavigne et al. 2021). Such evidence highlights the value of oral history, including recitations of legends that reveal changes in the social fabric in the aftermaths of such catastrophic events.

Archaeological research published from Hālawa Valley on Molokaʻi identified a culturally sterile sand layer fining inland that caps a habitation layer (Kirch and McCoy 2007). Considering its close proximity to the coast, additional research to determine if the culturally sterile sand derives from a high energy marine inundation event seems particularly warranted. Recognition of tsunami deposits in the archaeological record would prove particularly helpful in identifying both the frequency of this type of disaster and human responses to such events (e.g., McFadgen and Goff 2007; Salazar et al. 2022).

3.5 Pleistocene tsunamis: mega-tsunami versus lithospheric flexure

Researchers have published a substantial body of material on pre-Holocene marine sediment deposits found on the islands of Lānaʻi, Molokaʻi and Hawaiʻi (Moore and Moore 1984; Moore et al. 1994; Johnson and Mader 1995; McMurtry et al. 2004; Webster et al. 2006; Moore 2008). Moore and Moore (1984) and Moore and Moore (1988) identified a layer of fragmented coral, basalt boulders and sand and shell fragments (known as the Hulopoʻe gravel), first identified in the nineteenth century on Lānaʻi, as mega-tsunami deposits that date to 105 ka BP, with wave runups that reached 375 m above modern sea level. Other research on Lānaʻi identified additional material dated

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[5] Some accounts use the term pōauhulihia, or the time of the great overturning.

to between 240 and 200 ka BP, positioned 46–60 m above modern sea level (Moore et al. 1994).

Moore et al. (1994: 966) cited several lines of evidence to support their mega-tsunami hypothesis, including an absence of coral clasts in growth positions and the fact that no deposits contained sedimentary sorting, from which they inferred deposition under turbulent conditions. In their analysis of the data, McMurtry et al. (2004) noted the fragmented shell material formed a blanketing depositional pattern, suggestive of tsunami deposition. Johnson and Mader (1995) and McMurtry et al. (2004) posited that the source of these proposed mega-tsunamis were two catastrophic submarine failures off Hawai‘i Island’s Mauna Loa volcano, known as Alika I and Alika II, that occurred approximately 105 ka BP and between 240 and 200 ka BP, respectively.

Several scholars, however, have questioned the mega-tsunami hypothesis (Grigg and Jones 1997; Rubin et al. 2000; Keating and Helsey 2012). While none discount the possibility that very large tsunamis have impacted the Hawaiian Islands, they reach different conclusions about deposition of the Hulopo‘e gravel and similar deposits. Principal among these is lithospheric flexure, which can uplift deposits, leaving them unmodified and in their original location, which would not happen if the deposits had been deposited by a tsunami. Evidence of such intact deposits includes coral found in growth position at relatively high elevations and the increasing age of coral deposits with elevation, which sceptics of the mega-tsunami hypothesis suggest are indicative of lithospheric flexure (Grigg and Jones 1997). Perhaps the most important result of this debate lies in its focus on the frequency and destructive capacity of flank collapse, a catastrophic failure of the coastal portion of the shield volcano. As a result, these contributions to tsunami research have helped broaden our understanding of the risk and exposure Hawaiian coasts face from locally generated, catastrophic, high energy marine inundation events.

4 Gaps and outstanding questions about tsunami impact and hazard in Hawai‘i

Gaining a clearer understanding of the source locations, frequency, and intensity (particularly run-up heights and inundation distances) of tsunamis in the Hawaiian archipelago can lead to the development of policies and practices which are better designed to address tsunami hazards. Current knowledge gaps generally fall into three categories. First, there is currently a significant gap in our understanding of the sources of tsunamigenic events that impact the Hawaiian archipelago other than those from circum-Pacific subduction zones. Second, while there have been several island- and archipelago-wide models investigating coastal resonance (e.g., Munger and Cheung 2008), there is still considerable work to be done to better understand both runup amplification and inland inundation distances at specific sites, with models of past historical events even proving difficult to replicate accurately (e.g., See discussion in Chagué et al. 2018 for Hilo Bay). Third, little is known about the impacts of tsunamis on Hawaiian social and cultural dynamics, particularly in the pre-historic period.

As noted above, several of Hawai‘i’s tsunamis have unknown or poorly understood source locations and causes (Table 1). The 2022 Hunga-Tonga Hunga-Ha‘apai submarine volcanic eruption, whose impacts in Hawai‘i are documented, raises the issue of impacts from past volcanic events, such as the ~ 1452 CE Kuwae eruption in Vanuatu (Goff and Dudley 2021). Tsunamigenic submarine landslides in areas such as the atolls of Papahānaumokuākea (formerly the Northwest Hawaiian Islands) remain virtually unknown, although they are known to have occurred on atolls in the Cook Islands; indeed, the Pacific Basin is particularly vulnerable to such tsunamis (Goff 2011; Goff and Terry 2016; Goff et al. 2012).

Another poorly understood dynamic is the interaction of geomorphology, benthic and coastal topography on runup, inundation, and wave refraction during tsunamis (e.g., Chagué et al. 2018). Munger and Cheung (2008) highlight the relationship between tsunami wave resonance and the impact of edge waves along the coast; coastal land managers would benefit from a more detailed understanding of these dynamics. Liu (1995) explored the relationship between wave-wrapping and island geometry, and this continues to be an important topic for ongoing research since coastal managers will benefit from additional studies that illustrate impacts at specific sites across the Hawaiian archipelago.

Reducing the gaps in our understanding ought to include two approaches. First, historical analysis (including ethnographic research) can provide insights into tsunami frequency, source locations and impacts on coastal communities. Second, sedimentary analysis of past tsunami deposits can improve awareness of wave velocities, wave heights, and inundation distances, each of which contribute to a clearer understanding of tsunami intensity and destructive potential.

Addressing these gaps requires the use of multi-proxy studies that focus on the frequency of destructive tsunamis, the correlation of tsunami signatures with their destructive intensity, and orientation along the coast at specific locations. Coastal land managers and emergency service providers could use these data to prioritize mitigation strategies, particularly in ecologically or societally sensitive areas, such as high productivity wetlands with large populations of endangered species, or population centers. Research on Pleistocene mega-tsunamis and extensive studies on Hawai’i Island demonstrates the archipelago’s potential as an area worthy of further study—additional research is needed on the older islands of O’ahu, and Kaua’i to narrow current information gaps (La Selle et al. 2020).

Coastal abandonment, a particularly prudent strategy in the aftermath of a tsunami, has been noted at four locations on Maui and at ‘Āpua and Shinmachi Village on Hawai‘i Island. When seen through the lens of the story of chief Nu’u, it seems reasonable to assume that tsunamis had profound social impacts in Hawai‘i during the pre-historic period. The general lack of identified tsunami deposits in the pre-historic Hawaiian archaeological record stands in contrast to research conducted in other tsunami-vulnerable areas, such as other parts of Polynesia (cf. Saez et al. 2022; Hermann et al. 2016; Goff and Nunn 2016; McFadgen and Goff 2007), South America (Chunga and Toulkeridis 2014), and the Middle East (Dey et al. 2014). A sub-discipline in Japan focuses specifically on tsunami archaeology (*tsunami kokogaku*); a comparable program could prove fruitful in the Hawaiian context (Barnes 2021).

5 Tsunami risk mitigation in Hawai‘i

In the aftermath of the twenty-first century tsunamis in the Indian Ocean, Samoa and Japan, researchers have published useful data that coastal land managers and hazard reduction specialists can use to enhance resistance and resilience to high energy marine inundation (Lunghino et al. 2020; Thuy et al. 2012; Forbes and Broadhead 2007; Danielsen 2005).

These strategies include the construction of raised and reinforced structures, coastal retreat, and the deliberate design of native forests that can serve as bioshields (Chavez 2020; Shuto 2019). Indeed, post-tsunami research reveals that such protective forests, ideally when they consist of indigenous and endemic tree species, effectively (although with some limitations) reduce tsunami wave energy, erosion and sedimentation (Tanaka 2009; Nandasena et al. 2008; Thuy et al. 2010; Tanaka 2006).

Previous research on forested bioshields provides insights on three important points related to their design and efficacy that coastal managers should consider. First, the role of arboreal structure and function in tsunami mitigation: Tanaka et al. (2006) examined *Pandanus odoratissimus* (a closely related indigenous species, *Pandanus tectorius,* is common along Hawaiian coasts) and noted the efficacy of the aerial roots of *P. odoratissimus* in creating drag and reducing wave energy. Second, application of forested bioshield development raises the issue of the propensity of trees to break under tsunami conditions and their ability to reduce sediment loads deposited during these events (Thuy et al. 2012; Kusumoto et al. 2020). Although forested bioshields should, whenever possible, rely on indigenous and endemic species, tree breakage remains an important consideration for coastal managers intent on designing the most efficacious forested bioshield: more research is needed on the role of bioshield composition, including tree type and understorey structure, on tsunami mitigation. Third, scholars have examined forested bioshields to determine whether they can restore degraded ecosystems by accelerating biodiversity, ecosystem productivity, and resilience (Wanger et al. 2020), potentially providing conservation and carbon sequestration benefits in addition to tsunami mitigation (i.e., provision of multiple ecosystem services). Palynological studies from coastal or marginal wetlands offer additional insight into the composition of vegetated coastlines before human disturbance and modification (Strandberg et al. in review). In addition, paleoecology can provide information on changes in coastal forest communities, some of which are driven by relative sea levels, but also the arrival of humans and associated commensals (e.g., rats, plants; Strandberg et al. in review). Combining these analyses with specific paleotsunami research at known inundation sites offers the opportunity to better understand the interactions between specific events and the changing vegetation communities at the coast.

When attempting to maximize the efficacy of a forested bioshield, it is important to narrow the gaps in our understanding of coastal forest composition and structure. To date, no studies in Hawai‘i have attempted to determine whether coastal forests could mitigate the impacts of tsunami waves, although the state has recently begun an economic feasibility study of bioshield establishment. Coastal areas in Hawai‘i have undergone dramatic anthropogenic modification since the arrival of humans at the end of the first millennium. This fact complicates current efforts to identify indigenous species that could maximize the protective function of forested bioshields (Athens et al. 2014). However, some of these gaps can be filled through paleoenvironmental analysis (Athens and Ward 1993; Burney et al. 2001). For example, the analysis of paleoenvironmental proxies, such as wood remains and pollen, could lead to a better understanding of the species composition of coastal forests during past tsunamis and the capacities of different forest compositions and structures to reduce tsunami impacts (Pau et al. 2012; Stranberg et al. in review).

Although forested bioshields have the potential to advance ecosystem-based mitigation strategies, critics have noted their shortcomings. For example, some note that abandoning engineered structures in favor of forested bioshields could lead to higher human mortality, particularly in densely populated areas (Feagin et al. 2010). Coastal managers should perhaps see forested bioshields as an additional tool for ecosystem-based tsunami defense rather than as an alternative to appropriately engineered structures and warning systems, in an integrated coastal hazard management approach.

The establishment of forested bioshields is still in a very early stage in Hawai’i. As noted above, the State of Hawai’i has recently begun an economic feasibility study of bioshields at key locations subject to coastal inundation. Additionally, the Hawai’i Land Trust was awarded a North American Wetlands Conservation Act (NAWCA) grant in order to establish a bioshield around their Nu’u Refuge (Britten 2022). In 2022 and 2023, over 340 indigenous, endemic and Polynesian introduced plants were planted around the wetlands in order to reduce the impacts of high energy marine inundation events.

Other recent research has highlighted the role that nearshore coral reef ecosystems play in both mitigating and exacerbating tsunami impacts. This research has posited three important realities about coral reef ecosystems. First, compared to sandy substrates, coral reefs increase the drag coefficient by at least an order of magnitude (Kunkel 2006). Second, research in Samoa after the 2009 tsunami demonstrated that narrow fringing reefs mitigate wave energy far less than wider fringing reefs and can, in some instances, exacerbate tsunami impacts through a series of complex interactions between coastal bathymetry and incoming waves (Bosserelle et al. 2020). Finally, McAdoo et al. (2011) demonstrated that during a tsunami, healthy coral reefs reduce the quantity of material available for entrainment—an interesting point given that ocean warming is increasing the number of coral bleaching events.

Recalling Shepard et al. (1950) observation that, during the 1946 tsunami, fringing reefs contributed to wave reductions of over 5 m on O‘ahu‘s north shore, coral reef research constitutes an actionable item coastal managers can take as a meaningful tsunami mitigation strategy. With knowledge derived from a better understanding of the nature of historical tsunami impacts, managers can take appropriate mitigation measures. These can include, but not be limited to, integrated (coastal to nearshore) strategies such as increasing the density and depth of coastal forested bioshields to reduce terrestrial sediment loads or nutrient run-off, so enhancing or maintaining healthy fringing reefs. While Hawai‘i‘s coral reefs are not nearly as extensive as those in other parts of tropical Polynesia, in part because of the geological youth of the islands and their location in the northern tropics, their protective role may be significant. In the Hawaiian islands, fringing reefs are most extensive along the coasts of Kaua‘i, O‘ahu and Moloka‘i, with 50 km of Moloka‘i south coast protected by the archipelago‘s largest fringing reef (Juvik and Juvik 1998).

Coral reef protection and restoration as well as the development of forested bioshields would add to the array of options that coastal land managers could employ to mitigate the impacts of tsunamis. However, their usefulness remains contingent upon understanding the nature of past high energy marine inundation events—information that could gathered, in part, through in-depth reviews of field, archaeological, and ethnographic data.

6 Conclusions

Hawai‘i’s position in the center of the Pacific Basin makes it particularly vulnerable to tsunami impacts. Evidence of Hawai‘i’s tsunami history extends back in time to the Pleistocene and the Holocene, although only nineteenth, twentieth and twenty-first century tsunamis are documented in the historic record. Understanding the tsunami history of Hawai‘i is relevant to the efforts of coastal managers to mitigate their destructive impacts. More research is needed to more fully understand this history and its relevance to contemporary concerns. Historical and archaeological records potentially constitute a rich source of relevant information. Of particular interest is the issue of how Native Hawaiians (during the pre-historic and Historic periods) conveyed information about the destructive potential of tsunamis and employed indigenous plant species to protect coastal ecosystems.

This review takes a first step toward collating information about the frequency, intensity, and source of tsunamis over time in the Hawaiian Islands (including both recent (twenty-first century) events and those which pre-date the historical record in the Hawaiian archipelago). Tsunami research provides coastal managers and disaster preparedness professionals with tools to protect their communities, and for the reduction in tsunami risk. These tools include coastal reef protection and restoration and the creation of forested bioshields, in addition to hard engineered mitigation strategies. Understanding the history of tsunami impacts through paleo-tsunami research and analyses of archaeological, paleoenvironmental, and ethnographic data remain critical steps in this process.

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