Paleotsunami evidence on Kaua'i and numerical modeling of a great Aleutian tsunami

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The Hawaiian Islands' location in the middle of the Pacific Ocean is threatened by tsunamis from great earthquakes in nearly all directions. Historical great earthquakes $M_w > 8.5$ in the last 100 years have produced large inundations and loss of life in the islands but cannot account for a substantial ($\leq 600\,m^3$) paleotsunami deposit in the Makauwahi sinkhole on the Island of Kaua'i. Using high-resolution bathymetry and topography we model tsunami inundation of the sinkhole caused by an earthquake with a moment magnitude of M_w ~9.25 located in the eastern Aleutians. A preponderance of evidence indicates that a giant earthquake in the eastern Aleutian Islands circa 1425–1665 A.D.—located between the source regions of the 1946 and 1957 great tsunamigenic earthquakes—created the paleotsunami deposit in Kaua'i. A tsunami deposit in the Aleutians dated circa 1530–1660 A.D. is consistent with this eastern Aleutian source region.

1. Introduction

Basing estimates of maximum tsunami amplitude upon recent history is dangerous and ill-advised, as witnessed by the devastation in Japan from the tsunami generated by the 2011 M_w 9.1 Tohoku earthquake, as well as the disastrous Indian Ocean tsunami from the 2004 M_w 9.3 Sumatra-Andaman earthquake. In evaluating tsunami threats, it is necessary to consider the possibility of great, megathrust M_w 9+ earthquakes at most subduction zones [e.g., *McCaffrey*, 2008]. *Butler* [2012a] reviewed the tsunamigenic potential of the Aleutian Islands threatening the Hawaiian Islands and concluded that a giant earthquake in the eastern Aleutian Islands located between the 1946 and 1957 M_w 8.6 earthquakes, which generated the largest tsunamis recorded in Hawai'i, would focus substantial tsunami energy directed at Hawai'i.

A systematic analysis of giant earthquake sources ($M_w \geq 9.25$) along the Aleutian-Alaska arc was conducted for Hawaii State Civil Defense in order to verify the adequacy of current tsunami evacuation maps [*Butler*, 2014]. This analysis modeled earthquakes with the extremes of fault area, mean fault slip, and slip nearest the trench that characterized the largest megathrust earthquakes of the last century: 2004 M_w 9.3 Sumatra-Andaman, 1960 M_w 9.5 Chile, and 2011 M_w 9.1 Tohoku, respectively. The analysis concluded that a great M_w 9+ Aleutian earthquake could generate a tsunami in Hawai'i larger than historically observed, exceeding current tsunami inundation maps. To augment this theoretical, model-based approach to tsunami inundation along Hawaiian coasts, paleotsunami evidence was sought in the Aleutians and Hawai'i for events predating the historical record. A substantial tsunami deposit on the southeast coast of the Island of Kaua'i provides one data point corroborating the possibility of prior M_w 9+ events.

2. Paleotsunami Evidence

2.1. Hawaiian Islands

Although there is evidence for local megatsunamis caused by giant submarine landslides due to flank collapse of volcanic edifices making up the Hawaiian Islands [e.g., *Moore and Moore*, 1984; *Satake et al.,* 2002; *McMurtry et al.,* 2004], the youngest of these events is >10,000 years B.P. [*McMurtry et al.,* 2004]. There is scant evidence in the literature for more recent Holocene tsunamis, apart from depositional evidence from recent large tsunamis during the past century (e.g., 1946 and 1957). There is an archaeological and legendary reference to a tsunami at Kualoa Beach in Kaneohe Bay, Oahu, subsequent to its occupation by the Hawaiian people in circa 1040–1280 A.D. (see supporting information: Legendary Hawaiian References) [*Carson and Athens*, 2007; *Handy and Handy*, 1972]. A chant attributed to Huluamana and composed in the sixteenth century describes a tsunami-like event on the west coast of Molokai [*Lander and Lockridge*, 1989]. For the
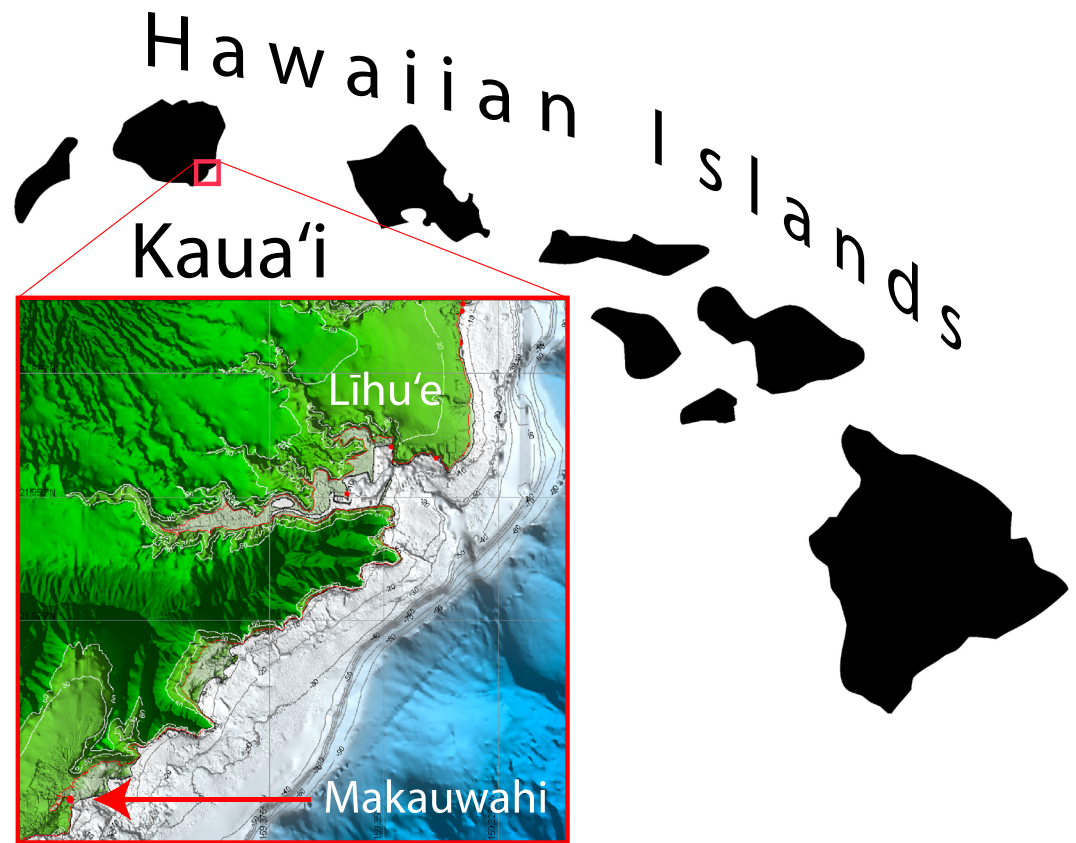
Figure 1. The inset map shows the location (red dot) of the Makauwahi sinkhole on the southeastern coast of Kaua'i in the Hawaiian Islands. The scale for the inset map is about 12.2 km on a side. The town of Līhu'e and Nawiliwili harbor are to the northeast.

Limahuli Bog on northwestern Kaua'i, *Burney* [2002] reports evidence suggesting a prior large tsunami event, "The wedge of sand about 50 cm below the surface along the northern edge of the bog is similar to the surficial material derived from the 1946 tsunami and perhaps represents a similar late prehistoric event such as the one *Burney et al.* [2001] recorded about 400 years B.P. at Maha'ulepu (Southeastern Kaua'i)."

The best paleotsunami evidence to date within the Hawaiian Islands is on Kaua'i in the Makauwahi Sinkhole (21.8883°N, 159.4188°W) on the southeast coast (Figure 1) about 10 km southwest of Nawiliwili Harbor, about 100 m from the shore [*Burney et al.*, 2001]. The sinkhole (see supporting information: Setting, Figures S1 and S2) is part of a limestone cave complex (within a Pleistocene eolianite—lithified calcareous dune deposits) where the central roof collapsed about 7000 B.P. A few large, partially redissolved speleothems (stalactites) to ~0.5 m diameter occur, notably along the walls of the sinkhole, and indicate that the sinkhole is a collapsed cave. The sinkhole is large, about 30 by 35 m, and the walls are 6 to 25 m high above the flat floor of the sinkhole, which is filled mostly with terrestrial sediment deposits. At the northern and southern end of the sinkhole, there are still caves opening into the sinkhole. The northern cave has a small portal opening facing the Waiopili Stream. This narrow portal serves as the only entrance to the complex.

Excavation of the site revealed the following [*Burney et al.*, 2001]:

"This gradual sedimentation was truncated by an extremely high-energy sedimentation event. About four or five centuries ago (calendar years A.D. 1430–1665), a severe marine overwash of the site, probably a tsunami, deposited allochthonous (originating at a distance from their present location) stones and fractured eolianite in a lens up to 1 m thick at the lowest point of the sinkhole rim along the east wall, thinning out in the far reaches of the caves as turbidite fans and gravel beds."

"The layer is composed of boulders, cobbles, gravel, and sand. These rocks, being highly fractured, mostly angular, and lacking an in situ patina, are consistent with an interpretation of the layer as the

result of a single high-energy event. Other components of the unit include marine elements such as coral fragments, abraded mollusck shells, and coarse beach sand."

"Likewise, classification of stones also shows a strong contrast with all other units, with a significant component of allochthonous stones, notably terra rossa (lithified red soil) and a dense black vesicular basalt in this unit only. Both rock types are common on the beach and on the slope seaward of the cave."

This paleotsunami layer is about 80 cm thick and found in excavations on both edges of the sinkhole and in cores in the middle. A core published by *Burney et al.* [2001] is shown in Figure S2, with pictures from a recent excavation site at the northern edge (Figure S3), showing the layer in situ and examples of the basalt rocks and coral found in the deposit (many boulders were >100 kg). The lowest edge of the sinkhole lies 7.2 m above mean sea level at the side adjoining the sea. Considering the area and thickness of the layer, the volume of rocks and material in the layer is estimated to be about 600 m³. This is a large volume, equivalent to about nine standard shipping containers.

In the north cave "all cores record a thin band of angular gravel." The portal entrance in the north cave is about 1.2 m tall and has been excavated to its maximum opening of about 2.5 m without evidence of the large basalt rocks of beach origin typical of the tsunami layer. The deposits in the southern cave "trace a turbidite fan thinning and fining southward into the rear of the cave." The southern cave's connection to the ocean was severed at about the time of the main roof collapse (7000 B.P.). Furthermore, excavation of the cave began a month before the 1992 Hurricane Iniki—the largest hurricane in the historical record—directly struck this corner of Kaua'i with great force, leaving a very different type of deposit in the sinkhole, consisting of plant debris and dune sands.

This paleotsunami deposit is unique in that it is 100 m inland and 7.2 m uphill from the sea, placing strong constraints on the causative tsunami. The largest historical tsunamis recorded in Hawai'i have runups measured in the vicinity of the sinkhole. The 1960 Chilean (M_w 9.55) tsunami had 3 m runup, the 2011 Japan (M_w 9.1) event had 1–2 m runup, and the 1964 Alaska (M_w 9.2) event showed no significant runup. There is no runup measurement from the 1952 Kamchatka (M_w 9.0) tsunami. Tsunami runups from the 1946 and 1957 Aleutian earthquakes (M_w 8.6) were 2.4 and 2.1 m, respectively. None of the tsunamis generated by the largest historic earthquakes in the circum-Pacific and the Aleutians have come close to inundating the Kaua'i sinkhole.

Only two possibilities present themselves for the means of the tsunami deposition: the tsunami deposit could have entered via the portal through the north cave, or else occurred as an overwash of the seaward eastern wall. In order to examine these possibilities firsthand, a visit was made to the sinkhole in February 2013. The recently excavated northern edge of the sinkhole presented the same ~0.8 m tsunami layer as previously observed by *Burney et al.* [2001] at the southern excavation site and cores in the middle of the sinkhole. Evidence was sought as to whether the tsunami filled the sinkhole via the northern cave portal, which has a lower elevation of ~1 m above mean sea level. To move this volume of material through a small portal would imply substantial hydraulic forces that would direct rocks as projectiles toward the cave ceiling (<3 m high) and walls. However, there is no evidence of projectile impacts on the north cave walls and ceiling. Further, there are abundant, fine speleothems undisturbed on the cave ceiling that may date back either before sinkhole roof collapse 7000 years ago or prior to the tsunami event. However, given uncertain conditions of evaporative exsolution of $CaCO_3$ in the open cave versus slow precipitation in the humid enclosed cave before roof collapse, this evidence is indeterminate. Nonetheless, other than a "thin band of angular gravel," the north cave lacks evidence of the tsunami deposit found within the sinkhole. Therefore, although a tsunami flood may have entered via the portal, much of the volume in the tsunami deposit must have overwashed the sinkhole wall at >7.2 m.

Burney et al. [2001] have dated the tsunami deposit to 1430–1665 cal year A.D. (calibrated range at 95% confidence interval). Although short-lived materials were used in dating to minimize inherent age bias, some ¹⁴C dates could be biased older, as some older, reworked material may be included in the tsunami deposit. Hence, the younger half of the distribution seems more likely. Better precision would be obtained from Uranium-series dating of fresh, unaltered coral found in the layer.

2.2. Sedanka Island in the Aleutians

The only known paleotsunami site explored in the Aleutians is on Sedanka Island near Dutch Harbor, Alaska, at the edge of the eastern Aleutians adjoining the zone of the 1946 earthquake [*Witter et al.*, 2013]. This site shows evidence of five large local tsunamis predating the 1957 event. This tsunami deposit on Sedanka Island reaches nearly a kilometer inland and 18 m above mean sea level. Prepublication results show that the deposits date back to about 1600 B.P., with the most recent, 1957 event horizon subsequent to a tsunami deposit dated circa 1530–1665 A.D. [*Witter et al.*, 2013].

2.3. Pacific Northwest

Progress has been made in identifying and dating paleotsunami evidence for the 1700 Cascadia earthquake that caused tsunamis in both the Pacific Northwest and Japan [e.g., *Atwater et al.*, 2005]. Nonetheless, an examination of the paleotsunami studies [e.g., *Peters et al.*, 2007] shows evidence for a tsunami prior to the 1700 Cascadia event at about nine sites from British Columbia to Oregon within the range of dates indicated by the Kaua'i and Aleutian studies.

3. Tsunami Models

We use NEOWAVE (Nonhydrostatic Evolution of Ocean Wave) of *Yamazaki et al.* [2009, 2011] to model each tsunami from generation at the earthquake source to inundation at the coastline of Kaua'i. The hydrostatic version of NEOWAVE that does not include the effect of dispersion was implemented for this study, due to the computationally intensive nature of the fully nonhydrostatic simulations ($>$1 month per simulation). The digital elevation model incorporates the National Geophysical Data Center ETOPO1 Global Relief Model at 1 arcmin resolution [*Amante and Eakins*, 2009], used for modeling Pacific basin-wide tsunami propagation, and increasingly detailed special data sets from many sources (see supporting information: Methods), and implemented in four levels of nested grids to model tsunami propagation across the Pacific and inundation at Kaua'i coastal area in the vicinity of the Makauwahi sinkhole. The resolution at the sinkhole is ~9 m. The NEOWAVE models for the sinkhole were supplemented with tsunami forecasts for the Japanese and U.S. Pacific West Coast using the NOAA Short-term Inundation Forecast of Tsunamis (SIFT)/Standby Inundation Models (SIM) code [e.g., *Gica et al.*, 2008], with a resolution in the harbors of about ~60 m. Earthquake sources with moment magnitude $9.0 > M_w \leq 9.6$ were distributed along the Aleutian-Alaska and Kamchatka subduction zones to assess the tsunamigenic effects in Hawai'i using the extreme faulting parameters observed globally in the largest megathrust earthquakes of the last 100 years [e.g., *Butler*, 2012a, 2014] (supporting information: Earthquake Sources and Tables S1 and S2).

4. Inundation Results at the Makauwahi Sinkhole

We modeled tsunami inundation at the Makauwahi sinkhole for nine earthquake scenarios $M_w \geq 9.25$. Each of the giant earthquake scenarios (Table S1 and Figure S4) that included the eastern Aleutians inundated the sinkhole. In Figure S5, the results are shown for the smallest event that inundated the sinkhole, a M_w 9.25 earthquake on a fault $600 \times 100 \, \text{km}^2$ with uniform 35 m fault slip. The high-resolution (~9 m/pixel) map clearly shows the tsunami overtopping the lower eastern wall of the sinkhole at an elevation of about 8–9 m. Therefore, giant M_w 9+ earthquakes along the Aleutian-Alaska arc could plausibly have caused the Kaua'i paleotsunami deposit. The M_w 9.2 Alaska earthquake of 1964 did not produce significant tsunami runup at the site because the subduction zone geometry directed the largest waves toward the southeast, away from the Hawaiian Islands.

We next considered the sensitivity of runup at the paleotsunami site to the source region of the earthquake along the arc of the subduction zone. Since the smallest M_w 9.25 event centered within the eastern Aleutians (fault $600 \times 100 \, \text{km}^2$ with uniform 35 m fault slip) may have inundated the sinkhole, we forecast tsunami inundations for two earthquakes with the same fault parameters, but in adjoining sections of the subduction zone, shifted eastward and westward in the eastern Aleutians (Figure 2 and Figure S6). The first is a comparable M_w 9.25 event situated along the Alaska Peninsula section of the Aleutian-Alaska arc to the east between the 1946 and 1964 events in the region of the Shumagin Islands and 1938 earthquake. The second is a comparable event to the west, across the 1957 earthquake zone. Neither of these simulations generated a tsunami that would inundate the Kaua'i sinkhole (Figure 3).
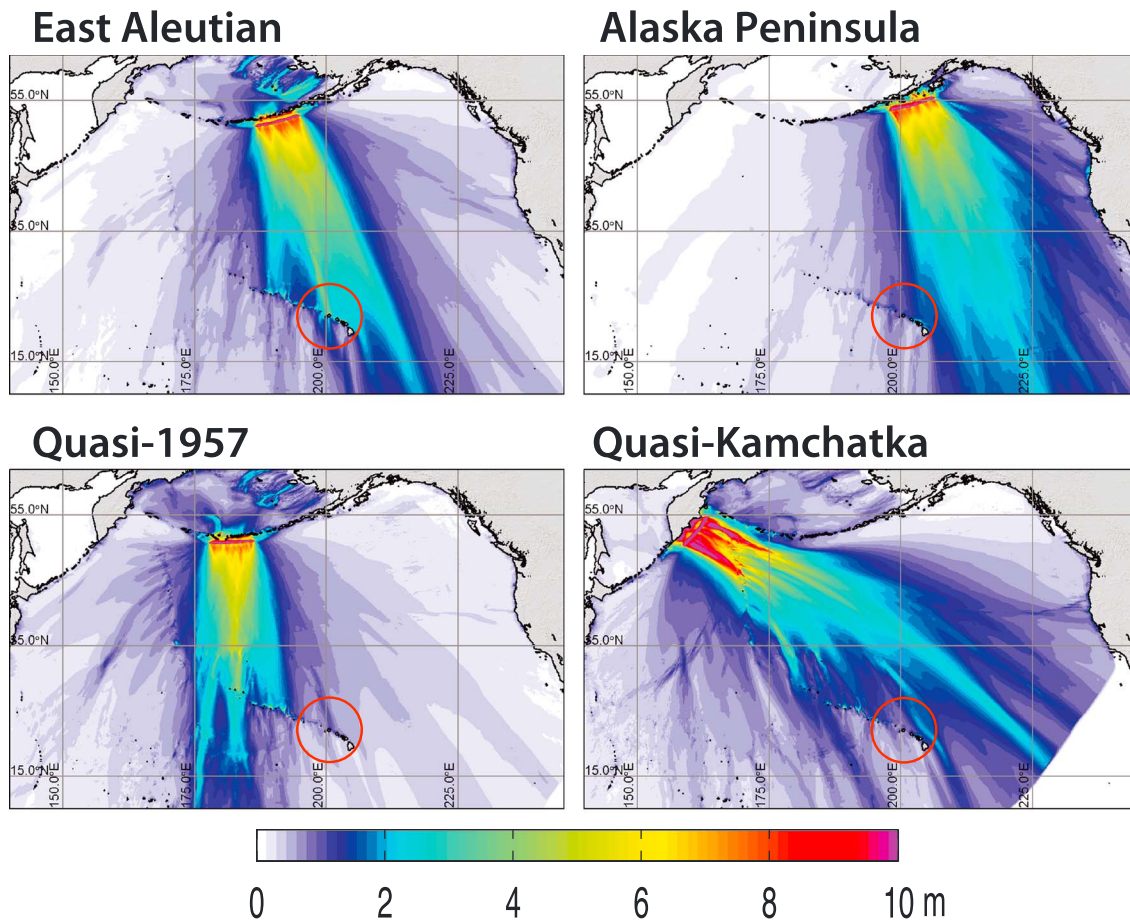
Figure 2. Maximum tsunami amplitudes in meters are forecast for identical (size, fault slip) M_w 9.25 earthquakes: (top left) the east Aleutians, (top right) the Alaska Peninsula region extending eastward from the Shumagin Islands to the west of Kodiak Island, (bottom left) a quasi-1957 event, and (bottom right) a quasi-Kamchatka event. The red circles are centered on Kaua'i and encircle the Big Island. Note that only the east Aleutian tsunami energy is directed primarily toward Kaua'i.

Although the M_w 9.0 earthquake of 1952 in Kamchatka did not produce a significant tsunami at the Kaua'i sinkhole, the geometry of the Kamchatka subduction zone nonetheless focuses tsunami energy toward the Hawaiian Islands. Modeling the 1952 earthquake, *Johnson and Satake* [1999] concluded that much of the slip on the fault occurred downdip from the trench, which diminishes tsunami excitation. We considered an M_w 9.25 Kamchatka earthquake (fault 600×100 km^2 with uniform slip of 35 m fault slip) where the faulting occurred within ~100 km of the trench (Figure S6). The tsunami forecast (Figure 2) for this Kamchatka event did not inundate the sinkhole in Kaua'i (Figure 3). Similarly for the Marianas—which also focuses tsunami energy toward Hawai'i and where there has not been a great historic earthquake and tsunami—forecast models (not shown) indicate that earthquakes comparable in size to Aleutian events generate smaller tsunamis from the Marianas Islands.

We then examined characteristics of an eastern Aleutian earthquake required to inundate the sinkhole. Keeping the average fault slip at 35 m, varying the slip from 20 to 50 m along the fault length did not yield significantly different results [*Butler*, 2014]. However, varying the fault slip with depth wherein the largest slip is nearest the trench, as observed for the 2011 Tohoku earthquake, does increase the tsunami inundation of the Kaua'i sinkhole. Successive tsunami forecasts were generated with earthquakes having decreasing uniform fault slip: 30 m, 25 m, 20 m, and 17.5 m (see supporting information: Tsunami Sensitivity and Table S2). The results indicate that about 35 m of slip (equivalent to a M_w 9.25) is required to achieve runups inundating the sinkhole (Figure S7).

Finally, using the NOAA SIFT/SIM forecast model, we calculated the inundation along the Pacific coasts of Japan, U.S., and Canada for the M_w 9.25 east Aleutian event. In Japan, the median coastal amplitude is only
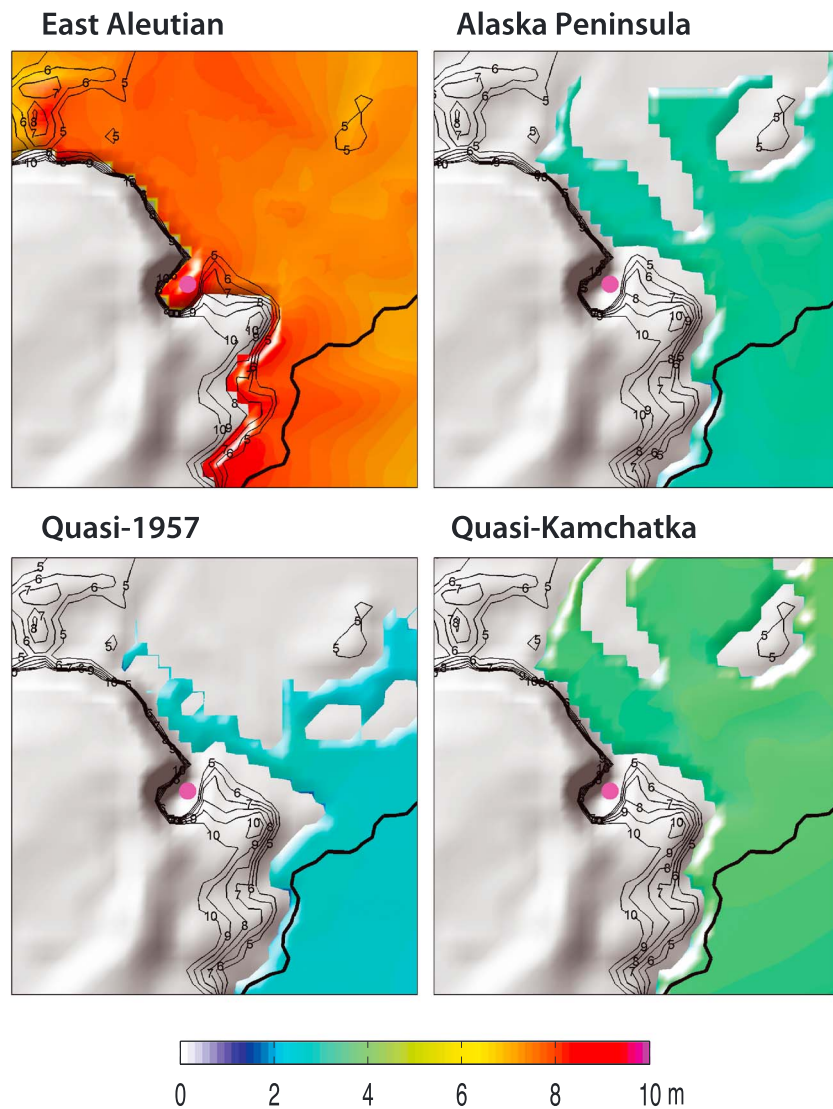
Figure 3. High-resolution tsunami inundation forecasts at the Makauwahi Sinkhole on Kaua'i are shown, respectively, for the M_w 9.25 events in Figure 1. The map scale is about 321 m on a side. (top left) Only the east Aleutian earthquake inundates the sinkhole, reaching 8 to 9 m above mean sea level. The center of the sinkhole is indicated with a small magenta dot.

64 cm, with a maximum of 103 cm. Unlike the Cascadia event, which directs energy toward Japan [e.g., *Atwater et al.*, 2005], an Aleutian event does not, and hence, the coastal tsunami amplitudes would be indistinguishable from the normal tidal variations without the aid of tide gauge instruments (K. Satake, personal communication, 2014). However, there is corroborating evidence consistent with the Aleutian event discussed herein along the Pacific Coast of U.S. and Canada, where maximum forecast tsunami amplitudes in harbors have a median of nearly 3 m and a maximum of nearly 9 m at Port San Luis of San Luis Obispo, California. Further, the SIFT forecast offshore of the Makauwehi sinkhole shows a 7 m tsunami amplitude—a detailed NOAA inundation simulation is not available for the site—that would lead to greater runup at the sinkhole itself, corroborating the NEOWAVE results.

5. Discussion

The paleotsunami deposit in the Makauwahi sinkhole on Kaua'i appears to be associated with an eastern Aleutian source region. None of the giant historical M_w 9+ earthquakes around the circum-Pacific have come

close to inundating the sinkhole, and these events have included azimuths to Japan, Kamchatka, Alaska, and Chile. However, earthquakes situated in the eastern Aleutians—where the orientation of the subduction zone is adverse to Hawai'i—with faulting parameters comparable to these extreme events have been shown to forecast tsunamis with sufficient energy and amplitude to produce the observed inundation at the sinkhole. The unique geometry of the east Aleutians with respect to the Hawaiian Islands focuses the tsunami energy. Comparable giant earthquakes adjacent to the eastern Aleutians do not forecast sinkhole inundation, even where the amount of average slip on the fault is as great as 35 m—the largest ever measured from earthquake source parameters. This does not mean that other earthquake zones could not have caused the Kaua'i paleotsunami deposit, but rather that such events would necessarily have to exceed the fault displacements seen historically in giant earthquakes.

The scant paleotsunami evidence available in the Aleutians is fortunately situated near the edge of the eastern Aleutians, west of the zone of the great 1946 earthquake and tsunami. Six paleotsunami sand deposits at the Sedanka Island site were observed [*Witter et al.*, 2013] including the recent 1957 deposit at the top of the soil stratigraphy. The next deeper paleotsunami layer on Sedanka Island has been dated circa 1530–1660 A.D., and fits within the range of dates, 1430–1665 A.D., associated with the age distribution for the Kaua'i paleotsunami deposit. Finally, corroborating evidence in paleotsunami dates on the Pacific West Coast of the U.S. and Canada are consistent with the Kaua'i data.

The Sedanka tsunami dates indicate six events in the last 1600 years. However, within the full range of the Kaua'i stratigraphy [*Burney et al.*, 2001], there was only one deposit evident. Therefore, it may be concluded that the second layer in the Sedanka stratigraphy represents the largest tsunami event of the group and further conclude that the Kaua'i event was among the largest earthquakes in the Pacific during the past 7000 years since the collapse of the Makauwahi cave roof into the sinkhole.

In summary, although there are alternate possible sources capable of causing the Kaua'i paleotsunami deposit (see supporting information: Alternate Hypotheses), their likelihoods are much less than the ongoing tectonic activity at subduction zones. Furthermore, based upon forecast studies, the known tsunamigenic earthquake zones in Hawai'i do not appear to generate local tsunamis with sufficient amplitude on Kaua'i to cause the paleotsunami deposit. A preponderance of evidence indicates that a giant earthquake in the eastern Aleutians generated a great tsunami between 350 and 575 years ago, leaving dated, paleotsunami evidence both on Kaua'i and Sedanka Island in the eastern Aleutians, and along the Pacific West Coast of the U.S. and Canada.

To match the observed inundation at the Makauwahi sinkhole on Kaua'i, an earthquake with M_w ~9.25 and with average fault displacement ~35 m is indicated by these hydrostatic tsunami simulations. Including dispersive effects into a full nonhydrostatic simulation will affect the phase relationships of the arriving energy but are unlikely to greatly influence the total tsunami energy arriving at the site. Given the volume of material in the paleotsunami deposit, the tsunami must not merely overtop the sinkhole, but rather overwash with sufficient flow depth and velocity to carry the debris into the sinkhole. Although no debris-flow dynamics have been calculated, earthquakes with M_w ~9.25 overwash the eastern edge of the sinkhole with over 1 m clearance, even considering the maximum peak-to-trough tidal variation of about 1 m in the vicinity of the sinkhole.

6. Conclusions

A preponderance of evidence indicates that a giant M_w ~9.25 earthquake centered in the eastern Aleutians occurred ~350 to ~575 years ago. This earthquake had an average fault displacement comparable to the largest earthquakes during the past 100 years. The effect of geometric focusing of tsunami energy due to the orientation of the subduction zone is fundamental. The model-forecast tsunami from this event exceeds all historical tsunamis in the Hawaiian Islands in the last 200 years.

Given the tectonic convergence rate of the eastern Aleutian subduction zone at 7 cm/yr or 7 m/century, there has been 24 to 40 m of convergence accumulated since this prior event—sufficient for another giant earthquake of nearly the same magnitude, if the contribution of fault creep is discounted (e.g., for the 2010 Chile earthquake *Lay* [2011] notes that largest slip occurred where the fault was partially creeping). There is no indication of when a similar Aleutian earthquake might happen, but simply that there is the capacity to

produce a comparable event. Indeed, the tsunami deposit in the Makauwahi sinkhole is unique in the 7000 year stratigraphy. It is unknown whether the uniqueness of this event reflects its rarity or rather a recent change in the style of faulting in the Aleutian subduction zone. Whereas six tsunami deposits are found on Sedanka Island going back nearly 1600 years [*Witter et al.*, 2013], only one of these—the second most recent layer—corresponds in time to an event with sufficient energy to inundate the Makauwahi sinkhole. Further paleotsunami studies in both the Hawaiian and the Aleutian Islands are needed to resolve the tsunami history of the Hawaiian Islands.

The focus of tsunami energy from the Aleutians directed toward the State of Hawaii, and the short 4.5 h tsunami propagation time, underscores the importance of tsunami readiness for Aleutian events. Hawaii State Civil Defense must make evacuation decisions 3 h prior to tsunami arrival. Other than the few NOAA DART® (Deep-ocean Assessment and Reporting of Tsunamis) buoys stationed near the Aleutian Islands, there are no sensors that can characterize a potentially great tsunami from the Aleutians as it propagates toward Hawai'i. Furthermore, key Aleutian DARTs are often down for months at a time, awaiting repair following the winter storm season. Deploying two additional next-generation tsunamimeters between Hawai'i and the Aleutians would substantially enhance coverage, corroborate near-field data and provide a level of redundancy, giving better warning system resilience to the loss of critical sensor data. The integration of tsunami sensors into the repeaters of undersea telecommunication cables traversing the North Pacific would greatly benefit our ability to rapidly resolve the tsunami wavefield in real time and augment tsunami preparedness [*Butler*, 2012b].

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