Sedimentary evidence of prehistoric distant-source tsunamis in the Hawaiian Islands

SEANPAUL LA SELLE*, BRUCE M. RICHMOND*, BRUCE E. JAFFE*, ALAN R. NELSON†, FRANCES R. GRISWOLD‡, MARIA E. M. ARCOS§, CATHERINE CHAGUE¶, JAMES M. BISHOP**, PIERO BELLANOVA††, HAUNANI H. KANE‡‡, BRENT D. LUNGHINO* and GUY GELFENBAUM*

*Pacific Coastal and Marine Science Center, U.S. Geological Survey, 2885 Mission Street, Santa Cruz, California 95060, USA (E-mail: slaselle@usgs.gov)
†Geologic Hazards Science Center, U.S. Geological Survey, 1711 Illinois Street, Golden, Colorado 80401, USA
‡Department of Geosciences, University of Massachusetts, Amherst, Massachusetts 01003, USA
§School of Biological, Earth and Environmental Sciences, UNSW Sydney, Sydney 2052, New South Wales, Australia
**Central Coast Regional Water Quality Control Board, 895 Aerovista Place, San Luis Obispo, California 93401, USA
††Neotectonics and Natural Hazards Group, RWTH Aachen University, Lochnerstrasse 4-20 52056 Aachen, Germany
‡‡School of Ocean and Earth Science and Technology, University of Hawai’i, Manoa, Hawai’i 96822, USA

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ABSTRACT

Over the past 200 years of written records, the Hawaiian Islands have experienced tens of tsunamis generated by earthquakes in the subduction zones of the Pacific ‘Ring of Fire’ (for example, Alaska–Aleutian, Kuril–Kamchatka, Chile and Japan). Mapping and dating anomalous beds of sand and silt deposited by tsunamis in low-lying areas along Pacific coasts, even those distant from subduction zones, is critical for assessing tsunami hazard throughout the Pacific basin. This study searched for evidence of tsunami inundation using stratigraphic and sedimentological analyses of potential tsunami deposits beneath present and former Hawaiian wetlands, coastal lagoons, and river floodplains. Coastal wetland sites on the islands of Hawai’i, Maui, O’ahu and Kaua’i were selected based on historical tsunami runup, numerical inundation modelling, proximity to sandy source sediments, degree of historical wetland disturbance, and breadth of prior geological and archaeological investigations. Sand beds containing marine calcareous sediment within peaty and/or muddy wetland deposits on the north and north-eastern shores of Kaua’i, O’ahu and Hawai’i were interpreted as tsunami deposits. At some sites, deposits of the 1946 and 1957 Aleutian tsunamis are analogues for deeper, older probable tsunami deposits. Radiocarbon-based age models date sand beds from three sites to ca 700 to 500 cal yr BP, which overlaps ages for tsunami deposits in the eastern Aleutian Islands that record a local subduction zone earthquake. The overlapping modelled ages for tsunami deposits at the study sites support a plausible correlation with an eastern Aleutian earthquake source for a large prehistoric tsunami in the Hawaiian Islands.
INTRODUCTION

Tsunamis pose a significant hazard in the Hawaiian coastal zone (Richmond et al., 2001; Wood et al., 2007). According to Dudley & Lee (1998), the Hawaiian Islands have experienced 95 tsunamis over 185 years (1813 to 1998 CE), an average of one every two years, with a damaging tsunami occurring on average every five years. Tsunamis affecting the Hawaiian Islands can be locally generated or originate from distant sources throughout the Pacific Ocean basin (Fig. 1). Locally generated events are especially hazardous because of the limited warning time and potential large runup and extensive inundation. Rare catastrophic tsunamis are believed to have been locally generated in the Hawaiian Islands when huge volumes of material slid into the sea via flank failure collapse creating large inland runups up to several hundred metres above sea level (Moore et al., 1989; McMurtry et al., 2004). Recent earthquake-generated submarine landslides caused significant local tsunamis that produced identifiable tsunami deposits.

Fig. 1. Inset globe shows the location of the Hawaiian Islands and the Aleutian Islands, the source of some of the largest tsunamis that have historically impacted Hawai‘i. The Fox Islands occupy a ca 480 km long segment of the Aleutian Islands. The hillshade map shows bathymetry and topography of the Hawaiian Islands with the locations of sites (red dots) cored in the search for tsunami deposits. Larger text and arrows label the three primary sites: Anahola Valley on Kaua‘i, Kahana Valley on O‘ahu and Pololū Valley on Hawai‘i.
along the island of Hawai‘i in 1868 and 1975 (Goff et al., 2006; Richmond et al., 2011).

Distant-source tsunamis that impact Hawaiian shores hours after they are generated can be destructive and deadly. Significant historical tsunamis (Table 1) include distant-source events from the Aleutians (1946 and 1957), Kamchatka (1923 and 1952), Chile (1960), Alaska (1964) and Japan (2011). Of these, the 1946 tsunami was the largest in most locations (Lander & Lockridge, 1989) and the deadliest (159 casualties) natural disaster of the last century in the Hawaiian Islands. The last tsunami with recorded runup greater than 10 m was in 1960.

Historic tsunamis impacting the Hawaiian Islands are well-documented while the record of prehistoric tsunamis has not been well-established. The development of the geological record of prehistoric tsunamis would improve understanding of the frequency and size of past tsunamis impacting Hawai‘i. Because of the islands’ location in the north-central Pacific Ocean an improved documented tsunami history could add clarity to the frequency and range of past events in the Pacific and so improve coastal hazard assessment throughout the Pacific Ocean basin.

This study presents research in the Hawaiian Islands that extends the record of distance-source tsunamis. Thirteen coastal wetlands were cored, searching for geological evidence of large tsunamis generated by great (>Mw 8.5) subduction zone earthquakes around the Pacific Rim. Stratigraphic, sedimentary and 14C age evidence from three sites on Kaua‘i, O‘ahu and Hawai‘i suggest that a large tsunami struck the Hawaiian Islands sometime between 1250 and 1450 CE, which overlaps with the ages of tsunami deposits in the eastern Aleutians (Witter et al., 2018). Historic tsunami deposits at two of the three sites, determined by 137Cs dating to be from the 1946 and 1957 CE tsunamis, also share an eastern Aleutian source.

SEDIMENTARY EVIDENCE OF HISTORICAL AND PREHISTORIC DISTANCE-SOURCE TSUNAMIS IN HAWAI‘I

Documentation of deposits due to inundation by distant-source tsunamis in the Hawaiian Islands is sparse, especially for prehistoric events. However, in the last 150 years, the Hawaiian Islands have been struck by several distant-source tsunamis that deposited marine sand and other debris onshore (Table 1). Most notable were the 1946 and 1957 Aleutian tsunamis, and the 1960 Chile tsunami.

Anecdotes and aerial photographs of damage due the 1946 tsunami at Kahuku Point, O‘ahu, show extensive sand deposits and tsunami related scour (Keating, 2008), but these deposits have not been preserved, most likely due to both aeolian reworking and anthropogenic activity. At the south-east corner of O‘ahu at Queen’s Beach, a road was damaged by the 1946 tsunami and photographs show coarse coral rubble mantling the road. Coarse clasts and gravel deposits are still present at Queen’s Beach from the 1946 tsunami and other more recent events (1952 Kamchatka, 1957 Aleutians and 1960 Chile) according to Keating et al. (2004).

Shepard et al. (1949) observed coral rubble and sand deposited inland in northern Kaua‘i by the 1946 tsunami. These authors reported observations of sand 1-2 m (4 ft) thick on the highway at Hā‘ena (northern Kaua‘i), thinner beds of sand covering roads in other places on Kaua‘i, O‘ahu and Maui, as well as taro patches covered in sand in Waipi‘o Valley, Hawai‘i.

Pololū Valley (Fig 1), on the north-east coast of Hawai‘i, was inundated by the 1946 and 1957 Aleutian tsunamis, with maximum runup heights of approximately 17 m and 10 m above mean sea level, respectively (Lander & Lockridge, 1989). Chagué-Goff et al. (2012) identified basaltic sand deposits within the upper half-metre of sediments in the valley, and used sedimentological, stratigraphic, geochemical, diatom, pollen, 210Pb and 137Cs data to attribute these sand beds to inundation from these events. The 1946 tsunami deposit was traced 250 to 350 m inland, thinned landward from 30 to 2-5 cm, and comprised multiple fining-upward sequences in several cores. The 1957 tsunami deposit was only observed in one of five cores, with a 1 to 2 cm thick basaltic sand bed overlying the 1946 deposit. Chagué et al. (2018) identified marine sands most likely deposited by the 1946 Aleutian and 1960 Chilean tsunamis in peat and soil at Shinmachi, Hilo.

The Makauwahi Sinkhole on the south-east coast of Kaua‘i may contain evidence of inundation by a prehistoric tsunami with a distant source, possibly in the eastern Aleutian Islands (Burney et al., 2001). The sinkhole, which is a remnant of a collapsed aeolianite cave complex, contains a bed of angular boulders, cobbles,
Table 1. Notable historical tsunami events impacting the Hawaiian Islands*.

| Source location   | Earthquake magnitude ($M_x$) | Approximate distance from Hawai‘i (km) | Maximum inundation distance (m) | Maximum water height (m) | Deposits |
|-------------------|-------------------------------|---------------------------------------|---------------------------------|--------------------------|----------|
| 1868 SE Hawai‘i   | 7.9                           | Local                                 | 400                             | 14-0                     | Boulder fields\(^1\),\(^2\) |
|                   |                               | Punalu‘u, Hawai‘i                      |                                 | Keauhou Landing, Hawai‘i | –        |
| 1869 S Pacific    |                               | 4300                                  | 300                             | 8.2                      | –        |
|                   |                               | Cape Kumukahi, Hawai‘i                |                                 | Puna Coast, Hawai‘i      | –        |
| 1896 Japan        | 8.3                           | 6000                                  | –                               | 5-5                      | –        |
|                   |                               |                                       |                                 | Keauhou, Hawai‘i         | –        |
| 1923 Kamchatka    | 8-1                           | 5200                                  | –                               | 6-1                      | Hilo, Hawai‘i |
| 1946 Aleutians    | 8-6                           | 3500                                  | 485 Hā‘ena, Kaua‘i              | 16-4                     | Wetland sand layers\(^3\),\(^4\),\(^6\),\(^7\),\(^8\) |
| 1952 Kamchatka    | 9-0                           | 5300                                  | –                               | 6-1                      | –        |
|                   |                               |                                       |                                 | Kawaiola Beach, O‘ahu   | –        |
| 1957 Aleutians    | 8-6                           | 3900                                  | –                               | 16-2                     | Wetland sand layers\(^7\) |
|                   |                               |                                       |                                 | Wainiha Bay, Kaua‘i     | –        |
| 1960 Chile        | 9:5                           | 11 000                                | 762                             | 10-7                     | Wetland sand layers, isolated boulders\(^7\),\(^9\),\(^10\) |
|                   |                               | Kahului, Maui                         |                                 | Hilo, Hawai‘i            | –        |
| 1964 Alaska       | 9-2                           | 3300                                  | –                               | 4-9                      | Waimea Bay, O‘ahu |
| 1975 SE Hawai‘i   | 7.7                           | Local                                 | 137                             | 14-3                     | Boulder field, sand layers, localized\(^1\),\(^2\) |
|                   |                               | Punalu‘u Bay, Hawai‘i                 |                                 | Keauhou Landing, Hawai‘i| –        |
| 2011 Japan        | 9-1                           | 6000                                  | 536                             | 5-4                      | Sparse thin deposits\(^11\) |
|                   |                               | Kahului, Maui                         |                                 | Kealakekua Bay, Hawai‘i | –        |

* From NGDC/WDS Global Historical Tsunami Database (doi:10.7289/V5PN93H7) and published accounts of deposits: \(^1\)Goff et al. (2006), \(^2\)Richmond et al. (2011), \(^3\)MacDonald et al. (1947), \(^4\)Shepard et al. (1949), \(^5\)Keating et al. (2004); \(^6\)Keating (2008); \(^7\)Chagué-Goff et al. (2012), \(^8\)Chagué et al. (2018), \(^9\)Trusdell et al. (2012), \(^10\)Eaton et al. (1961), \(^11\)Miller & Roeber (2012).
gravel, marine sand and coral fragments that suggest that much of the sediment was washed into the sinkhole. Butler et al. (2014) inferred that a tsunami had overtopped the sinkhole wall at its lowest point (7.2 m above sea level). Numerical tsunami modelling by these authors demonstrated that a Mw 9.25 earthquake centred in the eastern Aleutians would have been required to generate a tsunami large enough to overtop the sinkhole rim and create the deposit.

Based on 14C ages for kukui nuts and bottle gourds from the sinkhole deposit of 1430 to 1665 CE (520 to 285 cal yr BP) (Burney et al., 2001), Butler et al. (2014) proposed that the deposit was similar in age to a tsunami deposit on Sedanka Island in the Fox Islands of the eastern Aleutians, dated at 1290 to 1390 CE (660 to 560 cal yr BP) (Witter et al., 2016). More recently, 230Th–238U ages on detrital coral in the sinkhole deposit narrowed its age to 1551 to 1593 CE (399 to 357 cal yr BP) (Butler et al., 2017). Fox Island stratigraphy contains evidence of nine large tsunamis from approximately the past 2000 years (Witter et al., 2018), at least some of which are likely to have been triggered by an Aleutian subduction-zone megathrust rupture. Because the new precise coral age does not overlap with the ages of presently dated tsunami deposits in the eastern Aleutians (Witter et al., 2018), an Aleutian source for the Makauwahi Sinkhole deposit is unlikely.

Numerical modelling of tsunamis generated by large (Mw 9.3), trench-breaking megathrust earthquakes in the Aleutians predict runups of 10 to 40 m along the north shores of Kaua‘i and O‘ahu (Bai et al., 2018). Because the 1946 and 1957 tsunamis deposited marine sand preserved in coastal wetlands in Kaua‘i and Hawai‘i, similarly sized or larger prehistoric Aleutian megathrust earthquakes could trigger tsunamis capable of leaving behind similar or more extensive deposits. Presented below are the results of the current study’s search for prehistoric tsunami deposits on three Hawaiian Islands, which uncovered evidence of only one or two prehistoric events in the past 750 years.

STUDY AREA

One of the challenges of this research was to find locations where prehistoric tsunami deposits are likely to be preserved. Studies of tsunami deposits around the world have typically been situated in low-lying coastal wetlands, beach-ridge plains and lakes (Nanayama et al., 2003; Pinegina et al., 2003; Kelsey et al., 2005) due to the preservation potential of these environments and ease of differentiating sand-rich tsunami or storm deposits from background sediment such as peat and mud. Many coastal wetlands and beach-ridge plains in the Hawaiian Islands have been utilized for taro and rice farming making it difficult to avoid sites undisturbed by humans.

Slow sea-level fall over the past few thousands of years is another impediment to preserving tsunami deposits in Hawai‘i. An emerged intertidal bench at Kapapa Island on O‘ahu and a regressive marine contact in Hanalei coastal plain suggest that mean sea level was higher 5000 to 2000 cal yr BP than it is today (Grossman & Fletcher, 1998). This mid to late-Holocene highstand reached a maximum of about 2 m above present sea level around 3500 years ago. Subsequent regression led to development of strand plains in former embayments on Kaua‘i and O‘ahu (Calhoun & Fletcher, 1996). The island of Hawai‘i has experienced subsidence due to localized flexure of the oceanic lithosphere in addition to global eustatic sea-level rise (Ludwig et al., 1991; Fletcher et al., 2011), resulting in sediment backfilling of valleys (Chagué-Goff et al., 2012). Due to the highstand and subsequent progradation or infilling, the record of tsunami deposits preserved in wetland peat and mud is limited to the past few thousand years.

Reconnaissance of 13 sites on Hawai‘i, Maui, O‘ahu and Kaua‘i islands in 2015 revealed three sites (Anahola, Kahana and Pololū) with historical and prehistoric tsunami deposits along the north-eastern shores of Kaua‘i, O‘ahu and Hawai‘i, respectively (Fig. 1). Historical tsunami runups in the Hawaiian Islands show that the largest runups, on the north and north-east facing shores, are from tsunamis originating in the Aleutians (Lander & Lockridge, 1989). This study’s approach was to core in wetlands fronted by sandy ocean beaches with the assumption that flooding by a tsunami would deposit an identifiable sand bed within wetland mud and peat.

Anahola Valley, Kaua‘i

Anahola Valley is a ca 1 km wide valley fronted by a mostly detrital, carbonate-rich, 100 m wide, sandy beach (Fig. 2). Anahola Stream, which drains the Namahana and Kalalea mountains, has its mouth at the north end of the beach. Anahola Bay faces east and is backed by an
Fig. 2. Core locations and sand thicknesses in Anahola Valley, Kaua‘i. (A) Depositional environments and landforms in Anahola Valley. Core locations in the wetland on the north-west bank of Anahola Stream are marked by green numbered circles (vibracores) and white dots (gouge cores). (B) Thicknesses of sands A1 (green), A2 (yellow) and A3 (red) are represented by circle diameters. Sand A1 is only observed in a few cores in the north-east section of the wetland. Sand A2 is also confined to the north-east section of the wetland but thins inland and away from the riverbank. Sand A3 is observed in cores up to 650 m from the shoreline and gradually thins inland.

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estuary lined with wetlands that extend 1-2 km inland along the left bank of Anahola Stream (Cheng & Wolff, 2012). The right bank of the stream consists of sand dunes that extend up to 0-3 km inland [Department of Hawaiian Home-lands (DHHL), 2015]. Anahola Valley was traditionally farmed for taro and more recently for sugar (DHHL, 2010). In the wetlands an artificially elevated area on which structures have historically been built rises ca 1 m above the marsh and bisects the marsh into eastern and western sections.

Anahola Bay has been impacted by five historical tsunamis. The 1946 tsunami was the largest: the waves were up to 4 to 5 m high to the north of Anahola and 8-5 m high along the cliffs to the south (Shepard et al., 1949). Several houses suffered damage in Anahola during the event. Run-ups in the area for the 1957, 1960, 1964 and 2011 tsunamis were 4-9 m, 1-8 m, 1-0 m and 2-4 m, respectively (Loomis, 1976; Lander & Lockridge, 1989; State of Hawai`i, 2002; Miller & Roeber, 2014).

Kahana Valley, O`ahu

The wetland study area in Kahana Valley, which is on the north-east-facing shore of O`ahu, is part of the Ahupua`a O Kahana State Park (Fig. 3). The wetland is separated from the Pacif-ic Ocean and an 80 m wide beach consisting of carbonate sand, by a 3 m high coastal berm currently vegetated by Casuarina (ironwood) trees. The modern marsh, which covers an area up to 1-3 km inland and 0-5 km wide, is bisected by Kahana Stream and divided into two sections by the stream and bordering strip of swamp vegetation (Fig. 3). Marsh vegetation begins approximately 0-3 km inland from the beach. The shoreline is currently accreting at rates of up to 0-7 ± 0-3 m year⁻¹ (Fletcher et al., 2011). The valley has been used by both Native Hawaiian and post-contact peoples for agriculture (Beggerly, 1990). An organic geochemical study of the sediments below 50 cm depth in the wetland indicated low overall concentrations of anthropogenic markers and pollutants (Bel-lanova et al., 2019). An environmental recon-struction of Kahana Valley by Beggerly (1990) suggested that Kahana Valley was a marine embayment from the end of the Pleistocene through the mid-Holocene sea-level highstand. Beginning in the mid to late Holocene the estu-ary transitioned into a lagoon, followed by a marsh that formed 1000 to 2000 years ago.

Historical tsunamis had moderate runups in Kahana Valley (1946 = 2-1 m; 1952 = 2-0 m; 1960 = 2-5 m) (Shepard et al., 1949; Lander & Lockridge, 1989; State of Hawai`i, 2002). The 1946 tsunami only inundated about 100 m into the grove of palm trees (1-6 m above sea level) located on the south side of the highway at the head of the valley. Higher runups up to 2-8 m occurred along the valley walls in Kahana Bay (Shepard et al., 1949). However, a Mw 9-25 or larger eastern Aleutian earthquake, as proposed by Butler et al. (2014), would presumably result in much larger runups that would be capable of inundating far into the valley interior.

Pololu Valley, Hawai`i

Pololū Valley (Fig. 1), on the north-east coast of Hawai`i, is carved into basalts of Kohala Vol-cano (McDougall & Swanson, 1972), from which most of its beach and dune sediment are derived. As a result, the beach and dune sand here consist mostly of basaltic sand with trace amounts of carbonate, unlike the primarily carbonate-rich sand at Anahola and Kahana. A coastal marsh extends approximately 600 m inland and is bisected by the wide channel of Pololū Stream (Fig. 4). The mouth of the stream is constricted by a 30 m high sand dune and a seasonal beach berm and is typically only open to the ocean during periods of high stream flow. Pololū has been settled since the 13th Century and was subsequently abandoned by 1926 (Chagué-Goff et al., 2012) following utilization of the valley for rice cultivation. The 1946, 1957 and 1960 tsunamis are well-documented in Pololū Valley, with maximum runup heights of 17 m, 10 m and 3 m above mean sea level, respectively.

METHODS

Stratigraphy at each site was documented in the field with gouge cores (1 m long sections, 30 mm and 60 mm diameters), Russian cores (0-5 m long sections, 60 mm in diameter) and surface samples. Vibracores (up to 4-42 m long, 76 mm in diameter) were collected from Anahola and Pololū valleys. Core locations were selected to constrain sand deposit extent and geometry based on historical tsunami inundation.

All sample locations were determined using a handheld GPS unit (horizontal errors
ca $\pm$ 4 m). Gouge and Russian cores were described and photographed in the field. Gouge cores were logged by describing stratigraphy in detail or by noting only the thickness and depth of clean sand beds. At vibracore sites, adjacent gouge cores were collected as a guide to correcting contact depths for the amount of vibracore sediment compaction. Compaction during vibracoring ranged from 24 to 55% and was related to mud and/or peat content. Much of the data described below (core locations, core photographs, computed tomographic (CT) scans, descriptions, grain–size data, radiocarbon results, and sand depths and thicknesses) have been published in an accompanying US Geological Survey Data Release (La Selle et al., 2019).

**Computed tomographic scans**

Vibracores from Anahola and Pololū valleys, and a series of seven overlapping Russian cores
at one site from Kahana Valley, were scanned for structure using X-ray computed tomographic (CT) density measurements made at the College of Veterinary Medicine at Oregon State University with an Aquilion 64-slice at 120 peak kV and 200 mA, with a pitch of 0.5 sec (100 mA-sec) (Canon Medical Systems Corporation, Otawara, Japan). Image slices were generated every 2 mm across the core, with a voxel resolution of 500 μm in the downcore and across-core directions. The raw DICOM images were processed using Horos software (horosproject.com) to apply a normalized colormap of -200 to 2200 Hounsfield Units to each image (Hounsfield, 1973; Reilly et al., 2017).

Grain size

Grain-size analyses of three sand beds from Anahola Valley were performed at the US Geological Survey Pacific Coastal and Marine Science Center. Each sand bed was subsampled at 0.2 to 0.5 cm intervals. These samples were wet-sieved through 2.0 mm and 0.063 mm sieves and separated as gravel (>2.0 mm), sand (0.063 to 2.0 mm) and mud (<0.063 mm). The
gravel fraction was analyzed by sieving. The sand fraction was run through a long (2 m) settling tube. Measured settling velocities were converted to sizes of equivalent quartz spheres in Φ-phi size intervals. The mud fraction was analyzed using a Beckman Coulter LS 13-320 laser diffraction particle size analyser (Beckman Coulter Inc., Brea, CA, USA) at Φ-phi size intervals. Statistical parameters of the grain-size distribution (for example, mean grain size, Φ10, Φ90, median, mode, standard deviation, kurtosis and skewness) of the samples are calculated using the graphic methods of Folk & Ward (1957) using pcSDSZ and GradiStat software (Blott & Pye, 2001). Grain-size distributions were plotted vertically in order to identify suspension grading, a distinctive type of normal grading that is identifiable where the entire grain-size distribution shifts to finer sizes upward in a deposit. Suspension grading is found in deposits formed in high-energy flows, such as tsunamis and turbidity currents (Jaffe et al., 2012).

Cesium dating
Cesium-137 (137Cs) analyses of the upper half metre of peat in Anahola was conducted to determine if the uppermost two sand beds were likely to have been deposited by the 1946 and 1957 Aleutian tsunamis. Matching samples 1 cm thick from the upper 50 cm of sediment were combined from seven adjacent Russian cores near VC07 to collect enough sample material for analysis. Powdered samples were sealed in vials and 137Cs activity was measured using a high purity germanium (HPGe) well detector (Princeton Gamma Tech Instruments Inc., Princeton, NJ, USA) at the Pacific Coastal and Marine Science Center in Santa Cruz, CA, USA, following methods outlined in Appleby (2002).

Radiocarbon dating
The age of potential prehistoric tsunami deposits was investigated using accelerator mass spectrometer (AMS) 14C ages on seeds, shells and plant fragments; bulk organic-rich sediment and shells sampled from the sediment above, below and within selected sand beds in order to bracket the time of deposition (Table 2; Appendix S1). All radiocarbon ages were determined at the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) facility in Woods Hole, MA, USA. After sieving selected sediment intervals on a 180 μm mesh, small macrofossils, many identified to genus level, were selected for dating under a microscope (5 to 25×), rinsed with deionized water, dried for 24 h at 50°C and weighed (Table 2) (Kemp et al., 2013). Bulk sediment samples were rinsed with deionized water, and the majority of rootlets were removed with tweezers before drying the sediment sample for 24 h at 50°C. The AMS ages were calibrated with OxCal (version 4.3; https://c14.arch.ox.ac.uk/oxcal/) using the IntCal13 calibration curve (Reimer et al., 2013).

The OxCal stratigraphic ordering software (methods of Bronk Ramsey, 2008, 2009) was used with the 14C ages to develop age models for the times when sand beds were deposited (models similar to those described by Nelson et al., 2014; Table 1; Appendix S2). The accuracy of the models, however, depends on the interpretation of the context of each separate 14C sample (Bronk Ramsey, 2008), as well as consideration of the sedimentation processes that produced the wetland sequences containing sand beds (discussed for each dated core below). The ages on samples of bulk sediment were particularly difficult to evaluate: decayed, fine-grained carbon that was not fully removed by acid pretreatment could have been older than its host sediment. Four of eight bulk sediment ages are older than seed ages from the same levels in the cores (Table 2); but two bulk sediment ages are younger than seed ages from the same levels, probably because much younger, now decayed, roots grew into the sediment from above. Although the type of macrofossil dated and the likely stratigraphic context of each sample was taken into account, age models that consider the depth of each sample in sequence (Witter et al., 2018) are inappropriate because many of this study’s samples are clearly reworked, and because sedimentation rates within these coastal sequences may vary by orders of magnitude. Instead, ages were grouped in a simple sequence model into phases above and below potential prehistoric tsunami deposits at each site to calculate probability distribution functions for the times of tsunami deposition (Bronk Ramsey, 2009). Grouping all but the most obviously reworked seed ages into the unordered phases required fewer assumptions about the degree of reworking and the extent to which ages were maximum or minimum limiting ages than would be the case if only the most limiting maximum and minimum ages at each site had been used.
Table 2. Radiocarbon data and stratigraphic context for samples from cores bracketing the ages of sand layers A3 in Anahola Valley, Kaua’i, K1 in Kahana Valley, O’ahu and P3 in Pololū Valley, Hawai’i. *

| Estimated age (cal yr BP) | Calibrated age (cal yr BP at 2σ)‡ | Laboratory reported age (14C yr BP at 1σ)§ | Age interpretation¶ | Radiocarbon laboratory number | Core | Depth (m)** | Stratigraphic context†† | Description of dated material |
|--------------------------|----------------------------------|-------------------------------------------|-------------------|-------------------------------|------|-------------|--------------------------|--------------------------------|
| **Sand A3, Anahola Valley, Kaua’i 704–535** | | | | | | | | |
| 700 ± 15 | Outlier | OS-142978 | VC2 | 0.875–0.880 | In black silty mud, 6.0–6.5 cm above sand A3 | Schoenoplectus seeds |
| 835 ± 15 | Outlier | OS-127115 | GC21SP | 1.360–1.370 | In sandy mud with gastropods, 2.0–3.0 cm above sand A3 | Schoenoplectus seed |
| 740 ± 20 | Outlier | OS-124967 | VC8 | 0.600–0.610 | In muddy peat, 2.0–3.0 cm above sand A3 | Schoenoplectus seeds |
| 765 ± 20 | Outlier | OS-143169 | VC3 | 1.405–1.410 | In black silty mud, 1.0–1.5 cm above sand A3 | Schoenoplectus seed |
| **553–517** | **530 ± 15** | Minimum | OS-119969 | GC1 | 0.900–0.920 | In sandy mud with gastropods, 0.0–2.0 cm above sand A3 | Schoenoplectus and unidentified seeds |
| 550 ± 15 | Minimum | OS-142980 | VC2 | 0.935–0.940 | In black silty mud, 0.0–0.5 cm above sand A3 | Schoenoplectus seed |
| 730 ± 15 | Outlier | OS-142981 | VC2 | 0.935–0.940 | In black silty mud, 0.0–0.5 cm above sand A3 | Schoenoplectus seed |
| 630 ± 20 | Outlier | OS-127114 | VC4A | 0.830–0.840 | In mud with trace sand, 0.0–1.0 cm above sand A3 | Schoenoplectus seed |
| 750 ± 15 | Outlier | OS-119971 | RC1 | 1.240–1.250 | In muddy sand, 0.0–1.0 cm above sand A3 | Schoenoplectus seed |
| 100 ± 20 | Outlier | OS-119973 | RC1 | 1.240–1.250 | Muddy sand, 0.0–1.0 cm above sand A3 | Bulk sediment |
| 820 ± 20 | Outlier | OS-127113 | VC2 | 1.000–1.045 | Within sand A3 | Schoenoplectus seed |
| **731–679** | **785 ± 20** | Maximum | OS-127046 | VC6 | 1.200–1.250 | Within sand A3 | Schoenoplectus seed |
| 815 ± 20 | Maximum | OS-144586 | VC8 | 0.895–0.900 | In mud, 0.5–1.0 cm below sand A3 | Schoenoplectus seed |
| 505 ± 20 | Maximum | OS-119975 | RC1 | 1.330–1.340 | Sandy mud, 0.0–1.0 cm below sand A3 | Bulk sediment |
Table 2. (continued)

| Estimated age (cal yr BP) | Calibrated age (cal yr BP at 2σ) | Laboratory reported age (14C yr BP at 1σ) | Age interpretation | Radiocarbon laboratory number | Core | Depth (m) | Stratigraphic context | Description of dated material |
|--------------------------|----------------------------------|------------------------------------------|--------------------|-------------------------------|------|-----------|----------------------|--------------------------------|
| 975 ± 15                 | Maximum                          | OS-125037                                | VC8                | 0-900-0-910                   |      |           | In sandy mud, 1-0-2 cm below sand A3 | Schoenoplectus seed          |
| 945 ± 15                 | Maximum                          | OS-125038                                | VC8                | 0-900-0-910                   |      |           | In sandy mud, 1-0-2 cm below sand A3 | Unidentified grass            |
| 860 ± 15                 | Maximum                          | OS-144589                                | VC3                | 1-520-1-530                   |      |           | In mud with trace sand, 2-0-3 cm below sand A3 | Schoenoplectus seed          |

Sand K1, Kahana Valley, O‘ahu 605–490

| 645 ± 20                 | Outlier                          | OS-133451                                | gc13b              | 0-810-0-815                   |      |           | In sandy mud, 1-5-2 cm above sand K1 | Schoenoplectus seed          |
| 532–500                  | 470 ± 20                         | Minimum                                  | OS-133452          | gc14b                         | 1-240-1-245 | In sandy mud with gastropods, 0-5-1 cm above sand K1 | Schoenoplectus seed          |
| 380 ± 15                 | Minimum                          | OS-121987                                | RC3                | 1-065-1-075                   |      |           | Silty mud, 0-5-1.5 cm above sand K1 | Bulk sediment                 |
| 500–330                  | 375 ± 15                         | Minimum                                  | OS-132270          | gc02b                         | 1-330-1-335 | In sandy mud with gastropods, 0-0-0.5 cm above sand K1 | Schoenoplectus seed          |
| 646–547                  | 600 ± 15                         | Maximum                                  | OS-132271          | gc02b                         | 1-330-1-335 | In sandy mud with gastropods, 0-0-0.5 cm above sand K1 | Schoenoplectus seed          |

Sand P3, Pololū Valley, Hawai‘i 630–534

| 480 ± 15                 | Outlier                          | OS-134332                                | VC1                | 1-200-1-205                   |      |           | Silty peat, 3-5-4 cm above sand P3 | Bulk sediment                 |
| 970 ± 20                 | Outlier                          | OS-134258                                | VC1                | 1-200-1-205                   |      |           | Silty peat, 3-5-4 cm above sand P3 | Bulk sediment                 |
| 620–modern               | 375 ± 90                         | Minimum                                  | OS-134242          | VC1                           | 1-200-1-205 | In silty peat, 3-5-4 cm above sand P3 | Brachiaria seeds             |
Table 2. (continued)

| Estimated age (cal yr BP) | Calibrated age (cal yr at 2r) | Laboratory reported age (14C yr at 1σ) | Age interpretation | Radiocarbon laboratory number | Core | Depth (m) ** | Stratigraphic context †† | Description of dated material |
|--------------------------|-------------------------------|----------------------------------------|-------------------|--------------------------------|------|-------------|--------------------------|--------------------------------|
| 410 ± 15                 | Minimum                       | OS-134333                              | VC1               | 1.210–1.215                    | Silty peat, 2.5–3.0 cm above sand P3 | Bulk sediment |
| 513–modern               | 285 ± 100                     | Minimum                                | OS-134244         | VC1                            | 1.210–1.215                    | In silty peat, 2.5–3.0 cm above sand P3 | Brachiaria seeds |
| 924–525                  | 740 ± 130                     | Minimum                                | OS-133431         | VC1                            | 1.215–1.220                    | In silty mud, 2.0–2.5 cm above sand P3 | Brachiaria seeds |
| 957–560                  | 825 ± 110                     | Minimum                                | OS-133432         | VC1                            | 1.230–1.235                    | In sandy, silty mud, 0.5–1.0 cm above sand P3 | Brachiaria seeds |
| 665–545                  | 625 ± 45                      | Maximum                                | OS-134333         | VC1                            | 1.255–1.260                    | In silty mud, 0.0–0.5 cm below sand P3 | Unidentified seeds |
|                          | 590 ± 15                      | Maximum                                | OS-120804         | VC1                            | 1.250–1.260                    | Silty mud, 0.0–1.0 cm below sand P3 | Bulk sediment |
| 624–315                  | 445 ± 65                      | Maximum                                | OS-134245         | VC1                            | 1.270–1.275                    | In silty mud, 1.0–1.5 cm below sand P3 | Unidentified seeds |
|                          | 730 ± 110                     | Minimum                                | OS-133434         | VC1                            | 1.380–1.385                    | Sandy mud, 12.0–12.5 cm below sand P3 | Schoenoplectus seed |

*Ages are on detrital organic material collected above, below or within anomalous sand beds in vibracores, Russian cores and material extracted from 60 mm diameter gouge cores. **Best estimate of the age of sand deposition based on selected ages (in solar years; shown in bold italics) using the sequence analysis feature of the program OxCal (version 4.3; Bronk Ramsey, 2009; probability method). Sample 14C ages selected on basis of quality of material dated and stratigraphic context. Context and sample type were used to infer whether age is a maximum age, minimum age, or an outlier. Estimates represent 2σ time intervals of probability distributions between maximum and minimum ages calculated using OxCal. See OxCal files in supplementary information for more details. †Calibrated ages calculated from selected ages in bold in the third column. Ages in solar years calculated using OxCal (version 4.3; Bronk Ramsey, 2009; probability method), with the INTCAL13 atmospheric dataset (Reimer et al., 2013). Calibrated ages show time intervals of 95% probability distribution at 2σ. §Age reported by radiocarbon laboratory. Quoted errors for AMS ages are the larger of counting error or target reproducibility error. Macrofossil samples weighed 0.2–13 mg, yielding δ13C values between −6.5‰ and −27‰. Bulk peat samples weighed 3.5–17.9 g. A full list of dated samples is included in Table S1. ¶Interpretation of the provenance of the dated sample relative to the time the targeted sand was deposited. Maximum ages are on samples containing carbon judged to be older than the tsunami, minimum ages are on samples judged younger than the tsunami. Bold indicates ages used to set maximum and minimum limits on the ages of contacts with OxCal. **Depth interval (m) in the core from which each sample was collected. Depths are not corrected for compaction or position relative to the target sand layer. ††Descriptions of the sediment of sample intervals with approximate positions relative to the target sand.
RESULTS

Anahola Valley, Kaua’i

Cores from the marsh along Anahola Stream contained up to three carbonate sand beds within interbedded peat, mud and silt. At Anahola, eight vibracores and ca 130 gouge and Russian cores were taken in the floodplain north of the stream between 280 m and 680 m inland from the shoreline (Fig. 2A).

Most cores met refusal within a coarse carbonate sand bed that may have been deposited during a higher sea level in the late Holocene. Vibracores bottomed out between 2.8 m and 4.2 m depth within a dense carbonate sand bed overlain by a poorly sorted, muddy carbonate sand bed with shell fragments. The contact between these beds is sharp (<3 mm) in five of eight vibracores. However, the depth and mud content of these basal sand beds vary widely from core to core, with the upper depth of these beds ranging from 58 cm in VC1 to 250 cm in VC3. In cores where the tops of the basal sand beds are shallow, they are overlain by muddy peat units. Where the contact is deeper, the basal sand beds are overlain by sandy mud. A seed extracted from a peaty bed within the basal carbonate sand beds in VC4a returned an age of 704 to 535 cal yr BP (95 BCE to 26 CE; Appendix S1). This age is consistent with the time of strand plain formation in Hanalei, Kaua‘i, from 2160 to 1940 cal yr BP (Calhoun & Fletcher, 1996) and the initiation of coastal plain development in ’Upolu, Samoa from 2103 to 1899 cal yr BP (Kane et al., 2017).

The marsh sediments above the basal carbonate sands are characterized by peat interbedded...
with mud and silt beds with up to three anomalous sand beds. Of the two shallow carbonate sand beds in the north-east part of the marsh, the thinner (A1) is from 1 to 3 cm thick and only observed as a clean sand bed in VC8, which is ca. 300 m from the shoreline, and six gouge cores (Fig. 2B; Appendix S3). The thicker of the two sands (A2) is up to 10 cm thick and is observed in four vibracores and 31 gouge cores throughout the north-east marsh, typically between 20 cm and 50 cm depth (Fig. 2B; Appendix S3). Both sand units A1 and A2 are easily identified by their light tan colour and the sharp (<3 mm) upper and lower contacts with bounding mud or peat. In several cores (VC6 through to VC8), the lower contact appears to be erosional, with infilling of microtopography visible in core photographs and CT images (Fig. 5A). Where both A1 and A2 are observed, they are separated by 3 to 12 cm of muddy peat. Sand A2 is generally thicker in cores closest to the river mouth, and thinner towards the area of artificial fill (Fig. 2B). In VC8, the CT image shows roots penetrating through the entire unit, which is from 22 to 28 cm depth (Fig. 5A). Both sands A1 and A2 consist of poorly sorted, very fine to fine sand (Fig. 6A), based on grain-size analyses from Russian core RC1-BR (Fig. 2A). Vertical grain-size distributions are overall, fairly uniform in sand A2, but exhibit suspension graded intervals at 26 to 27 cm in A1 and 33 to 34 cm in A2 (Fig. 6A).

In the Anahola cores selected for $^{137}$Cs analyses, sand A1 and sand A2 are at depths of 36 to 37 cm and 49 to 50 cm, respectively. Due to the 50 cm length of the Russian cores used for sampling, the bottom of sand A2 was cut off and was not included in the $^{137}$Cs samples; in a nearby gouge core, Sand A2 is 5 cm thick. Cesium-137 activity in the upper 50 cm of sediment peaks at 32 to 33 cm depth (Fig. 7), indicating that this sediment was deposited about...
1963–1964, following the peak in nuclear testing that occurred in 1962 prior to the Nuclear Test Ban Treaty (Carter & Moghissi, 1977). Atmospheric nuclear testing started near the end of World War II (Pennington et al., 1973), but the onset of $^{137}\text{Cs}$ detectable in sediment began in 1954. In Anahola this is marked where the $^{137}\text{Cs}$ activity curve consistently exceeds 0.3 dpm g$^{-1}$ above 45 cm depth (Fig. 7).

A deeper carbonate sand bed (sand A3) within a sandy, muddy peat is found in six vibracores and 41 gouge cores between 63 cm and 180 cm depth, including most sites in the south-west marsh. Sand A3 thickness varies between cores and is thickest (25 cm) in VC8 in the north-east marsh, and thinner (3 cm) at the most landward site, VC5, 650 m from the shoreline (Fig. 2B; La Selle et al., 2019). Freshwater snail shells of the species Tryonia porrecta (Mighels, 1845; Cowie et al., 1995) in sandy mud just above sand A3 aids correlation among cores despite large variations in the depth, thickness, colour and sedimentary structures observed in the deposit. These shells occur only in the 1 to 10 cm of sandy mud above sand A3. The shells break very easily, but most are intact. In core VC8, sand A3 has very sharp (1 mm) upper and lower contacts. The upper 5 cm appear to be slightly bioturbated based on roots visible in the CT image and the tan colour of the sand, similar to the lower modern sand bed (sand A2). The lower 20 cm of sand A3 consists of whitish carbonate sand, with weak planar laminations visible in the CT image (Fig. 5A). The sand bed consists of very fine to medium sand, with a bulk $D_{50}$ of 2.6 phi (fine sand).

Like sands A1 and A2, vertical grain-size distributions of sand A3 from core RC6-BR (Fig. 6B) exhibit suspension-graded intervals (99.5 to 101.0 cm and 105.5 to 107.0 cm). With the exception of the suspension-graded interval, the upper 10 cm of the deposit appears massive. Normal grading is observed between 107.0 cm and 109.5 cm, indicated by the gradual upward decrease in the medium to coarse fractions of the distributions (Fig. 6B). This normally graded interval is capped by the suspension-graded interval at 105.5 to 107.0 cm, which contains a shift of the entire distribution from mostly fine sand to mostly very fine sand. The bottom-most 3 cm of the deposit exhibit a weakly inverse-graded interval.

In VC4a, ca 600 m from the shoreline, sand A3 is a bed of clean fine sand with gastropod shells in mud above it. In this core, sand A3 caps a sequence of poorly sorted and coarse basal carbonate sand and lacks a clear lower contact. In VC2, 475 m from the shoreline, sand A3 consists of 6 cm of muddy, bioturbated, carbonate sand overlying 3 cm of clean, fine to medium carbonate sand. In this core, sand A3 is
overlain by brown mud with *Tryonia porrecta* shells from 81·5 to 95·0 cm depth. On top of the mud is a 1 cm thick fine to medium carbonate sand with undulating, but sharp, upper and lower contacts. *Tryonia porrecta* shells were not observed above this sand, and this is the only core in which a clean carbonate sand was observed between sands A2 and A3.

Organic material from six cores was radiocarbon dated to determine the age of sand A3 (Table 2). The most commonly dated macrofossils were *Schoenoplectus* sp. (bulrush) seeds found above, below and within the sand bed. *Schoenoplectus* seeds in the muddy sand with gastropods overlying sand A3 returned ages ranging from 530 ± 15 to 835 ± 15 14C yr BP, demonstrating that the seeds are decay resistant enough to be reworked over centuries following deposition. Because it is inferred in this study that the seeds may be reworked, but cannot be significantly younger than their host sediment, the youngest *Schoenoplectus* seed (530 ± 15 14C yr BP) from 0 to 2 cm above sand A3 is considered as a minimum limiting age for the post-tsunami sediments. The youngest *Schoenoplectus* seed found within sand A3 returned an age of 785 ± 20 14C yr BP, which is a maximum limiting age for deposition of the sand. Based primarily on these minimum and maximum limiting *Schoenoplectus* seed ages, the OxCal sequence model in this study dates deposition of sand A3 at Anahola to 704 to 535 cal yr BP (1246 to 1415 CE) at the 95% confidence level (Fig. 8; Table 2). Bulk sediment, wood, grass and *Tryonia* shells above, within and below sand A3 were also dated, but the resulting ages were too wide ranging and inconsistent to be used in the OxCal model (Table 2). A bulk sediment age from just below sand A3 returned an age of 505 ± 20 14C yr BP, but CT scans and photographs suggest that
much younger roots may have penetrated into sand A3 and the peat below it. Tryonia porrecta shells returned ages that were typically hundreds of years older than Schoenoplectus seeds from the same intervals (Table 2), perhaps because these gastropods metabolized older carbon from carbonate sediment or seawater in the substrate (Dye, 1994; Pigati et al., 2010).

Kahana Valley, O‘ahu

The stratigraphy and sedimentology of Kahana Valley was investigated in 30 gouge and Russian cores, primarily along a shore-normal transect on the east side of the valley 240 to 680 m from the shoreline (Fig. 3). A landward thinning, carbonate sand bed (sand K1) was traced in cores between 238 m and 478 m from the shoreline in the freshwater marsh on the south-east side of Kahana Stream. Closest to the shoreline, sand K1 is thick (31 to 37 cm in cores gc13 and gc14; Fig. 3) and composed mostly of fine to medium sand. Although variable in thickness, the sand bed gradually thins to 1 cm at its inland limit (core gc05-FG). Sand K1 is overlain by sandy mud with Tryonia porrecta shells (Fig. 5B), the same species found above sand A3 in Anahola, in half of the cores containing sand K1 (6 of 12). A CT image of Russian core RC-02b shows that sand K1 is bioturbated, with upper and lower contacts ca 3 mm thick, and that its lower half consists of carbonate sand that is cleaner than in its upper half.

The upper 50 cm of sediment in all 30 cores along the transect consist of compact alluvial silt, resulting from rice and sugarcane cultivation, flooding from Kahana Stream, and mass wasting of sediment from deforested slopes (Beggerly, 1990). This silt bed was difficult to core through and was typically not described in detail. Below the silt is ca 0.5 to 1.0 m of silty peat grading down into dark, organic rich, muddy peat. Sand K1 overlies peat interbedded with muddy, poorly sorted, volcanic sand. Cores typically met refusal around 2 m depth in coarse sand. In the ten cores where it was recovered, this sand bed consisted mostly of subrounded volcanic grains with scattered shell fragments of probable freshwater gastropods or bivalves. At 680 to 880 m from the shoreline along the transect, cores bottomed out in the lower of two volcanic sand beds without carbonate grains.

This study attempted to determine the age of sand K1 by radiocarbon dating Schoenoplectus sp. (bulrush) seeds and bulk sediment (Table 2). Because the source of the carbon in the bulk sediment samples is uncertain, the bulk sediment ages are not used in the age model. Two Schoenoplectus seeds from just above sand K1 returned maximum ages (645 ± 20 14C yr BP and 600 ± 15 14C yr BP) that are interpreted as having been reworked from sediment below sand K1. Two other much younger seed ages from above sand K1 may also be reworked (470 ± 20 14C yr BP and 375 ± 15 14C yr BP), but because they are so much younger than the other seed ages, it is inferred that they are much closer minimum ages for the time of deposition of sand K1. The bulk sediment age from the same level in the core is about the same age (380 ± 15 14C yr BP; Table 2), but is difficult to evaluate. Because of uncertainties in the degree of reworking of the dated seeds, for the age model in this study the conservative interpretation that the youngest of the two seed ages is a minimum limiting age and the oldest seed age is a maximum limiting age for sand K1 can be made. With these assumptions this study’s OxCal sequence model gives a probability distribution range (with 95% confidence) for the time of deposition of sand K1 in Kahana Valley of 605 to 490 cal yr BP (1345 to 1460 CE).

Pololu Valley, Hawai‘i

In Pololu Valley, the nearshore, beach and dune sources of sediment are primarily basaltic sand, which can be difficult to distinguish from the fluvial sand sources towards the back of the marsh. Modern sand beds from the 1946 (sand P2) and 1957 (sand P1) Aleutian tsunamis have been mapped by Chagué-Goff et al. (2012). A third, deeper sand bed (sand P3) in vibracore VC1 shares some characteristics with sands P1 and P2.

Although five vibracores were collected, only two (VC1 and VC2) were deep enough to penetrate through the 1946 and 1957 tsunami deposits and well into prehistoric sediments (Figs 4 and 5). The site of vibracore VC1 is ca 250 m from the shoreline near an overturned World War II-era landing craft. Core PO1 of Chagué-Goff et al. (2012) (Fig. 4), which contained a 30 cm thick sand deposited by the 1946 tsunami, is within 10 m of VC1. The upper 0.5 m of VC1 consists mostly of dark brown peat, but at 15 cm depth a 3 mm thick bed of peat contains a trace amount of silt and very fine sand. This sand bed (sand P1) may correlate with the 1 to 2 cm thick 1957 tsunami deposit in core...
PO2 (Chagué-Goff et al., 2012), the only other location where the 1957 tsunami sand bed has been found in the Pololū Valley. Sand P2, interpreted by Chagué-Goff et al. (2012) to be the 1946 tsunami deposit, extends from 19:5 to 42:0 cm depth in VC1 (Fig. 5C). Here, sand P2 consists of dark grey, basaltic, very fine to fine sand with very sharp (<3 mm) upper and lower contacts, and a carbonate shell fragment in the lower 6 cm. The CT image (Fig. 5C) shows that the lower 15 cm of the core is weakly laminated, similar to sand A3 in the Anahola Valley. A lighter brown, peaty silt, which extends from 5:5 to 12:1 cm depth, abruptly changes to a sequence of silty peat and silt from 12:1 to 170-0 cm.

Sand P3 is a rapidly landward-thinning sand bed that was confidently identified in four cores along the west bank of stream, 230 to 260 m from the shoreline. In VC1, sand P3, at 121 to 124 cm depth, consists of very fine to medium sand that is discontinuous across the core (Fig. 5C). The CT image shows that the overlying strata and the upper contact of sand P3 are angled 40° from horizontal. From 170 cm to ca 400 cm depth in core VC1 is a distinct facies of alternating tan silt and silty peat beds (La Selle et al., 2019), which helps correlate overlying sand beds from two nearby gouge cores. In the seaward core (gc202), sand P3 is 24 cm thick (158 to 182 cm depth), and consists of a muddy, basaltic, medium to coarse sand. sand P3 in the inland core (gc201) is 1-5 cm thick (106:0 to 107-5 cm depth), and consists of basaltic very fine to medium sand with a sharp lower contact and a 3 mm long fragment of decomposed wood in the upper 5 mm of the sand bed. The deeper, tan silt and peat facies was observed up to 300 m inland but lacked overlying sand beds (except for sand P2 in the upper parts of some cores) beyond 260 m from the shoreline. Further inland, sand P3 was not identified, although sand P2 was found in the vibracores.

Core VC2, 475 m from the shoreline at the southern end of the marsh, generally has a higher silt content than VC1 (La Selle et al., 2019). Sand P2 in core VC2, from 54 to 64 cm depth, is an oxidized, orange and grey, fine sand with a sharp lower contact and decayed organic debris concentrated in its upper 5 mm. Gouge cores near vibracores VC3, VC4 and VC5, and on the landward side of the dune, contained one to two muddy, poorly sorted, basaltic sand beds of varying thickness (5 to 37 cm) in peat below sand P2.

Sediment above and below sand P3 in VC1 was sampled extensively for radiocarbon dating. Dated materials consisted of Brachiaria sp. (California grass) seeds, Schoenoplectus sp. (bulrush) seeds, unidentified round seeds and bulk sediment. All but one of seven seed samples returned ages with errors ≥±45 14C years, likely due to sample sizes <1 mg (Table 2). Because the source of the carbon in the bulk sediment samples is so uncertain, the bulk sediment ages were not used in the age model for this study. Of four ages on Brachiaria seeds above sand P3, two are old (740 ± 130 14C yr BP and 825 ± 110 14C yr BP) and so probably reworked. As at Anahola, the other two (285 ± 100 14C yr BP and 375 ± 90 14C yr BP) are much younger and so are likely minimum ages. However, the age difference between these two pairs of seed ages is ca 700 to 200 years, and their errors are very large (compared with other seed-age errors in Table 1), and so the accuracy and stratigraphic context of the ages is much more uncertain than for the seed ages at other sites. Below sand P3, an age on seeds from 12 cm below the sand bed is 730 ± 110 14C yr BP, a second on seeds from just beneath the sand bed (0 to 0-5 cm) is younger (625 ± 45 14C yr BP), and a third seed age is much younger (445 ± 65 14C yr BP). Because the seed ages span such a broad interval of time and have such large errors it is difficult to determine which most reliably date the sand bed. For this reason, all six ages within 4 cm of sand P3 were used in the OxCal sequence model to roughly constrain its age. Although the model results highlight the significant inconsistency in these ages, it yields a 95% confidence age for sand P3 of 630 to 534 cal yr BP (1320 to 1416 CE), which overlaps considerably with the age of sand K1 from the Kahana Valley (605 to 490 cal yr BP) and the age of sand A3 from the Anahola Valley (704 to 535 cal yr BP). Near the bottom of core VC1 (384:5 to 385-5 cm) dating of bulk sediment returned a calibrated age of 1713 to 1617 cal yr BP (237 to 333 CE; Appendix S1).

DISCUSSION

Tsunami origin of deposits

The sedimentology, distribution, vertical grain-size trends and thickness of the sand beds in Anahola, Kahana and Pololū valleys are consistent with marine inundation and suggest
deposition from high velocity flows, such as a tsunami. Sand beds A1, A2, A3 and K1 consist mostly of marine carbonate sand containing rounded coral and shell fragments. Their distinct carbonate mineralogy and grain size, when compared qualitatively to the composition of the mud and peaty deposits typically deposited in the marshes further inland, indicate that the beach and nearshore environments were sediment sources for the sand beds mapped at Anahola and Kahana.

Vertical grain-size trends in sands A1, A2 and A3 at Anahola exhibit characteristics typically observed in tsunami deposits. The presence of suspension graded intervals within the sand beds (Fig. 6A and B) suggest that during each depositional event, several waves inundated the marsh and that flow velocities were high enough to carry sand grains in suspension, which settled out of suspension as the flow decelerated. In sand A3, the pattern of an inverse graded interval at the base of the deposit, overlain by a normal graded interval and then a massive section is also observed in prehistoric tsunami deposits in the Aleutians (Witter et al., 2016; Fig. 6C) as well as in deposits from the 2011 Tohoku-oki tsunami in Japan (Jaffe et al., 2012; Fig. 6D). Suspension graded intervals are also observed in the 1957, 1946 and prehistoric sand beds at Anahola, as well as the Aleutian prehistoric tsunami and Japan 2011 tsunami deposits. All sands (A1, A2, A3, K1, P1, P2 and P3) exhibit sharp (<3 mm) upper and lower contacts in most cores, which is a characteristic of deposits formed in high velocity flows. In Anahola and Kahana valleys, sands A2, A3 and K1 gradually thin landward, another characteristic commonly observed in tsunami deposits (Morton et al., 2007).

In Pololū Valley, sand beds of marine and terrestrial sources are difficult to distinguish based on mineralogy because the beach, dune and nearshore environments are characterized primarily by black basaltic sand. However, Chagué-Goff et al. (2012) reported high concentrations of marine diatoms, brackish diatoms and low numbers of redeposited pollen grains in the 1946 and 1957 tsunami deposits, suggesting that these sand beds were sourced from the beach and nearshore. Sands P1 and P2 share several similarities with the 1946 and 1957 deposits identified by Chagué-Goff et al. (2012). Both sand beds are at approximately the same depth, are of the same thickness, and consist of clean, basaltic, very fine to medium sand, which strongly suggest that they were deposited by the 1957 and 1946 tsunamis, respectively. Because sand P3 is the only other well-sorted, basaltic, very fine to medium sand in cores VC1, gc201 and gc202, it is inferred that it is, most likely, a prehistoric tsunami deposit. Additional multi-proxy analyses, such as those used by Chagué-Goff et al. (2012), might confirm a tsunami origin for sand P3.

The presence of muddy peat with concentrations of Tryonia porrecta shells in the few centimetres above sand A3 in Anahola and sand K1 in Kahana may indicate a sudden environmental change in both valleys following tsunami inundation. Relatively high concentrations of Tryonia shells were also observed just above the 1551 to 1593 CE deposit in the Makauwahi Sinkhole (Burney et al., 2001). In the Hawaiian Islands, Tryonia porrecta frequents wetlands and ancient fishponds and taro fields (Christensen, 2018), but whether it is an endemic species to Hawai‘i, or if it was introduced during human settlement, is unknown. Although Tryonia porrecta is identified as a freshwater gastropod, studies of Tryonia porrecta in San Francisco Bay (USA) show its tolerance of brackish conditions (Kitting, 2015), and this species has adapted to an entirely benthic life cycle in hot springs throughout south-western North American deserts (Hershler et al., 2005). The lack of Tryonia shells observed below sands A3 and K1 suggests that they were not abundant in the marsh prior to tsunami inundation. Therefore, it is plausible that the Tryonia shells just above the sands could represent an allochthonous assemblage that was transported by a tsunami from stream channels, lagoons, fishponds and (or) taro fields into marsh environments that Tryonia then colonized. In some cores, such as VC6 at Anahola, the mud and sandy mud beds above sand A3 that contain Tryonia shells are up to 45 cm thick suggesting that this species was living in some sections of the marshes for a significant amount of time following a tsunami.

Although storm overwash as a source of the sand beds in Anahola, Kahana and Pololū valleys cannot completely be ruled out, observations of limited overwash sand deposition from two 20th Century hurricanes that have hit Kaua‘i (Category 1 Iwa in 1982 and Category 4 Iniki in 1992) support the interpretation that the sand beds in all three valleys were most likely deposited by tsunamis, because tsunamis deposit sand beds further inland than storms. The 1 to 5 mm thick laminae that are visible in
the CT images of the lower parts of sands P2 and A3 in several cores are more typical of coastal storm deposits than tsunamis (Morton et al., 2007), and the erosional lower contacts and inland thinning of the deposits are features of both tsunami and storm deposits. In a field survey following the 1992 Iniki hurricane on the island of Kaua‘i, Fletcher et al. (1995), mapped marine sand overwash with excursion distances of ca 20 to 250 m inland and elevations in the range of 4 to 9 m above mean lower low water. Debris lines used to measure inland excursion were composed mostly of vegetation or debris from man-made structures. Debris fields contained boulders derived from adjacent seawalls and deposits of beach and dune sand, although the inland limit of sediments was not noted. Localized areas on the west coast of Kaua‘i had sand sheets up to 10 cm thick that extended a few tens of metres inland. However, sands A2 and A3 in Anahola were found up to 380 m and 650 m inland, respectively. sand K1 in Kahana was traced between 240 to 480 m inland. In Pololū Valley, sand P2 was traced about 500 m inland and, although sand P1 was only observed in core VC1, it is 280 m from the shoreline. Kennedy et al. (2012) modelled 643 synthetic hurricane scenarios for the southern coasts of O‘ahu and Kaua‘i and concluded that none of the scenarios led to storm surges >3 m high.

Flooding from large rain storms is also capable of depositing silt, sand and fine gravel in all three valleys. At Kahana and Anahola, the marine carbonate sand in sand A3 rules out a fluvial source, but the source of basaltic sand in sand P3 at Pololū is more difficult to determine. Large floods tend to deposit muddy silt beds like those in the upper 50 cm of cores in the Anahola and Kahana valleys. Since 1914, at least 13 major rain storms have caused flooding of Anahola Stream (Fletcher et al., 2002), most notably in 1956, 1965, 1968 and 1991. Intense rainfall in April 2018 also caused major flooding. The muddy silts deposited during these events are visible in CT images in the Anahola vibracores (Fig 5A). In Kahana Valley, fluvial sand beds consisting of volcanic grains were found 680 to 880 m inland. In Pololū Valley, well-sorted, basaltic, fine sand below sand P3 was not observed in VC1 and VC2, suggesting that flood deposits in the lower reaches of the valley do not typically consist of basaltic sand, and that silt is usually deposited during large rain storms. Where Pololū Stream enters the wetland, a small alluvial fan consisting of angular basalt pebbles and coarse black sand suggests that silt is transported well beyond the fan further towards the shoreline.

In all three valleys, the position of the shoreline, geometry of stream channels, and extent of wetlands 500 to 700 years ago is not well-known. However, based on the mud and peat below sands A3, K1 and P3 in most cores, each valley hosted extensive wetlands at about this time. In Anahola Valley, sand A3 caps shallow basal carbonate sand in three cores, which may indicate that wetlands were less aerially extensive than today, and that marsh sediment was primarily accumulating in swales during prehistoric tsunami inundation. Cores on the east side of Kahana Valley lack a basal carbonate sand bed, but a core on the west side of Kahana Valley encountered an impenetrable, coarse, carbonate sand at about 1 m depth. The coarse carbonate sand is consistent with core descriptions from Beggerly (1990), who suggested that this bed represents a prograding coastal sand bar that had extended ca 550 m from the modern shoreline ca 1300 cal yr BP. Perhaps the basal carbonate sand underlies the east side of Kahana Valley as well but is below the reach of the hand operated gouge corers used in this study.

Subsidence of the island of Hawai‘i at a rate of about 2.6 mm year⁻¹ (Moore & Clague, 1992) from loading by active volcanoes and eustatic sea-level rise has led to sediment backfilling of Pololū Valley (Vitousek et al., 2010), which consists of marsh and fluvial sediments down to depths of at least 4 m. The bulk sediment age from the bottom of core VC1 (1713 to 1617 cal yr BP) suggests that the marsh has been accreting for at least the past 1700 years at an average rate of roughly 2 mm year⁻¹.

**Timing of events**

Sand sheets in Anahola, Kahana and Pololū valleys record at least three different tsunamis over the past 700 years. At Anahola and Pololū, the upper two sands beds were deposited by the 1946 and 1957 Aleutian tsunamis. A deeper sand bed at all three sites is consistent with deposition by one or two tsunamis between 750 and 500 cal yr BP.

Based on ¹³⁷Cs activity in the upper 50 to 70 cm of sediment at Anahola, the two carbonate sand beds were deposited during inundation by the 1946 and 1957 Aleutian tsunamis. The
carbonate sand bed in muddy peat from 36.5 to 38 cm depth is attributed to the 1957 tsunami given its position about 4 cm below the peak in $^{137}$Cs (reached between 1963 and 1964). Because runup near Anahola from the 1957 tsunami was higher (4.9 m) than for the 1960 tsunami (1.8 m), it is assumed that this sand bed was deposited by the 1957 event. The lower carbonate sand in these cores is about 5 cm below the depth marking the onset of nuclear testing (1954), and therefore was probably deposited by the 1946 Aleutian tsunami.

For the prehistoric tsunami deposits, the 95% confidence intervals on the modelled ages at the three sites overlap the ages of tsunami deposits found on multiple Aleutian Islands between 660 and 560 cal yr BP (1290 to 1390 CE) (Witter et al., 2016, 2018) (Fig. 8). In addition to the contemporaneous tsunami deposit ages, it is suggested that the eastern Aleutians are the most likely source because the Aleutian subduction zone is known to possess the highest tsunami threat to Hawai’i due to its geometry and propensity for large tsunamigenic earthquakes (Bai et al., 2018), and because the shorelines fronting Anahola, Kahana and Pololū valleys all face the eastern Aleutians. The geological records of prehistoric earthquakes and tsunamis on Simeonof, Chirikof and Sitkinak islands, 400 km, 650 km and 775 km east of the Fox Islands, respectively, do not contain events that clearly overlap in age with the Hawaiian prehistoric deposits (Briggs et al., 2014; Witter et al., 2014; Nelson et al., 2015). Other potential tsunami source areas with prehistoric evidence of tsunami deposits that may overlap an age range of 750 to 500 cal yr BP include subduction zones such as the Kuril-Kamchatka (Nanayama et al., 2003; Pinegina et al., 2003; Bourgeois et al., 2006), Peru–Chile (Atwater et al., 2013; Kempf et al., 2017) and Cascadia (Priest et al., 2017). These non-Aleutian sources for the prehistoric tsunami deposits observed in Anahola, Kahana, and Pololū cannot be fully discounted without running tsunami models and further dating of deposits to better constrain age models.

Although their 95% confidence ranges overlap by almost a century, the estimated age of the deposit at Anahola may be older (704 to 535 cal yr BP; 1246 to 1415 CE) than the deposits at Kahana (605 to 490 cal yr BP; 1345 to 1460 CE) and Pololū (630 to 534 cal yr BP; 1320 to 1416 CE). Therefore, the deposits at all three sites may have been deposited by a single far-field tsunami with an Aleutian source. Although more unlikely, it is also possible that the oldest sand bed at Anahola was deposited by an older tsunami, possibly sourced in the western Aleutians, Kamchatka, or even by a submarine landslide, perhaps triggered by a local earthquake. An expanded effort to date suitable material in cores containing prehistoric tsunami deposits at these and other sites could reduce the uncertainty in these broad age distributions.

The age of the deposit in Makauwahī Cave (399 to 357 cal yr BP; 1551 to 1593 CE) (Butler et al., 2017) is younger than the ages of sands A3, K1 and P3. The only sand bed observed that could have overlapped in age with the Makauwahī deposit is at 81 cm in core VC2 in Anahola. It is possible this sand bed is a tsunami deposit younger than sand A3, but it could not be found in any other core at Anahola and matches no comparable deposits at Kahana or Pololū. Given the degree of preservation of deposits from the 1946 and 1957 Aleutian tsunamis at Anahola and Pololū, and the presence of prehistoric tsunami deposits at all three sites, it is very unlikely that deposits from a tsunami generated by a Mw 9 $+$ earthquake in the eastern Aleutians in the past half-millennium would not be present in these wetlands.

CONCLUSIONS

Previously unidentified prehistoric tsunami deposits on three separate Hawaiian Islands in the Anahola, Kahana and Pololū valleys exhibit sedimentological and stratigraphic characteristics common to tsunami deposits around the world, such as normal and suspension grading, inland-thinning sand beds and sharp lower contacts. Based on these characteristics and broad, overlapping age distributions for their times of deposition, it is inferred that these deposits record one, or possibly two, distant-source tsunamis. Deposits of the 1946 and 1957 tsunamis at Anahola (determined through Cesium-137 dating) were also identified, and in Pololū Valley the previously studied 1946 deposit was traced up to 500 m inland.

Although the prehistoric tsunami deposits in Anahola Valley (704 to 535 cal yr BP; 1246 to 1415 CE) may be up to a century older than the deposits in Kahana Valley (605 to 490 cal yr BP; 1345 to 1460 CE) and Pololū Valley (630 to 534 cal yr BP; 1320 to 1416 CE), the broad, modelled age ranges for these events overlap with the ages of prehistoric tsunami deposits in the
eastern Aleutians, suggesting a common earthquake source. Alternatively, the deposit in Anahola Valley could record an older event, possibly from a source further west in the Aleutians that only affected Kaua‘i. Future dating of more delicate, less reworkable macrofossils could demonstrate that the Anahola, Kahana and Pololu deposits are of similar age or older than the deposits in Makawahi Cave, the only other known locality in the Hawaiian Islands with a prehistoric tsunami deposit from the last 750 years.

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Supporting Information

Additional information may be found in the online version of this article:

Appendix S1. “S1 Uncalibrated radiocarbon ages of sediments in Anahola, Kahana and Pololū valleys, HI.pdf”: this table contains the uncalibrated radiocarbon ages of all samples submitted from these three sites.

Appendix S2. “S2 OxCal Models for Sands A3, K1, P3.docx”: the codes for each model used to determine the ages of sand beds A3, K1 and P3.

Appendix S3. “S3 Sand thicknesses Anahola Kahana Pololū.xlsx”: this is a Microsoft Excel® (version 16.14.1) file with a tab for each site: Anahola Valley, Kahana Valley and Pololū Valley.