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The largest local tsunami in 20th century Hawaii

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Abstract

The 1975 Kalapana tsunami had waves that ran up to 14.6 m high. It deposited a discontinuous basalt boulder and carbonate sand veneer on the Halape–Apua Point coast of the island of Hawaii. These deposits fine up to 320 m inland and 10.4 masl. The deposit is an unusual sedimentary association in which sand-sized material is a minor component. Both boulders and sand fine inland over the same distance, not in a continuum, and they terminate at approximately the same point. Boulders were transported and deposited by only one wave, the second, whereas the sand deposit was, in part, reworked by subsequent smaller waves.

Boulder transport by one wave in association with a relative paucity of finer sediment reduced internal clast interference and helped to impart a marked fining-inland sequence. This fining-inland sequence is at odds with work that proposes a chaotic or random nature of boulder emplacement by tsunamis. Where there is abundant sediment, clast interference during entrainment will impede the fining inland of larger material. In cases where it is difficult to determine the nature of inundation or the number of tsunamis, a chaotic pattern may simply reflect deposition by storm, tsunami, or a combination of the two.

Keywords: Hawaii; tsunami; volcano; flank collapse; boulder deposit; storm

1. Introduction

Hawaii's historic record of tsunamis comprises both distantly and locally generated events. Given the overall loss of life and damage to the built environment caused by these events it is perhaps surprising that only recently have there been any comprehensive attempts to examine the sedimentary record of historic tsunamis in the Hawaiian Islands (e.g. Felton, 2002; Noormets et al., 2002, 2004).

The evolution of rocky shorelines is primarily event driven and, in the Hawaiian Islands, dominated by tsunamis and storms (Noormets et al., 2002). Differentiating between tsunami and storm deposits however is problematic worldwide (e.g. Hearty, 1997; Nott, 1997, 2003; Nanayama et al., 2000; Goff et al., 2004), but particularly so with relatively small historic tsunamis on rocky coasts (Noormets et al., 2002). It is therefore not surprising that research in the Hawaiian Islands has tended to focus more on ancient mega-tsunami deposits such as those proposed by McMurtry et al. (2004).

An aid to identifying the sedimentary evidence of relatively small historic tsunamis is the contemporary record of such events. Noormets et al. (2002, 2004) for example used aerial photographs and wave runup data to try and differentiate between storm and tsunami em-

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placement, and movement of megaclasts on a coastal rocky platform on Oahu. Their study showed the importance of distantly sourced events, such as the 1946 Aleutian tsunami, for the evolution of Oahu's rocky shoreline.

Active volcanism is a major contributor to the evolution of the rocky shoreline of Hawaii, and also contributes to the propagation of locally sourced tsunamis. The continuous and gradual subsidence of Kilauea volcano's southern flank (Fig. 1), as opposed to catastrophic failure, does not produce destructive Pacific-wide mega-tsunamis, but it does propagate locally significant ones (Tilling et al., 1976; Pararas-Carayannis, 2002). It is estimated that on the south flank of Kilauea these events can be expected to occur at least once every 200 years (Pararas-Carayannis, 1976).

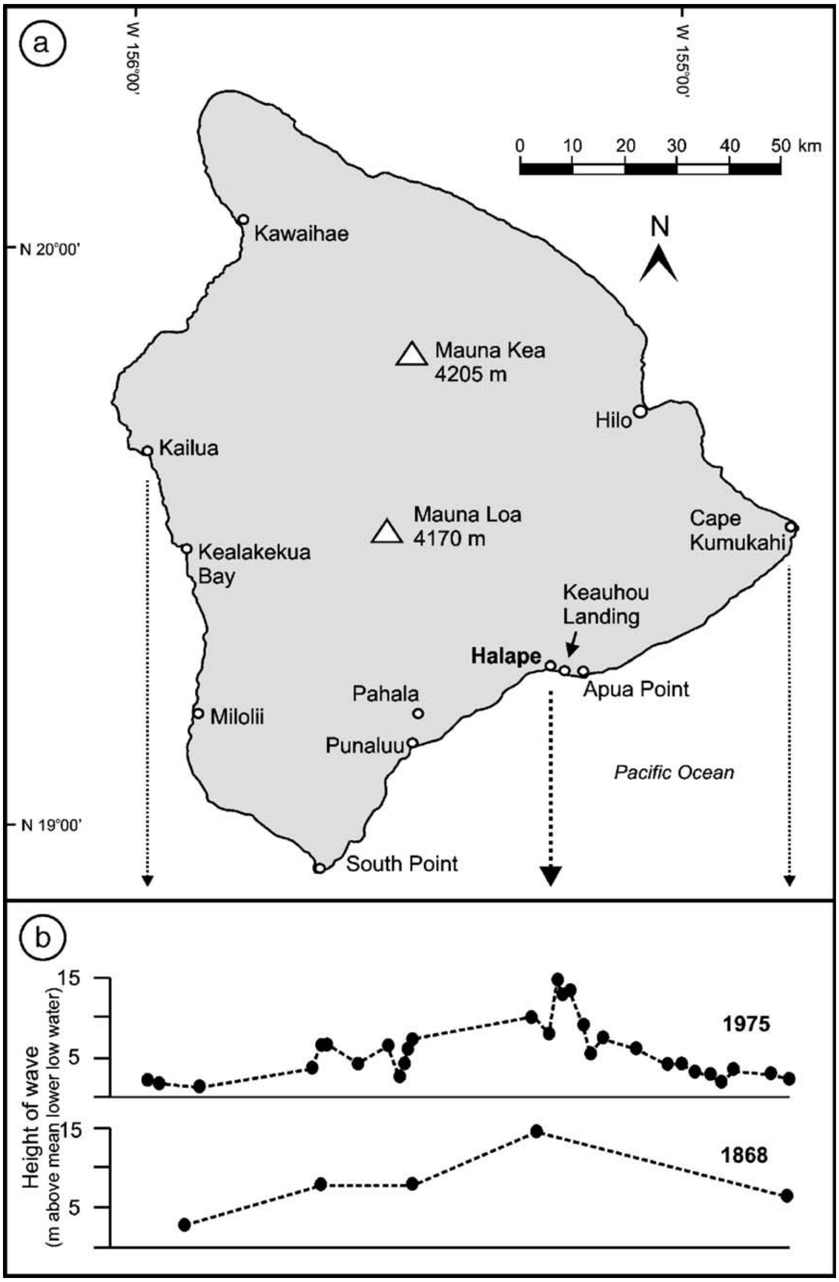

Fig. 1. Big Island, Hawaii: a) Location of Halape; b) Max. runups for the 1868 and 1975 tsunamis at locations in the southern half of the island (max. runups are recorded from west to east, from Kaulua to Cape Kumukahi; after Tilling et al., 1976).

This study is focussed on the sedimentary record of the locally sourced 1975 Kalapana tsunami resulting from the most recent of a series of small slope failures off the southern flanks of Kilauea volcano. This was the largest local tsunami in 20th century Hawaii (Dudley and Lee, 1998). It is representative of the type of locally generated tsunami that can be expected in the foreseeable future around Hawaii and similar volcanic islands worldwide.

Contemporary data sources for the event are more limited than for Pacific-wide tsunamis, but include a report (Tilling et al., 1976), a book chapter (Dudley and Lee, 1998), and several personal accounts. These data augment this study of the sedimentary record.

2. Study area

The Halape region is located on the south flank of Kilauea volcano, Hawaii (Figs. 1 and 2). Geologically, the coast is composed of numerous basaltic lava flows varying in age from 750–1500 yr B.P. to 1969–1974 (Wolfe and Morris, 1996). This is a region of active landsliding, with the Hilina fault system marking the landward head of the submarine Hilina slump block (Lipman et al., 1985). The slump comprises mainly slope sediments underlain by a detachment 3–5 km deep that is subject to both coseismic and aseismic displacements (Morgan et al., 2003). Past historic seismicity on the south flank includes events in 1823, 1868, 1954, 1975, and 1989 (Morgan et al., 2003). However, the only two historic events that produced displacement along the Hilina fault system were the great Kau earthquake of 1868 (M 7.9) and the 1975 (M 7.2) Kalapana earthquake (Tilling et al., 1976).

Sediments in the study areas discussed below are composed of basalt (and rare coral) boulders and carbonate sands. Basalt boulders are derived from the numerous lava flows that define the rocky shoreline and seafloor in the area. Rare coral boulders and carbonate sand are sourced from offshore. Coral is relatively rare on the south coast of Hawaii, but 18 species of hard corals have been recorded at Halape, including *Montipora capitata* and *Pocillopora eydouxi*, *P. meandrina*, *Porites compressa* and *P. lobata* (David Gulko, coral ecologist, pers. comm., 2005). The algal community is also quite diverse. *Halimeda opuntia*, *Dictyota flabellata*, *Lobophora varigata*, and *Predaea weldii* have all been recorded in the area (Okano, 2005).

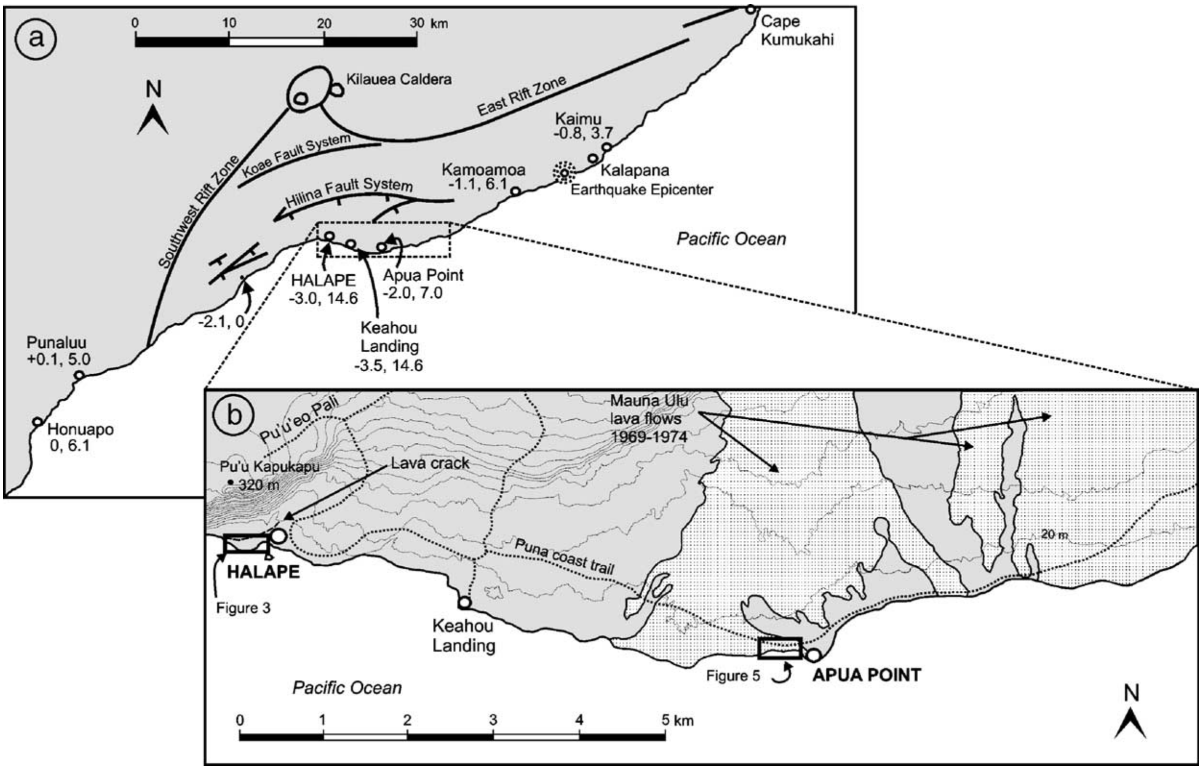

Fig. 2. Halape region, SW Hawaii: a) The fault system associated with the 1975 Kalapana earthquake. Numbers (e.g. −1.1, 6.1) indicate the amount of subsidence (−) and tsunami runup at given locations (after MacDonald and Abbott, 1970); b) Locations reported in the text. Areas not covered by the 1969–1974 Mauna Ulu lava flows are composed of flows > 200 years BP (after Wolfe and Morris, 1996) (contours are at 20 m intervals).

2.1. Halape

Halape Bay is a small, 100 m long embayment at the foot of Hilina Pali (cliff) and Puu Kapukapu peak on the Puna Coast Trail (Figs. 2–4). Offshore bathymetry indicates a moderately gentle slope of about 1:10 extending out towards the submarine volcano, Loihi (Morgan et al., 2000). Onshore the beach is backed by a gently rising topography cut across by a lava crack sub-parallel to the coast approximately 250–300 m inland. The lava crack widens eastwards over a 400 m length creating a linear depression 3–4 m deep with a few brackish water ponds (Fig. 3). The land rises markedly beyond the 20 m contour to form the 300 m high Hilina Pali topped by Puu Kapukapu (Figs. 2 and 4).

A short basalt boulder spit (with rare coral boulders and pebbles) incorporating the remnants of a pre-1975 palm grove partially protects a small sand beach on the southwestern side of the bay (Fig. 3). To the west the spit continues as a boulder beach ridge that overlies 750–1500 yr B.P. lava flows. To the east a narrow strip of yellow sand extending up to 100 m inland backs a similar ridge-lava association. Two distinct groupings of boulders are present. First, a scatter of small boulders and coral pebbles extends about 50 m inland. Further inland, there is a discontinuous veneer of greyish-yellow sand and small to large basalt boulders. The discontinuous veneer of basalt boulders extends inland to the steep landward face of the lava crack.

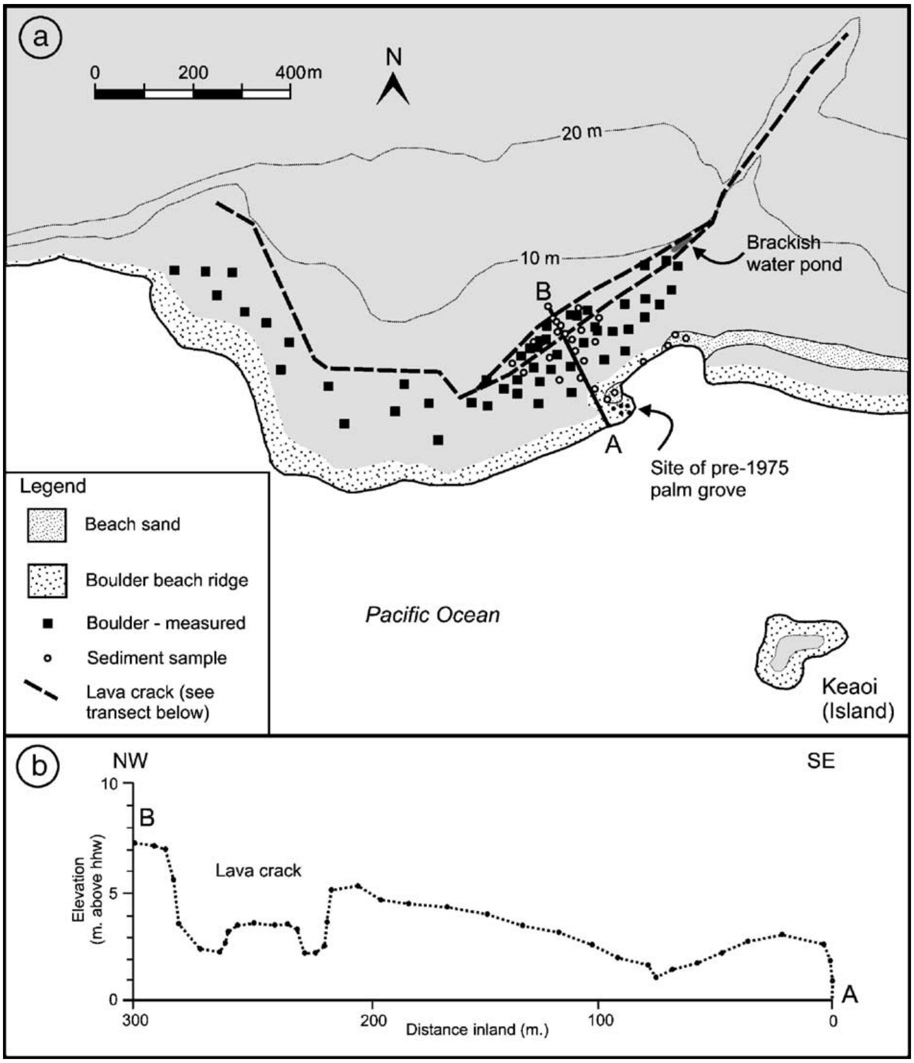

Fig. 3. Halape: a) general morphology of site indicating sediment and boulder sampling points; b) elevation changes along transect A–B.

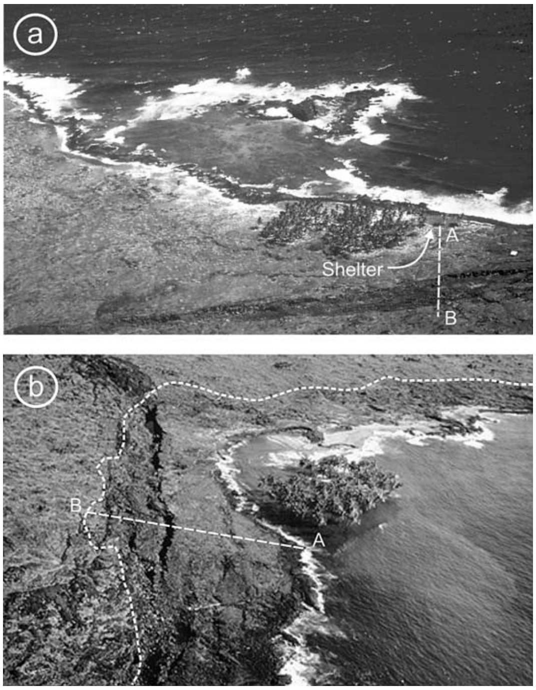

Fig. 4. Halape: a) pre-earthquake and subsidence view looking SE. (Photo: Don Reeser, National Park Service); b) post-earthquake and subsidence view looking NE. (Source: http://hvo.wr.usgs.gov/earthquakes/destruct/1975Nov29/deformation.html. Approx. location of transect A–B is shown on both photos.

2.2. Apua Point

The small carbonate sand pocket beach adjacent to Apua Point is bounded on both sides by basalt boulder beach ridges with rare coral pebbles and underlain primarily by the 1973 Mauna Ulu lava flow (Fig. 5). 200–750 yr B.P. lava flows are exposed on the surface about 100 m inland. A discontinuous veneer of basalt (and rare coral) boulders overlies the 1973 and 200–750 yr B.P. lava flows. The veneer can be traced about 300 m inland from a point 50–75 m from the shore (Figs. 5 and 6a). Landward of the boulder veneer is a line of desiccated vegetation sub-parallel to the shore up to 320 m inland and 10.4 masl (Fig. 6b).

3. Historical evidence for the 1975 Kalapana earthquake and tsunami

The M 7.2 Kalapana earthquake on November 29, 1975 was preceded by a relatively small Mag. 5.7 foreshock at 3:35 a.m. local time. The second, larger earthquake occurred at 4:48 a.m, with an epicentre near Kalapana (Fig. 2). Its focal depth was only 8 km below the surface, near the magmatic chambers of the Puna Volcanic rift zone (Tilling et al., 1976).

The tsunami, generated by the second earthquake, was destructive along the southern coast of the island with lesser damage observed along the eastern and western parts. The first wave observed at Halape was about 1.5–2.5 m high (Dudley and Lee, 1998; Pacific Tsunami Museum Archive., 2001a). However, the second wave was 7.9 m (Dudley and Lee, 1998). This wave carried campers inland toward the base of the cliff where they remained until the waves subsided, many trapped in the lava crack along with boulders, vegetation, remnants of a camping shelter, and other debris (Pacific Tsunami Museum Archive., 2001a, 1996; Dudley and Lee, 1998). There is some confusion about the exact number of waves, but there appear to have been three relatively large ones of which the second was the largest (Pacific Tsunami Museum Archive., 1996, 2001a,b; Dudley and Lee, 1998). Several additional smaller waves are recorded as washing over the survivors in the lava crack about 250 m inland, whose seaward lip lay at about 5 masl (Dudley and Lee, 1998). Tide gauge observations in Hilo indicate that the tsunami consisted of five or more distinct waves (Tilling et al., 1976). Maximum tsunami runup of 14.6 m was measured at Keauhou Landing (Fig. 2) (Tilling et al., 1976).

The high splash mark in the Halape–Apua Point area was marked by a debris line of dead trees, bagasse, rocks and other material and by the inland margin of a zone of withered leaves and grass killed by salt water (Tilling et al., 1976). However, only rarely were boulders and coral washed so far inland (Tilling et al., 1976).

Post-earthquake surveys of the south coast showed that a large crustal block had slid horizontally towards the ocean and subsided. Maximum horizontal displacement of approx. 8 m and vertical subsidence of approximately 3.5 m occurred near Keauhou Landing (Lipman et al., 1985). Displacements decreased to the east and west from this area. Subsidence rapidly decreased to the west and at Punaluu, the shoreline uplifted by about 0.1 m (Fig. 2). At Halape, the large coconut grove adjacent to the beach subsided by as much as about 3.0 m (Tilling et al., 1976).

An area of seafloor approximately 70 km long and 30 km wide was affected with the long axis of the displaced block parallel to the coast. The entire offshore block rose approximately 1.2 m. Therefore, offshore crustal displacement was an uplift while the onshore section subsided and moved outwards (Morgan et al., 2000). The summit of Kilauea volcano also subsided 1.2 m and moved seaward by about the same amount (Tilling et al., 1976).

4. Geological evidence for the 1975 Kalapana tsunami

Carbonate sands were analysed following the general procedures described by Friedman et al. (1992). Organic material was removed with hydrogen peroxide treatment, and salts and acids were removed with distilled water. Sands were dry sieved at 1 Φ intervals between −2 and 5 Φ. The *a*, *b*, and *c* axes of all boulders were measured. Boulder surfaces were studied

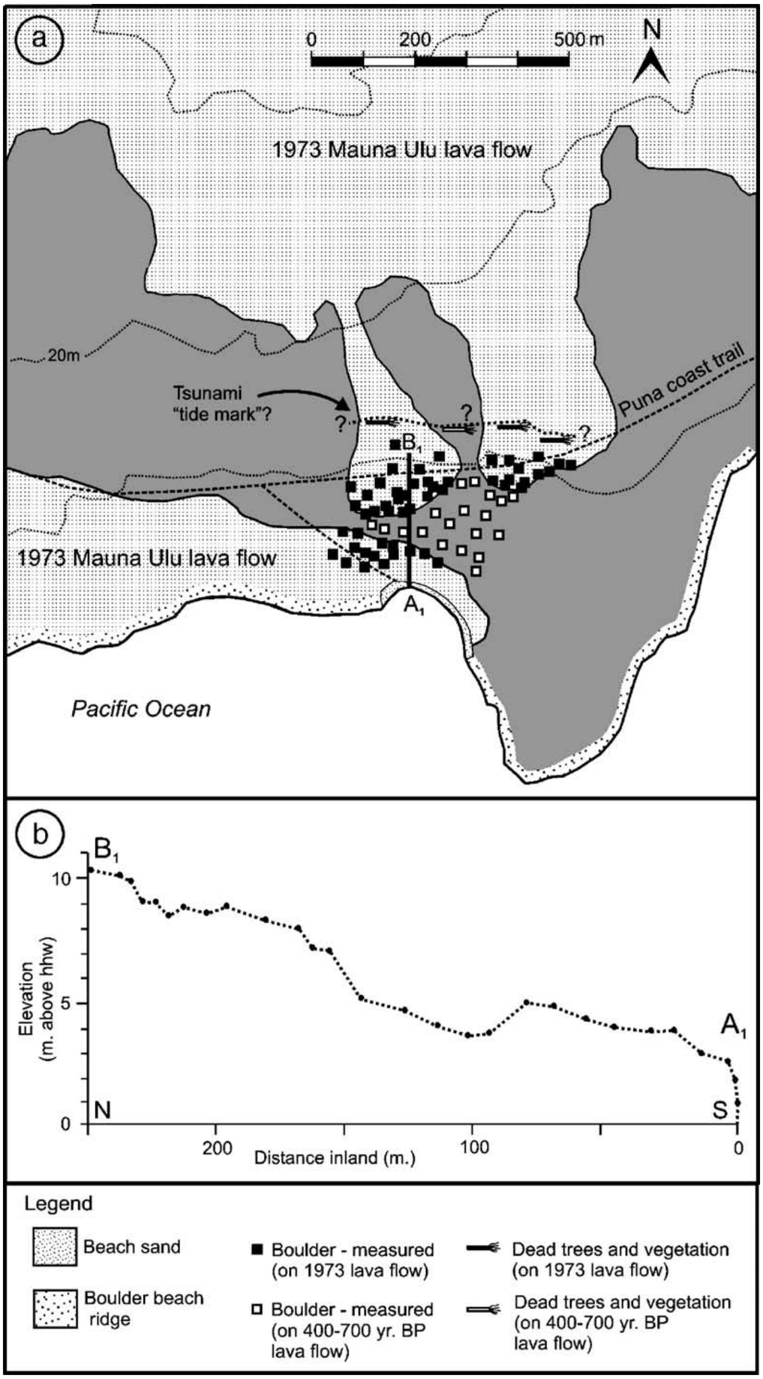

Fig. 5. Apua Point: a) general morphology of site indicating boulder sample points and probable maximum line of inland inundation; b) elevation changes along transect A^1–B^1. Areas not covered by the 1973 Mauna Ulu lava flow are composed of flows > 200 yr B.P. (after Wolfe and Morris, 1996).

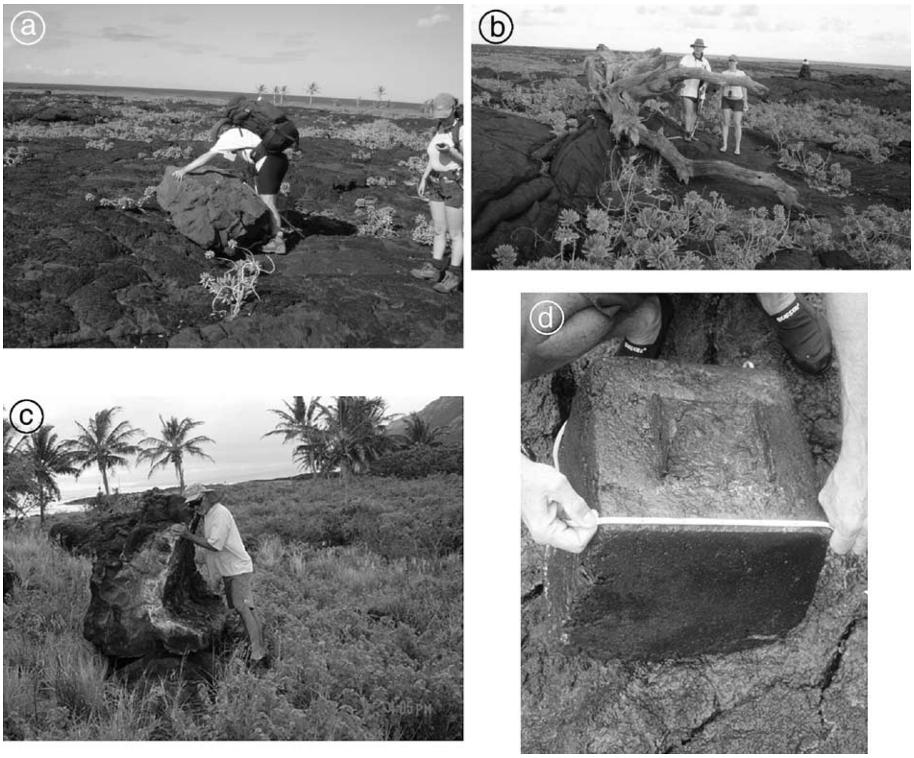

Fig. 6. Surficial deposits at Apua Point and Halape — a) Basalt boulder overlying 1973 Mauna Ulu lava flow approx. 300 m inland at Apua Point; b) desiccated Ironwood tree (*Casuarina equisetifolia*) overlying 1973 lava flow approx. 320 m inland at Apua Point; c) basalt boulder with *vermetid* sp. worm tubes approx. 250 m inland at Halape; d) concrete footing of old shelter found in lava crack at Halape.

for impact marks, scratches, remnants of adhering shellfish, and weathering.

The sampling regime at Halape assumed that any materials deposited by the 1975 Kalapana tsunami within about 100 m of the post-1975 Halape shoreline have probably been reworked by storms. This assumption is based upon site observations noted in Section 2.1. There is a separation between yellow (fresh) and greyish-yellow (weathered) sand around 100 m inland, and two distinct groupings of boulders. Small boulders extend about 50 m inland. In some places these are separated from a second, landward group, by up to 50 m of yellow sand. An arbitrary separation point was therefore selected 100 m inland. At Apua Point, an arbitrary separation point was selected 50 m inland, landward of modern beach sand and rare small boulders.

The area and density of boulders were determined by measuring only those with a markedly marine origin. This was verified by the presence of preserved *Vermetid* sp. gastropod tubes. It is unlikely, although not impossible, that any of the boulders measured related to the earlier 1868 tsunami because gastropod tubes are unlikely to have survived sub-aerial exposure in this coastal environment for such a length of time (J. Gardiner, marine ecologist, pers. comm., December 2004).

Many marine boulders also showed variable degrees of rounding. Some were rounded on only one side suggesting that they may have formed part of the shore platform (Fig. 6c). It was assumed that rounding indicated marine boulders had been submerged most or all of the time, although some or all of the rounding might also have been developed during high-velocity tsunami transport.

4.1. Halape bay

At Halape Bay, the tsunami deposit occurs as a discontinuous veneer of basalt (and rare coral, ~1%) boulders and carbonate sand that fine inland. It is underlain by lava bedrock (Figs. 7 and 8). The greyish-yellow sand veneer covers an area of more than four hectares. It is up to 5 cm thick, has a minimum volume of at least 2000 m^3, and rises up to 7.5 m above present sea level where it pinches out about 300 m inland from the coast (Fig. 3). A similarly discontinuous veneer of basalt (and rare coral) boulders complements the car-

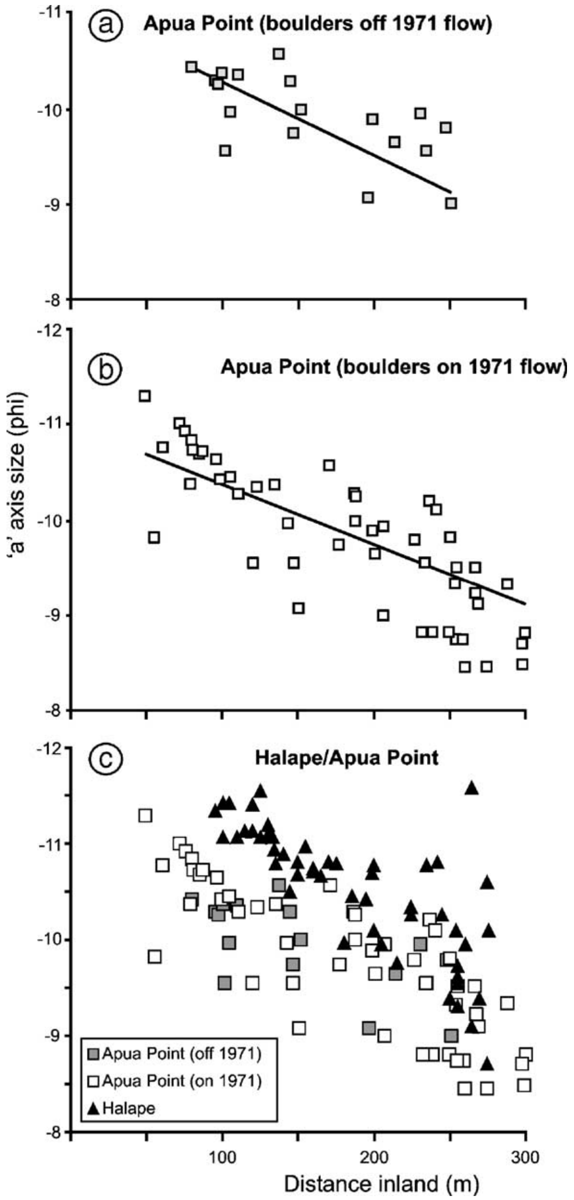

Fig. 7. Boulder distribution. Clasts divided into those "off" (a) and "on" (b) the 1971 Mauna Ulu lava flow at Apua Point; (c) combined Apua Point and Halape data.

bonate sand deposit. In the study area, marine boulders extend inland to within 10 m of the maximum landward margin of carbonate sand, but are laterally more extensive along the shoreline covering an area of about 400,000 m^2, with an estimated volume of 80,000 m^3 (Fig. 3).

At no point do marine boulders overlie the carbonate sands, although the two deposits appear to be contemporaneous. Both the marine boulder and carbonate sand deposits have a similar inland extent. Carbonate sands extend a mere 10 m further inland as a washover splay landward of the lava crack. They terminate abruptly at this point. There appears to have been insufficient wave energy to emplace marine boulders beyond the lava crack.

Three shells (*Cypraea mauritiana* — a Humpback Cowrie, 10 cm long, sub-tidal to inter-tidal rocky substrate; *Conus* sp. — cone shell, 8 cm long, sub-tidal rock substrate; *Cellana talcosa*? — Opihi or limpet, 7 cm, sub-tidal rocky substrate) were found pinned under large marine boulders in the lava crack. Infaunal remains from within two of these shells, *C. mauritiana* and *C. talcosa*?, were analysed indicating that these were undoubtedly dead prior to transport with an accumulated sub- and inter-tidal debris consistent with transport from a beach and/or nearshore position (Table 1).

Other debris found within the lava crack more specifically indicates transport by the 1975 tsunami. One of the concrete supports for the Halape shelter (Fig. 4a) was found in the lava crack (Fig. 6d). In addition, an intact Primo beer bottle with a design dated to the early 1970s (http://www.beercan.com/primbot.html) was found pinned under large marine boulders in the lava crack.

Suggesting that all the debris (shells, concrete support, beer bottle) in the lava crack relate to tsunami deposition may be considered speculative, however all except the concrete support were trapped beneath large (>1 m '*a*' axis) marine boulders believed to have been deposited by the 1975 tsunami.

Most tsunami deposits show considerable spatial variability in thickness but are generally in the order of 0.5–30 cm thick and (e.g. Gelfenbaum and Jaffe, 2003). At Halape Bay the carbonate sands are never more than 5 cm thick. As opposed to this reflecting the variable energy environment of the tsunami (Gelfenbaum and Jaffe, 2003), it seems most likely to reflect a distinctly bimodal sediment supply of numerous marine boulders and a paucity of carbonate sand.

In this instance the available material produces a somewhat unusual particle size distribution with a complete absence of clasts in the -1 to -8 Φ size range (Fig. 9). It also produces the relatively thin, and discontinuous veneer of carbonate sand found at Halape Bay. The deposit could not be reliably sampled to investigate any fining upward trend, but a marked fining inland was recorded with minor variations towards the landward end. Variations in grain size at the landward end were probably caused by wave reflection and refraction inside the lava crack. We believe this inference is borne out by survivors' accounts indicating

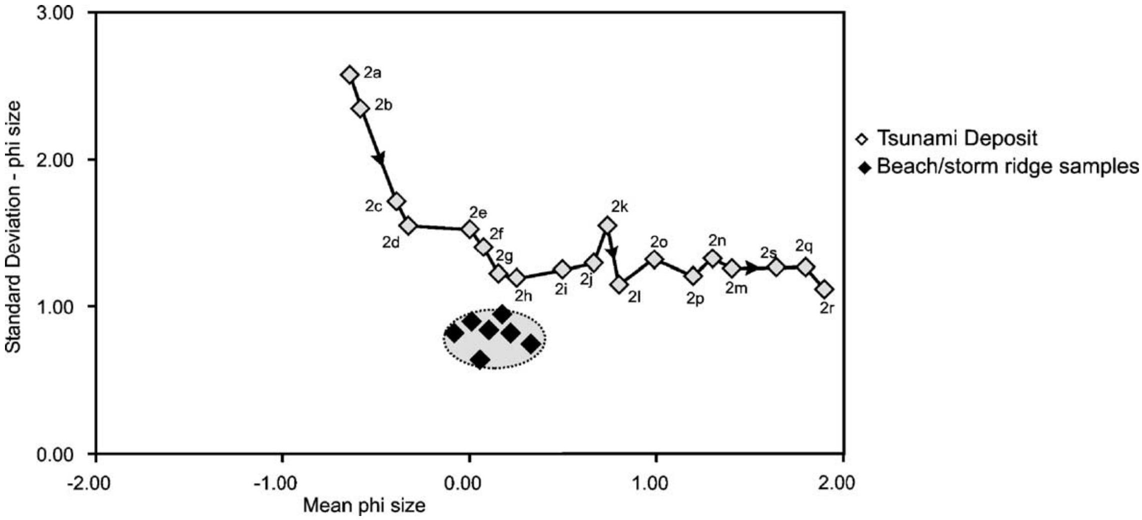

Fig. 8. Halape: bivariate plot of mean grain size against standard deviation for the tsunami sand deposit (after Tanner, 1991). Arrowed line indicates the progression of tsunami deposit samples from seaward to landward locations. Area grouped by ellipse encompasses storm/beach samples.

that being in the lava crack was like being "inside a washing machine" (Tilling et al., 1976).

Beach and storm sands are slightly better sorted and less weathered (yellow as opposed to greyish-yellow) than the equivalent tsunami material. They are also finer than the most seaward samples of tsunami sand (Fig. 8). However, any conclusions about differences in depositional processes drawn from these data should be treated with caution since they compare contemporary sediments with those laid down in 1975 in markedly different bathymetric and sediment supply conditions. In general terms, the contemporary sediments at Halape Bay are coarser than average for exposed beaches with similar gradients in Hawaii (Gerritsen, 1978). This may reflect ongoing adjustment to new coastal geomorphology, or a particularly exposed site, or a combination of both.

Table 1
Species identified in material from two shells, *Cypraea mauritiana* and *Cellana talcosa*? found under boulders in the lava crack at Halape

Species	Details	Habitat
Non-Mollusca		
Pseudoliomera speciosa	Crab carapace/claw	Sub-tidal coral
Echinothrix and/or *Echinometra*	Urchin spines	Inter-tidal–sub-tidal
Mollusca — gastropods		
Merelina hewa (Rissoidae)	1 complete/2 partial shells	Tide pool – 20 m depth
Vitricithna marmorata (Rissoidae)	3 partial shells	Rubble, 3–40 m depth
Diodora sp. (Fissurellidae)	1 shell (juvenile)	Sub-tidal
Lophocochlias minutissimus (Skeneidae)	1 shell	Tide pool, bench
Tricolia variabilis (Phasianellidae)	4 complete shells/3 fragments	Inter-tidal—100 m depth
Thalotia subangulata (Trochidae)	2 complete shells/2 fragments	Tide pool–ringing reef
Rissoina miltozona? (Rissoidae)	2 partial shells	Tide pool—65 m depth
Bittium zebrum (Cerithiidae)	1 complete/2 partial shells	Fringing reef
Berthelinia or *Julia* sp. (Juliidae)	2 partial shells	Sub-tidal?
Synaptocochlea concinna (Stomatellidae)	3 partial shells	Fringing reef
Mitrella rorida (Columbellidae)	1 partial shell	Inter-tidal–sub-tidal
Atlantid sp.	1 partial shell	Pelagic, open sea
Cerithiid spp.	4 partial shells	Probable sub-tidal
Mollusca — others:		
Acanthochiton viridis?	1 chiton plate	Tide pool
Ctena or *Ervilia*	1.5 bivalve shells	Probably sub-tidal

N.B. Approx. 1/3 of the material was identifiable. The remaining 2/3 contained approx. 20% unidentifiable molluscan material and 70% carbonate sand derived from offshore corals and similar in composition to the other deposited sand.

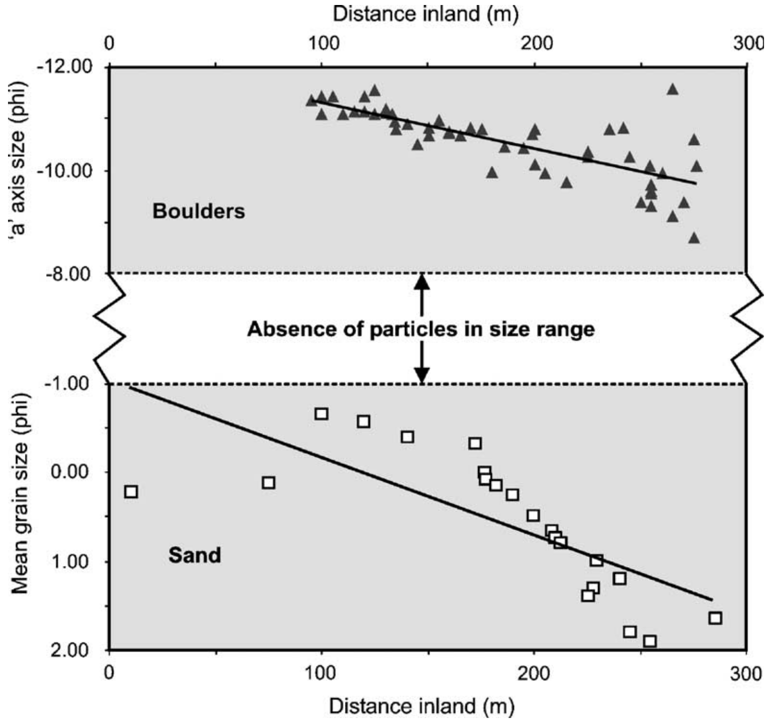

Fig. 9. Distribution of particle size at Halape; note absence of particle sizes in the −2 to −8 phi size range.

4.2. Apua Point

At Apua Point a discontinuous veneer of marine boulders extends from 50 to 300 m inland and up to 10.4 masl. There is no carbonate sand layer. This is not surprising given that the recently deposited 1973 Mauna Ulu lava flow formed the bulk of the coastline in the area immediately prior to tsunami inundation, covering any sand deposits. Marine boulders overlie both the 1973 and 200–750 yr B.P. lava flows (Figs. 5 and 6a). Maximum runup was determined from a line of dead trees and vegetation about 320 m inland from and sub-parallel to the coast (Fig. 6b). This material also overlies both lava flows (Fig. 5).

In addition to the general sampling assumptions, marine boulders overlying the 1973 Mauna Ulu lava flow could not have been laid down by the 1868 event. It is possible however, that some seaward boulders between about 50–100 m inland were deposited by storm events. We do not believe this to be the case because they fit within a general fining-inland sequence characteristic of tsunami sediments (Fig. 7) as opposed to a more random pattern associated with storm deposits. This difference has been noted at sites where direct comparison between storm and tsunami deposits have been made on the same stretch of coast (e.g. Nanayama et al., 2000; Goff et al., 2004; Tuttle et al., 2004), albeit in different physical and meteorological settings to Hawaii.

5. Discussion

Studies of historic tsunamis benefit greatly from the ability to compare physical evidence with personal accounts. This was particularly evident in the extensive use of personal accounts by geologists studying the 1998 Papua New Guinea tsunami (e.g. Davies, 2002). While it is now a standard practice to actively seek and record (in whatever form) personal accounts related to recent tsunamis, this was less rigorously recorded in the past. As a result there is a paucity of survivors' accounts for many relatively recent events around the world. The Pacific Tsunami Museum in Hilo, Hawaii has made a concerted effort to record as many survivors' accounts as possible, and has collated an impressive database for Pacific-wide (e.g. 1946 and 1960) and local (1975) tsunamis. Such accounts can prove useful in understanding the nature of tsunamis.

Tilling et al. (1976) used personal accounts to help describe the general characteristics of the 1975 Kalapana tsunami. More recent archival material has provided additional information concerning the event. While boulders were dislodged from the cliffs by both earthquakes, none of them came close to the campground (Pacific Tsunami Museum Archive., 2001a) and it is therefore highly likely that most of the boulders at the site were emplaced by tsunamis even though some show no obvious signs of marine origin and have not been included in this study. The first wave was sufficiently strong to wash most campers inland, but it did not penetrate as far as the lava crack. It was the second wave that washed most people into the lava crack, and they record being carried near the front of the wave with other debris in suspension around them (Pacific Tsunami Museum Archive., 2001b). This second wave was more turbulent than the first and transported trees, debris from the shelter, marine boulders and sand into the crack. One man died from burial in the sediment, and others swallowed seawater and sand while immersed in the water (Dudley and Lee, 1998; Pacific Tsunami Museum Archive., 2001b). Subsequent waves were smaller, but continued to wash over the survivors in the lava crack. These later waves do not appear to have introduced further sediment into the crack and may simply have reworked existing material.

The main characteristics of the 1975 tsunami deposit at Halape and Apua Point are listed in Table 2 and compared with a more comprehensive list that summarises the results of previous work worldwide. Geological evidence indicates that the deposit at Halape is locally extensive, rising in altitude inland (7.5 masl) with the sand terminating abruptly landward of the lava crack. Marine boulder and carbonate sand deposits both fine inland over approximately the same distance (~300 m). This is an unusual sedimentary association. Tsunami deposits tend to consist of units that fine inland and/or upwards (e.g. Goff et al., 2001). Survivors' accounts indicate that most, if not all, the sediment was transported inland by the second wave. Indeed, subsequent waves seem to have merely "washed over" survivors in the lava crack (Dudley and Lee, 1998). If all the sediment was transported inland by the second wave, then given the general particle size range, a consistent fining inland from large marine boulders to fine sand might be expected if all sediment was in suspension. This is not the case.

Table 2
A comparison of diagnostic characteristics for tsunami deposits with the deposits of Halape and Apua Point

Diagnostic characteristics for tsunami deposits (after Goff et al., 2001)	Halape	Apua Point
Deposit is locally extensive	√	√
Deposit generally fines inland and upwards within the unit	√ — no upward fining measured	√ — no upward fining measured
Deposits often rise in altitude inland	√ — up to 7.5 masl	√ — up to 10.4 masl
Deposits tend to extend over 100+ m inland	√ — inland extent: 300 m	√ — inland extent: 320 m
Particle/grain sizes can range from boulders to clay — depends upon sediment availability at site. Usually all available size ranges moved	√ — boulders to very fine sand (excl. −1 to −8 phi). All available size range moved	√ — boulders (> −8 phi)
Distinct upper/lower sub-units representing runup and backwash can be identified	X — but carbonate sand reworked by several waves	X
Lower contact is unconformable or erosional	X — lower contact is bedrock	X — lower contact is bedrock
Can contain intraclasts of reworked material, but these are not often reported	X	X
Loading structures often at base of deposit	X	X
Generally associated with increase in abundance of marine-brackish water diatoms. Foraminifera (and other marine microfossils) present. Pollen concentrations diluted.	X — rare marine diatoms (*Paralia sulcata)* in beer bottle, no other diatoms present. Insufficient for full count. No other microfossils studied	X — not studied
Elemental concentrations indicate saltwater inundation and/or marine shell content	X — not studied	X — not studied
Individual shells and shell-rich units are often present (shells are often articulated)	√ — shells under boulder in lava crack. Infaunal marine mesofauna also present. Gastropod tubes on boulders	√ — Gastropod tubes on boulders
Often associated with buried plants/soil	X	X
Shell, wood, less dense debris often form splash/tide mark	X	√ — tide mark of dead vegetation
Often associated with reworked archaeological/historical remains	√? — early 1970s beer bottle found among tsunami boulders	√ — remnants of worked timber in tide mark debris

The most likely explanation seems to be provided by a consideration of particle size data, geomorphology, survivors' accounts, and sediment transport processes. The second wave transported most, if not all, of the sediment. However, much of this material was trapped in the lava crack, a marked depression running sub-parallel to the coast. Only a small washover splay of sand is found landward of this point. Backwash from the second wave was strong, carrying one man out to sea (Dudley and Lee, 1998). It would also have reworked much of the carbonate sand across the relatively smooth lava surface. Subsequent waves washed over the survivors and it felt like being "inside a washing machine" (Tilling et al., 1976). It is probable that one or more of these waves reworked the carbonate sands at Halape until finally there was a marked fining inland as far as the lava crack. Turbulent reworking of sands within the lava crack appears to have imparted no distinct landward fining although there is a marked coarsening in the most seaward sample (Fig. 8, sample 2k). Sample 2r (Fig. 8), landward of the crack, is noticeably finer and was most probably deposited by the second wave and not subsequently reworked.

There are no survivors' accounts for Apua Point, but the sedimentary evidence is less complex than Halape Bay. Marine boulders become smaller inland to an elevation of about 10.4 masl and 300 m inland. The marine boulders terminate abruptly and are separated by about 20 m from a tide/splash mark of driftwood and dead trees that define maximum runup. Clast sizes are similar to those at Halape (Fig. 7) with none less than $-8\ \Phi$, but they are consistently smaller (0.5–1.0 Φ) at the same elevation and distance inland (Figs. 1,3,7c). Given that tsunami wave velocities are easily capable of moving all the material found (e.g. Nott, 1997), we believe that this variation is most likely a combination of a more sheltered location at Apua Point coupled with wave focussing at Halape Bay caused by greater coastal subsidence (e.g. McSaveney et al., 2000). The coastline at both sites is young, but variations in marine boulder size are also probably caused by much of the coast adjacent to Apua Point being renewed by the 1973 Mauna Ulu lava flows.

Maximum wave runup (14.6 m) was recorded at Keauhou Landing and so the absence of marine boulders and any identifiable tsunami deposit is unusual. Tilling et al. (1976) noted that few marine boulders were seen here either on land or in the sea. This is most probably merely a function of ongoing sediment transport by longshore currents away from the headland creating a paucity of material, although the possibility of removal by tsunami backwash cannot be discounted.

In the contemporary environment, as opposed to Keauhou Landing, Halape and Apua Point act as small pocket beaches. Photographic evidence from Halape indicates that this was also the case prior to 1975. While lava flows immediately prior to the 1975 tsunami may have altered the coastline around Apua Point, the general morphology of the area prior to inundation suggests that boulder and sand sediment accumulation probably occurred here. Coastal sand deposits may have been largely smothered by lava flows, while boulders, further offshore, remained available for transport.

The discontinuous veneer of marine boulders along the Halape–Apua Point coastline was deposited by one wave, the second. There may have been some minor reworking by later waves, but survivors' accounts make no mention of subsequent boulder movements, even though they were listening and watching in the dark. These deposits therefore provide us with a snapshot view of marine boulder transport by one wave in a tsunami, with an almost complete absence of other sediments.

Most boulder deposits attributed to tsunami are imbricated, chaotic or random assemblages (e.g. Kelletat and Schellmann, 2002), or boulders that appear as isolated clasts in finer sediments (e.g. Dawson and Shi, 2000). This diversity of depositional character makes it difficult to model the movement of large boulders by tsunamis (Noji et al., 1993). Even when recent research appears to be overcoming these problems (e.g. Nott and Bryant, 2003), the boulder deposits attributed to tsunamis do not fine landward, as does sand. There are three probable explanations. First, a relatively chaotic or random nature is imparted to boulder deposits as a result of clast interference during entrainment. Second, boulder deposits purported to relate to one tsunami are actually composite features developed over long time periods. Third, they are not tsunami deposits but have a chaotic or random nature related to emplacement by storms (e.g. Nott, 2004). Unlike storm waves, individual tsunami waves reach a point of zero velocity prior to running back to the sea (Dawson and Shi, 2000). In this case, if velocity falls off steadily as elevation rises, it should leave a deposit that fines inland. This is what has occurred for boulder-sized clasts and sand-sized material in the Halape–Apua Point region, probably because a relative paucity of sediment reduced internal clast interference.

The coincidence of independent landward-fining in the coarse and fine size modes at Halape Bay suggests that all the material was not transported in suspension, but rather that there was a combination of suspended and bed load. No impact marks associated with either clast interference or contact with the bed however were found on any marine boulders, although some of an individual boulder's roundness may have been imparted by high-velocity bed load transport. Rare, short (max. 20 cm), unidirectional (landward) scratch marks in the underlying lava bedrock indicate some contact with the bed, albeit close to where they came to rest. Scratches were only preserved beneath the seaward side of some large marine boulders suggesting that post-depositional sub-aerial weathering of both boulder and bedrock surfaces may well be rapid in the area.

It is highly likely that many of the more weathered, basalt boulders of possible marine origin were laid down by the 1868 tsunami. However, given that the evidence for marine origin in this instance is less convincing (an absence of preserved *Vermetid* sp. gastropod tubes), and that many of the boulders at Apua Point are now covered by recent lava flows, it is doubtful whether any useful data can be compiled in the Halape–Apua Point area for this earlier event. Similarly, while the 1868 and 1975 events are the only historically documented local tsunamis in the area, the nature of ongoing flank collapse means that numerous prehistoric inundations probably occurred. There is no satisfactory way to investigate this further using the remnant boulder deposits. An alternative approach would be to search for records of multiple palaeotsunamis deposits in the coastal wetlands of Punaluu and Honuapo (8 km SW of Punaluu). Preliminary work by one of the authors (JG) in a coastal pond in an old lava flow at Hilo has shown that tsunami deposits (1946) are preserved in such environments.

No marine boulders measured in the study area were specifically identified as storm deposited, although there was a visibly random scatter of less weathered clasts and sand up to 50 m landward of the coast at Halape Bay. Other researchers note similar differences between storm and tsunami deposits (Nott, 1997; Nanayama et al., 2000; Goff et al., 2004).

6. Conclusions

A combination of geological evidence and survivors' accounts have produced a more detailed picture of the 1975 tsunami inundation along the Halape–Apua Point coastline than has previously been reported. There were several waves, although it was the second that washed people and most of the sediment and other debris inland.

Geological evidence bears many, although not all, of the diagnostic characteristics of tsunami deposits reported elsewhere. Most of the missing criteria such as geochemical and micropalaeontological evidence could not be recorded because of the nature of the deposit; a discontinuous veneer of marine boulders and carbonate sand. This is an unusual sedimentary association for several reasons. First, sand-sized material is a minor component of the deposit. Second, both boulders and sand fine inland over the same distance and terminate at approximately the same point. Third, no sediment was found within the -1 to -8 Φ size range.

The lava crack at Halape trapped marine boulders as they were transported inland and, with the exception of one sand splay, served as an effective barrier to all further sediment transport inland. The sloshing of seawater in the lava crack reworked sand-sized material disrupting the general fining-inland trend. This was not the case at Apua Point where there was a lack of significant inland obstruction. In a more classic sequence of inundation, the sedimentary component of the tsunami deposit terminated abruptly about 300 m inland and was separated by about 20 m from a tide/splash mark of driftwood and dead trees that defined the maximum runup.

Boulders were transported and deposited by only one wave, the second, whereas the sand deposit was, in part, reworked by subsequent smaller waves. In the absence of an alternative explanation we believe that sediment transport took two forms, suspended and bed load, with boulder transport as bed load in association with a relative paucity of carbonate sand in suspension. Bed load transport took place in an environment of reduced clast interference and helped to impart a marked fining-inland boulder sequence. This indicates that while many researchers propose a chaotic or random nature of boulder emplacement by tsunamis, this is not necessarily the case. Where there is abundant sediment, clast interference during entrainment will impede the fining inland of larger material. In cases where it is difficult to determine the nature of inundation or the number of tsunamis, a chaotic pattern may simply reflect deposition by storm, tsunami, or a combination of the two.

Without historical documentation the interpretation of coastal boulder deposits is problematic. Are they chaotic depositional features or is there a more complex history underlying their formation? A coincidence of good historical data with recent lava flows in one of the study areas has provided a unique opportunity to study the marine boulder and carbonate deposit of the 1975 Kalapana tsunami. The sedimentary record of earlier events is far from clear on this stretch of coast, but a record of multiple palaeotsunamis including 1975 might be found in the coastal wetlands of Punaluu and Honuapo to the west.

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