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Tsunami Deposit Research: Fidelity of the Tsunami Record, Ephemeral Nature, Tsunami Deposits Characteristics, Remobilization of Sediment by Later Waves, and Boulder Movements

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1. Introduction

Historically, much that has been reported about tsunamis has been based upon mathematical modeling. However, modeling tells little about the impact of tsunami on land and people, inundation and run-up, drain back, movement of sediments and boulders, the natures of deposition and erosion, the carrying capacity of waves, etc. In order to study these topics, the question can be asked, what do tsunami deposits tell us about tsunamis?

Since the Hawaiian Islands have experienced numerous tsunamis it is an ideal place for field studies. Observations and analysis have been carried out on the North Shore of Oahu. The objectives were: to observe tsunami vs. storm activity, document the impact of the 1946 Aleutian and 2006 Kuril Tsunami, observe the nature and distribution of sediments associated with these events, and quantify the nature of transport of mega-boulders, and calculate the transport factor.

The results indicate: (1) There was little difference in the sedimentary record and inundation record between the November 2006 Kuril Islands Tsunami and the December 2006 Winter Storm. (2) The 2006 tsunami and storm deposits were ephemeral, i.e., the tsunami record was removed by the winter storm. (3) The sedimentary record is of low fidelity in discriminating and preserving tsunami and storm events. From the analysis of the 1946 Aleutian Tsunami, the real-time aerial photography proved invaluable, since the patterns of inundation and drawback become obvious. A sand sheet, with only isolated and rare boulders, covered the inundation zone. The drain back utilized pre-existing drainages in a limited way. A stratigraphy is found in the archaeological sampling showing that cultural items were relocated by the tsunami and some vegetation was buried in place.

The study of mega-boulders suggests that giant waves are capable of moving rock boulders around on the reef platform, but did not significantly displace them. The waves surging over the platform plucked rocks from the back or leeward side of the mega-boulders. The fragments of boulders struck the karstic platform and broke off additional rock. The

transport paths of the fragments could be followed intermittently across several meters length on the shoreward side of the platform. No large boulders were added or removed from the platform by the storm. Transportation calculations indicate Hawaiian giant surf and tsunamis occupy the lower range of transport values, when compared globally. There is remarkable similarity between the boulders of Hawaii and Morocco that are presumed to be of tsunami origin. This similarity likely reflects the changing sea level within a shallow carbonate beach and back beach setting.

One of the most valuable products of the tsunami deposit studies is their potential for revealing the periodicity of tsunami, and thus allows risk assessments. The Kahuku study provides evidence that a high-resolution geologic record of tsunami activity is unlikely, and thus the possibility of establishing reliable recurrence records is low. The study also indicates that the Kahuku beach, dune field, and back beach coastal facies are poor choices for obtaining a complete record of tsunami recurrence. Future research should evaluate the submarine setting as a favorable environment.

2. Geologic setting

The island of Oahu is famous for its scenic coastal plain, fringing reef, and surf. The coastal plain extends around the periphery of the island and is interrupted by drainages and becomes very narrow at the eastward and western tips of the island, coincident with the ancient volcanic rift zones (Stearns, 1974). The sediments of the coastal plain generally consist of lithified sand dunes, reef deposits and talus, and in places stream deposits and soils. Wells drilled around Oahu show that the carbonate sediments underlying the coastal plain extend to –400 m depth, with the thickest sediments in valleys and the outer edges of the exposed coastal plain (Stearns and Vaksvik, 1935). The coastal plain rocks display several terrace levels and erosional unconformities marking shifts in global sea level.

Stearns (1970) suggested that the island of Oahu shows important evidence for sea level changes, including: (1.) The presence of sea cliffs separated from the sea by emergent marine deposits, (2.) Evidence that there are older marine deposits at elevations of up to 30 m, and (3.) The base of coastal sand dunes and the lithified beach rock occurs several meters below sea level (mbsl) indicating that sea level was at this (modern) position or slightly lower during dune accumulation. Modern studies of changes in sea level indicate that global sea level has not been significantly higher than present during the last several hundred thousand years.

Because Oahu is situated near the northern fringe of the live Pacific Ocean coral distribution, isolated from the source of Indo-Pacific coral larvae (which do not remain viable over such great distances) and separated by the barriers of sub sea mountain chains and circulatory gyres, the coral reef growth is limited. The reefs of Hawaii favor small numbers of coral species associated with more abundant lime-secreting algae mat. Where a modern fringing reef is present, it is narrow, extending only 0.1-0.3 km from the shore.

The coastal zone from Turtle Bay to Kahuku Point consists of modern coastal deposits superimposed on lithified Pleistocene calcareous reef rock and lithified dune ridges. The modern beach consists of unconsolidated calcareous sands, adjacent to exposures of lithified beach rock and platform reef rock of Pleistocene age. The lithified beach rock platform is approximately the same width as the unconsolidated modern beach.

The dune ridges extend 4.5–6 m above sea level (masl) and are for the most part stabilized by vegetation. At Kahuku Town, southeast of Kahuku Point, several patches of older dunes reach a maximum height of 15.2 m, approximately 0.8 km inland (Stearns, 1970). The Kahuku Town dune sands show good cross bedding and poor consolidation. The deposits are readily differentiated from modern beach sediments by their smaller grain size. Radiometric dating of samples from the Kahuku dunes yield ages of 114,000-122,000 yrs (Szabo et al., 1994), and an age of 121,000 yrs (Ku et al., 1994). The lithified beach rock along the shoreline at Kahuku Point is cut by numerous fractures and the upper surface displays deeply pitted karst micro topography as well as pitting from bio-erosion. Slabs of lithified beach rock have been detached from the uppermost rock platform and transported landward (vertical change of 2 m and horizontal distance of 6 m observed in several instances). Many white scars suggest that more slabs have been quarried and transported however there is an insufficient inventory of boulders in the near vicinity. A likely scenario is that ongoing mechanical degradation has reduced the slabs to loose sand within the wave zone.

3. Fidelity of the tsunami record

The exposed northern coastline of the island of Oahu, Hawaii, is vulnerable to tsunami inundation and extreme winter storm swells. Because this shoreline has yet to be altered by development, it is an excellent location for studies of inundation and sedimentary processes related to tsunamis, giant surf, and sea level changes. The results of field studies on the North Shore (see map, Fig. 1) are presented here, including: observations of a Nov. 15, 2006 tsunami and a winter storm event during December 2006, observations of the 1946 tsunami, and an quantitative analysis of boulder movements. (North Shore is a geographic name, thus capitalized.)

The 2006 Kuril Earthquake, a large magnitude (M=8.3) event, with relatively shallow focal depth and long duration, was tsunamigenic and provided an opportunity to observe a tsunami and evaluate the environmental parameters, sedimentary processes and the extent of tsunami deposits left in the environment. The observation of modern tsunamis is fundamental to understanding sedimentary processes, establishing recurrence rates, for risk assessments involving flooding in coastal zones. Studies of tsunami recurrence rates generally focus on obtaining records of marine inundations (paleo-seismic or paleo-tsunami records). The fidelity of these records is problematic since it is yet to be determined if tsunami deposits and storm deposits can be differentiated.

3.1 Earthquake and tsunami

The 2006 Kuril Tsunami arrived in Hawaii at 7:16 a.m., during the transition from low to high tide (projected tidal range for November 15 was 0.3 m). Real-time reports to the Tsunami Bulletin Board (ITIC, 2006) indicated that the initial run-up at tide gauges in the Kuril Islands near field was less than 1 m. Gusiakov (2006) provided an initial model of tsunami propagation using a low-angle thrust mechanism typical of the Kuril region and a 4-m movement on a fault plane and dimensions of the source area of 200 by 60 km. The analysis suggested that the main energy of the tsunami propagated into the NW Pacific and central part of the Okhotsk Sea. The maximum peak-to-trough tide gauge measurements, Pacific-wide, did not exceed 1 m (Pacific Tsunami Warning Center, 2006).
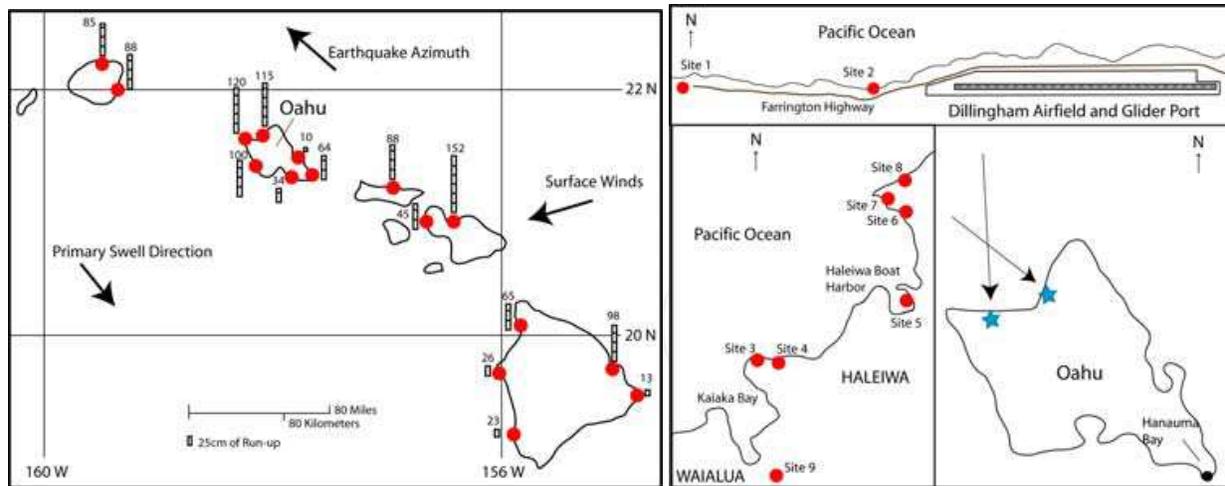
Fig. 1. A map of the Hawaiian Island chain is shown at left. The observed run-up from this study and the maximum trough-to-peak heights recorded by tide gauges are indicated by columns on the map at left (bars on the vertical axis are at 25 cm intervals, and with the recorded data values listed above) based on the NOAA Pacific Tsunami Warning Center, 2006 (Tsunami Observations Kuril Tsunami by Tide Gauges website). The map of Oahu is at the lower right. Wind and wave directions shown by arrows on map were obtained from the Preliminary Local Storm Report (Wroe and Caldwell, 2006). The azimuth to the earthquake source was obtained from the report of Titov (2006). The maps (to the right) show the locations of run-up observations (GPS) Latitude (N); Longitude (W): Site 1 Trail Head to Kaena Point 21°34.6, 158°14; Site 2 W. Dillingham Air Field Mokuleia Army Beach 21° 34.6, 158°13; Site 3, West end of site 4 Kaiaka State Recreation Area 21°35.4, 158°07; Site 4 North side of Kaiaka State Recreation Area 21°35.4, 158°07; Site 5 Pier at Haleiwa Small Boat Harbor 21°35.6, 158°07; Site 6 Surfing beach, eastern side Haleiwa beach park 21°36.1, 158°06; Site 7 Near Puaena Pt. (west side) 21°36.1, 158°06; Site 8 North side of old Haleiwa airfield (east of Puaena Pt.) 21°36.2, 158°06; Site 9 Road bridge 21°34.7, 158°07; Puuiki Beach (West of Haleiwa) showed no changes 21°35.1, 158°08. Locations and Place Names from Bryan's Sectional Maps Oahu, 2007 Edition, EMIC Graphics, Waipuhu, HI. The maximum runup for each site is listed in Table 1.

3.2 2006 Tsunami impact

Dr. Dan Walker (University of Hawaii seismologist and resident of the North Shore of Oahu) made direct observations of tsunami activity from the Highway 930 Bridge at Haleiwa Road over Paukauila Stream (Location 9 in Fig. 1). The first indication of the 2006 tsunami was the rapidly increasing seaward movement of leaves floating on the stream. The water then rose and flooded the nearby sand bar; traveling faster than a person could run. Turbulent flow began in the stream as the tsunami flooded inland and overcame the outgoing stream flow. Black sediment boiled up from the stream bottom as the first wave receded. Four significant tsunami waves covered the sand bar at the mouth of the river. Oscillations associated with the tsunami continued for at least 10 hours after the onset of the tsunami. In attempting to measure run-ups along the banks of the stream just prior to sunset Walker was surprised to be caught in additional significant high water oscillations that prevented any valid run-up measurements at that time. On the next day, the maximum measured run-up on the banks of the otherwise quiet stream was 1 m.
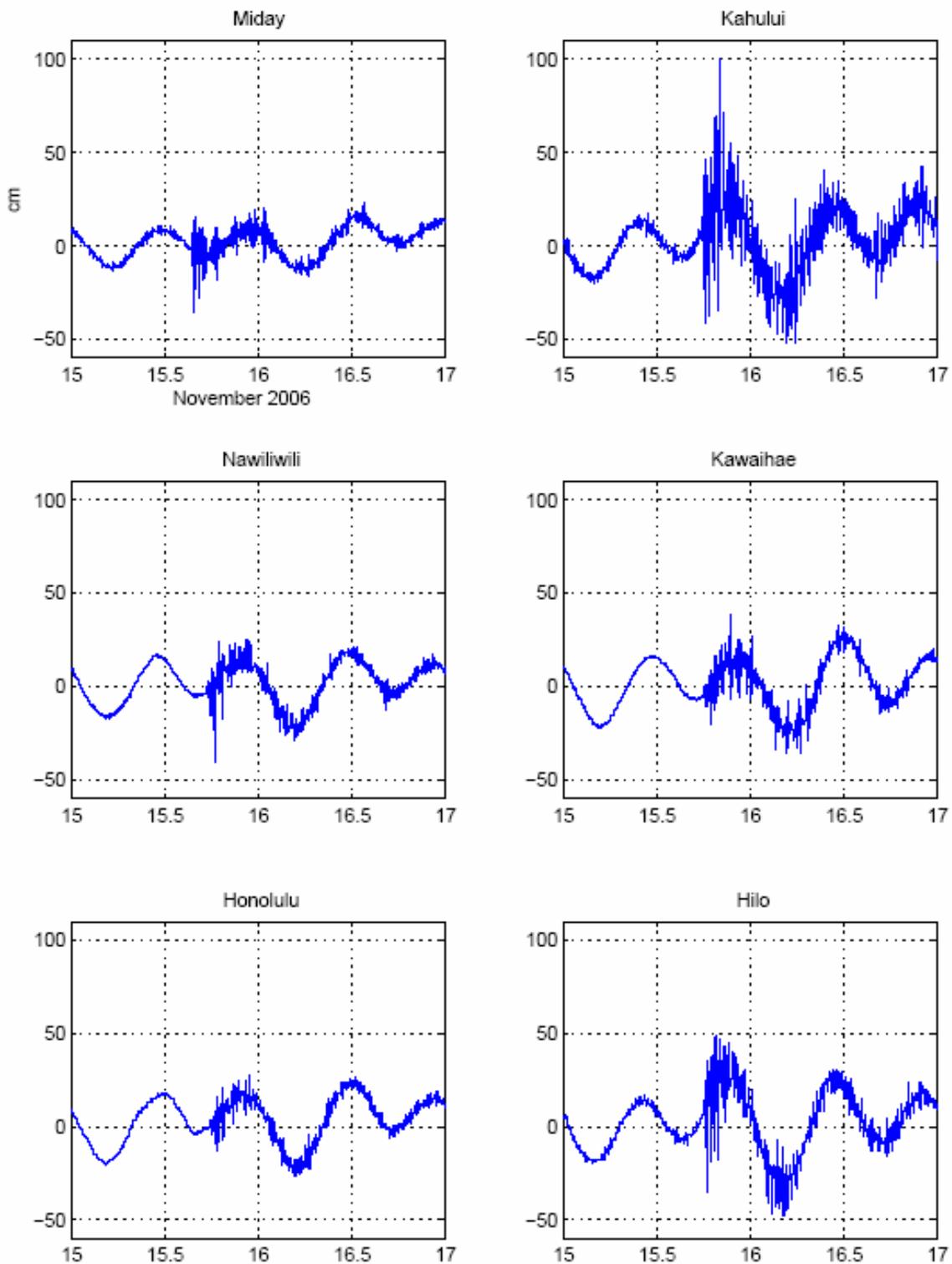
Fig. 2. Tide gauge records of the 15 November 2006 tsunami for various Hawaii ports
(courtesy of Hawaii Sea Level Data Center). Note the extended duration of the event as
energy from the earthquake was reflected from bathymetric features and the coastlines of
the Pacific basin.

Hanauma Bay, the underwater park on the SE shore of Oahu, was closed for 2 days. The strong currents within the bay raised concerns that inexperienced swimmers might be carried out of the sheltered bay into deep waters. The closure of the park is unprecedented, and was a consequence of the chaotic nature of wave and current activity that continued well after the tsunami passed (KGMB News, 2006). The tide gauge records on the east and south shore of the Hawaiian Islands generally showed tsunami wave amplitudes of about 20 cm.

A Coast Guard video of tsunami activity on Kauai (next island to west) also shows strong water movements associated with inundation and flow-back (U.S. Coast Guard, 2006). The tide records (Fig. 2) show that the series of oscillations associated with the tsunami continued for a day and a half after the tsunami passed the Hawaiian Islands. Newspaper and television reports indicate that there were also strong currents on the north sides of the islands of Kauai and Oahu associated with the tsunami.

3.3 Coastal traces

The 2006 tsunami inundation of NW Oahu left a record, observed 3 days after the event, even though these beaches have high usage by local surfers, tourists and residents. The tsunami left a small but significant debris line 1.2 m above the sea level (tsunami plus tide) at several localities (see the list of locations and paired post-tsunami and post-storm photographs). A photograph (from television news) shows a man standing in knee-deep tsunami waters on the submerged pier walkway at the Haleiwa Small Boat Harbor during the tsunami (Location 5, Figure 3a and 3b). The largest of the tsunami waves flooded to the grass line, just above the embankment in these pictures.

Fig. 3. a & b. The photograph on the left was taken during the tsunami by KGMB News (2006) Channel 9 television and appeared on their web site. The photograph shows a man standing in water to his mid-leg on the flooded dock and walkway next to the Shark Encounters boat and sign (published with the kind permission of the photographer). Fig. 3b. The photograph (at right) shows a person at the same location on the pier after the tsunami (Site 5, Fig.1). (Please note that both the boat and the sign in the photograph on the left are absent in the photograph at right, and the photograph on the left was taken using a fish-eye lens.) The tsunami inundation exceeded the high tide mark evident on the pier and the concrete embankment by more than a half meter. Notice that in the photograph at left, that there is a heavy sediment load suspended during the tsunami.

Fig. 4. a & b. At Location 6, lines of coral and basalt clasts were observed lying on an exposed reddish-brown soil horizon. The tsunami inundated the sandy beaches at the east end of Haleiwa Beach Park and Puaena Point (Locations 7 and 8 on Fig. 1). Fig. 4a (left) shows the bay after the tsunami and Fig. 4b (right) shows the shoreline after the winter storm.

Fig. 5. a & b. These images were taken on the North Shore of Oahu, at Haleiwa, Site 8, shown in Fig.1. The scenes have in common, a fragment of a WW II concrete bunker (straight arrows) and the stump of a palm tree (bent arrows). The stump was situated on the exposed coral platform was moved onto the beach sand by the tsunami. A line of vegetation was washed away by the tsunami (above, right). The white lines on the images mark the maximum run-up.

At the Haleiwa surfing beach (Location 6 on Fig. 1), lines of coral and basalt clasts were observed lying on an exposed reddish-brown soil horizon (Fig. 4a and 4b). The tsunami inundated an elevated fossil reef and sandy beach at the east end of Haleiwa Beach Park and Puaena Point (Locations 7 and 8 on Fig. 1). The tsunami and superimposed surf left numerous small sedimentary features and desultory clastic debris traces on the scoured and eroded reef platform, and transported debris westward, depositing it near and in the eastern margin of Waialua Bay.

Only at the beach location 0.5 km west of the glider port (Location 2 on Fig. 1) did the debris line extend above the beach into the dune or back beach to an elevation of 2 m. At this location, the incoming waves can be observed to wrap around an offshore feature and focus

into one small area of the beach, where a locally double run-up and inundation were measured.

3.4 Winter swell and strong trade winds

Waves from a North Pacific winter storm reached high levels on the North Shore of Oahu on December 6 and by the evening, they were in the extra-large category, with peaks of 6.6 to 8.5 m on December 7-8. Concurrently, a weak front with strong E-NE trade winds passed over the western Hawaiian Islands on Dec. 7-8. Sustained winds at (25mph) 45 km/h with gusts as high as (50mph) 80 km/h resulted in reports of roof damage, windows shattering, fallen trees, telephone, and power poles (Wroe and Caldwell, 2006).

Following the tsunami, winter swell, and wind event, each of the coastal sites were reexamined and photographed. The winter surf, and strong winds left debris lines, composed predominantly of decaying vegetation, situated only a few cm above the previously photographed tsunami debris lines. At one site, on the exposed coast NE of Haleiwa Bay (Location 7 on Fig 1), the winter swell, augmented by the strong winds, scoured the fossil reef platform of the small and isolated accumulations of sand, shell, and coral rubble left by the tsunami. In some areas, the fossil reef surface was scoured to a depth sufficient to observe a change the color of the rock from gray to white, indicating an apparent beach retreat of roughly 1 m (Fig. 7). In addition, at the eastern end of Haleiwa Beach Park, (Location 6, Fig. 1) the distribution of clasts on the beach was altered by the winter swell and there was visible infilling of sand around the coral clasts.

A sample of the coarse winter swell deposit at Location 7 contained coral fragments, algal nodules, beach rock, twigs, bi-valve fragments, whole micro-mollusk, portions of worm tubes, gastropods, mono-valve shells, and echinoderm spines, with a mean grain size of 0.6 cm with rare clasts 2 - 4 cm across. The coral-algal mixture included rounded, angular, and fragmented clasts; preservation of both whole shells and broken fragments was good (the colors of the sea shells were still intact). A debris line of mostly dead and dry vegetation, with only occasional sparse collections of shell and coral hash debris was also present.

Fig. 6. The 2006 tsunami inundated an elevated fossil reef and sandy beach at the east end of Haleiwa Beach Park (left) and Puaena Point (right); Locations 7 and 8 on Fig. 1.

The high surf event of December 7-8 was more intense and of longer duration than the tsunami and effectively removed all visible traces left by the Kuril tsunami by eroding and remobilizing traces of the tsunami into a higher storm event debris line. Moreover, the seasonally high surf left an event debris line that included floating debris and in most places minor concentrations of coarse sand and coral gravels that were not associated with the previous tsunami trace.

3.5 Ephemeral high-energy record

The 2006 tsunami produced debris lines on several beaches, but at other intervening locations, no obvious traces were observed. The storm scouring of the fossil reef platform and erosion of clastic sediments from Puaena Point (Locations 7 and 8; 7a-7b) exceeded the

Fig. 7. At Haleiwa Bay (Location 3) the beach rock was scoured to a depth sufficient to observe a change of the color of the rock from gray to white, suggesting a beach retreat of roughly 1 m.

deposition and erosion caused by the tsunami. By comparing post-tsunami and post-storm photographs, it was observed that the sedimentary trace of the winter swell was consistently higher than that of the tsunami; with the storm traces situated a few centimeters up the beach slope. Because normal coastal processes easily remove the traces of tsunami and large swell events, smaller events such as those described here are unlikely to be preserved in the geologic record. The absence of these events will result in a low fidelity paleo-tsunami record.

4. The 1946 Tsunami at Kahuku, NE Oahu, Hawaii

The 1946 Aleutian Tsunami was analyzed in the second phase of this study in order to evaluate the tsunami damage, patterns of erosion and deposition, areas of flooding and inundation, and pene-comtemporaneous drain back patterns.

The Hawaiian Islands are prone to flooding damage from far-field tsunamis generated around the Pacific Rim, and the near-field sources within Hawaii. Walker (1994) found that 11 tsunamis, with runup greater than or equal to 1 meter, have occurred on Oahu since 1837. The far-field tsunamis are more numerous and have had significant impact within the Hawaiian Islands. Walker (2004) generated maps of the Hawaiian Islands showing the runup values for large, Pacific-Wide 20th Century Tsunamis. These maps show that Kahuku experienced tsunamis having maximum runup of 7.2 m (1946 Aleutian Islands Earthquake), 1.2 m (1952 Kamchatka Peninsula Earthquake), 6.9 m (1957 Aleutian Earthquake) and 1.2 m (1960 Chilean Earthquake). Shepard et al. (1950) and MacDonald et al. (1947) published post-tsunami surveys; offshore bathymetry was described by Pararas-Carayannis (1965); and known run-up levels for all islands were published (Walker, 2004). The runup values for sites along the North Shore of Oahu are summarized here. The sites are distributed from the northeast point of the island, Kahuku Pt., to the northwest point, Kaena Pt., shown in Fig. 8.
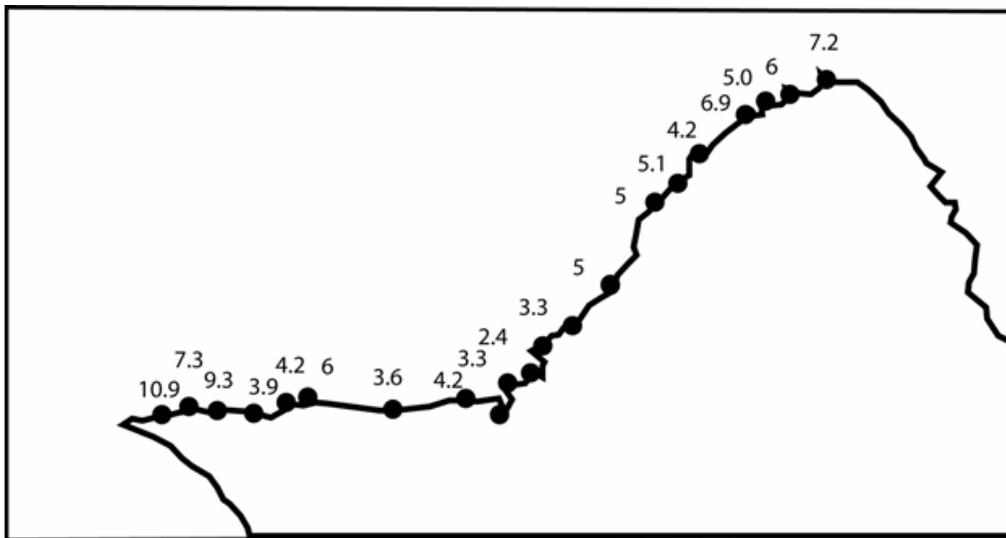

Fig. 8. Map of the North Shore of Hawaii showing the locations of the published 1946 tsunami runup measurements (in meters) between Kahuku Point (at right) and Kaena Point (left), also see Table 1. These values indicate that the maximum tsunami runup (in meters) occurred at the NE and NW tips of the island. Adams (1977) suggests that the bathymetry around both points allows refraction and focusing of the incoming tsunami waves, leading to increased run-up.

Kahuku Pt. 7.2, Kawela Bay 6, Waialee 5.7, Sunset Beach 6.9, Waimea Bay 4.2, Kawailoa Beach NE 4.2, Kawailoa Beach 5.1, Kawailoa Beach 5.7, Puaana Pt. 3.0, Waialua Bay 3.3., Kaiaka Pt.3.3, Kaiaka Bay 2.4, West side of Kaiaka Bay 2.4, Mokuleia Beach 3.6, West of Dillingham Airfield 4.2, Kaena Pt. Trail Head 3.9, Kaena Pt. Trail (west of railhead) 6.0, Kaena Pt. (Intermediate site along trail) 9.3, Kaena Pt. coastal plain 7.2, Kaena Pt. (old light house) 10.2 meters.

Table 1. List of 1946 Runup Values (in meters) by Site Name, (East to West along North Shore, Walker, 2004)

4.1 Historical background

The history of tsunami in the Hawaiian Islands (Daniel Walker, 1994) indicates that tsunamis with runup greater than 1 m have occurred four times during the last century. At Kahuku, the maximum 1946 tsunami runup was reported to be 7.0 m with a nearby measurement at 8.5 m (Shepard et al., 1950). Jagger (1946) reported that 20 waves from the 1946 Aleutian Tsunami were recorded on the Honolulu tide gauge. Some of the tsunami waves were sufficient to over-wash the sand dune ridge along the coast. A second tsunami in 1957 was reported to have reached 7.3 m high (Walker, 1994). A photograph of Kahuku Point coast, taken in 1968, shows that the Kahuku beach was nearly devoid of unconsolidated beach sands, at that time.

The 1946 Aleutian Tsunami took place 9 months after the end of World War II. The military command in Hawaii sent airplanes aloft to photograph the damage to the airfields in the coastal zone around the island of Oahu. The resulting photographs have proven to be extremely valuable resource information and they provide insight into the processes of tsunami inundation and drain-back. The aerial photographs were found in the Hawaii State Archives and scanned for this study. The goal was to analyze the images, delineate the tsunami inundation, observe tsunami-generated features, and to employ reconnaissance-level geologic fieldwork to examine the modern day distribution of the tsunami deposits. Aerial photographs of the vacant land prior to building the Kahuku air base were taken in 1940. The airfields and facilities were constructed largely with wooden buildings constructed between 1941 and 1942 (Allan, 1950). The aerial photographs of the Kahuku Air Base discussed here were taken during the 1946 tsunami and compared to aerial photography from 1951.

4.2 Methods of investigation

The Hawaii State Archives holds the Governor Stainback Photographic Collection, consisting of a folder of oblique aerial pictures of the 1946 tsunami damage. The collection contains numerous photographs of Queens Beach (S. Makapu'u Pt., SE Oahu), Kahuku Field, and a few other airfields. The locations of the photographs can generally be identified using known coastal features since no time code is available. It proved difficult to relocate all of the photographs without a base map. Many roads present in the photographs taken during 1946 have disappeared and are no longer on modern maps; also roads names have changed. Finally, a golf course has been built on top of the NE-SW runway. In an attempt to remedy this limitation, archaeologist Nancy Farwell, was able to provide copies of two schematic drawings of portions of the air base electrical systems. A 1943 Army Corp of Engineers map was also located (University of Hawaii map collection). Bath et al. (1984) included 3 pages of blueprints and aerial photos (taken in 1951) in an unpublished report. Prior to analyzing the photographs, a field expedition (Fig. 9) was organized to examine the study area. No unambiguous evidence of a past tsunami was obvious on the surface, largely due to overgrowth of vegetation.

The first iteration of the analysis focused on establishing the sequence of the photographs using the frame numbers present on most, but not all photographs. This examination revealed that there are two sets of images- wide-angle photographs and close-up pictures. The close-ups are mixed in the same numbering sequence as the wide-angle photographs. The second iteration of the analysis involved trying to relocate the photographs (in an over-lapping sequence) using common features, e.g., runways, control tower, a circular distribution of buildings, or large warehouses. From this study, three different areas of the

air base became obvious: the two long runways, the NE-SW runway (closest to Kahuku Pt. and 1920 m long) and the eastern runway (here called Kahuku Runway, 1500 m long) and the control tower located at the junction of the 2 intersecting runways. The air base east of the runways contained numerous white canvas tents and large wooden barracks. The warehouse district, furthest inland and at a seemingly higher elevation was not damaged.

Fig. 9. Elongate slabs (left) were situated at the modern shoreline. Several slabs of rock had been overturned leaving the dark (weathered) side down and the light side on top. In addition, a large coral-algal boulder (approximately 1 m across) was found in a back-beach setting.

4.3 Observations

The aerial photographs show that the airfield was extensively flooded. The flooding and deposits of white sand extends to the lower left corner of the photograph (Fig. 10), and they show sand transported a maximum of 1.6 km (1.4 miles) from the coastline and deposited along the landmark road (Brooks Drive). The tsunami waves overtopped the sand dunes and transported the sand (from beach and dunes) across the coastal zone, forming a large sheet of sand (Fig. 11 & 12). The NE-SW runway (Fig. 11) was also partially buried by sand transported landward by the tsunami flooding. Several of the buildings were washed off their foundations by the tsunami. The drain back of the tsunami waves carried the buildings near the coastline seaward.

At Kahuku, several military buildings seaward of the runways were moved off their foundations, into the entrance of one of the c-shaped ground works situated in the lee of the sand dunes, other buildings were transported and left standing in the middle and seaward edge of the runway (Fig. 11). The seaward flow directions are evident in the area where coastal vegetation was flattened (lower left in photo) and where plant debris was carried onto the beach (lower right of photograph).

Along the seashore, large ground-works were constructed to protected aircraft, with interior concrete walls. The tsunami stripped much of their vegetation from the seaward side of the structures and the ground-works were subsequently partially buried under a layer of sand. In addition, in the landward view (Fig. 13), it is clear that the sand sheet left after tsunami drain-back was extensive, extending across much of the air base. There is limited evidence that mega-boulders (i.e., boulder larger than 1 m) were moved by the tsunami (lower half of image). One mega-boulder was observed on the aircraft runway seen in close-up views. This mega-boulder is also present in photographs taken in a post-tsunami survey by Shepard et

al. (1950). Wooden military buildings situated landward of the runways were washed off their foundations in a landward direction (by incoming waves). When several buildings were moved, they often collided so that they were literally stacked one upon one another (Fig. 13).

In the upper and center portion of Fig. 14, gray areas of ground are visible on either side of an area that was scoured and the sand transported seaward during the tsunami drain back phase. In this gray ground, there appears to be an exposure of the gray hard-ground (weathered coral and algal reef) and cemented beach-rock that can be seen today exposed at the beach. Between the stripped surfaces, an area of white rock and sand is exposed. At this site, evidence can be seen that the erosion due to drain back has been localized. In addition, the drain back was focused in low ground and pre-existing drainages. This localized drain back produced a desultory geologic record of tsunami wave activity. In Hawaii, residential buildings of the 1940's were traditionally built with single wall construction. During tsunami inundation, these homes often have the walls collapse and the roof fall intact to the ground. Few of the military buildings however displayed this problem, indicating that different building standards were used. Some of the wooden buildings were built on concrete foundations, and the vacant foundations can easily be identified in photographs. Other barracks buildings that were situated further inland, appear to have been built on the ground, leaving slightly different traces.

The aerial photographs show little debris scattered on the ground. Reports in the *Honolulu Advertiser* (1946) indicate that World War II surplus supplies and equipment were being sold or shipped out of Hawaii when the tsunami took place. The majority of the airfield buildings were probably empty by April 1946. Abundant material from the air base was incorporated into the sediments (Bath et al., 1984).

Observations from Aerial Photographs: Buildings can be carried either seaward or landward, Collisions of building against building obvious, Debris occurs locally near damaged buildings, Foundation are exposed, Sand sheet covers inundation zone, Sand Dunes were lowered or removed and the sand was transported elsewhere, One giant boulder was observed, Tsunami Flooding left some buildings flooded to the eves of the roofs. Walls washed away, Glass broken by tsunami flooding, Items having buoyancy, e.g., wharfs, lawn furniture, etc. were washed away, Vegetation was killed, damaged or bent over parallel to the drain back direction, Salt waters penetrated the ground, making agriculture ineffective until the rains washed out salt from the seawater.

Geologic Impact: Deposition of a large sand sheet, Scouring of the reef surface, and erosion of tens of feet of dune sand (measured laterally from the beach, Adams, 1977), Deposition on reef surface, Minimum inundation was l.6 km inland.

Human Impact: One person died within the Marconi or RCA Building at the Kahuku Air Base (p. Comm., Dan Walker), 150 people dead and 163 badly injured or missing in the Hawaiian Islands and $25 million dollars of property damage (Shepard et al., 1950).

Table 2. Tsunami observations and impact

Fig. 10. This oblique aerial photograph (Frame 71 close-up photograph, taken after a tsunami wave drain-back) shows the junction of the NW-SE Runway and the Kahuku south runway. The Flight Control Tower can be seen near the center and left in the bottom quarter of this photograph. The runways are largely covered by a sheet of sand derived from the beach and coastal dunes. The large square in the photograph with white debris and small trees near the center (bottom) of the image appears to be a garden (?) with walls toppled by the tsunami. A rectangular, wooden building lies at the middle of the sand-covered runway.
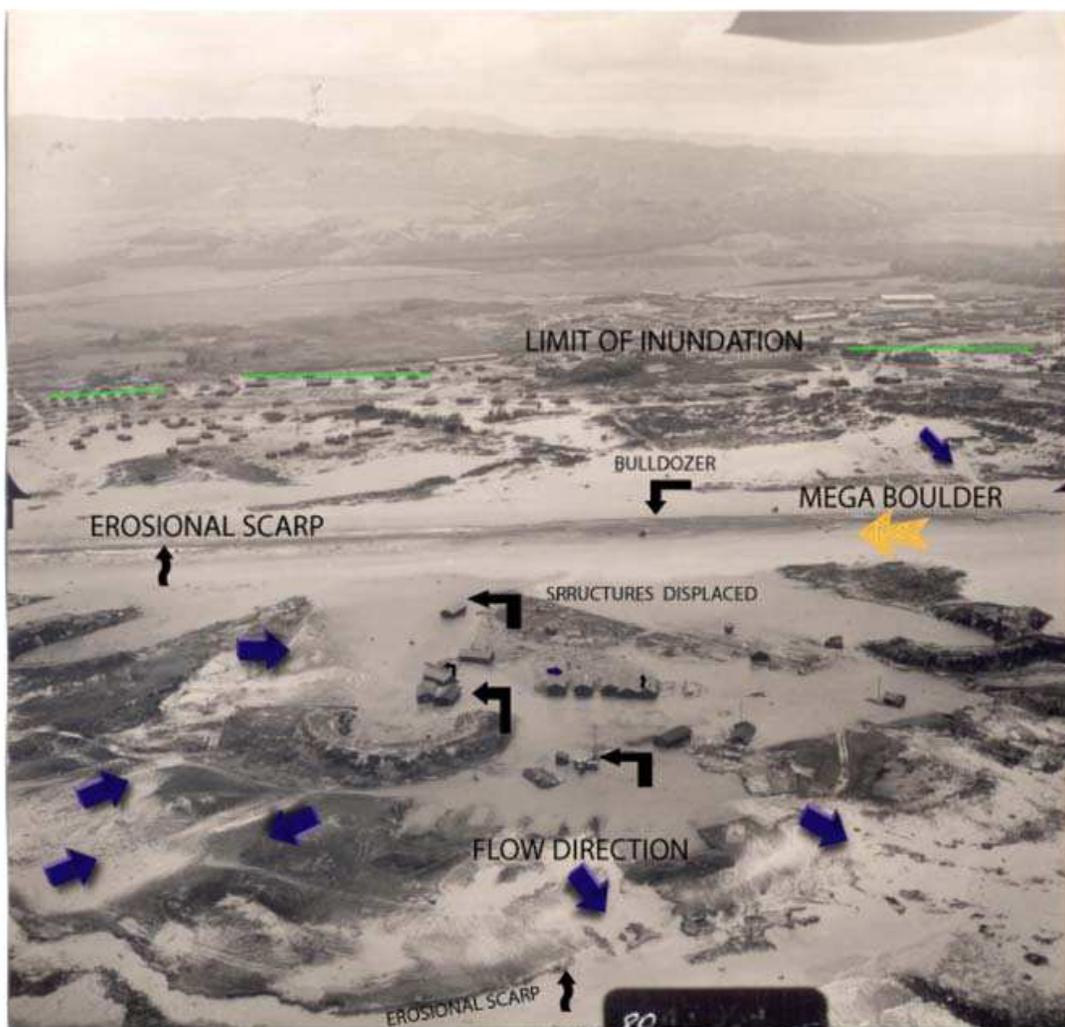
Fig. 11. Looking landward in this oblique aerial photograph (Frame 80), it is clear that the sand sheet left after tsunami drain-back was extensive, extending across much of the air base. The sand sheet completely buries the NW-SE runway. A line on the image marks the limit of inundation. There is a mega-boulder that is comparable in size to a bulldozer sitting nearby on the runway (right-center). An erosional scarp can be seen at the landward edge of the runway. The bent arrows, at the bottom of the picture, mark the displaced buildings. Broad arrows, at the lower edge of the picture, mark the seaward (drawback) flow directions. In the former dune ridge, hard ground having a marked seaward erosional scarp is evident as dark areas in the bottom of the photograph. The drain-back direction can be identified (lower right of photograph) where plant debris has been carried on to the beach (marked by a broad arrow).
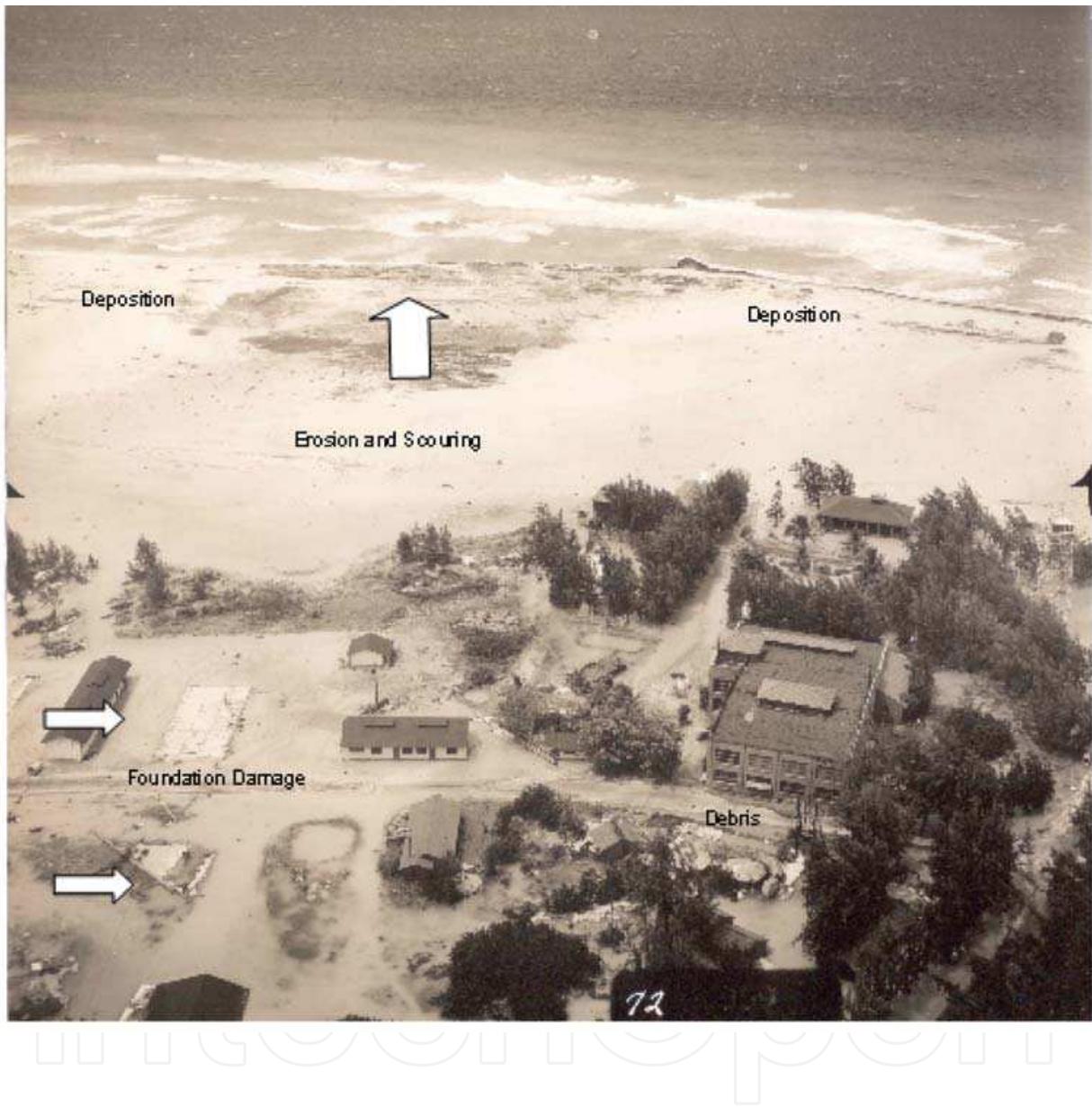
Fig. 12. In this oblique aerial photograph (Frame 72, seaward-looking direction) the flight control tower can be seen at the right and center edge of the photograph. Water is standing on the ground near the buildings. The NE-SW Runway lies buried seaward of the buildings (upper half of the image). On the left, bottom corner of the photograph, the foundations of three building can be seen (bright white areas). In the upper and center portion of the photograph, a gray area is visible. This shore appears to be the underlain by gray hard-ground (weathered coral and algal reef, and beach-rock) that was scoured and exposed during tsunami drain back. On either side of this area, the sand sheet remains intact.
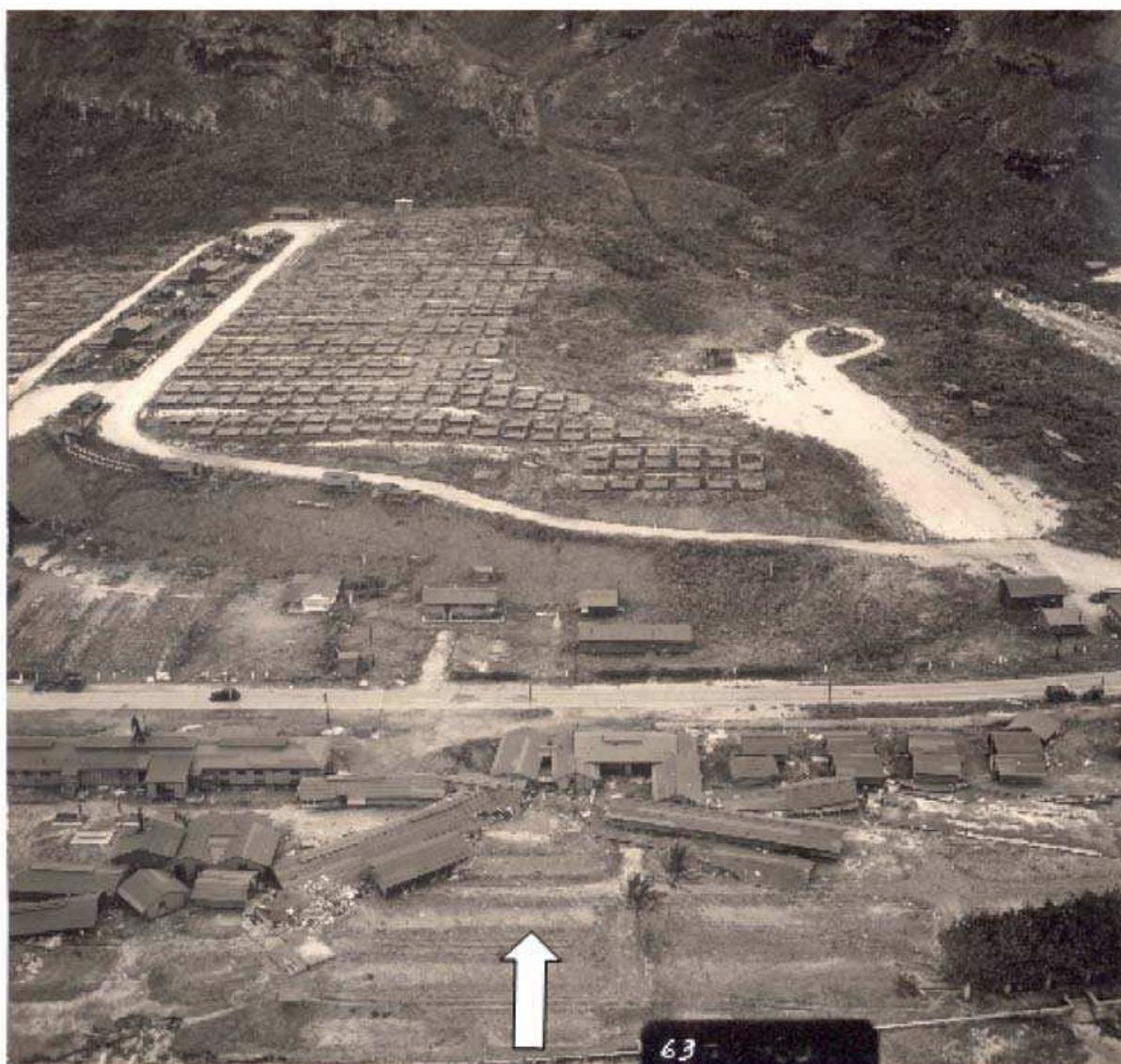
Fig. 13. The aerial photograph (Frame 63, taken during a drain back phase) shows a barracks area (in the lower portion of the picture) and a tent barracks area (upper portion of the photograph). At the bottom center, several buildings have collided with one another. (The precise location of this photograph is unknown. The frame number is appropriate for the Kahuku area and the layout matches a fragment of a map (also from Kahuku). The arrow at the bottom of the image indicates the inundation direction.
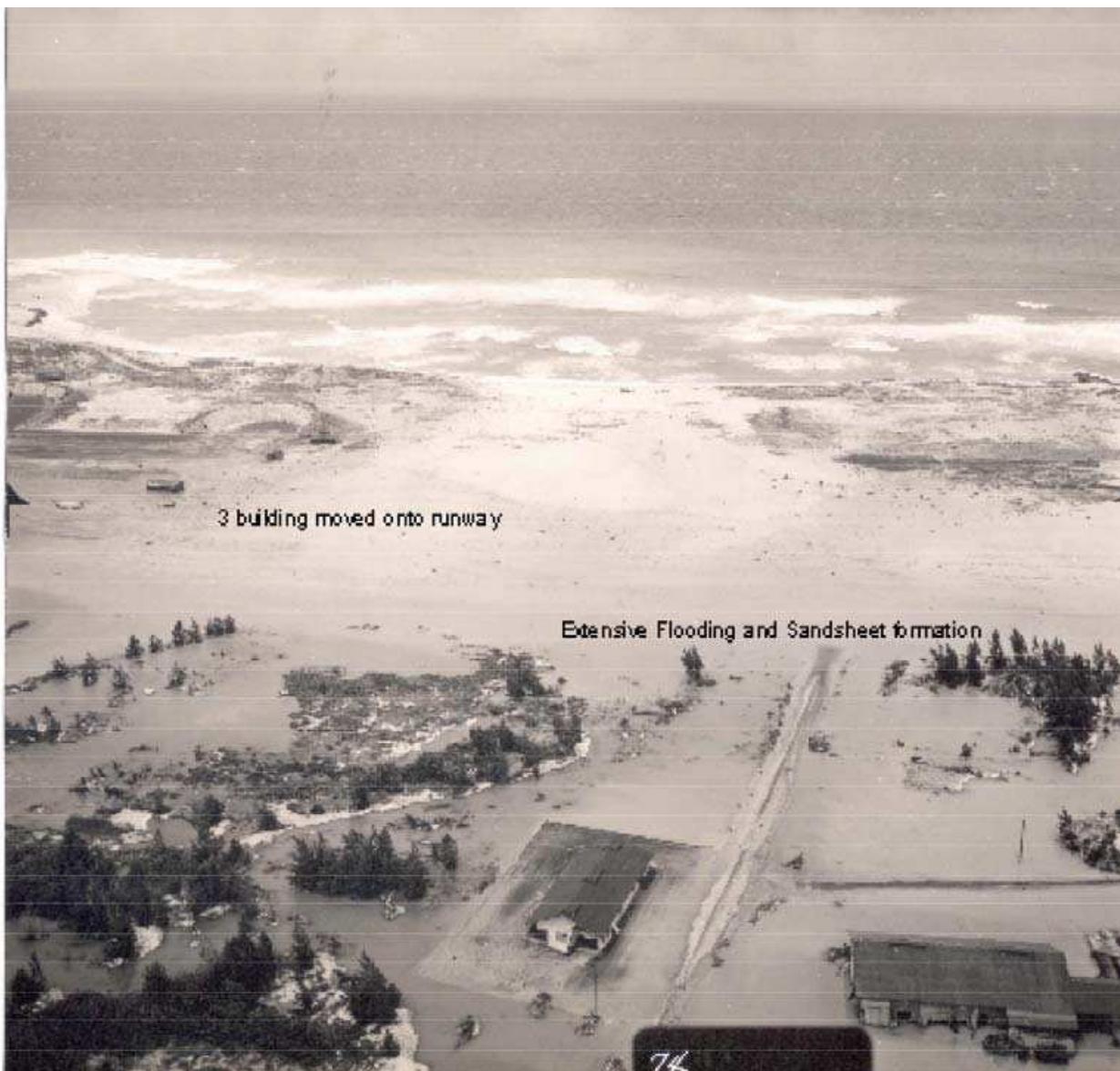
Fig. 14. The oblique aerial photograph (Frame 78, was taken with a seaward-looking view, during the drain back phase) shows evidence of extensive flooding. The flooding and depositions of white sand extends beyond Brook Drive (lower left corner). The inundation measured from Brooks Drive to the coastline is 1.6 km (1.0 to 1.4 miles). Compare this image to Fig. 12 (Frame 72) to see the extent of the water standing on the ground.

Following the tsunami, the vegetation was killed or damaged by the physical effects of the flooding or by damage done to the flora by salt in the water. The seawaters penetrated the ground, making agriculture nonviable until the rains wash away the salt. Effects of the tsunami on vegetation can best be seen in a photograph published in the *Honolulu Advertiser* (04-03-1946, p. 11).

Since the tsunami took place 9 months after the end of WW II, the extensive damage to the base lead to the facility being abandoned, eventually the land reverted to the State of Hawaii and the Campbell Estate. Some of this land has since been converted to the James Campbell Wildlife Refuge, while the Campbell Estate continues to push for permits to build 4 or 5 Condominium buildings on the site most vulnerable to tsunami damage.

Based upon the study of the aerial photographs a model is suggested to describe the processes associated with tsunami activity. Five phases of activity are outlined in Fig. 15, however, since there are multiple waves in a tsunami wave train, thus the full sequence is repeated. During Phase 1, the leading wave is a negative, meaning the sea recedes (N-wave). The first wave, of course, can be either positive or negative (thus this phase may be absent). During Phase 2a the tsunami inundates the inter-tidal zone and beach face. During Phase 2b, the tsunami inundation reaches the back-beach. Phase 3, the stand still phase, is when the water movement reaches a near-zero velocity, and any sediment suspended in the water is deposited. After the stand still, the drain down phase, Phase 4, takes place. As the tsunami waters drain back to the sea, they channelize and erode the underlying deposits. Phase 5, represents a phase that may or may not be present, that is when an incoming wave overrides the outgoing wave. The profile below illustrates the additive nature of the tsunami wave height. This entire sequence of activities will be repeated multiple times.

4.4 Archaeological studies

The archaeological survey of the Kuilima Resort Project by Bath et al. (1984) is an extremely valuable source of information and provides insight into the processes involved in tsunami inundation. The report, written in 1984, predates modern geological studies of tsunami, thus the observations were strictly interpreted in archaeological terms, e.g., if a layer contained human bones or modern or ancient artifacts it was designated a cultural layer. Despite this, evidence of modification was obvious and restated repeatedly through the report (available in the Hawaiian Collection, University of Hawaii Hamilton Library). Bath et al. (1984) carried out a subsurface archaeological survey, for the Campbell Estate Resort Expansion Project at Turtle Bay (western portion of the airbase), which documents the nature and distribution of sediments in the study area. The field study involved subsurface sampling of several sites as well as a general subsurface reconnaissance. The majority of the subsurface sampling was done with augur sampling. In areas associated with surface drainages, the field crew cut the surrounding banks back to obtain an exposure of the underlying rock.

4.5 Observations

At Kewala Bay, modern aeolian sand or mixed deposits were found overlying the cultural horizon (layer containing artifacts of occupation). Furthermore, the thinness of deposits and their position at the surface indicated some truncation had occurred. A representative profile for this area consisted of (top to bottom): 30 cm of fine silty calcareous sand, with roots common and a smooth but abrupt boundary above 30-150 cm of calcareous sand with common coral fragments. A Soil Conservation Service stratigraphic profile lists three C-horizons. In some profiles, a layer 10 cm thick, contained coral fragments, a bone fishhook, several artifacts, a fragment of human bone, and charcoal.
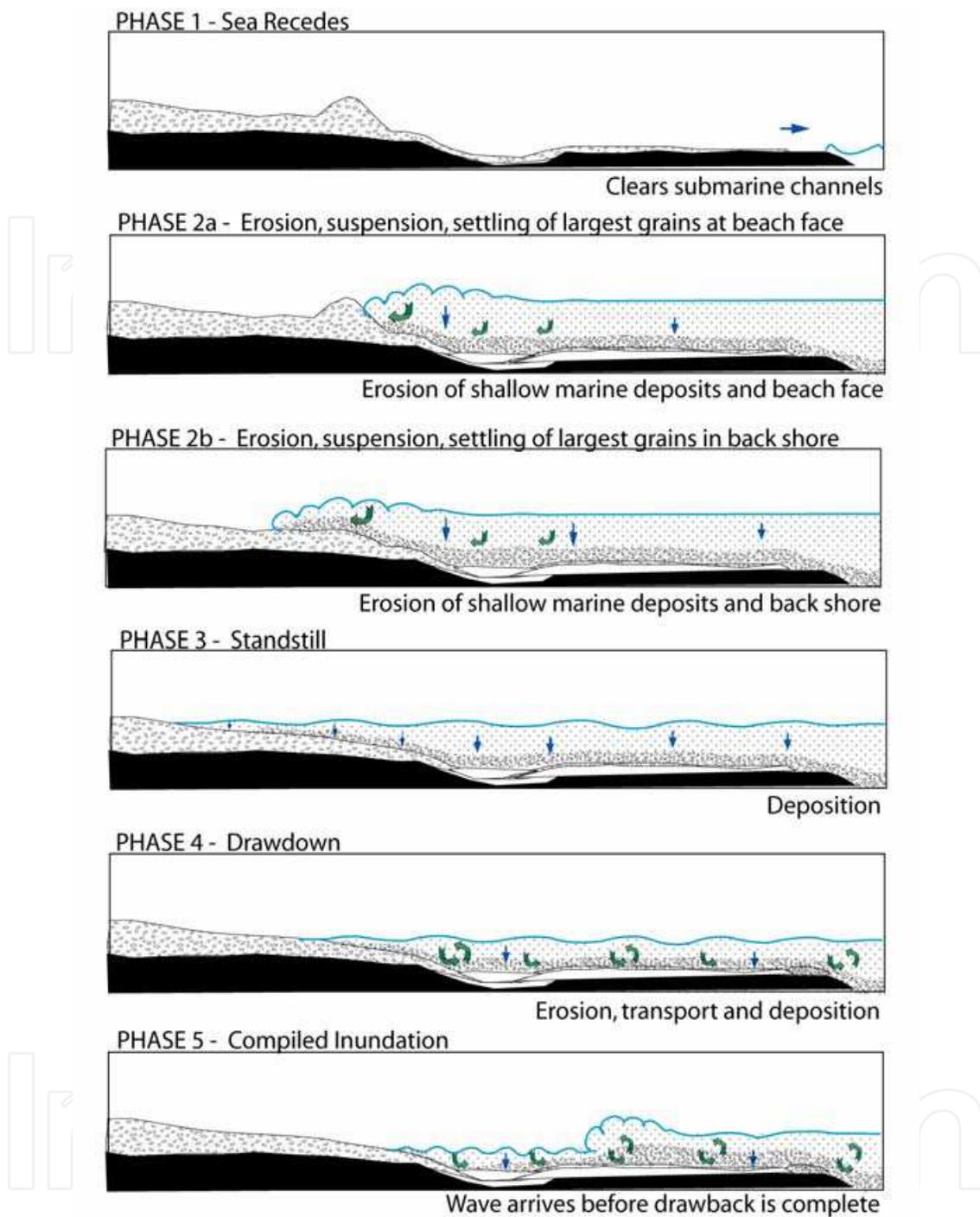
Fig. 15. Above: A series of five illustrations are used to describe the processes associated with tsunami activity. Phase 1, (top panel) the leading wave is a negative, meaning the sea recedes (N-wave). The first wave, of course, can be either positive or negative (thus this phase may be absent), Phase 2a (next panel; top to bottom) shows the inundation of the inter-tidal zone and beach face. Phase 2b, or the inundation in the back-beach. Phase 3, the stand still phase in which the water movement reaches a near-zero velocity. Phase 4, the drain down phase when the tsunami waters drain back to the sea locally in channels. Phase 5, an incoming wave overrides the outgoing wave. This profile illustrates the additive nature of the tsunami wave height.

Along the Kawela Stream Alignment, the B-horizon clay deposit contained charcoal and other flecks of organic material. Three distinctly different stratigraphic profiles were discovered. Inland from the beach, there is substantial alluvial sedimentation. Two units containing angular blocky structure were found from 1-80 and 80-140 cm. It was suggested that at some time in the past the drainage channel had been scoured. Flecks of organic material were thought to represent material from former agricultural activities or natural processes, rather than occupation.

At the Turtle Bay Beach situated behind the berm, the sampling found a remnant pocket of an older deposit. The archaeologists interpreted the stratigraphy as implying that the beach berm had been reworked by wave action in the possibly recent past.

On the east side of Kulima Point, sampling along the berm revealed, "lens of darker sand" at various depths. Between 50-265 cm, the sand layer contained shoe leather, modern glass, and cement fragments. Along the coastal stream alignment, inland of the berm, a buried horizon contained ironwood cones and needles (Ironwood trees were introduced to Hawaii during the 19th century). Bath et al. report that the beach berm itself does not appear to be a natural deposit (Kraft, pers. comm.). In other profiles, a typically fine-grained calcareous beach sand became progressively coarser with depth.

West of Kahuku Point, a minimum of 2 and maximum of 3 layers were found containing cultural material, buried beneath sand. Unit 3, a calcareous sand with dark charcoal, was found from 35-47 cm, and Unit 4, a fine to crumb sand with charcoal, at 47-60 cm, contained aluminum pop-top tabs. The archaeological report suggests these layers may well be

> **A: Unit: Historic event:** 1946 Aleutian Earthquake and submarine Landslide? **B: Author:** Keating (2008) and this paper **C: Age:** 1946, **D: Place:** Kahuku, NE Oahu, HI, **E: Deposition:** sand sheet, **F: Sorting:** Normal, **G: Soil** A, B, C, and Layers, **K. Fine grain component:** beach and dune sand, **L. Coarse grain component:** "crumb" or pebble, and blocky structure, **M: Boulders:** limited, **N: Rip up clasts:** "some clay films on some ped faces" by Archaeologists Bath et al (1984), **O: Marine Conglomerate:** called midden remains by Archaeologists, Bath et al (1984); **P: Upper Boundary:** desultory, **Q: Couplet:** Sand and coral fragments on clay or peat, **R: Lower Boundary:** abrupt smooth boundary, **S: Nature of basin**: open coastal plain, **T: Environment:** beach and sand dunes, and back beach, **U: Matrix:** Sand, **V: Geomorphic Change:** offshore reef alternately covered with sand then scoured free of sand, **W: Layers:** 3-5, **X: Thickness:** roughly 20 to 200 cm, **Y: Run-up:** 6 m or 24 ft., **Z: Inundation:** 1.6 km or 1 mile, **AA: Publication:** Conference Paper and Field Trip Guide, **AB: Dating:** Observed 1946 Tsunami Event, and Carbon dated organic material 3,865 BC. to 1630 A.D. Bath et al (1984), **AC: Archaeological Site?** Yes, and human burials, **AD: Location:** between Kahuku town and Turtle Bay, **AE: Latitude** 21° 41′ N; **Longitude:** 157° 59′ W, **AF: Erosion Features:** Scoured ground surface, scoured river drainage, abrupt boundaries between units, **AG: Vegetation:** Damaged by salt water and flooding, **AH: Wave Height:** 7.5 m (Adams, 1977), **Number of waves:** 20 in Honolulu (tide gauge), **AI: Sampling:** Reconnaissance Archaeology by Bath et al (1984) over 100 auger holes and cut or trench sections, **AJ: TDDB #** 1001, **AK: Notes:** The study area (Kahuku Field) was a large Air Base during World War II.

Table 3. Characteristics of 1946 Tsunami Deposits on NE Oahu (Tsunami Deposit Data Base Format per NOAA Geophysical Tsunami Data Base)

intrusive. Charcoal and midden material was retrieved from deeper layers. The report states that the Turtle Bay area and Kulima Point area both provide evidence that these areas were recently modified by storm activity [here interpreted as disruptions that resulting from the 1946 tsunami].

At the west side of Kahuku Point, calcareous sands were found with sparse charcoal and human skeletal material (not in-situ) and abrupt but smooth boundaries, at 50-70 cm the remains of a fire pit (of blackened stones) were found. A single flake of volcanic glass and a rusty metal fragment were found at 0-12 cm, a shell casing and a carbon rod were collected at the surface. Other military artifacts were found on the beach. At a proposed water hazard on the current golf course, the surface layer contained broken glass, leather, a wooden post, glass bottles (3 ink bottles, 3 pickle/preserve bottles, 2 medicine bottles), a nail, a single piece of shell and a ceramic insulator. The surface layer consisted of humus with a crumb structure, a sandy loam with fine angular to sub-angular blocky structure, underlain by sandy clay, all with very abrupt but smooth boundaries. A stratigraphic section along the railroad right of way contained inverted stratigraphy, and assigned a construction related origin.

Four sites were described as coastal midden remains, and contained: gastropods, bivalves, echinoderms, crustaceans, bird fish and mammal bones and land snails, kukui nuts, and charcoal. Thus shallow water, reef, land animals, and vegetation were recovered. Dating studies suggest transport of alluvium from the uplands down to the coastal plain. Additional sites to the south of the runways are not described here for brevity sake. They describe peat and clay units, underlying sand, near the Punahoolapa Marsh.

4.6 Discussion

Modern studies of tsunami sediments (Keating et al., 2008) now allow us to characterize tsunami deposits. The deposits described by Bath et al. (1984) share characteristics with other known tsunami deposits. Bath et al. (1984) interpreted the thin layers (10-20 cm thick) at the surface as indication that some truncation had occurred. Similarly, roots were common in deposits as well as flecks of organic matter. The lower boundaries of the sedimentary units were abrupt but smooth. Sands contained a mix of common coral fragments; artifacts, human bones, shell or broken coral that were described as not being in-situ. Remnant pockets and lens of older (clay) sediments were found in stratigraphic profiles. The beach berm was reworked. Layers that contain cones, needles, seeds and tree trunk were found. Sand units were described with normal sorting (fining upward). Sedimentary layers contained crumb or irregular angular and blocky structures. Some sedimentary units contained mixed assemblages of organisms from different environments (shallow water, reef and land). The program also found a stratigraphy of sand overlying clay, and/or peat. All of these characteristics are consistent with reworking associated with tsunamis.

5. Boulders deposits

The North Shore of Oahu has routinely been exposed to tsunamis as well as large seasonal storms. Both events are capable of moving boulders. When compared to other published reports, these Hawaiian storms and tsunami have transport parameters in the lower range of published values. Noormets et al. (2002, 2004) published studies of large boulders at Shark's Cove on the North Shore of Oahu. The field studies were augmented by the laboratory study of a set of aerial photographs. The observations from Kahuku Point, thus allow us to extend the initial Shark's Cove studies by Noormets et al. and provide insight into the nature and

carrying power of tsunami and storm waves. By comparing the geomorphology, rock units, and types, numbers, and distribution of boulders on the North Shore to deposits elsewhere, it was observed that both Hawaii and Rabat, Morocco, display similar geologic features, that reflect the sea level change along a coastline dominated by calcareous rocks.

The winter swell of 2006 provided an opportunity to test whether giant winter surf could move boulders and mega-boulders. The wave climate in Hawaii includes swell heights that can reach a maximum of ca 14 m or face heights of about 24 m (Noormets, et al. (2004). During the winter of 2006, the mega-boulders at Shark's Cove were photographed. In Dec 2006, the high surf associated with a winter swell produced waves that reached 14 m high at Shark's Cove. The same boulders were again photographed one month after the storm. During the storm, heavy surf broke at the outer margin of the reef platform, and flooded over the platform and around the mega-boulders. The flooding of the reef platform (between 1-2 m deep) rose to roughly half the vertical dimension of the largest mega-boulder at Shark's Cove (Fig 16).
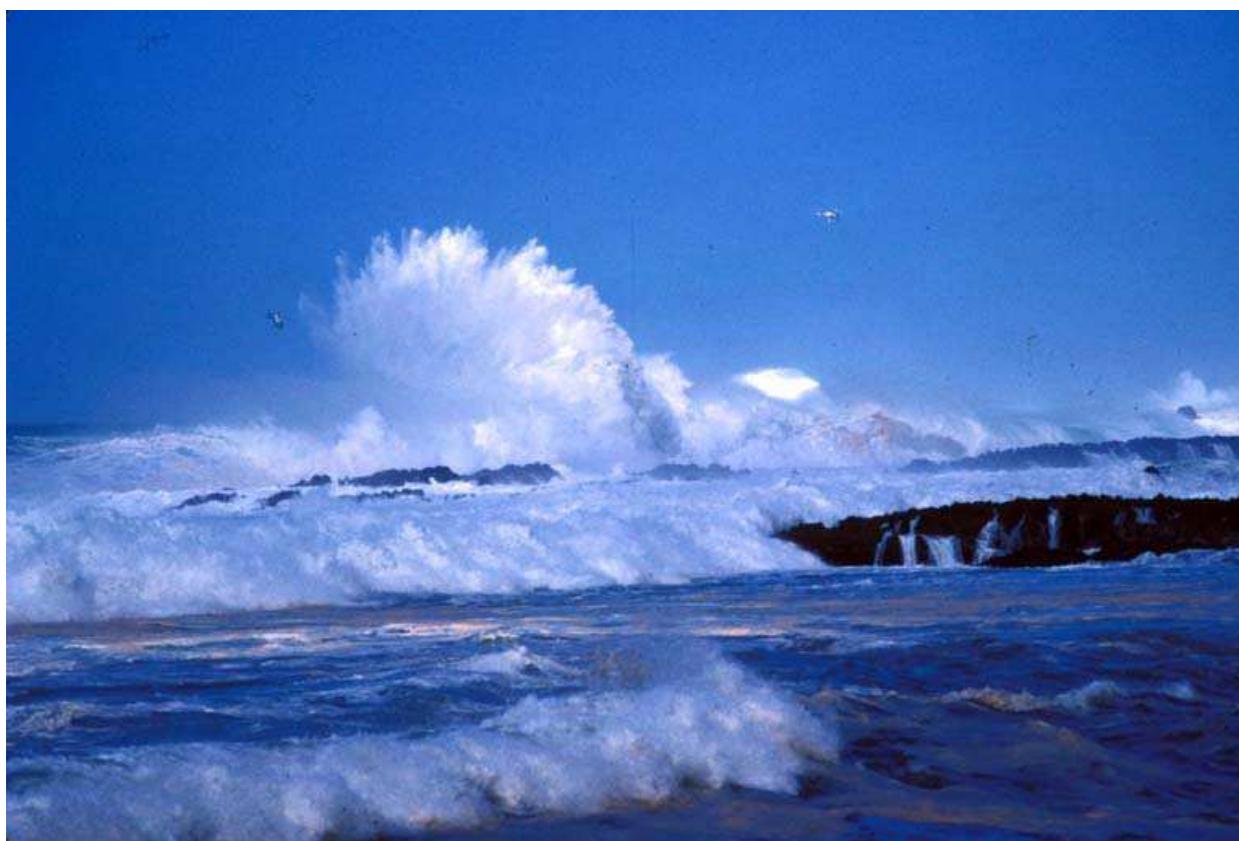
Fig. 16. A photographic image of the surf breaking on the edge of the reef at Shark's Cove, during the 2006 giant swell.

The mega-boulders at Shark's Cove are porous, i.e. contain many cavities filled with air, and consist of low-density rocks. By comparing "before" and "after" photographs, no clear or significant transport of mega-boulders could be identified. However, the largest mega-boulder shows evidence of limited movement. Six large nails (ca 20 cm long) had been driven into the reef near the bottom of the largest mega-boulder. After the winter storm, five out of the six nails were gone. While the winter surf did not substantially transport the mega-boulder, it appears that the mega-boulder did jostle around on the reef surface, to a

degree sufficient to remove the nails. The largest of the mega-boulders sits in a shallow depression, it appears to have remained roughly in the same position but ground down the shallow depression. The roughness of the platform (which is significant) obviously plays a part in boulder transport or absence thereof.

Fragments of rock were plucked from the leeward side of the mega-boulders, exposing a white colored interior. The surficial scars occurred on the lee side of megaclasts, at their base, midsection, and upper edge. In addition, many more (cobble size) rock fragments were present in the micro karst pits on the shoreward side of the platform after the storm. The extreme swell did erode the boulders and platform but only in a limited fashion.

At Kahuku a mega-boulder moved by the 1946 tsunami was seen in the aerials photographs, roughly the size of a bulldozer. Observations of the tsunami damage associated with the 2004 Indian Ocean Tsunami in the Maldive Atolls shows that tsunamis can deeply scour poorly consolidated sediments around dug pits such as toilet trenches, water collection trenches, etc. Thus, it is possible that the mega-boulder observed on the runway at Kahuku was plucked from the poorly consolidated sediments around the edges of the runway during runup and was not transported a great distance. Thus, the transport of this boulder may be a "special case" related to tsunami scour of a poorly compacted man-made feature.

Boulders on the order of 1m in diameter were also observed on the airfield runway. In addition, 0.5 m size boulders were observed in another photograph and another phase of the tsunami. The latter appears to be a relic deposit of isolated boulders where the sand size portion of the feature was winnowed away from the boulders. The deposit is widest inland and narrowest at the beach where the margins are marked by vegetation debris with drain back of a tsunami wave. The 1.5 m cores collected from the Kahuku-Turtle Bay area for archaeological evaluation (Bath et al., 1984) show desultory sand units bounded by erosional conformities and containing: metal roofing material, bone fragments (from ancient Hawaiian burials) and vegetation (including trunks still standing).

5.1 Comparison of geologic features

Mhammmdi et al. (2008) describe mega-boulders situated along the Rabat Coast of Morocco and suggests that the emplacement of the boulders was associated with the Nov. 1st 1755 A.D. Lisbon Tsunami. The emergent deposits exposed along the Kahuku shore (Fig. 17) are very similar to the descriptions of the lithified dunes of Morocco, in terms of the geomorphology, rock units, and types and numbers of boulders. We compare the Rabat observations to that of the North Shore, where the coastline is exposed to tsunamis as well as large seasonal winter storms. The comparison shows that the sites have similar geologic settings, distribution of large boulders upon platforms, and similar types and groupings of large boulders.

When the schematic cross-sections are compared (Fig. 20) to that of the North Shore of Oahu, both coastlines are characterized (seaward to landward) by: 1) An offshore "Plateforme a vasques", 2) A notch at modern sea level, (3) An ancient rock unit with a karst surface, (end of the Ouljian in Morocco and Pleistocene Waimana high stand in Hawaii), 4.) Red soils containing land snails in Hawaii and Morocco (Soltanian red clays in Morocco), 5.) a thin lithified rock unit with karst surface, 6.) Boulders or slabs on top of the wave-cut platform, 7.) Modern unconsolidated sand beaches with poorly lithified beach rock in Hawaii, generally containing microfossils as old as 5 kya in Hawaii, 8.) The modern sand dune ridge, (Flandrian/Mellahian, 5,000-6,000 yrs in Morocco), and 9) A dune belt (dated at 114-122 kya at Kahuku, Oahu).
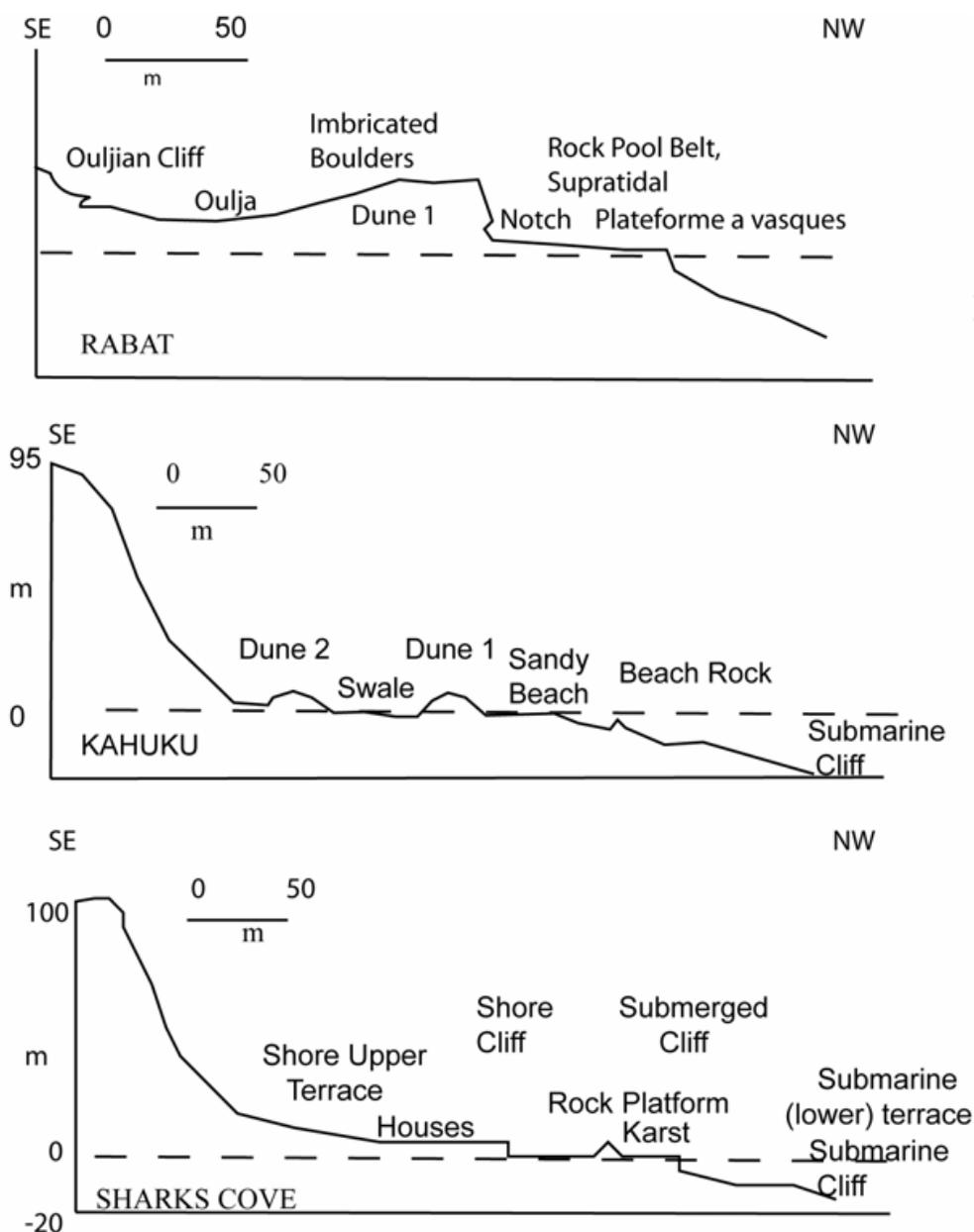
Fig. 17. Comparison of the schematic cross sections of Rabat Coast (Morocco, at top) with that
of Kahuku Point of Oahu (middle) and Shark's Cove (bottom). The dashed line marks sealevel.

At Rabat, Morocco, the coast consists of relatively small sand beaches separated by rocky
cliffs and lapiezed platforms. The area displays great biodiversity with species that modify
the development of the landscape by their construction and bio-erosional activities. In
Morocco, the morphology of the coastal dune system has been divided into two types: a
generally flat "dissolution-driven type" and a mechanically driven type. Mhammdi et al.
(2008) point out that the "dissolution type" can be broken down into several zones. They
include: 1) lapiez and pools, 2. "Plateforme a vasques", and 3) the area of break-up of the
Plateforme a vasques. The salient points of the Mhammdi et al. (2008) description are
compared to similar morphological features observed on the north shore of Oahu in Table 4.
Mhammdi et al. (2008) describe large platy boulders (slabs) that sit upon the coastal
outcrops. The weight of the boulders ranges from a few tons to 100 tons. Several types of

arrangements were observed: single boulders, imbricate boulder trains, large chaotic clusters, or more rarely trains or ridges, with the amount and arrangement of the boulders quite variable from one site to another. The dimensions range from large blocks 3 to 6 m in width and a maximum length of 8.4 m. Noormets et al. (2002) and Whelan and Keating (2004) observed: solitary mega-boulders (Fig. 18), as well as a large chaotic cluster, and imbricate clusters. At Kahuku Point, we see a chaotic cluster of slabs one to two meters long with largest dimension of one to two meters. In addition, the boulders in Morocco occur above the shore cliff. In Hawaii, the mega-boulders were described by Noormets et al. (2002, 2004) and lay on the rock platform adjacent to or within meters of the modern sea level rather than on cliffs.

Fig. 18. This photograph was taken after heavy winter surf (8 m wave face). The extreme waves broke at the edge of the carbonate platform (at left) and then flooded on the platform to roughly half the height of the mega-boulders without significant displacement of the boulders. A branch of a tree has been washed in and trapped at the base of the rock. A walking stick can be seen in the lower right. Six large nails (several cm long) had been driven into the reef along the bottom of the "mega-boulder" prior to the winter storm (source unknown). After the winter storm that took place less than one month later, five of the six nails were gone.

Like Rabat, the boulders at Kahuku Point are derived from the coastal rocks; their source is the fractured rock pool belt, the lithified sand dunes and fragments of platy beach rock. The boulders and outcrops show vermetids, carvings of sea urchins, seashells, encrusting corals and thick algal layers. The exposed fractures within the rocks at Kahuku Point are numerous and many incipient boulders appear perched along fracture surfaces, with the narrow pedestals of the rock between them sometimes intact.

The boulders at Kahuku Point are significantly smaller than those at Shark's Cove. The boulders at Shark's Cove are a mixture of mega-boulders 3-4 m in diameter and weighing 1.5 to 96 tons and boulders of lesser size. At Kahuku and Shark's Cove (15.3 km away) we find the amount, arrangement, and sizes are also quite variable. Mhammdi et al. (2008) suggested the greatest number of boulders occur where the platform is widest. A similar relationship is observed at Shark's Cove and Kahuku Point, Hawaii.

5.2 Quantitative assessment

Mhammdi et al. (2008) applied the general formula of Noormets et al. (2004) in order to assess the role of breaking waves in the displacement of boulders. In the Rabat case, the scenario used was that of a joint bounded block (as described by Noormets et al., 2004). Mhammdi et al. (2008) report that the lift required in order to overturn a ten-ton boulder would require a storm wave of at least 18.5 m. They concluded that because the weights of mega-boulders in South Rabat were in the 20-100 ton range, that storm waves could be excluded. These authors believe that only tsunami waves would be capable of overturning boulders due to their higher flow velocity.

Mhammdi et al. (2008) applied the formula to estimate the height of waves on a platform. They found the tsunami waves were capable of moving the blocks much further than storm waves, largely related to the longer period of the tsunami wave. They also applied the formula for quantifying the energy of displacement of a boulder. The resulting value is called the Transport figure (Tf). They reported a Tf of 3,000, for a twenty-ton block transported 150 m (taking into account the height reached). They also report a Tf value of 1,500-6,000 for a 30 to 60 ton block moved 10-20 m inland to an elevation of +5m.

Noormets et al. (2004) examined the forces necessary to dislodge and transport a mega-boulder at Sharks Cove, a distance of 20 m and concluded that "balancing the overturning and resisting moments, show that breaking swell waves as well as turbulent bores are capable of quarrying large clasts from the edge of the cliff given that sufficient fracturing is present." Noormets et al. (2004) suggests, "the large number of clasts on the sea floor suggests that waves of the breaking swell were capable of quarrying the megaclasts but are seldom capable of emplacing them onto the platform… However the historical records exclude a tsunami as a viable transporting event for the most recent 30 m movement of the megaclast to its current location."

Parameters affecting the transport of a boulder include: weight, shape, density, porosity, water velocity, water depth, duration, roughness of platform, steepness of beach, direction and rate of flow, etc. Scheffers and Kelletat (2005) studied the tsunami relics in the coastal landscape of Portugal. They found: single large isolated boulders, imbricate boulders, boulder ridges, pebbles and shells high above the modern storm level, etc. They conclude, "There is only one force which can move boulders of this size high above the surf line, namely tsunami waves" (reference is to boulders weighing 10-20 tons at ca 29 masl).

Studies suggest that the shape of the boulder is critical both to quarrying and to transport. In Hawaii, e.g., at Shark's Cove and Kahe Beach (SW Oahu), many boulders and mega-boulders break from pre-existing fractures and eventually fall from cliffs without being transported. Since many of the boulders near the shore have fallen from outcrops, rather than being actively pried off, or quarried away from the reef by wave energy, many of the assumptions made by Noormets et al. (2004) would not apply.

It is possible to examine additional information from Hawaii based upon several examples (see Table 4): (1) 0.45 m diameters round coral, entrained in the surf at Waimea Bay, Oahu. 2) A 1 m diameter round coral and conglomerate at Kahuku Point, 3) A 2 m slab of sandstone moved 3.5 m inland, and 2 m upward by storm waves, Kahuku Point. 4) 0.5m round boulders moved 15 m inland, and 4 m vertical, during a winter storm (the boulders were thrown up from the ocean and filled the lower story of a condominium).

The use of a "Transport figure" (Tf) is a method of quantifying the energy of displacement of a boulder as has been shown by the Scheffers and Kelletat (2005) equation:

$$Tf = W \times D \times V \tag{1}$$

where W is weight (tons); D is distance moved (m), and V is the vertical distance (m). The value of 2,000 is considered the upper limit of storm wave transport energy. To compare the observations in Hawaii with those reported elsewhere in the world, boulder volumes were estimated and appropriate densities between 2 gm/cc and 3 gm/cc were assigned to each boulder depending on rock type, lithification, and amount of porosity observed on the surface faces. Our results, along with two of Mhammdi's examples, are shown in Table 4.

Mhammdi 1	W= 20 tons	D=159	V=	Tf = 3000	Petit Val d'Or
Mhammdi 2	W= 30-60	D= 10-20	V 5m	Tf = 1,500-6,000	Average
Winter Storm	W= 0.3 tons	D= 15 m	V=2 m	Tf =5.0	Waimea Bay
Tsunami ?	W= 2.68 tons	D= 6m	V=2.1	Tf = 33.8	Kahuku Point
Winter Storm	W= 28.8 tons	D= 6m	V= 2m	Tf =28.8	Kahuku Point
Winter storm	W= 90 tons	D= 20m	V= 0.5	Tf = 900	Shark's Cove
Winter Storm	W= 0.3 tons	D=15 m	V=4m	Tf =39.4	Kona, HI
Winter Storm	W= 1.6 Tons	D=13	V=4m	Tf =83	Kona, HI

Table 4. Comparison of mega-boulder Transport Figures from Morocco and Hawaii

With the exception of one large boulder, the sizes moved during storms were restricted, ca. 1 m or less, and the transport figures were small varying from 5.0 to 83. The Transport figure, Tf, for the Hawaii data set (Table 4) was combined with those of Scheffers and Kelletat (2005). Table 4 shows that the Hawaii storm data clustered at low values; while the data associated with tsunami have higher Tf values and larger block sizes. While, the Tf

numbers are small and seemingly insignificant the observations are important since they are associated with a known (rather than inferred) storm origin.

6. Discussion

A considerable amount of discussion can be found in the literature regarding the emplacement of boulders by tsunami vs. storm. Among those examining boulders and comparing tsunami vs. storm origins are: Nott (2004) from Western Australia; Scicchitano et al. (2007) from SE Sicily (Italy); Susmilch (1912) from E. Australia; Goff et al. (2004) from the North Island, New Zealand; Hindson et al. (1996) from the Algarve Coast, Portugal; Whelan and Kelletat (2005) from Cabo de Trafalgar, Portugal, and others.

Were the boulders at Kahuku Point transported by tsunami or storm waves? Clearly, the observation of movement during storm events documents that storms can move boulders up to 100 tons in size across the relatively flat surface of a platform. But they probably could not have been responsible for their initial placement on the platform. The clastic slabs (beach rock) are less resistant to mechanical abrasion than the limestone. The more-resistant reef blocks are clearly reduced in size by bio-erosion, mechanical erosion and dissolution and probably have a longer shelf life. The smaller boulders and tabular slabs of beach rock can easily be moved by storm waves. At Kahuku, boulders 1-3 m (a-axis) were transported onto the runways, based upon the study of the 1946 aerial photographs (Keating, 2008). Intense storm activity at Sharks Cove shows that erosion of boulders can take place without significant transport. The boulders at Shark's Cove appear to be sufficiently far from the reef edge that they are not necessarily moved by waves that break at the outer reef edge and then flood the platform. These observations provide insight into the nature and carrying power of tsunami and storm waves.

These observations are not unique to Hawaii; clearly similar observations are likely to vary at different sites around the world that have similar settings. Likewise, the observations described here are not unique in terms of tsunami and storm activity within Hawaii. Both storms and tsunami are variable in nature. If there is no source material of mega-boulder size to be transported by storm or tsunami, the carrying power of the waves will not be reflected by the deposits. Likewise, the source, intensity, and direction of movement of storms and tsunami are variable. The use of the Tf parameter may be misleading for materials having undergone large displacement for it may be that the large displacements are the result of an accumulation of many small displacements, such as has been observed for the largest megaclast on the platform at Sharks Cove. Each displacement episode for the largest block seems to be in the 10 to 30 m range (Noormets, et al., 2002). The cumulative displacement is substantially larger, thus it's Tf value is smaller than would be calculated if the total displacement from a presumed source location were used.

The Hawaii and Rabat examples discussed here represent a geologic environment in which reef and dune sediments are preserved. The stratigraphy at both sites reflects the oscillation of sea level during the Pleistocene. In both places, the mega-boulders/boulders are most abundant in a setting with a broad shallow submarine platform. During times of glaciations, when waters are locked up in glaciers, the sea level drops and the beaches shift seaward; a regressive sequence is formed capping the former reef platform (Stearns, 1978). Later in time, but still during the low stand, aeolian sands cap the platform and karst topography is locally developed. We now see sand dunes exposed at Kahuku Point that were formed

when the sea was lower than the modern sea level. The base of the deposits occurs offshore, and below modern-day sea level. Upon rise of sea level, these lithified dunes and the margins of the platform become sources for blocks of material that can be transported by both storms and tsunami. Since the sea level changes take place globally, it is reasonable that coastal carbonate sequences around the world would display a similar patterns of mega-boulder/boulder distribution (Table 5) e.g., Western Australia (Nott, 2004); Caribbean (Scheffers and Kelletat, 2004); Cyprus (Kelletat and Schellmann, 2002); Curacao, Netherlands Antilles (Schnellmann et al., 2004). The positive correlation appears to be in large part controlled by a similar geologic setting of the sites and reflect the impact of changes in climate and sea level.

Based upon studies in Cascadia, Nelson et al. (2006) suggested that there are thresholds for creating and preserving evidence of earthquakes and tsunami. Clearly, the Kuril Islands Tsunami with a 1 m tsunami runup and a limited inundation zone did not pass the preservation threshold in the Hawaiian high-energy beach sites. Nelson et al. (2006) further suggest that depositional sites must favor preservation for a tsunami event to leave a geologically identifiable trace. Clearly, the Hawaiian beach facies studied does not constitute a positive preservation regime. Sediment availability, erosion, deposition, steep seasonal beaches, and meteorological conditions that include high winds, large swells, heavy rain, etc. combined together to quickly remove the visible traces of the November 2006 Tsunami. Our observations suggest that within the seasonally high-energy coastal environment such as Hawaii, tsunami traces can be easily and quickly erased.

The modern run-up data shows that the greatest number of occurrences of run-up values occur within the 0-1 m range (Keating et al., 2008). This study shows that tsunami recurrence rates, based on the absence of sedimentary data, are likely to be improperly estimated even if only M8+ events are used, e.g. the 2006 Kuril Tsunami. Furthermore, the inability to differentiate storm from tsunami deposits suggests that the paleo-tsunami record at least in Hawaii has low fidelity.

Ref	Place	Rock Type	Karst	Max. Size (m)	Wt. tons	Im-bricate	Storm or Tsunami	Source
1.	Sicilly	Calcareous	Yes Yes	8,8,0.7	182	Yes	Tsunami	Edge of platform
2.	W. Australia	Eolianite Sandstone	No Yes	Several m.	100	Yes	Tsunami	Edge of platform
3.	S. Spain	Eolianite Sandstone	No Yes	8,5,1	75	Yes	Tsunami	Intertidal platform
4	Bahamas	Eolianite Limestone	Yes Yes	13,11.5,6.5	2300	No	Tsunami	Adjacent cliffs
5	Antilles	Limestone Beachrock	Yes	0.2-2	195	Yes	Tsunami	Adjacent cliff or subtital

Notes- References: 1. Scicchitano et al. (2007), 2. Nott (2004), 3. Whelan & Kelletat (2005), 4. Hearty (1997), 5. Scheffers and Kelletat (2003)

Table 5. Summary of mega-boulder deposits and their geologic characteristics

7. Conclusions

The major findings of this study regarding the 1946 Tsunami includes: widespread inundation (flooding from the sea) was sufficient to destroy the wooden barracks buildings, even if they were well constructed. Wooden buildings literally became sandwiched together by collision (which would have resulted in disastrous consequences to occupants, had the Kahuku barracks been occupied); construction glass and other materials become incorporated into the tsunami deposits during the turbulent runup of the tsunami and added to the hazards. The sand that was transported in the tsunami flood deprived the beach of protective cover. The sand moved by the tsunami covered everything inland as a sand sheet. At Kahuku the inundation zone was 1.6 km wide (a broad inundation zone) and the flood of salt water mechanically and chemically damaged the vegetation.

Eyewitness observations at the only non-beach site (Paukauila Stream) revealed that the Kuril tsunami did inundate the bay and the stream that drains the coastal wetlands. Although floating debris, e.g. plastic items, especially food wrappers, that were deposited to heights of 1 m along the stream provided evidence of an approximately 1 m run-up, the only sediments observed in transport in those backwaters was mud in water moving seaward. Conceivably, the long periods of a larger tsunami could have carried sands derived from beach into the quiet waters of the wetland. However, the 2006 Kuril Tsunami did not overflow stream banks where preservation may be possible, and any sand in the channels was likely to have been removed by the receding part of the tsunami wave, by tidal action, or the next rainstorm.

The wave action associated with the 1946 Aleutian tsunami repeatedly eroded sand during inundation, deposited the sand during the standstill phase and then selectively scoured the deposits (from the inundation and stand-still phase) during the drain back. The tsunami also eroded and widened drainages, leaving the ground surface covered by a giant sand sheet. During the course of the tsunami activity, large pools of water ponded in low areas after individual tsunami waves drained away.

The archaeological studies (by Bath et al., 1984) revealed desultory distribution of deposits, changing stratigraphy over a small area in discontinuous layers or lens, coral-rich units containing marine organisms from the shallow offshore, charcoal-rich units showing organic matter including trees, needles, seeds, etc derived from land and mixed with marine organisms as the tsunami drain back remobilizes sediment. These layers are generally thin (10-20 cm), have abrupt lower boundaries associated with tsunami waves scouring the back beach sediments and drainages, evidence of beach berm or dune being modified and showing "crumb" or blocky internal structures, and "midden" material consisting of shells, fish bones, animal bones, etc., often mixed with sand, coral and cobbles that may also be called a marine conglomerate. These characteristics of the 1946 tsunami are shared with other tsunami deposits worldwide. [The end]

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The Tsunami Threat - Research and Technology

Edited by Nils-Axel Mörner

Submarine earthquakes, submarine slides and impacts may set large water volumes in motion characterized by very long wavelengths and a very high speed of lateral displacement, when reaching shallower water the wave breaks in over land - often with disastrous effects. This natural phenomenon is known as a tsunami event. By December 26, 2004, an event in the Indian Ocean, this word suddenly became known to the public. The effects were indeed disastrous and 227,898 people were killed. Tsunami events are a natural part of the Earth's geophysical system. There have been numerous events in the past and they will continue to be a threat to humanity; even more so today, when the coastal zone is occupied by so much more human activity and many more people. Therefore, tsunamis pose a very serious threat to humanity. The only way for us to face this threat is by increased knowledge so that we can meet future events by efficient warning systems and aid organizations. This book offers extensive and new information on tsunamis; their origin, history, effects, monitoring, hazards assessment and proposed handling with respect to precaution. Only through knowledge do we know how to behave in a wise manner. This book should be a well of tsunami knowledge for a long time, we hope.

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