# TSUNAMI DEPOSITS AT QUEEN'S BEACH, OAHU, HAWAII – INITIAL RESULTS AND WAVE MODELING

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## ABSTRACT

Photographs taken immediately after the 1946 Aleutian Tsunami inundated Queen's Beach, southeastern Oahu, show the major highway around the island was inundated and the road bed was destroyed. That road bed remains visible today, in an undeveloped coastline that shows like change in sedimentary deposits between 1946 and today (based on photographic evidence). Tsunami catalog records however indicate that the beach was repeatedly inundated by tsunami in 1946, 1952, 1957, and 1960. Tsunami runup was reported to have reached between 3 and 11 m elevation. Eyewitness accounts however indicate inundations of up to 20 m in Kealakipapa Valley (Makapu'u Lookout) during 1946 and photographic evidence indicated inundation reached 9 m in 1957. The inundation of Kealakipapa Valley has been successfully modeled using a 10-m tsunami wave model.

A comparison of the modern beach deposits to those near the remains of the destroyed highway demonstrate that the sedimentary deposits within the two areas have very different rock characteristics. We conclude the modern beach is dominated by the rounding of rocks (mostly coral) by wave activity. However, in the area that has experienced prior tsunami inundations, the rocks are characterized by fracturing and a high component of basaltic material. We conclude the area near the destroyed highway reflects past tsunami inundations combined with inevitable anthropogenic alteration.

## Introduction

The sedimentologic investigation of tsunami deposits is a fairly new field of research (DAWSON 1999). The impact of tsunami waves on coastlines is unlike that of storm waves since tsunami waves have greater wavelengths and wave periods. If there is sufficient sediment supply, tsunami waves are constructive as they move inland, and transport a variety of grain sizes ranging from silt to large boulders. The retreating waves can remobilize and erode sediments.

Literature on tsunami deposits may be organized into three primary categories (WHELAN & KELLETAT 2003): large clasts (e.g. boulders), coarse and fine sediments (e.g. gravel, sand, silt), and other fairly obscure deposits such as wash-over fans. The nature of tsunami deposits is largely determined by sediment supply. The most commonly investigated tsunami deposits are fine sediments that, most frequently, occur as sediment sheets. Large clasts were reported by DAWSON (1994) immediately after 1992 Flores Tsunami in Indonesia. BRYANT et al. (1992) observed anomalous boulder masses, highly bimodal mixtures of sand and boulders, and dump deposits consisting of well-sorted coarse debris along the Australian coast and attributed them to tsunamis. Additional boulder deposits were attributed to tsunamis by PASKOFF (1991) in Chile, by JONES & HUNTER (1992) on the southern shore of Grand Cayman Island, by HEARTY (1997) along the coastline of North Eleuthera Island, Bahamas, by NOTT (1997 and 2000) on the Australian coast, by SCHEFFERS (2002) on Aruba, Curacao, and Bonaire, by WHELAN & KELLETAT (2003) on the southern Spanish Atlantic coast, and others.

Most geomorphic or sedimentologic studies have been carried out on tsunami deposited sediment sheets. Worldwide, the majority of research has been conducted along the coastlines of the Pacific Ocean, especially along the North American Pacific Coastline (e.g. CLAGUE 1997; ATWATER & MOORE 1992; DARIENZO & PETERSON 1990; NICHOL et al. 2002). Other notable studies include the deposition of sediment sheets investigated by SHI et al. (1995) who studied sediment accumulations after the 1992 tsunami of Flores, Indonesia.

Both boulder deposits and coarse tsunami deposits were observed in the Queen’s Beach coastal zone located on southeastern coast of the island of Oahu, Hawaii (Figure 1). Queen’s Beach was inundated by tsunamis at least four times during the last century, by the Aleutian tsunamis of 1946 and 1957, the 1952 Kamchatka Tsunami, and 1960 Chile Tsunami. This study identifies tsunami deposits that provide new insights into the runup of past tsunamis in the Queen’s Beach coastal zone.

The Queen’s Beach locality is of interest since it is the site of known historic tsunami activity with deposits photographed during and immediately after the 1946 tsunami. This paper presents initial geological investigations of the Queen’s Beach locality, which were undertaken 1.) to document the nature of historic tsunami deposits within the Hawaiian Islands, 2.) in search of a modern analogy to the controversial marine conglomerates on the island of Lanai (MOORE & MOORE 1984, 1988); and 3.) to better understand the nature of the ash-dominated coastal zone of southeastern Oahu.

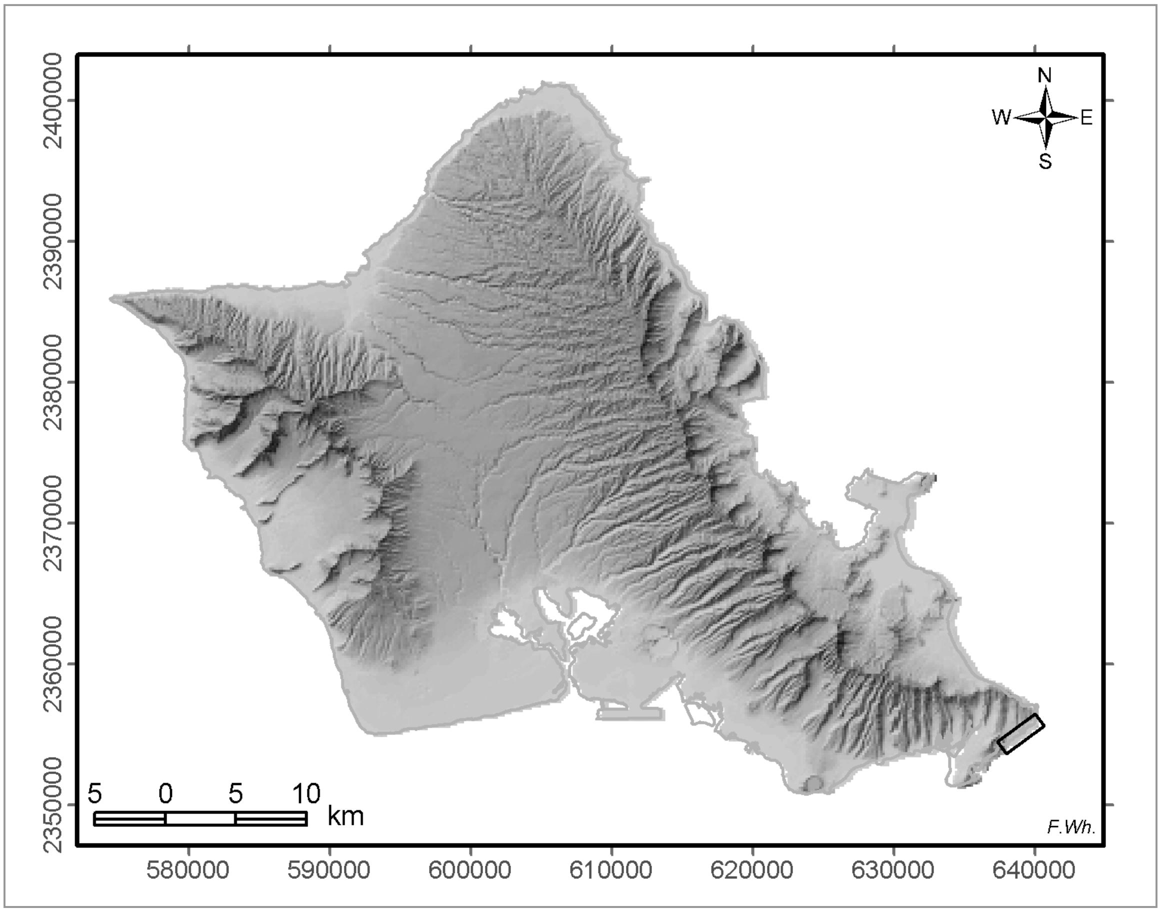


Figure 1: Location of the Queen's Beach coastal zone (small box at lower right) on the Island of Oahu, Hawai'I (UTM, WGS84).

## Study Area

The coastal plain between Sandy Beach and Makapu'u Head is referred to as Queen's Beach. Queen's Beach currently displays geomorphic and sedimentologic evidence for tsunami impacts, however the area is destined to become the site of the Ka Iwi Regional Park. Honolulu City and County, as well as state and federal agencies intend to preserve the coastal zone as a park and nature preserve. The proposed park will include shoreline access, a visitor center, paved parking lots, access to Makapu'u Lighthouse, footbridges over high water areas, a system of bike and hiking trails, reforestation, re-vegetation, and interpretative signs.

The study area is located within the Tsunami Inundation Zone (Figure 2), which is defined as an area subject to flooding by the 100-year tsunami (Insurance Rating V22; U.S. DEPT. OF HOUSING AND URBAN DEVELOPMENT 1980; CITY AND COUNTY OF HONOLULU, DEPARTMENT OF PARKS AND RECREATION 1984). The nature of historic tsunami inundation is of particular interest here since the proposed park is likely to greatly alter geomorphic and sedimentologic tsunami evidence due to new construction and increased use.

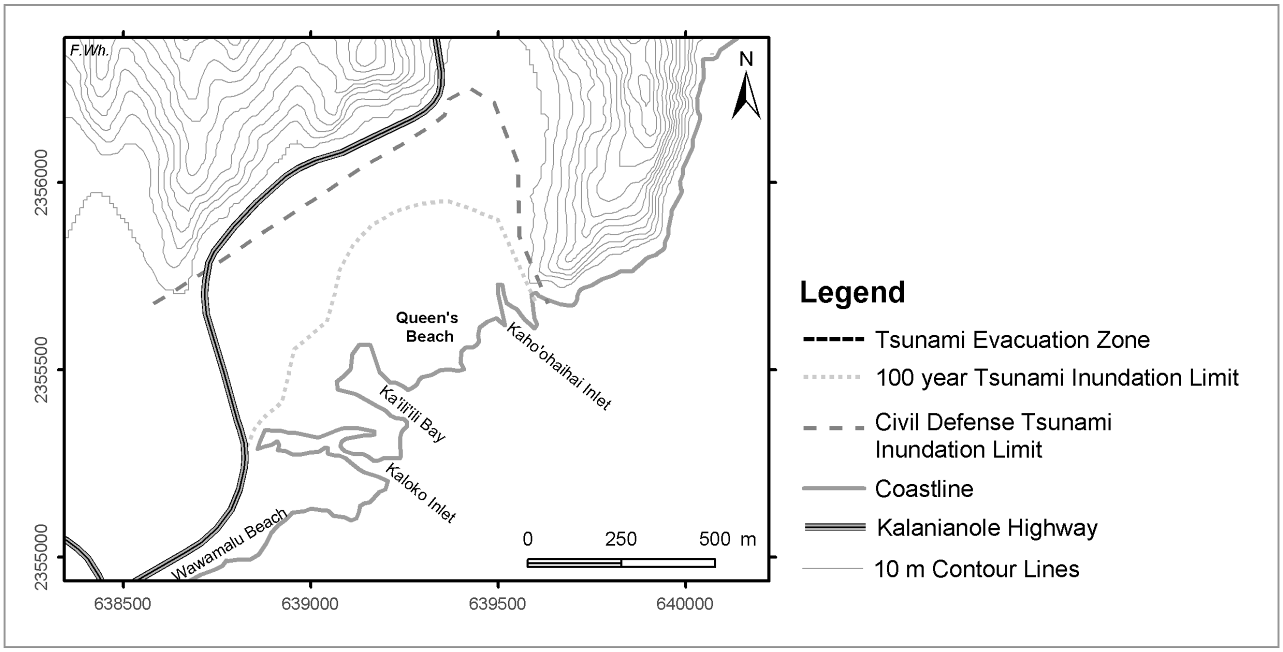


Figure 2: Tsunami inundation limits and tsunami evacuation zones within the Queen's Beach Coastal Zone (UTM, WGS84). (Tsunami Evacuation Zone data were provided by the State of Hawaii Civil Defense and published in County Telephone Directories by GTE in 1991.)

## Historic tsunami impacts

As illustrated in Figure 3, the Queen's Beach coastal zone was inundated by tsunamis at least four times during the last century, involving the Aleutian tsunamis of 1946 and 1957, the 1952 Kamchatka Tsunami, and 1960 Chile Tsunami.

The 1946 Aleutian Trough Tsunami originated in the northern slope of the seafloor trough, south of Unimak Island, Alaska. As a consequence of the tsunami, more than 150 people were killed in the Hawaiian Islands, 163 people were injured, and property damage exceeded 25 million dollars (MACDONALD et al., 1947). Based on SHEPARD et al. (1950), who reported on the affects of the April 1, 1946 tsunami at Queen's Beach, the tsunami waves reached 11.1 m (36.4 ft) above sea level (asl) on the north side of Makapu'u Head, 5 m (15 ft) at Kaloko Point located 1.6 km (one mile) southwest of Makapu'u Point, and 9.3 m (31 ft) asl at Koko Head. Since the tsunami originated north of the Hawaiian Islands, both Kaloko Point and Koko Head were affected by tsunami waves that wrapped around the island (Figure 3 and SHEPARD et al. 1950). Based on eyewitness testimony from Alan Davis, the waves inundated the coastal plain and ran northward up the slope of Kealakipapa Valley (CLARK 1997). The tsunami destroyed all of the recorded archaeological sites within the coastal plain.

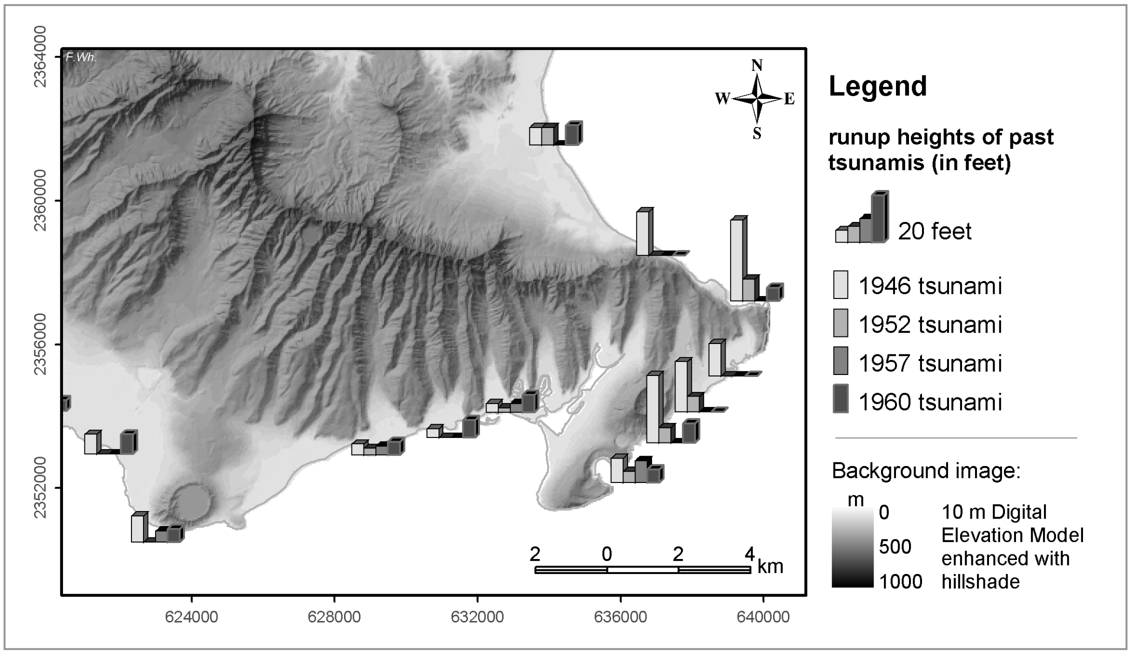


Figure 3: Tsunami wave runup heights in the vicinity of Queen's Beach (UTM, WGS84). (Data based on HAROLD G. LOOMIS 1976, digitized by OFFICE OF PLANNING Staff in 1999.)

SHEPARD et al. (1950) published photographs of tsunami debris on the coastal highway along Queen's Beach and the bay northwest of Makapu'u Head (Plates 15 a and b in SHEPARD et al. 1950, respectively). The appearance of the remnant of the coastal highway immediately after the 1946 tsunami was hardly different from the present (Figure 4). Blocks of basalt, coral, and pavement are clearly visible on the surface despite repeated tsunami inundation and continued use of the coastal zone by hikers, fishermen, and swimmers.

The 1946 tsunami demolished a group of houses just inland of Queen's Beach. One of the owners, Alan Davis, waded through water up to his armpits escaping the advancing wave. While most of the houses were swept inland and deposited in form of debris piles against trees roughly 150 m (500 ft) inland, at least one house was swept out to sea. Arriving at Makapu'u Gap (modern day parking area and lookout) Mr. Davis and his family watched as the following wave completely destroyed their home. The next wave rolled up almost the entire length of Kealakipapa Valley. Fearing the next wave would wash up the valley and top the gap, the family drove up to the lighthouse near the top of Makapu'u Ridge (CLARK 1997). JAGGER (1946) reported that the Honolulu tide gauge recorded 20 fluctuations in four hours.

The 1946 tsunami seemed to have considerably affected the geomorphology of the Queens Beach coastal zone. Based on a photograph published by SHEPHARD et al. (1950, Plate 15a), much of the asphalt highway, constructed in 1932, was washed out by the tsunami. Steep beach faces were left, and large sand dunes were truncated, leaving steep seaward cusps. Recorded runup was extremely high for the coastal zone immediately to the southwest of Queens Beach. In between Queen Beach and

Hanauma Bay, runup was recorded at 9.3 m (31 ft) and (6.9 m) 23 ft for the 1946 tsunami (WALKER 1994 and 2003).

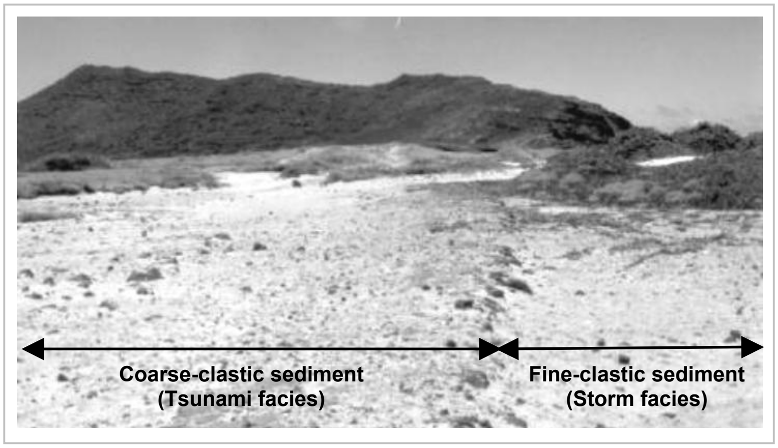


Figure 4. A modern photograph of the tsunami deposits and the destruction of the old highway that occurred as a result of the April 1, 1946 tsunami.

Subsequent tsunamis also inundated the Queen's Beach coastal zone. For example, WALKER (1994) reported a runup of 3.3 m (10 ft) asl at Makapu'u Point from the 1952 tsunami. The U.S. ARMY CORPS OF ENGINEERS (1978) studied the historical recurrence of tsunami around the Hawaiian Islands and suggests that Queen's Beach is likely to be inundated every 25 years by tsunami waves of 2.4 m (8 ft) asl and every 100 years by a tsunami with wave heights of 6.6 m (22 ft) asl.

## Geology of the coastal zone

The Queen's Beach coastal plain extends from Koko Head to Makapu'u Ridge (the eastern-most extent of the Koolau Mountain Range. The Koolau mountain ridge consists of volcanic lava flows, vent breccias, and dyke intrusions associated with the caldera complex. The Koolau volcano is of late Pliocene or early Pleistocene age (activity ceased one to two million years ago, MACDONALD et al. 1983). Volcanic activity resumed in the eastern end of the Koolau Range after a roughly 1-2 million-year-long period of post-volcanic erosion, during which the Nuuanu Pali (cliff) was formed, and the Honolulu Volcanic Series became active. This Series consists of cinder, spatter, and ash cones, and lava flows (see Figure 5-8 in STEARNS 1985). Koko Head, Hanauma Bay Crater, Kahauloa Crater, and Kalama Cinder Cone belong to the Honolulu Volcanic Series (MACDONALD et al. 1983). MACDONALD et al. (1983) reported that Honolulu Series lavas have ages ranging from 500,000 (Black Point) to 32,000 yrs (Kaupo Lava Flow near Makapu'u Point). There is a great deal of difficulty in dating these young volcanic rocks so the ages are subject to large errors. OZAWA, et al. (2003, abstract) carried out new K-Ar age determinations on Honolulu Volcanic Series rocks in the Queen's Beach coastal plain, that indicated the age of the volcanic rocks should be close to 100,000 yrs.

Immediately southeast of Makapu'u Ridge, the coastal plain associated with the Honolulu Volcanic Series is underlain by Kalama lava flows and Honolulu Volcanic series ash deposits that extended the shoreline of the island between up to 1 to 3 km to the south and east. Because this coastal zone is constructed largely of soft ash deposits, coastal erosion processes and repeated sea level changes have eroded the rock formations leaving wave-cut notches, sea stacks, beach deposits, and wave-cut platforms in the coastal plain.

## Geomorphology of the Queen's Beach coastal zone: field investigations

The Queen's Beach coastal zone displays several distinct morphological units (Figure 5):

1.) The lowest unit, an alternating rocky and sandy beach, as well as a near-shore storm ridge consisting of coral boulders and sand dunes, is associated with modern sea level. There, sands and coral rubble display a bleached white color.

2.) Along the rocky shoreline, beach sands cemented together with basalt and coral clasts and abundant sea shells form isolated and limited inliers (a group of rocks surrounded by rocks of younger age). These inliers of cemented beach sands occur where fresh water is discharged at sea level, facilitating the diagenesis (chemical alteration) and cementation of sand-dominated deposits into beach rock.

3.) A platform truncated at a level of roughly 5.7 to 6 m (19 to 20 feet, based on 1999 USGS topographic map) is located inland of the modern beach. The terrace consists of volcanic outcrops, yellowish-orange clay (altered ash deposits), basalt boulders, and abundant fossils. The pronounced platform at Queen's Beach roughly corresponds to a sea level stand associated with a 6.6 m high wave-cut notch described by STEARNS (1978). STEARNS (1978) identified marine notches at 6.6 and 8.1 m asl (22 and 27 feet, respectively, as illustrated in Figure 14 in STEARNS 1978) that were cut into aeolianite (wind-blown sands) near Kailua on the eastern coast of Oahu, approx. 10 km northeast of Queen's Beach. A third ancient shoreline at the same location occurs at 3.6 m (12 ft) asl and was assigned a similar age by STEARNS (1978).

Uranium series dates from those deposits yielded ages ranging from 120,000 to 125,000 yr (KU et al. 1974; STEARNS 1974). Fossils cover the platform in the form of a thin, spotty veneer of weathered gray color coral clasts and mollusk shells. At the seaward slope and foot of this platform, an assemblage of marine organisms (Table 1) typical of sub-surf zone depths was identified (BAILEY-BROCK 2002, pers. comm.). The gray color of coral and shell deposits, as well as the yellowish-orange color of sands on top of this terrace stand in marked contrast to modern shoreline deposits (Figure 5) and is interpreted as resulting from longer exposure to weathering.

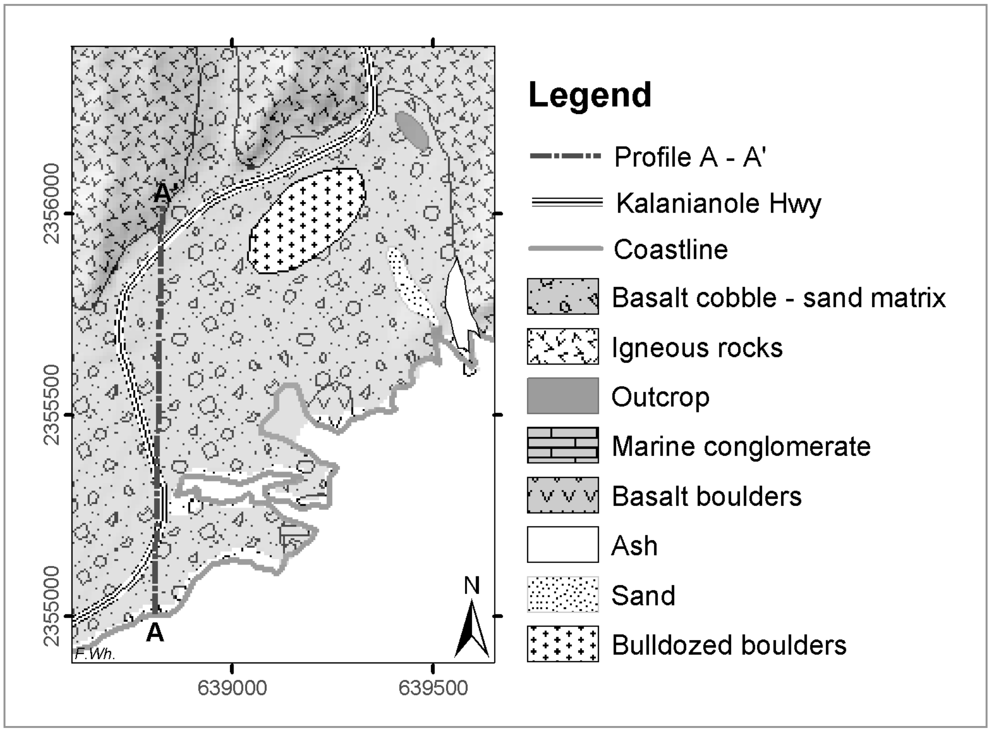


Figure 5. Sketch map (UTM, WGS84) of the geologic units exposed at Queen's Beach. The location of the transect A-A' is displayed on the left. The location of the construction debris (volcanic boulders) is shown southeast of Kalanianole Highway.

| **Identified Species** |
|---|
| *Spirorbid* tubeworms- Polychaeta, Serpulidae. Dextral species, most likely *Neodexiospira steueri* and sinistral species (operculum full of developing embryos), most likely *Pileolaria militaris.* (for polychaete worms see BAILEY-BROCK 1987) |
| Sepulid species - *Protula atypha*. |
| Gastropoda-Vermetidae |
| Foraminifera – *Gypsina* sp. (PHILIPS 1977) |
| Coral - *Pocillopora meandrina* |
| Bryozoan - single zooids of a species of bryozoan nestled in a depression in a piece of basalt. |
| Coralline algae crust (Rhodophyta) |

Table 1: Species identified at Queens Beach (by Julie Bailey-Brock, University of Hawaii, Dept. of Zoology). *All of the surface fossils are species currently alive in Hawaiian waters.

Figure 6: Marine deposits on the shoreline of the Queen's Beach coastal zone. Note the difference in color between older deposits (associated with the platform in the background) and modern deposits in the foreground.

4.) The forth morphologic unit is of anthropogenic origin and consists of debris bulldozed from the Hawaii Kai subdivision and golf course lands by the Kaiser-Aetna Corporation between 1972 and 1975 (BISHOP MUSEUM FEASIBILITY REPORT 1984) and boulders from the construction of a well near Makapu'u lookout. The debris was stockpiled in the coastal plain adjacent to the realigned and rebuilt Kalanianaole Highway. The pile of boulder debris is roughly 3 to 4 m high, and contains Kalama Flow basalt boulders that range from 1 to 3 m in diameter. Instead of limiting future studies of tsunami impact on the coastal zone, this debris pile might present a natural laboratory for determining what grain size and boulder volume is moved by any future tsunamis.

The debris is restricted to the near-vicinity of the highway and is readily identified and distinct from the underlying platform. Brown soils that are highly expansive form a stratigraphic horizon directly above 6.6 m, at the toe and lower elevations of Kealakipapa Valley.

5.) Other morphologic features include cemented beach sands that occur in a bath-tub ring type distribution at roughly 21 m above sea level on the east side of Kealakipapa Valley. The beach sands are exposed below the paved Makapu'u lighthouse access road on the west side of Makapu'u ridge. Additional fossils were observed in the center of Kealakipapa Valley below the lighthouse access road. Marine fossils were also identified on the eastern flank of Makapu'u Ridge adjacent to the access road.

At the edge of the coastal zone, notches have been cut by wave activity into the lava flows of the eastern and western sides of Kealakipapa Valley. The notches are roughly

17 m (59 ft) high and are evident elsewhere around the periphery of the valley. The notches are best visible north of Hawaii Kai Golf Course entrance and at the foot of Makapu'u Ridge (i.e., the east and west sides of Kealakipapa Valley). The knob at the base of Makapu'u Ridge would have been a sea stack when sea level carved the notches and terraces surrounding the knob (Figure 7).

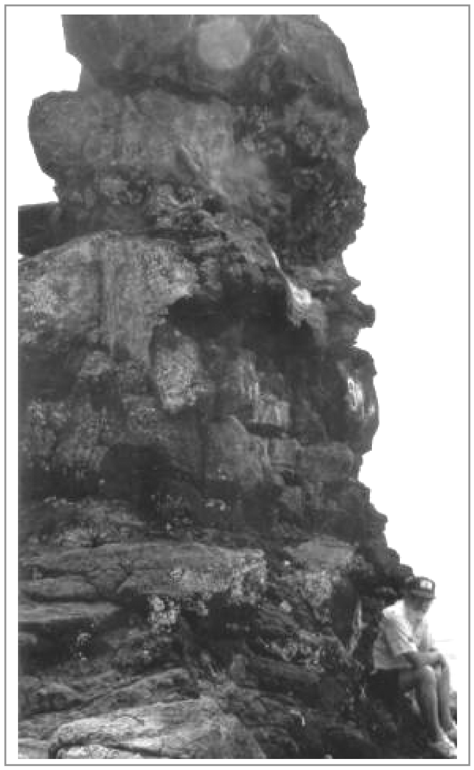

Figure 7. Fossil Sea Stack. The knob at the base of Makapu'u Ridge would have been a sea stack when sea level carved the notches and terraces surrounding the knob. The base of the sea stack is 19 m (63 ft) above sea level.

The coastal zone contains four drainages (from south to north) including Kaloko Inlet, Ka'ili'ili Bay, an unnamed inland basin, and Kaho'ohaihai Inlet (see Figure 2 for site locations). Two additional drainage canals were cut to Kaloko Inlet and Ka'ili'ili Bay during the construction of the Hawaii Kai golf course.

## Records of anthropogenic alterations in the Queen's Beach coastal zone

As summarized in the *Queen's Beach Park Feasibility Study* (CITY AND COUNTY OF HONOLULU, DEPARTMENT OF PARKS AND RECREATION 1984), the Queen's Beach coastal zone has been subject to several anthropogenic alterations. In the 1800's, vegetation, including Naio and perhaps beach sandalwood was removed from the area and was replaced by Kiawe (mesquite) and Wiliwili for cattle feed. Between 1930 and 1949, the

Davis family leased a ranch from Bishop Estate at Queens Beach. During this period three homes and a pool were built along the coast. Between 1959 and 1964, the Hawaii Kai Development Corporation and its successors began removing large trees from the site and began land modification. After the death of Henry Kaiser, this development corporation was reorganized several times and changed names, without completing the land modifications underway. While feasibility studies for a community park date back to 1984, development activities for Kaiser Aluminum and Chemical Corporation including an Environmental Impact Statement for a golf course were prepared and considered as late as 1997. Queens Beach was proposed to Congress as the "Ka Iwi National Scenic Shoreline" (KA IWI NATIONAL SCENIC SHORELINE PROPOSAL 1992) and a reconnaissance survey was later carried out by the U.S. NATIONAL PARK SERVICE (1992). The land was eventually purchased by local government in order to stop development and provide for preservation of the land as a park.

In order to survey the Queen's Beach coastal zone, aerial photographs and maps were examined. Neither the aerial photographs taken in 1952 and 1959 nor a military topographic map (DEPARTMENT OF ENGINEERING TOPOGRAPHIC MAP 1943) showed that any inlet existed immediately south of Makapu'u Head (Pu'u o Kipahulu). However, an aerial photograph of 1-14-1963 (month-day-year) shows a newly created inlet and groins extending out into the sea, as well as the enlarged bay. Based on the *Queen's Beach Park Feasibility Study* (CITY AND COUNTY OF HONOLULU, DEPARTMENT OF PARKS AND RECREATION 1984), the three inlets were artificially enlarged and a massive groin and a smaller groin were constructed on the north and south sides of Kaho'ohaihai Inlet, respectively. The mauka (mountain-side) portions of Kaloko Inlet and Ka'ili'ili Bay were dredged to form mud flats. Additionally, a 5 m wide dirt drainage channel and a parallel overflow ditch were excavated from the Hawaii Kai golf course to Ka'ili'ili Bay. A sand beach was artificially deposited at the mountain edge of Kaho'ohaihai Inlet and a coral and lava cobble beach was deposited behind the jagged shoreline at Ka'ili'ili Point and northeast of Ka'ili'ili Bay. The basalt boulders forming the groin are 1-2 m in diameter. Wave erosion of the last 40 years has rounded the rocks of the northern groin within the active surf zone.

A rock outcrop at the toe of Makapu'u Ridge was removed to create a flat spot for a proposed restaurant. Kaho'ohahai Inlet and Ka'ili'ili Bay were bulldozed inland at depths of 0.3 to 0.6 m (1 to 2 ft). The beginning of a proposed curved moat to connect Kai'ili'ili Bay to Kaha'ohaihai Inlet was bulldozed, but not completed.

Offshore sand was taken from the location of the groin and inlets and stockpiled on the south side of Kaho'ohaihai Inlet and west of Ka'ili'ili Bay. Kaloko Inlet was deepened and extended with shaped charges and dragline. Dredge spoils were stockpiled around Kaloko Inlet (CITY AND COUNTY OF HONOLULU, DEPARTMENT OF PARKS AND RECREATION 1984).

Vehicle access to the area was restricted in 1975 when large boulders were strategically placed around the periphery finally limiting access to the area by 4-wheel drive vehicles. Since the anthropogenic alterations at Queens Beach have been recorded and reconstructed, there is no doubt that the coral bearing conglomerates observed on the margins of Ka'ili'ili Bay and Kaho'ohalai Inlet are dredge spoils unrelated to tsunami activity.

**Observations of surficial tsunami deposits**

The Queen's Beach coastal zone displayed three distinct units of deposits that were interpreted as tsunami-genic, including 1.) gravel to cobble-size clasts of coral and basalt, 2.) gravel-size coral deposits mixed with man-made items, and 3.) isolated conglomerate layers. Two additional units have been identified that were associated with development activity, the stockpiled boulders, and the dredge spoils.

The first rock unit is a semi-continuous sheet of gravel to cobble-size clasts that are generally sub-rounded to rounded. The sediment sheet is one clast size thick, extends approx. 200 m inland, and consists of basalt and coral clasts (broken fragments and rounded fragments), both are clearly from the ocean environment. The majority of the basalt pores are filled with coralline algae. Several clasts display worm tubes and are burrowed. The individual clasts are larger than those of the present storm beach. NICHOL et al. (2002) described similar deposits on a coastal barrier on the Great Barrier Island, New Zealand. Both there and at Queens Beach, the deposits' elevations reach well beyond the extent of storm surges. This was verified in November 2003, when a storm generated 30-foot surf on the east side of Oahu. The elevation of the deposits therefore suggests tsunami as the likely transport mechanism.

A survey of the sedimentary deposits was carried out in form of several line transects perpendicular to the coastline. All transects stretched from the present coastline and modern beach to Kaloko Inlet or to the new highway. The initial transect (A-A') presented in this study intersected the modern beach, remnants of the old highway washed out by the 1946 tsunami, and the area seaward of the new highway. Clast size, angularity and rock type were analyzed (Figure 8). Subsequently, additional profiles were sampled and the rocks were analyzed using three different sampling methods. The comparison of sampling methods, details of the clast distribution, as well as GIS analysis (including aerial photography) will follow in a separate publication.

This study focuses on initial results of the field investigations and presents one preliminary transect (A-A'). The starting point for the beach profile was 20º45.453' N; 156º53.677' E (Garmin Etrex GPS barometer elevation 0 - 1.5 m or 0 - 5 ft) and the starting point for the back beach profile (adjacent to destroyed highway) was 20º44.87' N; 156º54.892' E (GPS barometer elevation 2.4 m or 5 ft). The angularity of the clasts was determined by visual comparison to the FOLK (1968) scale.

Transect A-A' extends from south to north across the Queen's Beach coastal zone. The beginning of the transect (A) is characterized by modern beach and storm deposits. The clasts within the modern beach were dominantly coral, having a very white, bleached appearance. A berm at the top of the modern beach largely consist of beach sand and sub-rounded to rounded coral fragments embedded in a sandy matrix that range in size from approx. 2 to 7 cm in diameter. The structure is interpreted as a storm berm and was roughly 2 m in width.

Tsunami deposits were identified inland beyond the storm berm, where both grain size and rock type change considerably (Figure 8). Sedimentary deposits reach diameters of 0.5 m, but generally range between 2 to 4 cm. These rock types are dominated by basalt, coral, and shells within an unconsolidated sand matrix (of a few cm thickness). The clast-rich deposit is generally only one clast thick in several cm of unconsolidated sand. The deposit overlays a well-cemented orange-red clay (interpreted as altered ash). The tsunami deposit ends on the west side of the highway (in the vicinity of the golf course clubhouse), where expansive soils have modified the deposits.

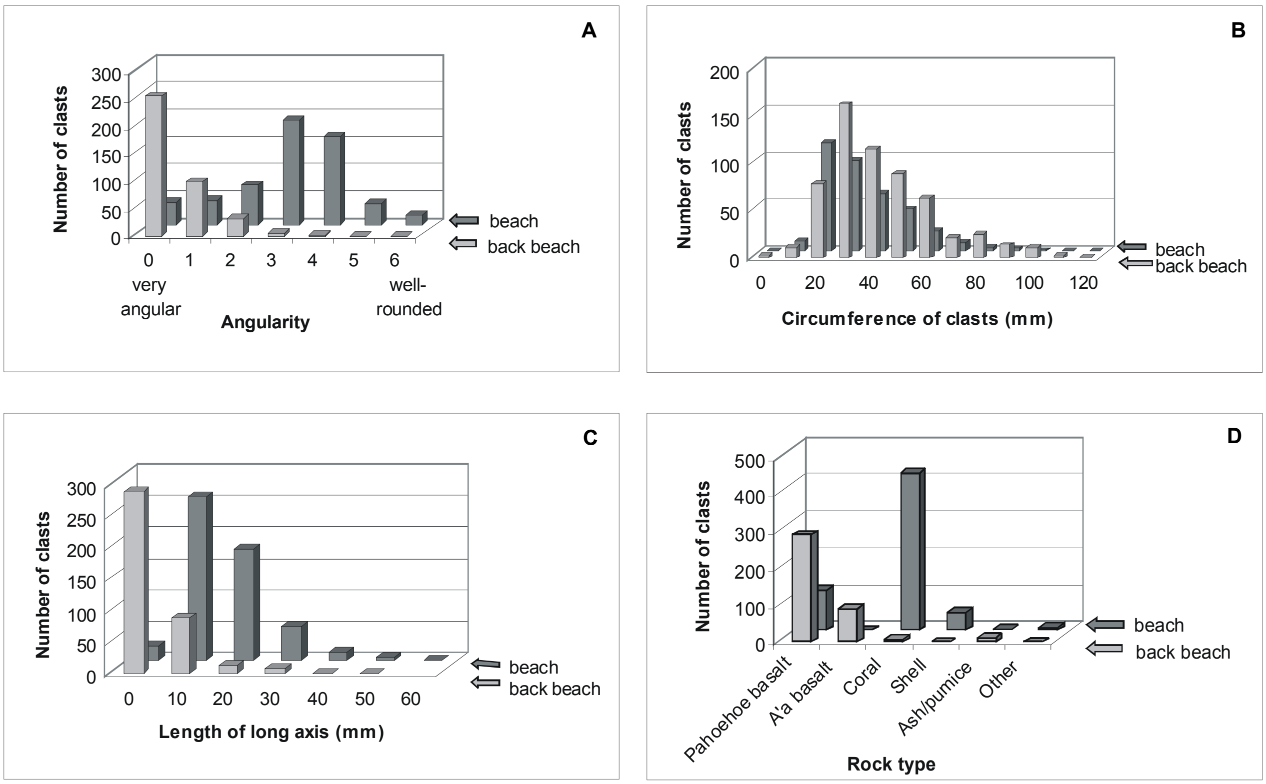


Figure 8. Comparison of rock characteristics between the modern beach deposits and the back beach deposits interpreted as resulting from tsunami activity. The comparisons include A) angularity determined on a 0 to 6 scale after FOLK (1968), with increments including very angular, angular, sub-angular, sub-rounded, rounded and well-rounded; B) circumference of clasts (mm); C) length of long axis (mm); and D) rock type, including Pahoehoe basalt, A’a basalt, coral, shells, ash or pumice, and other (e.g. glass).

The investigations indicate that the surface deposits in the vicinity of the remnant of the 1932 roadway destroyed by the 1946 tsunami, Kalolo Point, and the toe of Makapu’u ridge represent tsunami deposits correlating with historic tsunami records. The surface deposits observed in the vicinity of Kaloko Point are rich in coralline algae. Dr. J. Bailey-Brock (Zoology Dept., University of Hawaii) identified several clasts within the deposit and determined that all species were current species indicating that these deposits to an elevation of roughly 3 m (9 ft) are likely to be associated with historic tsunami.

The histograms in Figure 8 above demonstrate that the rock characteristic of the two deposits are very different. While the modern beach deposits are well-rounded by abrasion associated by wave activity, the rocks in the back beach are angular, reflecting breakage. The back beach clasts are darker in color interpreted as increased weathering, smaller in size, more fractured, and dominated by lava fragments rather than coral. These result indicate that the rock groups were produced by different processes. The beach deposits are dominated by modern wave activity, while the back beach deposits appear to preserve the influence of historical tsunamis.

The distribution of clasts along this preliminary transect represents the composite distribution of multiple tsunami and anthropogenic activities. The area of the A-A' transect is the area most accessible to the public and, therefore, most anthropogenically influenced. However, few beaches have ever been left undisturbed after a tsunami event and some degree of anthropogenic activity is common almost to the point of being inevitable. However, the initial observations along A-A' served as a valuable starting point for characterizing historic Hawaiian tsunami deposits and as a baseline for a time series of observations associated with further tsunami and storm events.

Coral fragments are intermixed with material of anthropogenic origin at Ka'ili'ili Bay. There, a series of five graded beds are exposed in the banks of the inlet on the southwest side of Ka'ili'ili Bay (Figure 9) and are dominated by calcium carbonate sediments ranging in size from gravel-size coral clasts through shell hash, to fine grain carbonate sediments. Two layers contain rounded coral boulder beds comparable to those forming the base of the storm berm at the back of the modern beach. The lowest layer contains ceramic tile, blocks, and aged glass fragments, including a Coca Cola bottle fragment, which are likely remnants of the Davis family's home destroyed by the 1946 tsunami deposits.

Figure 9. Photograph of an outcrop on the southwest side of Ka'ili'ili Bay (see Figure 2 for site location) containing a stratigraphic sequence of five graded beds showing gradations from gravel size clasts at the base of the bed, shell hash in the interior of the bed, and fine mud carbonate at the top of each bed.

At the toe of Makapu’u Ridge, there are two thin (0.5 m) isolated horizons of marine conglomerate (Figure 10). These 2 horizons give the appearance of additional cemented inliers of beach-rock present on the modern beach but they outcrop at 1.5 and 2 m asl. Alternately, these conglomerate units could be paleo-tsunami deposits. These rock units will be the subject of further study. Radiometric dating of the coral may provide further evidence of their origin.

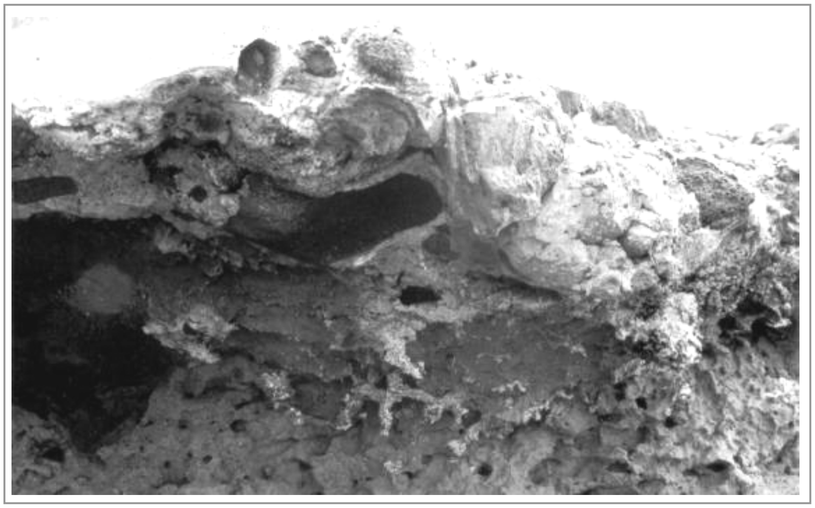

Figure 10. Photograph of one of two well-cemented marine conglomerate horizons at the base and south side of Makapu’u Ridge (Pu’u o Kipahula). The conglomerate rests on Honolulu Series ash deposits. The conglomerate contains basalt and coral clasts and shells cemented in a sandy matrix. The base of the unit does not appear to be erosional but instead appears to be transitional to finer-grain clasts.

The Queen’s Beach coastal zone displayed two rock units that were interpreted as not related to tsunami deposits. These included: a unit of relatively small area that consists of large basalt boulders deposited east of the highway at the foot of the Kealakipapa Valley. The boulders are covered with grassland. The aerial photographs of the Queens Beach coastal plain established that the boulders located there were deposited during construction projects (golf course and the water shaft at Makapu’u Lookout) and are not the result of tsunami activity. The remaining unit, consitsting of abundant basalt clasts, coral calsts, and sea shells, is confied to the margins of Kaloko Inlet (Figures 11a and 11b) and Kaho’ohaihai Inlet within the Tsunami Inundation Zone. The deposits on the inlet banks on the north side of Kaloko Inlet and on the south side of Kaho’ohaihai Inlet display irregular layering and teepee layering, and are the products of dredging. A species of mollusk, currently extinct in the Hawaiian Islands, was found at the base of the slope on the north side of Kaloko Inlet (Figure 11b; were identified by Dr. R. Grigg of the Oceanography Department, University of Hawaii). The record of development activities show that this unit represents dredge spoils, not tsunami activity.


Figure 11: A) Coral-bearing conglomerate with coral and basalt clasts exposed in the northeast bank of Kaloko Inlet (center of the photograph above). B) Close-up photograph of the outcrop. Historical records (University of Hawaii library, Hawaiian collection) prove materials are the dredge spoils associated with deepening the bay.

## Tsunami modeling

MADER (2002; Science of Tsunami Hazards CD distributed at the Tsunami Society's second Symposium) published tsunami models for the 1946 Aleutian Tsunami inundation of Queen's Beach or Sandy Beach (Figure 12). The tsunami animations were performed using SWAN code (MADER 1988). The analyses show that when a 3 m high tsunami wave is modeled, the runup does not reach Kealakipapa Valley (behind Makapu'u Ridge). However, based on eyewitness reports by the Davis family, waves ran up almost the entire length of the valley. Davis reported that he feared the waves would overrun the gap (Makapu'u Overlook) and flood down onto Makapu'u beach below. The 10 m tsunami wave model (MADER 1988 and 2004; see animation sandy.zip on web site http://t14web.lanl.gov/Staff/clm/tsunami.mve/tsunami.htm) shows the runup in Kealakipapa Valley and accurately fits the eyewitness reports.

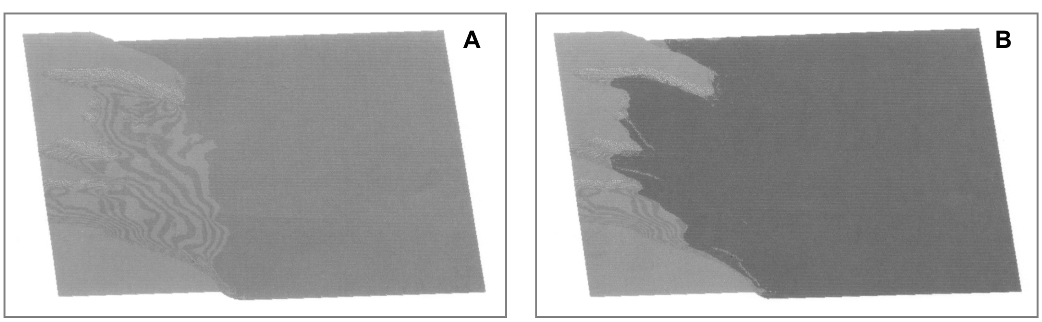


Figure 12: Animation of the 1946 Aleutian tsunami inundation at Queens Beach/Sandy Beach, Oahu, HI. A) Inundation by a typical offshore 3-m-high wave. B) Inundation by a maximum expectable offshore 10 meter high, 2000 second tsunami wave (MADER 1988 and 2004).

## Summary

The Queens Beach coastal zone was subject to significant tsunami inundation during the 20th century. This study presents initial investigations of geomorphic and sedimentologic tsunami evidence preserved in the Queen's Beach coastal zone. The deposits consist of coarse clasts and gravel deposits. Based on the presence of glass, ceramics, etc. and surrounding geomorphic cues, the surface deposits appear to originate from the inundations of the 20th century. Comparing the relatively high frequency of tsunami inundation of Hawaiian shorelines with the minimal amount of preserved tsunami deposits, the Queens Beach coastal zone provides a valuable record of the nature of deposits due to tsunami inundation and runup.

Marine conglomerates are identified in the modern beach setting that appears to result from cementation of clasts associated with the discharge of fresh water at the shoreline. Two additional horizons at 1.5 and 2 m asl may represent ancient deposits of the same origin or paleo-tsunami records. Additional studies of these units are required.

The lava flows and ash units at Queen's Beach preserve abundant evidence of fossil sea level stands (e.g., platforms, wave cut notches, sea stacks) above modern sea level. This is due in part to the young age of the Honolulu Series and to the soft nature of the volcanic ash. Elsewhere on Oahu, coastal outcrops occur in volcanic rocks millions of years old, or they are faulted coastlines where much of the volcanic structure has been down-dropped below sea level.

The catalog of tsunami activity for the Hawaiian Islands (WALKER 1994) indicates the Queen's Beach coastal zone was inundated by 4 recent tsunamis: the Aleutian Tsunamis of 1946 and 1957, the 1952 Kamchatka Tsunami, and the 1960 Chile Tsunami. The catalog reports a maximum runup of 3 m (9.8 ft) at Makapu'u Point from the 1952 Kamchatka Tsunami and a 4 m runup for an unspecified location, possibly Kuliouou at the SE corner of Oahu for the 1960 Chile Tsunami. A photograph of a man escaping the 1957 Aleutian tsunami (see Figure 4.7 in DUDLEY AND LEE 1998) shows that the tsunami runup reached the ridge behind the Queen's Beach coastal plain at an elevation of roughly 9 m (or 30 ft based upon comparison of landforms in the photograph and the topographic map).

The 1946 tsunami waves reached 11.1 m (36.4 ft) asl on the north side of Makapu'u Head, 5 m (15 ft) at Kaloko Point located 1.6 km (one mile) southwest of Makapu'u Point, and 9.3 m (31 ft) asl at Koko Head. However the eyewitness accounts from the Davis family indicate the runup in Kealakipapa Valley approached the gap behind Makapu'u Point where the elevation reaches 45 m (150 ft) but apparently did not effect the access road to the lighthouse at roughly 24 m (or approximately 80 ft), which would be consistent with a runup of perhaps 20 m within Kealakipapa Valley. Tsunami modeling indicates that 10 m tsunami waves were sufficient to replicate the eyewitness observations.

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