G. Schernewski und T. Dolch (Hrsg.): Geographie der Meere und Küsten
Coastline Reports 1 (2004), ISSN 0928-2734
S. 77 - 82

Tsunami Deposits on the Island of Oahu, Hawai'i

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Abstract

Repetitive, catastrophic tsunamis have been credited as a causative mechanism for geomorphic change in coastal landforms. This study presents tsunami evidence on the Island of Oahu, Hawai'i. 'Signature' remnants of historic tsunamis, such as dislocated large boulders and conglomerate fields, provide evidence for historic tsunami events and their magnitude. GIS and remote sensing data sets, such as high-resolution aerial imagery, and complementary geomorphic field work, permit the spatial analysis for evidence of these high magnitude, low frequency events.

1 Introduction

The sedimentologic investigation of tsunami deposits is a fairly new field of research (Young & Bryant 1992 and 1993; Einsele et al. 1996; 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 the 1992 Flores Tsunami in Indonesia, by Bryant et al. (1992) and Nott (1997 and 2000) on the Australian coast, 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 Scheffers (2002) on Aruba, Curacao, and Bonaire, by Whelan & Kelletat (2003) on the southern Spanish Atlantic coast, and others.

2 Field observations: tsunami deposits on Oahu, Hawai'i

This study presents two representative sites with tsunami deposits on Oahu, Hawai'i. Both boulder deposits and coarse tsunami deposits were observed in the Queen's Beach coastal zone located on southeastern coast of the island. Large boulder deposits were observed at Shark's Cove on the north shore of Oahu. Oahu's coastlines were 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.

2.1 Queen's Beach deposits

The coastal plain between Sandy Beach and Makapu'u Head is referred to as Queen's Beach. As illustrated in Figure 1, 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. Historic tsunami activity and associated deposits were photographed during and immediately after the 1946 tsunami. 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 above sea level (asl) on the north side of Makapu'u Head and 9.3 m asl at Koko Head. The tsunami destroyed all of the recorded archaeological sites within the coastal plain (Keating et al. 2004).

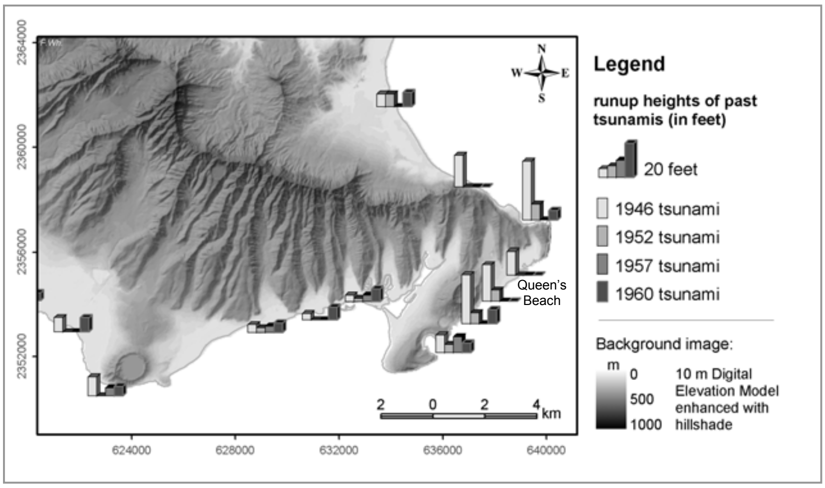

Fig. 1: Tsunami wave runup heights of historic tsunamis in the Queen's Beach coastal zone (UTM, WGS84). Data based on H. G. Loomis 1976, digitized by Office of Planning Staff in 1999. (Modified after Keating et al. 2004)

The 1946 tsunami seemed to have considerably impacted the geomorphology of the Queen's Beach coastal zone. This tsunami left steep beach faces and large sand dunes were truncated creating steep seaward cusps. Recorded runup was extremely high for the coastal zone immediately to the southwest of Queen's Beach. In between Queen's Beach and Hanauma Bay, runup was recorded at 9.3 m for the 1946 tsunami (Walker 1994 and 2003). As illustrated in Figure 1, subsequent tsunamis also inundated the Queen's Beach coastal zone. The U.S. Army Corps of Engineers(1978) studied the historical recurrence of tsunamis around the Hawaiian Islands and suggested that Queen's Beach is likely to be inundated every 25 years by tsunami waves of 2.4 m asl and every 100 years by a tsunami with wave heights of 6.6 m asl (Keating et al. 2004).

The Queen's Beach coastal zone displays 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 sub-rounded to rounded clasts. The sediment sheet is one clast size thick, extends approx. 200 m inland, and consists of basalt and coral clasts (broken and rounded fragments). Both are clearly from the ocean environment as indicated by coralline algae in basalt pores, by worm tubes and burrowing. 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 Queen's Beach, the deposits' elevations reach well beyond the extent of storm surges. This was verified in November 2003, when a storm generated 10-meter surf on the east side of Oahu. The elevation of the deposits therefore suggests tsunami as the transport mechanism.

A survey of the sedimentary deposits was carried out in the 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) 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 2). The preliminary transect extended from south to north across the Queen's Beach coastal zone. The beginning of the transect is characterized by modern beach and storm deposits. The clasts within the modern beach were dominantly coral and have a very white, bleached appearance. A berm at the top of the modern beach largely consists 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 2). 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 (Keating et al. 2004).

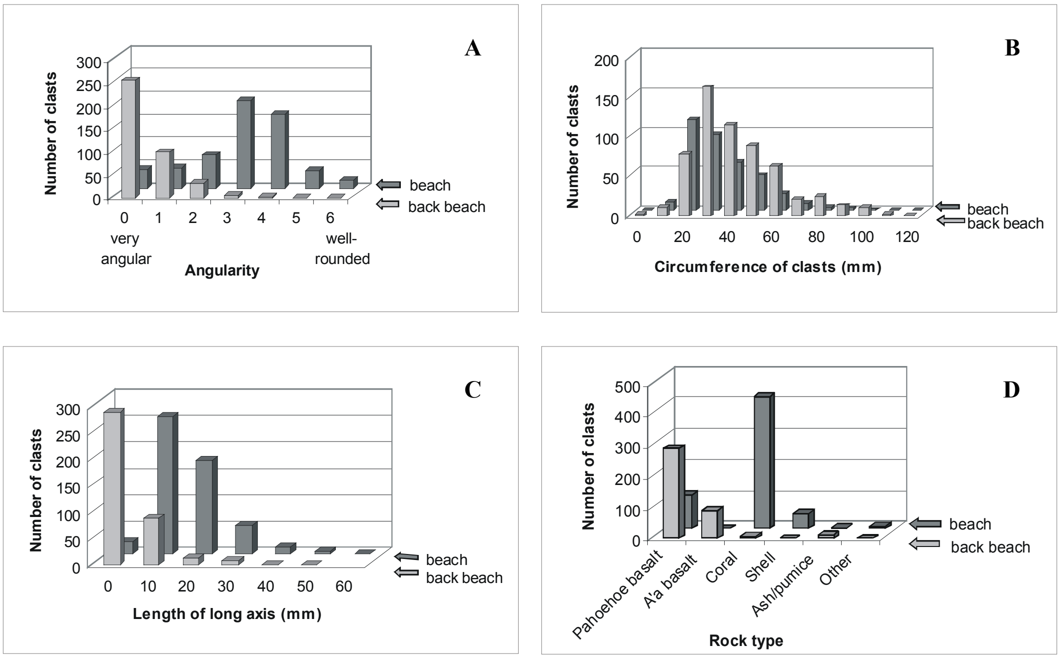

Fig. 2. Comparison of rock characteristics between the modern beach deposits and the back beach deposits interpreted as resulting from tsunami activity. The comparisons include A) angularity determined on a 0 to 6 scale after Folk (1968), with increments including very angular, angular, sub-angular, 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 (modified after Keating et al. 2004).

The investigations indicate that the surface deposits in the vicinity of the remnants of the 1932 roadway destroyed by the 1946 tsunami, Kaloko 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 Hawai'i) 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 are likely to be associated with historic tsunami.

The histograms in Figure 2 demonstrate that the rock characteristic of the two deposits are very different. While the modern beach deposits are well-rounded by abrasion associated with wave activity, the rocks in the back beach are angular, reflecting breakage. The back beach clasts are darker in color, which is interpreted as increased weathering, smaller in size, more fractured, and dominated by lava fragments rather than coral. These results 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 (Keating et al. 2004).

2.2 Shark's Cove deposits

The Shark's Cove or Pupukea coastal platform is a prominent headland west of Keiki Beach on the north shore of Oahu. It is subject to extreme wave energy. It is an erosional rock platform cut into coral limestone of Late Pleistocene age (Noormets et al. 2002, Muhs & Szabo 1994). The rock platform is located between a shallow bay (Shark's Cove) and a sandy beach and ends with a steep cliff on its seaward side. Holocene notches are clearly visible at sea level. Noormets et al. (2002) describes the rock platform in detail. Landward, the platform is heavily eroded and displays a rugged karst morphology. Several extremely large boulder deposits are stuck between the karst features consisting of solution pools surrounded by extremely sharp-edged rims.

Twenty-six extremely large coral limestone boulders were observed on the rock platform between Shark's Cove and Keiki Beach (Figure 3). Boulder weights reach 550 t. Field work included mapping these boulders using a Global Positioning System (GPS), measuring boulder axes and orientation, and relative and absolute dating. Boulder dimensions exceeded 10 m^3, the largest boulder has a volume of 110 m^3. Boulder dimensions range from 2 to 11 m in length, 2 to 6 m in width, and 0.8 to 5 m in height. The breaking of one boulder into two pieces during deposition suggests a high magnitude event, such as a tsunami wave, which carried the boulder in suspension until dropped onto the platform. Boulder material and boulder morphology resembles that of the coastal platform. For example, the largest boulder resembles the smooth morphology of the seaward section of platform surface on its side, and displays several sea urchin holes.

Fig. 3: Deposited tsunami boulders on the Pupukea rock platform between Shark's Cove and Keiki Beach on the north shore of Oahu. (1) Overview of tsunami boulders, (2) example of coral reef boulder deposit, (3) sample collection for C14 dating, (4) oyster shell sample for C14 dating – see Euro coin for size comparison.

GPS data allowed for GIS analysis and visualization and the geo-referenced overlay of the mapped data with aerial imagery. The potential runup and intensity of the tsunami was determined based on hydrodynamic wave formulas developed by Nott (1997) and based on surface analysis using a Digital Elevation Model (DEM) and bathymetry data. Noormets et al. (2002) overlayed historic aerial imagery and suggested that boulder movement was indicated by minor deviations between aerial photographs from different years. However, these deviations may only partly be explained by change analysis, since imagery distortion and the lack of georeferencing information introduce a significant amount of error. Geo-referencing aerial imagery of that area is very difficult since the few cues or control points are largely limited to the platform edge. However, in the aerial photography the platform edge appears differently during different surf and lighting conditions,. The relatively poor photogrammetric quality and varying scales of the historic imagery (i.e. 1928, 1940, 1950s, 1960s) may also lead to inconclusive results. No boulder movement was detected after winter storms in November 2003, when storm-generated surf reached 45 feet on the north shore of Oahu.

Relative and absolute dating suggests that the large boulders were placed onto the platform by one tsunami event. C14 dating results based on samples from three individual boulders indicated that the majority of the large boulders were deposited on the platform simultaneously by one event approx. 500 years BP, uncalibrated (Whelan in prep.). Relative dating complemented these findings and was based on the Hawaiian legend of these Pupukea boulders. They are called Pele's (Hawaiian goddess) followers. Based on the legend, they were loyal friends of Wahine Kapu who turned them into massive stones so that they can become immortal (Evans-Mason 2001). The legend either suggests that the boulders were deposited on the platform before the first Hawaiians arrived (800 years BP) or they were deposited there all at once (legendary for "petrified").

3 Discussion

The Hawaiian Islands are highly susceptible to tsunami impact and therefore pose an ideal study site for deposition and erosion associated with tsunamis on modification of the coastal geomorphology. While the majority of world-wide tsunami studies focus on fine sediments, the magnitude and effects of historic tsunami events on Hawai'i are best revealed by studying the location and distribution of large clasts and coarse sedimentary deposits. Both boulder and cobble deposits were observed and attributed to tsunami impact. Derived from the deposits in the Queen's Beach coastal zone, this study proposes new insights into the differences and signatures of storm versus tsunami deposits. The north shore boulders were also deposited by tsunamis and provide new evidence for the magnitude of historic tsunami events.

Acknowledgements

I would like to thank the Deutsche Forschungsgemeinschaft (DFG) for their support (Project WH 10/6-1).

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