Prepared in cooperation with the U.S. National Park Service

Geologic Resource Evaluation of Pu‘ukoholā Heiau National Historic Site, Hawai‘i; Part I, Geology and Coastal Landforms

Open-File Report 2008-1190

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By Bruce M. Richmond, Susan A. Cochran, and Ann E. Gibbs

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U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2008

Suggested citation:
Richmond, Bruce M., Cochran, Susan A., and Gibbs, Ann E., 2008, Geologic resource evaluation of Pu‘ukoholā Heiau National Historic Site, Hawai‘i; part I, geology and coastal landforms: U.S. Geological Survey Open-File Report 2008-1190, 23 p. [http://pubs.usgs.gov/of/2008/1190/].

Front cover:
Oblique aerial photograph showing Pu‘ukoholā Heiau (upper structure) and Mailekini Heiau (lower structure) and surrounding areas at Pu‘ukoholā Heiau National Historic Site. The coastal engineering structure in the lower left is part of the Kawaihae Harbor revetment. View towards the east. Photograph courtesy of Brian Powers, Hawaiian Images Photography and Video, Kailua Kona, Hawai‘i.

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Geologic Resource Evaluation of Pu‘ukoholā Heiau National Historic Site, Hawai‘i Part I: Geology and Coastal Landforms

By Bruce M. Richmond, Susan A. Cochran, and Ann E. Gibbs

Introduction

Geologic resource inventories of lands managed by the National Park Service (NPS) are important products for the parks and are designed to provide scientific information to better manage park resources. Park-specific geologic reports are used to identify geologic features and processes that are relevant to park ecosystems, evaluate the impact of human activities on geologic features and processes, identify geologic research and monitoring needs, and enhance opportunities for education and interpretation. These geologic reports are planned to provide a brief geologic history of the park and address specific geologic issues forming a link between the park geology and the resource manager.

The Kona coast National Parks of the Island of Hawai‘i (fig. 1) are intended to preserve the natural beauty of the Kona coast and protect significant ancient structures and artifacts of the native Hawaiians. Pu‘ukoholā Heiau National Historic Site (PUHE), Kaloko-Honokōhau National Historical Park (KAHO), and Pu‘uhonua O Hōnaunau National Historical Park (PUHO) are three Kona parks studied by the U.S. Geological Survey (USGS) Coastal and Marine Geology Team in cooperation with the National Park Service. This report is one of six related reports designed to provide geologic and benthic-habitat information for the three Kona parks. Each geology and coastal-landform report describes the regional geologic setting of the Hawaiian Islands, gives a general description of the geology of the Kona coast, and presents

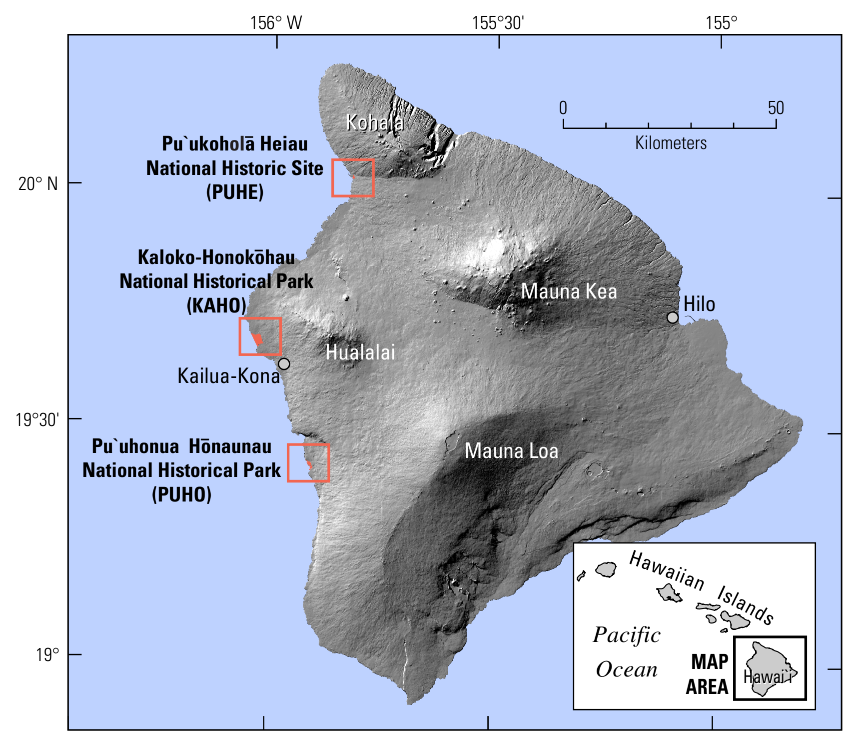
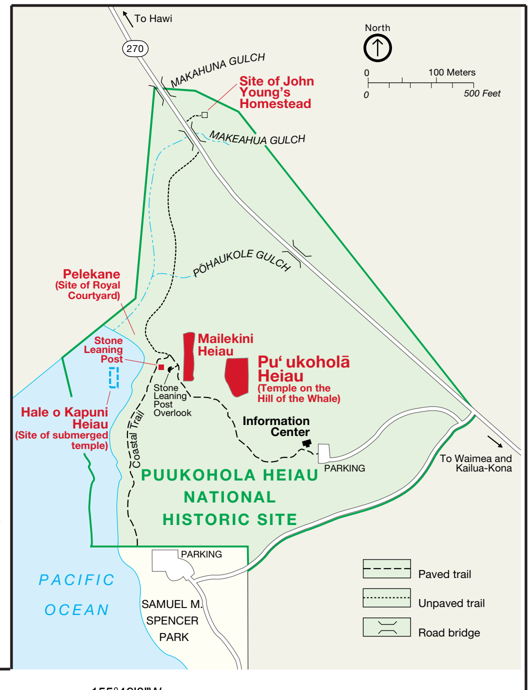


Figure 1. Index map of the Island of Hawai‘i showing the location of the three National Parks along the Kona coast. Volcano names are shown in white.

the geologic setting and issues for one of the parks. The related benthic-habitat mapping reports discuss the marine data and habitat classification scheme, and present results of the mapping program.

Pu‘ukoholā Heiau National Historic Site (PUHE) is the smallest (~86 acres) of three National Parks located on the leeward Kona coast of the Island of Hawai‘i (fig. 2). The main structure at PUHE, Pu‘ukoholā Heiau, is an important historical temple that was built during 1790-91 by King Kamehameha I (also known as Kamehameha the Great) and is often associated with the founding of the Hawaiian Kingdom (Greene, 1993). The temple was constructed to incur the favor of the king’s personal war god Kūkā‘ilimoku during the time that Kamehameha I waged several battles in an attempt to extend his control over all the Hawaiian Islands. The park is also the site of the older Mailekini Heiau, which was used by the ancestors of Kamehameha I, and an offshore, submerged temple, Hale O Kapuni Heiau, that was dedicated to the shark god. The park occupies the scenic Hill of the Whale overlooking Kawaihae Bay and Pelekane Beach.

The seaward-sloping lands of PUHE lie at the convergence of lava flows formed by both Mauna Kea and Kohala Volcanoes. The park coastline is mostly rocky, with the exception of a small be ach developed at the north boundary where an intermittent stream enters the sea. The park is bounded to the north by Kawaihae Harbor, to the south by Samuel M. Spencer Beach Park, and to the west by a broad submerged reef. The adjacent reef area is discussed in detail in the accompanying report by Cochran and others (2006). They mapped from the shoreline to depths of approximately 40 m, where the shelf drops off to a sand-covered bottom. PUHE park boundaries extend only to the mean high-tide line, however, landscape impacts created by development around the park are of concern to Park management.



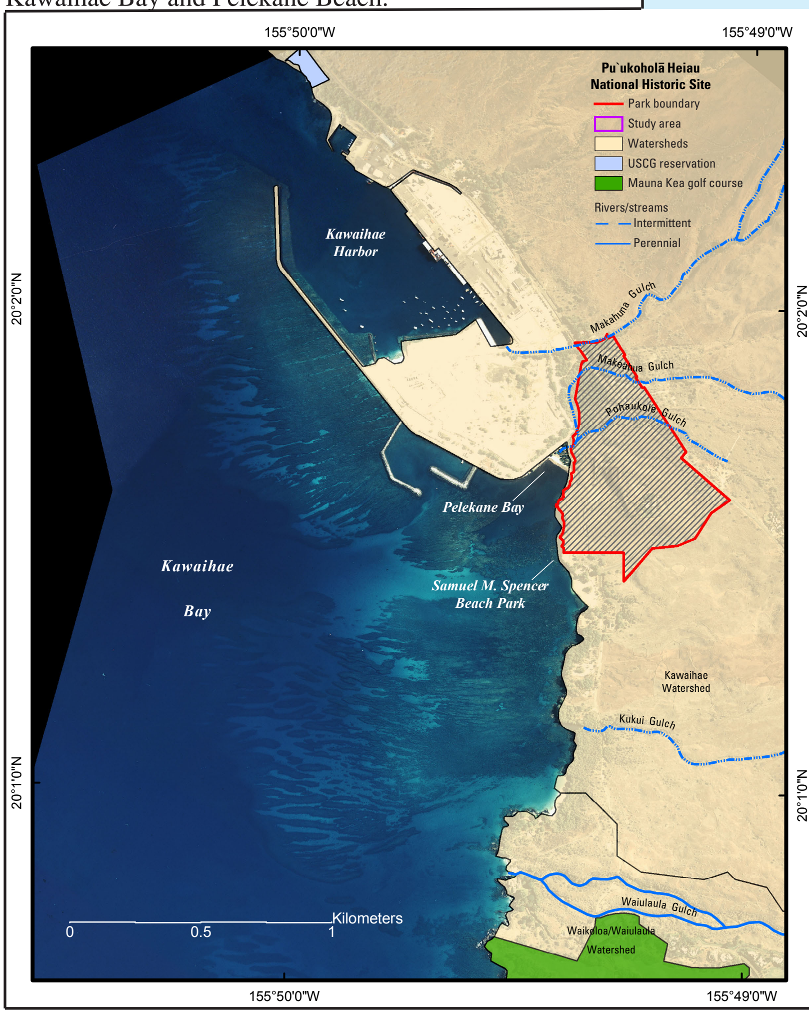


Figure 2. Aerial photomosaic of Pu‘ukoholā Heiau National Historic Site showing park boundaries and geographic locations. Inset park map from the National Park Service.

Regional Geologic Setting

The Hawaiian Islands are the tops of very large volcanic mountains formed on the floor of the Pacific Ocean. The islands are thought to have originated as the Pacific tectonic plate slowly moved over a relatively stationary hot spot in the underlying mantle (Macdonald and others, 1983). The formation of the Hawaiian Island chain has recently been shown to be a much more complex process than this simple model of a fixed thermal deep-mantle plume (hot spot), as discussed in a recent work by Foulger and others (2005).

The islands are part of the Hawaiian-Emperor volcanic chain, which extends for nearly 6,000 km across the Pacific sea floor. The Hawaiian Island segment of the chain is less than about 43 million years old (Clague and Dalrymple, 1987) and extends about 2,600 km, from the Island of Hawai‘i in the southeast to Kure Atoll in the northwest. Island age increases towards the northwest. Within the main Hawaiian Islands, there are two roughly parallel trends of volcanoes (Moore and Clague, 1992). The northern Kea trend includes the volcanoes of Kilauea, Mauna Kea, Kohala, East Maui (Haleakala) and West Maui. The southern Loa trend includes Lo‘ihi (the newest volcano forming on the sea floor), Mauna Loa, Hualālai, Māhukona (a submerged volcano), Kaho‘olawe, Lāna‘i, and West Moloka‘i (fig. 3). Age of the shield stages for the main Hawaiian Islands range from less than 1 Ma for the Island of Hawai‘i to 5.8 – 3.9 Ma for the Island of Kaua‘i (Clague and Dalrymple, 1987). Hawai‘i volcanic geology is thoroughly discussed in the two-volume U.S. Geological Survey Professional Paper 1350, Volcanism in Hawai‘i, edited by Decker and others (1987).

Island of Hawai‘i has the Earth’s largest volcanic mountain, Mauna Loa, its tallest volcano from the base to summit, Mauna Kea, and one of the world’s most active volcanoes, Kilauea. Despite its great

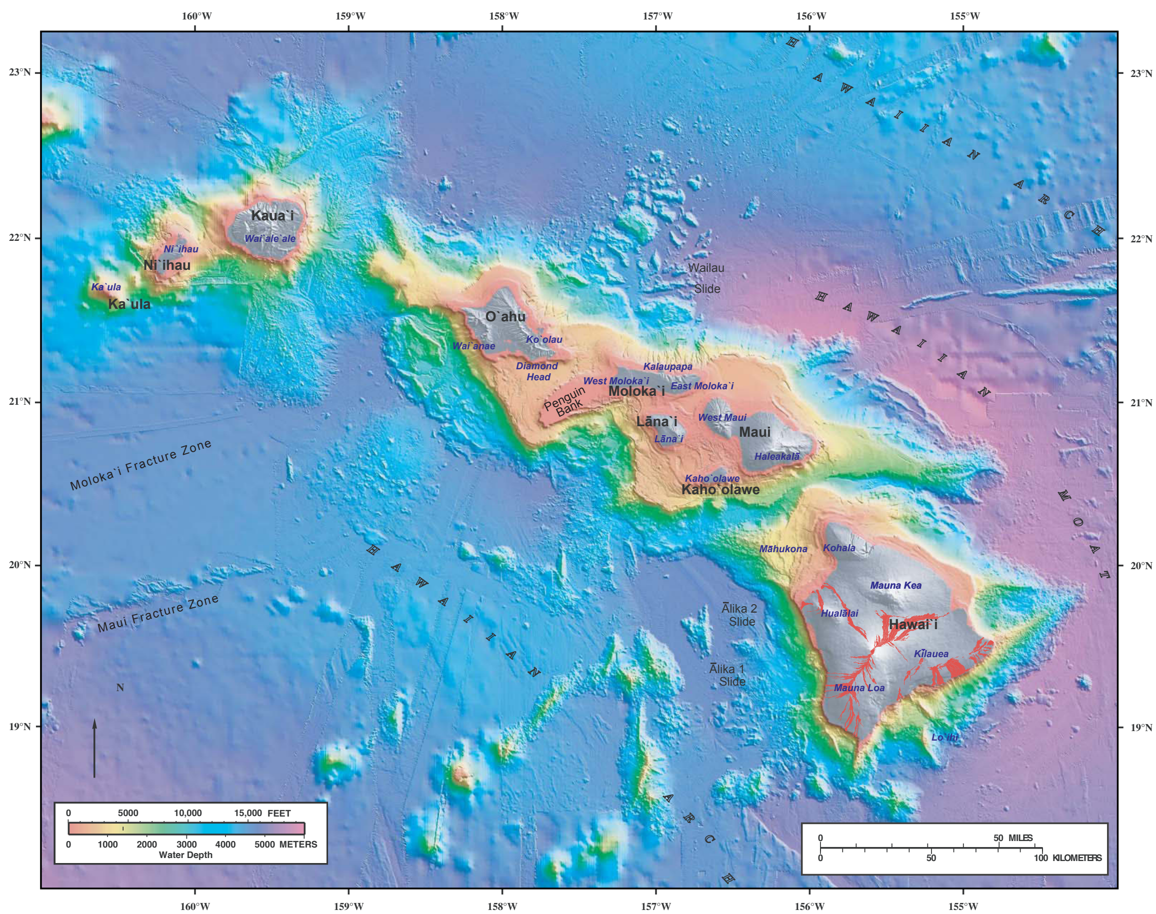


Figure 3. Topography and bathymetry of the main Hawaiian Islands (U.S. Geological Survey base image from Eakins and others, 2003). Island dissection and age increase towards the northwest. The red areas on the Island of Hawai‘i show the location of historical lava flows.

height, Hawai‘i has subsided a total of nearly 1.2 km at a rate of about 2.6 mm/yr over the past 450,000 years because of flexural loading associated with the volcano-building processes (Zhong and Watts, 2002). Other notable geologic features of the island include several huge submarine landslide deposits that cover large areas of adjacent sea floor and represent some of the Earth's largest mass-wasting features (Moore and others, 1989); highly visible fault scarps along the flanks of Mauna Loa and Kilauea; modern coral reefs, as well as submerged terraces formed by older drowned reefs; and dramatic beaches composed of a wide range of sediment, from reef-derived white sand beaches to volcanically derived black and green sand beaches.

The Island of Hawai‘i is formed from five separate subaerial shield volcanoes—Kohala, Mauna Kea, Hualālai, Kilauea, and Mauna Loa (fig. 4)—and two submarine volcanoes, Lo‘ihi, which is currently active, and Māhukona (Moore and Clague, 1992). Mauna Loa, Kilauea, and Hualālai have been active in historical time. Mauna Kea has been dormant for about the past 4,500 years, and Kohala's last eruption was around 60,000 years ago (Macdonald and others, 1983). Hawaiian shield volcanoes typically evolve through a sequence of four eruptive stages termed preshield, shield, postshield, and rejuvenated (Clague and Dalrymple, 1987). Each stage has a characteristic lava composition and eruptive rate, with most of the resulting volcano composed of shield-stage rocks. The exposed portion of the Island of Hawai‘i is formed primarily of Mauna Loa and Kilauea shield-stage rocks and Kohala, Hualālai, and Mauna Kea shield and post-shield volcanic rocks (Langenheim and Clague, 1987). The two primary types of lava flows in Hawaiian shield volcanoes are the smooth, ropy pahoehoe and the rough, angular ‘a‘a. Both types of lava are compositionally similar, and both can occur within the same flow. The type of lava that forms appears to be related to the physical characteristics of the lava and the amount of stirring it has undergone (MacDonald and others, 1983). Well-stirred viscous lava favors the formation of the ‘a‘a-type flow.

Modification of the volcanic landforms through erosion and weathering processes varies dramatically on the Island of Hawai‘i, primarily because of variations in precipitation. A marked difference in the degree of erosion is evident between the wet, windward (eastward-facing) slopes and the much drier, leeward (western-facing) exposures. Large canyons and surface gullying tend to be more prominent along windward slopes with high annual rainfall rates. Along the west-facing leeward slopes at lower elevations, much of the original volcano surface is preserved because of the drier conditions and lower rates of erosion. The leeward coast of the Island of Hawai‘i typically averages less than 500 mm of rain per year, and the NPS park averages are 280, 360, and 610 mm/yr for PUHE, KAHO, and PUHO respectively (data from Western Regional Climate Center, http://www.wrcc.dri.edu/, last accessed on December 1, 2008). Rates of precipitation increase inland because of the orographic effect of the high volcanoes. The Kona coast on the west side of the island of Hawai‘i is unique in the Hawaiian Islands in that it is the only region to receive more rainfall in the summer than in the winter.

Natural Hazards

The Hawaiian Islands are at risk from a number of natural hazards, which include volcanic and seismic activity, coastal inundation from tsunamis, high waves and storms, stream flooding, and land loss related to coastal erosion and sea-level rise. Volcanic hazards on the Island of Hawai‘i include direct threats from lava flows, tephra (volcanic ash) eruptions, pyroclastic surges, and volcanic gas emissions, as well as indirect threats such as ground failures, subsidence, and earthquakes. These hazards are identified and mapped by Mullineaux and others (1987). Typically, thousands of earthquakes associated with the active volcanism and island-building processes on the Island of Hawai‘i occur each year, although most are too small to cause damage. On October 15, 2006, a magnitude 6.7 earthquake occurred about 15 km north-northwest of Kailua Kona (preliminary data available online from the U.S. Geological Survey, http://earthquake.usgs.gov/eqcenter/eqinthenews/2006/ustwbh/#summary, last accessed December 1, 2008). The earthquake caused numerous minor injuries to people and damaged more than 1,100 buildings, including ancient Hawaiian structures protected by the parks. The shake and associated landslides damaged roads and caused power outages throughout the Hawaiian Islands.

Occasional larger earthquakes, such as the magnitude 7.9 shock of 1868 located on the south flank of Mauna Loa, can cause more serious property damage and may generate local tsunamis when seawater is displaced by either fault movement or large landslides. For example, in November 1975, a locally generated tsunami with heights up to 14.6 m struck southeastern Hawai‘i as a result of a magnitude 7.2 earthquake (see http://hvo.wr.usgs.gov/earthquakes/destruct/1975Nov29/, last accessed on December 1, 2008) that caused rapid coastal subsidence along the southeast coastal terrace. This was the largest locally generated tsunami to impact Hawai‘i in the 20th century, and it produced deposits as much as 320 m inland and up to 10 m above sea level (Goff and others, 2006). The last large tsunami of distant origin to affect the Hawaiian Islands was generated by a great (magnitude 9.5) earthquake in Chile in 1960, and it caused extensive damage in the Hilo area (Dudley and Lee, 1988). There has been widespread and intensive human development along the Hawaiian shoreline since the 1960 tsunami.

Fossiliferous marine conglomerates along the northwest coast of Kohala Volcano have been interpreted as megatsunami deposits generated by a flank-failure submarine landslide on western Mauna Loa (McMurty and others, 2004). That landslide and tsunami occurred about 110,000 years ago; the tsunami had an estimated runup more than 400 m high and an inundation greater than 6 km inland. Catastrophic flank failures are extremely rare geologic events but are an important process in volcanic island evolution.

In addition to volcanic, seismic, and tsunami hazards, a number of other natural hazards impact the Kona parks, including stream flooding, seasonal high waves, storms such as hurricanes and Kona storms,

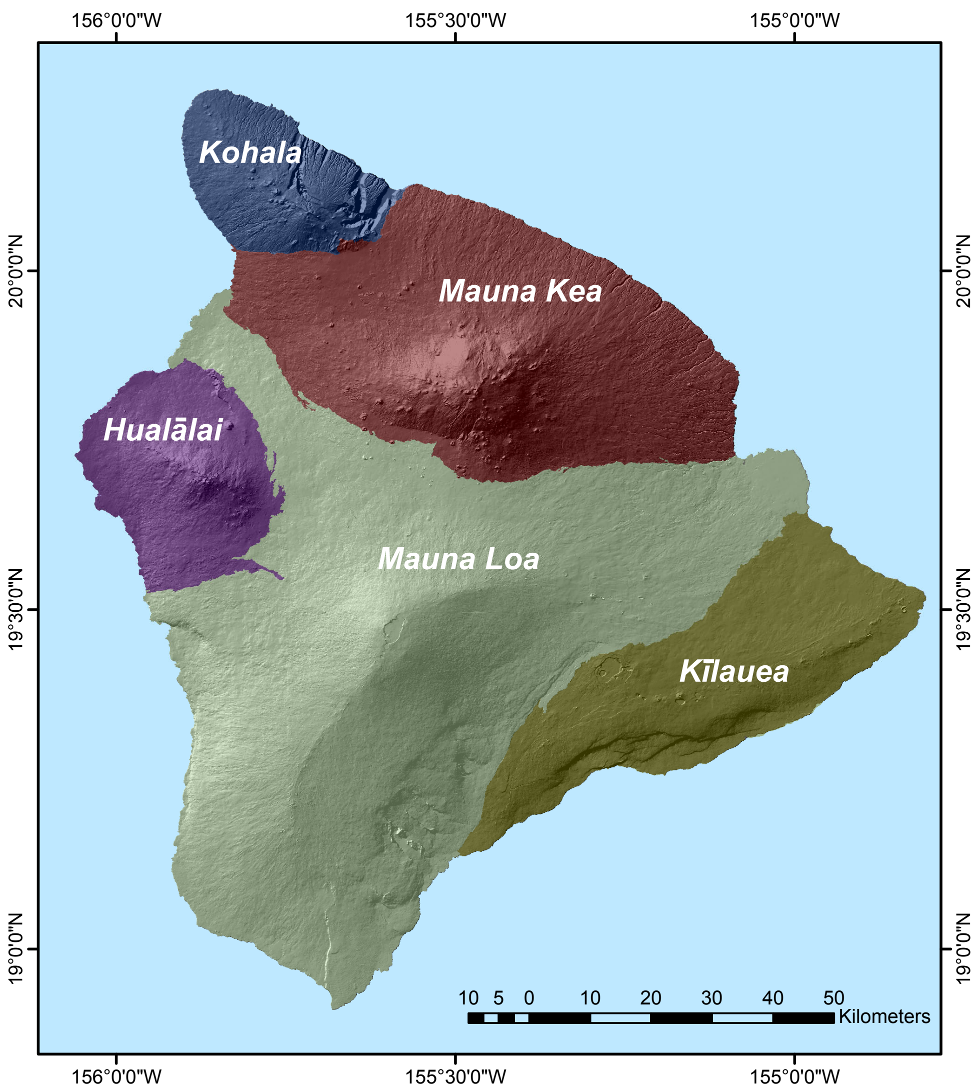


Figure 4. U.S. Geological Survey digital elevation model showing the five subaerial volcanoes that form the Island of Hawai‘i. The different colors show the approximate extent of the surface flows from each volcano. Geology data from Wolfe and Morris (1996) and Trusdell and others (2005).

coastal erosion, and long-term relative sea-level rise (Richmond and others, 2001; Fletcher and others, 2002). Watersheds in Hawai‘i are typically small, averaging less than 2.6 km^2 (Peterson, 1996), and are characterized by steep slopes with little channel water-storage capability. Consequently, intense rainfall events often result in a rapid rise of water level within streams, causing flash flooding. Coastal flooding of low-lying areas and rapid discharge of sediment into littoral environments are common effects of intense rains in Hawai‘i but are not typical occurrences along the Kona coast. Seasonal high waves generated by north Pacific storms, south Pacific swell, and local Kona storms (fig. 5) are nearly an annual occurrence. Kona storms are locally generated storms that typically occur in winter months and are often accompanied by strong winds and heavy rains that approach from leeward (kona) directions. Hurricane Iwa, which devastated the island of Kaua‘i in 1982, was the first major damaging hurricane to strike the Hawaiian Islands in nearly 50 years. Iwa was followed in 1992 by Hurricane Iniki, which also caused major damage to Kaua‘i and leeward O‘ahu. The Island of Hawai‘i experienced large surf and some coastal erosion from both hurricanes. Coastal erosion is a widespread and chronic problem in the Hawaiian Islands. Although recent comprehensive data are not available for the Island of Hawai‘i, erosion has caused beach loss or narrowing on nearly one-quarter of O‘ahu's beaches and as much as a third of the beaches on Maui (Fletcher and others, 1997; Coyne and others, 1996). All the coastlines of Hawai‘i have the potential to be impacted by storms and sea-level rise. As coastal lands increase in both economic and social value, it becomes imperative to develop a better understanding of the processes that shape the coast and affect the people who live there.

Kona Coast Parks – General Background

Pu‘ukoholā Heiau National Historic Site (PUHE), Kaloko-Honokōhau National Historical Park (KAHO), and Pu‘uhonua o Hōnaunau National Historical Park (PUHO) are situated on the leeward west coast of the island of Hawai‘i along the flanks of Kohala, Mauna Kea, Hualālai, and Mauna Loa Volcanoes (fig. 4). In addition to the seaward-sloping volcanic landscapes, these parks include beaches, basalt shore platforms, ponds and wetlands, anchialine pools, coastal cliffs, and adjacent reef areas. These features are described below. A map depicting the bedrock geology of the island of Hawai‘i was compiled by Wolfe and Morris (1996) and was recently released as a USGS digital database (Trusdell and others, 2005, http://pubs.usgs.gov/ds/2005/144/, last accessed December 1, 2008). Following are brief summaries of the bedrock geology and coastal landforms for the Kona Coast.

Shoreline Geology

The beaches of the Hawaiian Islands provide critical habitat for such animals as the threatened green sea turtle, are both a recreational and economic resource, and are features of cultural significance to ancient Hawaiians. In times of high surf, beaches present a natural buffer to the coast from storm-wave attack. The older islands typically have a higher percentage of sand-beach coastline because of a longer time span of land erosion, greater reef maturity, and development of suitable coastal embayments to trap sediment (Richmond, 2002). For example, the Island of Hawai‘i has a total estimated beach-sand reservoir of 1,300,000 m^3 and a beach-sand volume of 3,000 m^3/km of coastline (Moberly and Chamberlain, 1964). For comparison, the older island of Kaua‘i has 10,700,000 m^3 and 59,000 m^3/km, respectively.

Important factors that determine beach morphology include the elevation, slope, and orientation of the adjacent basalt bench or platform, exposure to waves, and availability of sediment. The lava flow morphology at the time of formation and the subsequent erosion along the water's edge strongly influence the type of coastal deposits that occur. The volcanic rocks provide the base substrate for subsequent reef growth offshore and sediment deposition onshore. Rates of basalt erosion vary depending on initial rock strength and wave exposure. In general, basalt flows are very resistant to erosion and most of the coastline geometry is a product of the initial basalt-flow morphology. Benches or terraces that are elevated above present sea level promote the formation of perched beaches, whereas low, subtidal benches lead to reef-flat development and intertidal beach deposition. Intertidal beaches are common worldwide, whereas perched beaches on rock platforms are much less common and require specific coastal geomorphic settings. Intertidal beaches are the most common beach type in Hawai‘i and are influenced by tide- and wave-driven variations in water level. Supratidal perched beaches are composed of deposits that lie above the normal influence of waves and tides. These beaches may be active for only days or weeks out of the year during episodes of large waves and high tidal levels (Hapke and others, 2005). On the Island of Hawai‘i, perched beaches typically occur on low-relief, gently sloping basalt terraces that lie near or slightly above average high tide levels.

In the three Kona parks, both intertidal and perched beaches are present. The intertidal beaches are typically fronted by a submerged reef flat or sand channel. The heights of the berm and back-beach areas

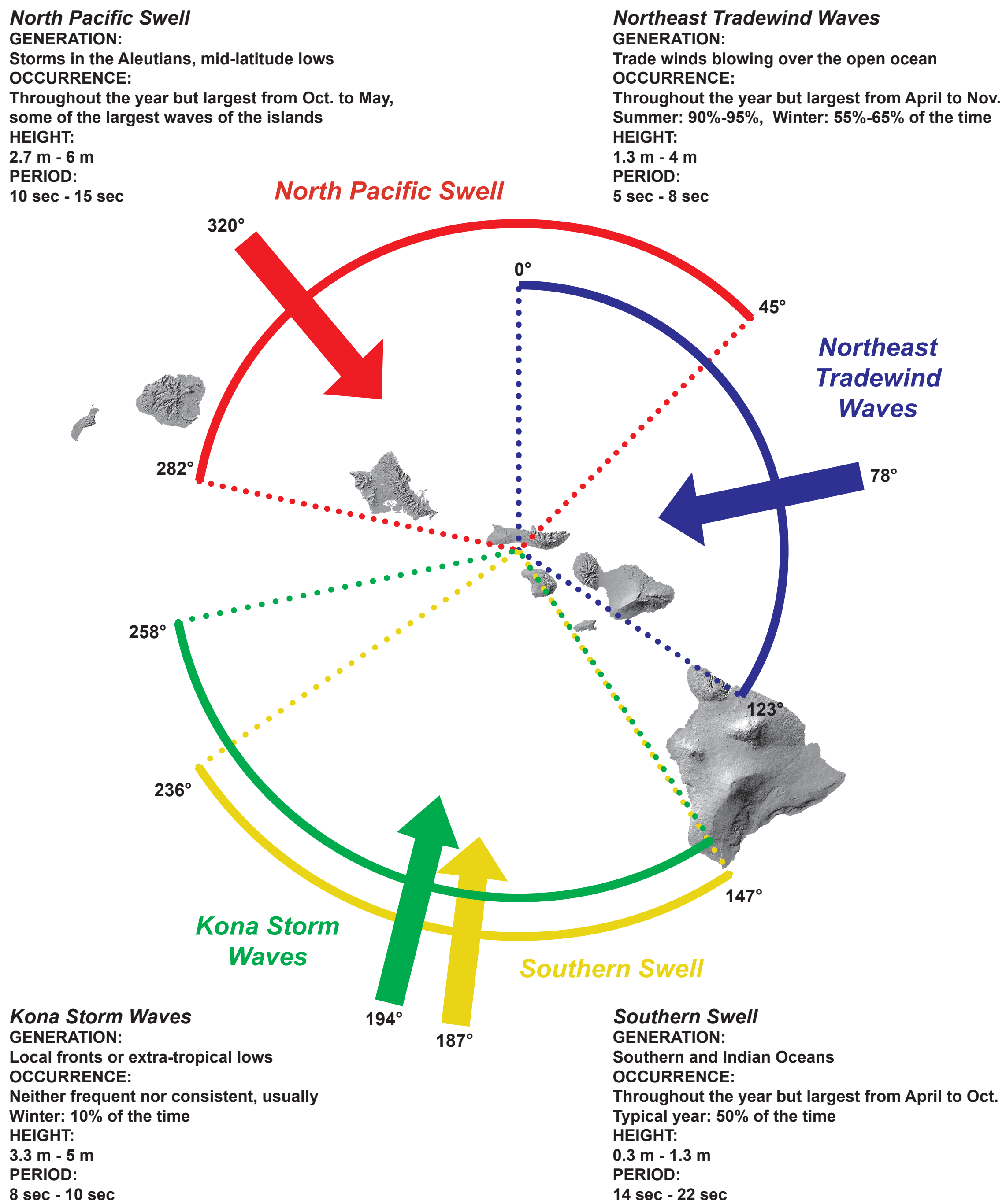


Figure 5. Diagram showing the wave-energy regime for the Island of Hawai‘i (modified from Moberly and Chamberlain, 1964). This figure summarizes the generation area, time of occurrence, and typical wave height and period for waves reaching the Hawaiian Islands.

are related to exposure and runup heights of storm waves. The higher elevations of the beach-sand body typically occur where the offshore morphology and orientation of the coast allow higher wave energy and runup to reach the shoreline. Along the Kona coast, open exposure to northwesterly winter storm surf and occasional southern swell, as well as Kona storm waves (fig. 5) produce the higher beach berms. Perched beaches on the Kona coast are common along the low-lying basalt terraces that front the coastline. Sediment, primarily reef-derived carbonate material, is deposited on top of the terraces during episodes of large waves. The perched beaches contain all the morphologic features of intertidal beaches (beach face, berm, and back beach) but are active for only limited periods during the year.

Cliffed coasts are common in Hawai‘i and are formed by one or more of several processes, including wave erosion of the land, coastal landslides and mass wasting, and deposition of lava into a steep nearshore zone, creating a steep front of the advancing lava. Cliff height varies with wave energy; age of the volcanic deposits and rock type forming the shoreline; relative uplift or subsidence rates; and general slope of the coast. Higher cliffs generally occur in areas of older rocks and high wave energy, such as on the northeast side of Kohala Volcano, where cliffs as high as 400 m are found. Of the three Kona national parks, the best developed cliffs are along the south PUHO coast, where moderately young lava flows (5 - 3 ka) have been truncated to form cliffs tens of meters high.

Anchialine (from Greek, meaning “near the sea”) pools are inland bodies of brackish water that are tidally connected to the ocean via underground tunnels (lava tubes in many cases) or through highly fractured and porous rock. In other words, they have a subterranean connection to the sea. Anchialine pools are unique features of the Hawaiian coast, and the majority of these pools occur along the west coast of the Island of Hawai‘i between Kawaihae and Kailua-Kona (Brock and Kam, 1997). Depressions within the lava flows and/or lava tubes near the coast are generally favorable for development of anchialine pools. They vary in size from small cracks and depressions in the lava to larger pools on the order of 100 m^2 and are typically shallow, with depths generally less than 1.5 m (Brock and Kam, 1997). Rare and fragile ecosystems occur in the pools, and they are often threatened by habitat loss and/or invasive species. It is estimated that more than 70 percent of the anchialine pools on the Island of Hawai‘i are on the Kona coast, where an estimated 420 pools are found (Brock and others, 1987).

Sedimentology

There are two primary sediment sources for the Kona coast: eroded products from the basement volcanic rocks (terrigenous sediment) and eroded products from the adjacent reef system. Most beach deposits on the Island of Hawai‘i are a mixture of the two types of sediment, although some relatively pure end-members occur in areas where one source dominates (fig. 6). The relative proportion of each sediment type is a reflection of local availability and the processes of sediment transport. Terrigenous sediment is delivered to the coast either by streams, through downslope creep associated with alluvial fan development, by coastal cliff erosion and mass wasting, or, more rarely, by littoral volcanic explosions that produce glassy volcanic detritus (Macdonald and others, 1983). The reef sediment is derived by natural physical, biological, and chemical breakdown of the coral, calcareous algae, and other associated carbonate skeletal material. Nearshore waves and currents transport the reef-derived sediment to the shore. Sediment size generally reflects both the size of the available source material and the relative wave energy. Beach sediment in high-wave-energy settings tends to be coarser because the fine fraction is hydrodynamically unstable and transported to less energetic locations.

Marine Setting

The leeward setting of the Kona coast is characterized by drier conditions and warmer weather than the Island of Hawai‘i’s windward east coast. The trade winds blow offshore in Kona, but they are often replaced by afternoon sea breezes. The mixed, semidiurnal tides are microtidal (<2 m), with two uneven high tides and two uneven low tides per day. The diurnal range of the tides (Mean Higher High Water to Mean Lower Low Water) at Kawaihae near PUHE, the nearest tide gauge, is about 0.65 m (National Oceanic and Atmospheric Administration, Tides and Currents Web site, http://tidesandcurrents.noaa.gov/, last accessed December 1, 2008). Most of the waves reaching the Kona coast are either north Pacific swell,

Figure 6. Photographs of coarse sediment beaches of the Kona coast. *A*, A predominantly coral pebble beach about 10 km south of PUHE. *B*, Basalt pebble beach about 30 km south of PUHE. Both beaches have minor components of the other's clast type.

Kona storm waves, or southern swell (fig. 5). Recent nearshore circulation studies conducted along the Kona coast yield some interesting results (after Storlazzi and Presto, 2005, and Presto and others, 2007):

- Nearshore water flow is primarily controlled by tides and local winds, except during periods of large surf when wave-driven currents predominate. For example. Large northwesterly swell events in December 2005 and January.2006 resulted in strong southwesterly current flow at KAHO.
- Falling tides draw warm freshwater offshore, while rising tides bring deeper, cooler, and more saline water onshore.
- Periods of low winds are accompanied by warming of shallow surface waters, except in areas of pronounced submarine groundwater discharge, which can lead to local cooling and associated decreased salinity.
- Large wave events are associated with increased water turbidity, presumably by either local resuspension or advection of suspended material from the nearshore.

In summary, the nearshore waters are a mixture of freshwater, warm surface seawater, and cool deeper seawater. Water quality near the coast is constantly in a state of flux because of changes in freshwater input and circulation variations driven by changing tide, wind, and wave conditions.

In general, large coral reefs are absent on the Island of Hawai‘i because of the relatively young age of the volcanic substrate and the rapid rate of local relative sea-level rise, which is estimated to be about 3.36±0.21 mm/yr as measured at Hilo (Pendelton and others, 2005). During the shield-building stage, regular fluctuation of the shoreline position, rapid subsidence of the islands due to lithospheric loading, and deposition of volcanic products in the ocean all contribute to the inhibition of reef growth. In the Hawaiian Islands, coral reefs are best developed after the volcano shield-building stage, when more stable shoreline conditions exist (Moore and Clague, 1992). Kona coast reefs tend to be relatively thin coral veneers established on a volcanic substrate. Reef-front spur-and-groove tracts are limited to the better developed reef areas such as Kawaihae Bay (Cochran and others, 2006).

Pu‘ukoholā Heiau National Historic Site (PUHE)

Geology

The stratigraphic framework of the Island of Hawai‘i consists of coalesced shield volcanoes (Langenheim and Clague 1987). PUHE straddles the boundary between Pleistocene volcanic rocks from Kohala and Mauna Kea Volcanoes (fig. 7). The Kohala deposits include the Hawi Volcanics, approximately 230-120 ka in age, and the older Pololu Volcanics that range in age from approximately 700-250 ka (Wolfe and Morris, 1996). Volcanic rocks from Mauna Kea cover most of the park and belong to the Hāmākua Volcanics that range in age from approximately 250 to 65 ka. The Hawi Volcanics from Kohala Volcano are overlain by the Hāmākua Volcanics of Mauna Kea Volcano.

The gently seaward-sloping park extends from the shoreline to an elevation of about 50 m. At the surface, the lava flows are weathered (fig. 8) and locally mantled by airborne tephra deposits. The Hawi lava flows mapped within the park (Wolfe and Morris, 1996) are composed of benmoreite, an extrusive igneous rock of the alkali basalt magma series that originated from vents on the flank of Kohala Volcano. The Pololu Volcanics within the park consist mainly of basalt lava flows. As with the Hawi and Pololu Volcanics, the Hāmākua Volcanics are highly weathered at the surface and are commonly mantled by tephra and weathering products (fig. 8). They consist of basaltic lava flows of both ‘a‘a and pahoehoe types and include the rocks underlying the visitor center and large heiau. The Hawi rocks consist of differentiated alkalic lava of the postshield stage, whereas the Hāmākua rocks are thought to represent shield-stage volcanism. The geologic map of Hawai‘i (Wolfe and Morris, 1996) shows no faults mapped within PUHE.

There is a greater degree of dissection and gullying within the older Kohala deposits than the younger Mauna Kea deposits, as shown in figure 9. The greater dissection is most likely the result of longer expo-

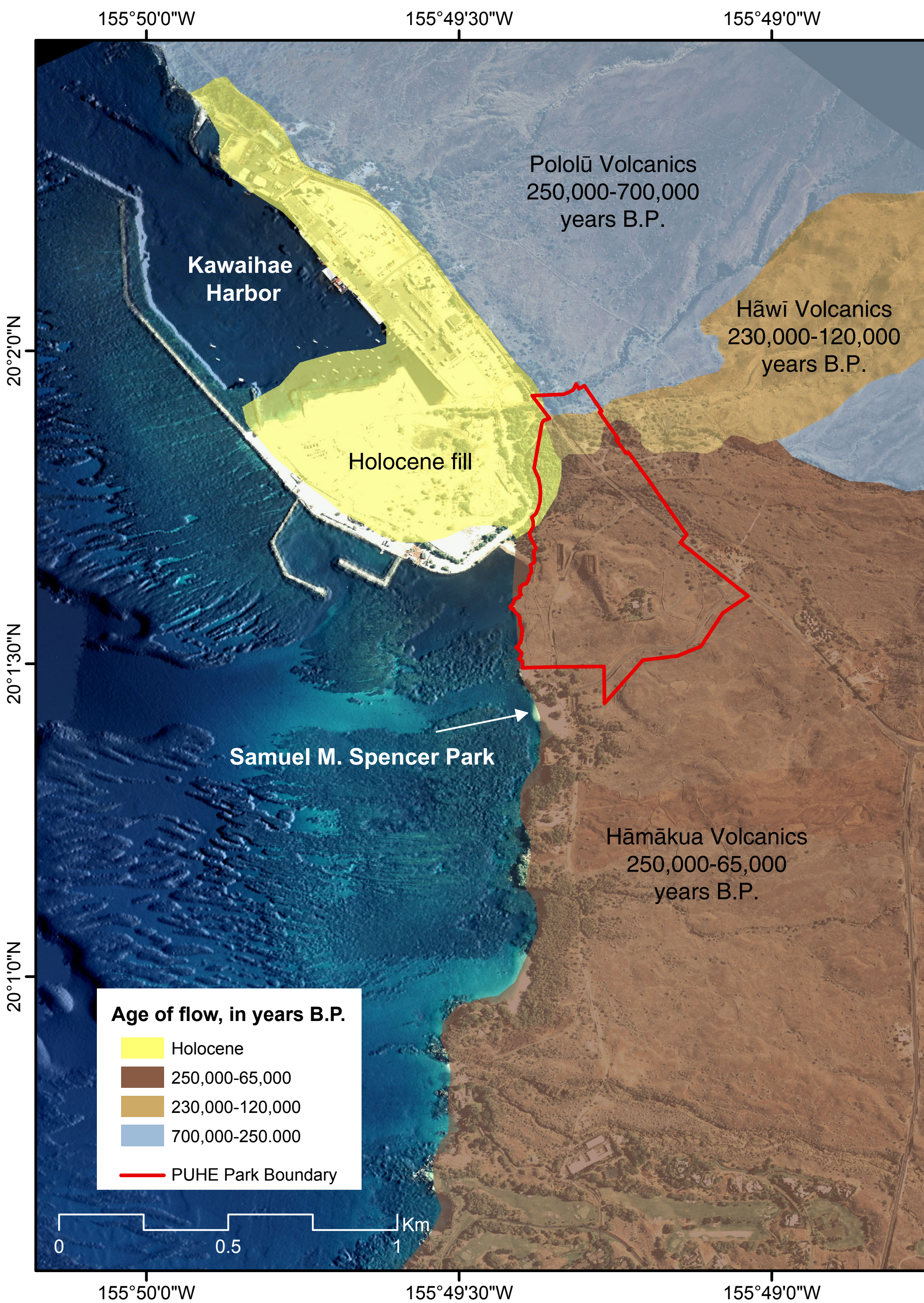


Figure 7. Aerial photomosaic showing bedrock geology, age of the volcanic flows, and offshore morphology of the PUHE area (geology layer from Trusdell and others, 2005). The area of Holocene fill is mostly material used for the construction of the Kawaihae Harbor. In the offshore zone, Quickbird satellite imagery is overlain on 2000 U.S. Army Corps of Engineers SHOALS bathymetry.

sure to terrigenous weathering processes. Offshore, marine erosion and Holocene reef growth have masked differences in the underlying bedrock morphology.

The soils of PUHE are part of the Kawaihae series as mapped by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS). The soil maps and accompanying descriptions are available online (http://www.ctahr.hawaii.edu/soilsurvey/soils.htm, last accessed December 1, 2008). The soils are described by the NRCS as "excessively drained extremely stony soils that formed in volcanic ash". Most of PUHE the soils consist of the "Kawaihae extremely stony very fine sandy loam" (KNC) in NCRS terminology. The northern corner of PUHE has KOC soils that are "very rocky very fine sandy loam," which are similar to KNC, except that rock outcrops occur on 10-20 percent of the surface.

Figure 8. Photograph of bedrock exposure of basalt flows (Hāmākua Volcanics) along an eroded bank of Pohaukole Gulch as viewed from the Highway 270 bridge (see fig 2). The thickest flow visible, the gray unit in the center of the photograph, is about 1 m thick. Soil development is sparse, and rubble has accumulated at the base of the exposure.

Coastal Landforms

The main depositional coastal feature at PUHE is Pelekane Beach, a small barrier beach at the north park boundary. Pelekane Beach is an intertidal beach that is fronted by a broad, gently sloping, sediment-covered reef flat. This low-lying beach is ~1-2 m high and is the seaward margin of a small coastal plain (fig. 10) developed within the stream embayment. Pelekane Beach (fig. 11) formed in the stream valley near the confluence of two intermittent streams, Makeahua and Pohaukole. A semipermanent pond has developed landward of the beach along the north park boundary (fig. 12). Makeahua Stream originally entered the ocean further north and was redirected during the construction of Kawaihae Harbor (Greene, 1993). The stream beds are dry most of the year, except near the coastal plain where the pond occupies the stream bed. During periods of high rainfall the streams are active and flood-delta deposits may blanket the inner reef flat. Flood deposits have buried an ancient offshore structure, Hale O Kapuni Heiau, which was used for

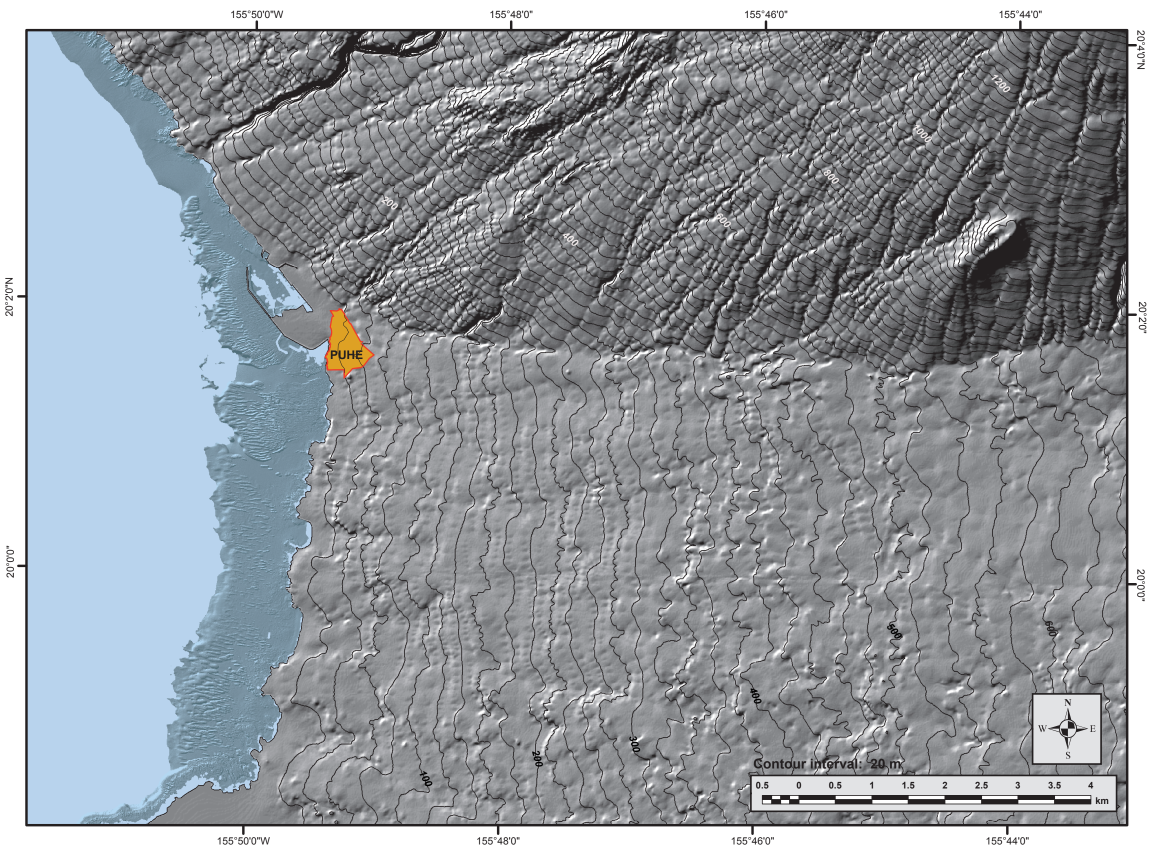


Figure 9. Shaded relief map showing the physiographic setting of PUHE (park in brown). The older Kohala deposits (top half of diagram) are steeper and have a greater degree of dissection and gullying than the younger Mauna Kea deposits (lower half of diagram). Marine erosion and reef growth has masked the underlying volcanic surface morphology offshore. U.S. Geological Survey 10-m digital elevation model used for the on-land base, and U.S. Army Corps of Engineers 2000 SHOALS data used for the offshore physiography. Contour interval 20 m.

shark feeding and worship (Clark, 1985). Both streams are steep and short and deliver coarse sediment to the coast, resulting in a relatively high percentage of terrigenous sediment on the beach.

Early accounts of the area, as reported in Green (1993), describe a fishpond at the mouth of the gulch, with another fishpond and saltpans farther to the north. The mouth of Makeahua Gulch was extensively modified during the construction of the Kawaihae Harbor jetty system. Construction of the deep-draft harbor began in 1949 and included construction of a 260-m-long jetty and breakwater. It is not clear how much depositional sandy shoreline was present before harbor construction, but there was probably some destruction of beach habitats to accommodate the harbor (Green, 1993). The north park boundary near the coast is marked by riprap emplacement of the jetty. Construction of the Kawaihae Boat Harbor modified the coastline of the north park area and changed the drainage patterns of the two intermittent streams, (Makeāhua and Pohaukole).

The remainder of the shoreline at PUHE consists of a rocky shoreline composed of low-lying basalt with scattered boulders and debris (fig. 13). Vegetation is absent below the approximate mean high water mark, leaving an exposed basalt surface. The offshore benthic habitats are described in detail by Cochran and others (2006).

Coastal Sediments

The coastal sediment at PUHE is derived primarily from the streams entering the coast and from the adjacent reefs. Makeāhua and Pohaukole are intermittent streams that deliver mud- through gravel-size

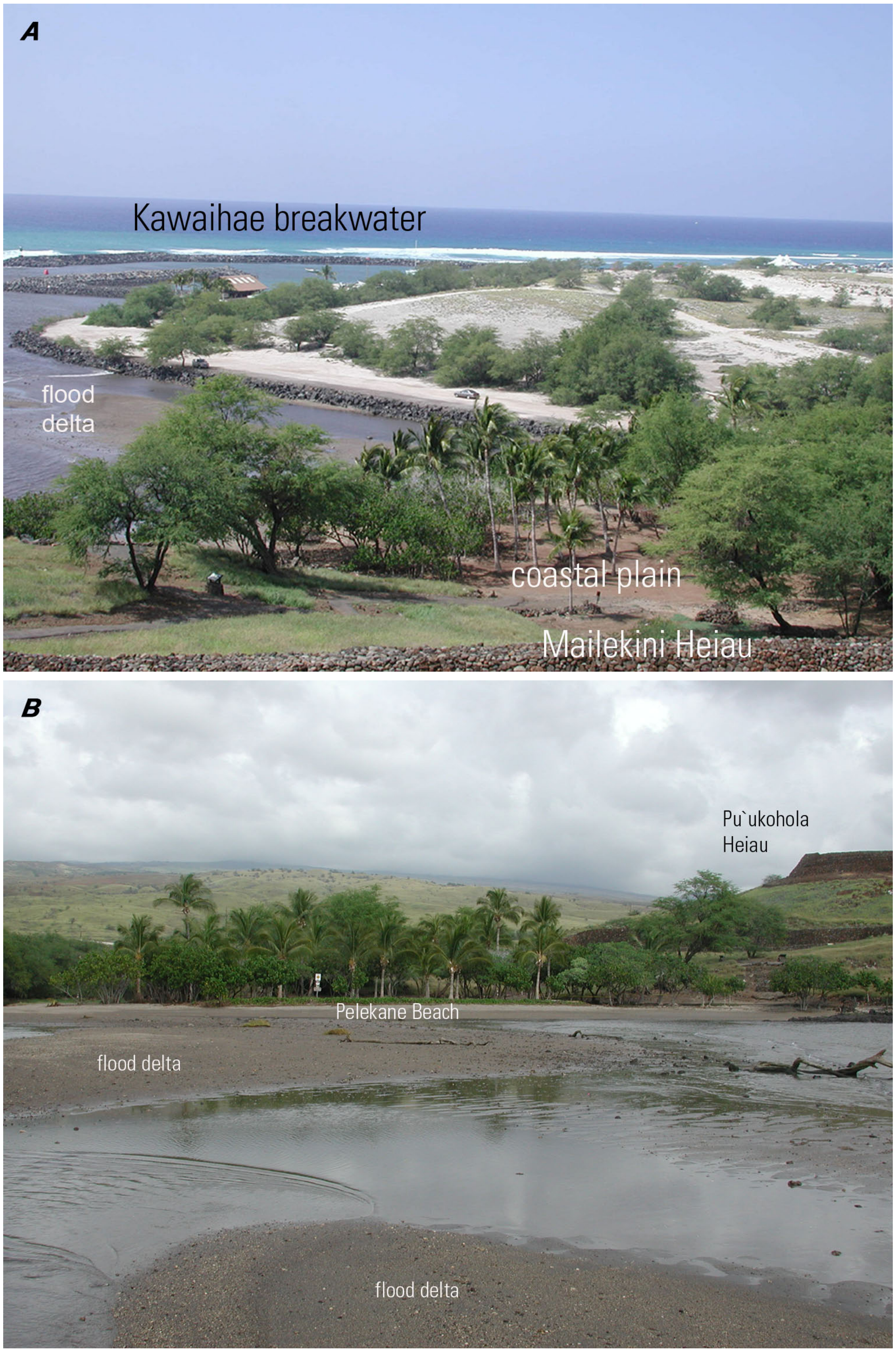


Figure 10. Photographs of Pelekane Beach and coastal plain. *A*, View to the north from the Hill of the Whale overlooking the coast showing the coastal plain, flood delta, and Kawaihae Harbor at the north boundary at PUHE. Coconut palms mark the back beach area. Kawaihae Harbor breakwater is in the background and a portion of Mailekini Heiau is in the foreground. An ephemeral flood delta composed of mostly terrigenous sediment lies on part of the inner reef flat. Photograph taken in February 2004 after a period of heavy rains. *B*, View of Pelekane Beach from the ephemeral flood delta deposits on the reef flat at the north end of PUHE (view to the east; February 2004).

volcanic sediment to the coast. Figure 14 shows the sand- through boulder-size material along the axis of the dry Pohaukole Gulch channel. The presence of boulders suggests periods of intense flooding capable of transporting coarse debris. The boulders are angular to slightly rounded, indicating that they have not traveled great distances.

Pelekane Beach sediments are predominantly volcanic-derived sands with a minor, locally variable, reef-derived carbonate component (fig. 15). These sediments are a combination of mostly moderately- to well-sorted, medium to coarse sand, and scattered pockets of fine gravel.

Figure 11. Photograph of Pelekane Beach and coastal park setting at PUHE (view to the south; August 2004).

Natural Hazards

The natural hazards for the coastal area surrounding the park have been identified and mapped (fig. 16, from Fletcher and others, 2002). Because of its coastal setting, PUHE is vulnerable to hazards that increase ocean-inundation potential, such as tsunamis, storms, and sea-level rise. Lander and Lockridge (1989) identified five historical tsunamis that struck Kawaihae since 1896. The tsunamis ranged in height from 1.2 m to 4.3 m, with the largest runup occurring from the 1946 tsunami originating in the Aleutian Islands. A similar event occurring today would most likely severely damage the beach and park infrastructure at Pelekane Beach, while causing less damage to the rocky shoreline of the park.

The Kawaihae Harbor breakwaters and the adjacent shallow reef areas partially protect the park coast from high waves and storms. Although there are no historical records of damaging high waves in Kawaihae Bay (Fletcher and others, 2002), storm waves arriving on a direct approach to the park have the potential to damage the coastline and adjacent reefs. For example, a hurricane traveling north along the west coast of Hawai‘i could cause significant coastal damage from a combination of high waves, storm surge, strong winds, and heavy rainfall.

Because the Island of Hawai‘i is an actively growing volcanic island, subsidence due to lithospheric loading results in higher rates of relative sea-level rise than those experienced on more stable islands. The average rate of relative sea-level rise for the Hilo tide gauge is 3.36±0.21 mm/yr (reported in Pendelton and others, 2005). This rate includes contributions from both eustatic and tectonic components at Hilo, which may be slightly different from the conditions at PUHO. Accelerated sea-level rise could result in flooding of low-lying infrastructure and erosion of park beaches over a time period of decades. Continued sea-level rise will eventually threaten many of the park’s beach facilities, coastal plain, and associated wetlands. Coastal

Figure 12. Photograph of pond area at the north end of Pelekane Beach near the confluence of Makeāhua and Pohaukole gulches (view to the east; August 2004).

erosion at present is episodic and related to the passage of high surf from seasonal local storms and/or long-distance swell.

During periods of heavy rain, severe stream flooding culminating in flash floods could affect both Makeāhua and Pohaukole Streams. An intense flooding event could result in erosion of parts of Pelekane Beach that block the stream channel and transport of sediment through the streams and deposit it as a flood delta on the reef flat. The impounded wetland/pond behind the beach would most likely be swept clean of sediment and debris. Heavy rains would also cause increased gullying and surface erosion in park uplands.

The entire park is subject to potential seismic and volcanic hazards. The October 15, 2006 Kīholo Bay earthquake, whose epicenter was less than 50 km away, caused severe damage to Pu‘ukoholā and Mailekini Heiaus (Medley and Zekkos, 2007). The unmortared rock walls of the heiaus suffered partial collapse and bulging. The adjacent Kawaihae Harbor suffered liquefaction and lateral spreading, damaging numerous structures. The lava flow, tephra fall, and pyroclastic surge hazards for the park are relatively low (Mullineaux and others, 1987; http://pubs.usgs.gov/gip/hazards/maps.html, last accessed online December 1, 2008).

Figure 13. Photograph of view to the north from near the south park boundary of PUHE showing the sloping hillside and exposed basalt flows along the shoreline. The revetment of Kawaihae Harbor can be seen in the background. Note the high turbidity of the nearshore water that is typical for this site (August 2004).

Hydrogeology

Ground water resources in Hawai‘i provide most of the water consumed and are directly related to aquifer geology and recharge rate. The best developed Hawaiian aquifers are in volcanic rocks that formed during the main shield-building stage of the volcano (Gingerich and Oki, 2000). Thin basalt flows, ranging in thickness from less than a meter to several meters, form aquifers characterized by thin freshwater lenses with high permeability and rapid discharge. In other words, ground water tends to flow rapidly from the mountains to the sea. Recharge occurs through infiltration, primarily from precipitation, and by inflow from upslope ground-water systems.

There are no ground water monitoring wells within PUHE, and the nearest monitoring station is located at Hāpuna Beach Park approximately 4 km to the south. This well is situated about 75 m above sea level on Pleistocene Hāmākua Volcanics. Water level in the well has varied from 0.4 to 1.5 m above sea level over the past 25 years, with an average level of 1.1 m above sea level for water year 2004 (data online at http://hi.water.usgs.gov/, last accessed on December 1, 2008).

Surface water within the park streams is intermittent and is generally restricted to periods of high rainfall. Neither Makeāhua nor Pohaukole Streams is gaged, and the nearest stream-gaging station is on Waikoloa Stream, about 18 km east of the park at an elevation of 1,055 m, That stream enters the ocean near Waiulaula Point, about a kilometer south of the park. At the gaging station the average discharge for 57 years of records is 9.31 cubic feet per second (cfs) (data online at http://hi.water.usgs.gov/, last accessed on December 1, 2008). The maximum and minimum discharge values recorded are 3,410 and 0.34 cfs, respectively. March and April typically record the highest flow, and July through October record the lowest flows. Makeāhua and Pohaukole streams are often dry but subject to flash flooding, as suggested by the boulder-filled channels.

Figure 14. Photograph of view upstream along the dry stream bed of Pohaukole Gulch about 150 m from Pelekane Beach. The channel sediment is a poorly sorted volcanic sand and gravel mixture (green notebook, 20 x 27 cm, for scale).

Resource Management Information

Puʻukoholā Heiau is clearly the focus of Puʻukoholā Heiau National Historic Site and is nationally significant for its association with King Kamehameha I and the unification of the Hawaiian Islands (National Park Service 2004). The park occupies the scenic Hill of the Whale overlooking Kawaihae Bay and is a popular site for enthusiasts of ancient Hawaiian history and day hiking. In general, the park is relatively stable geologically although there are some areas of potential concern.

1. Pelekane Beach, one of the more visited sites within the park, is susceptible to long-term shoreline erosion and potential marine inundation during storms and tsunamis. Any development on the coastal plain should take into consideration potential inundation and shoreline-change possibilities. The elevation of the 1946 4.3-m tsunami serves as a guide for potential inundation-zone elevation. Variation in the shoreline position of the beach is a natural process and any development near the shore would be subject to the natural variability of the shoreline position.
2. The area where Makeāhua and Pohaukole Streams enter the sea is often blocked by sediment, forming a brackish pond within the coastal plain that is potentially subject to poor water-quality conditions. Because the mouth is often blocked with sediment, increased flooding of coastal areas is likely during periods of high rainfall and related high stream flow.
3. Sediment delivered to the coast by the streams probably contributes to the sedimentation problems of the submerged Hale O Kapuni Heiau. Increased sedimentation would also have an adverse effect on nearby coral reefs. Activities that would greatly change sedimentation patterns can adversely affect the PUHE watershed.

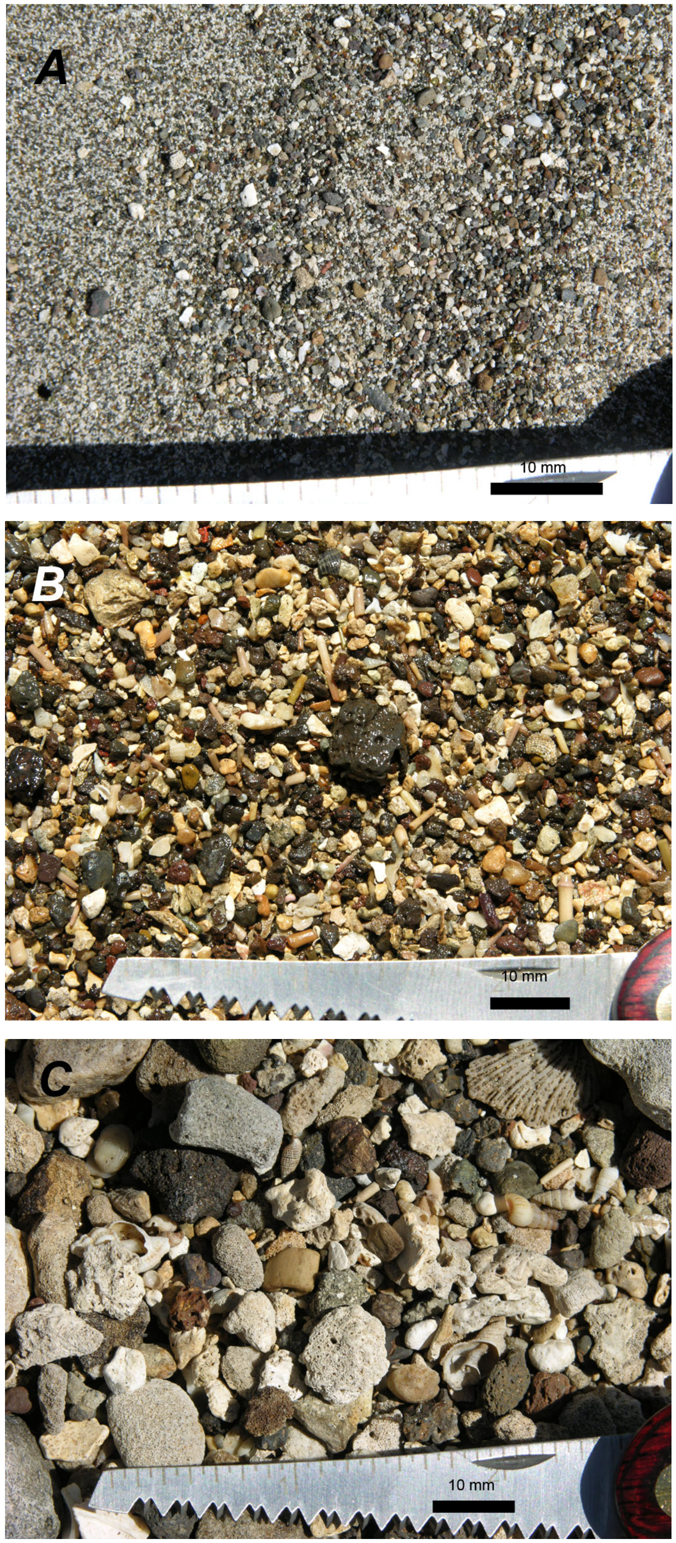


Figure 15. Photographs showing the variation in sediment size, sorting, and composition at Pelekane Beach. The photographs were taken at the north end of the beach in August 2004. Note the high percentage of lithic fragments (typically the darker grains). *A*, Upper beach-face sand showing two coarse bands of sediment which were most likely deposited at the upper limit of wave swash. *B*, Mid-beach fine gravel deposit showing a mixture of terrigenous and reef-derived sediment. *C*, Swash-zone deposit of coarse sand composed of mixed sediment.

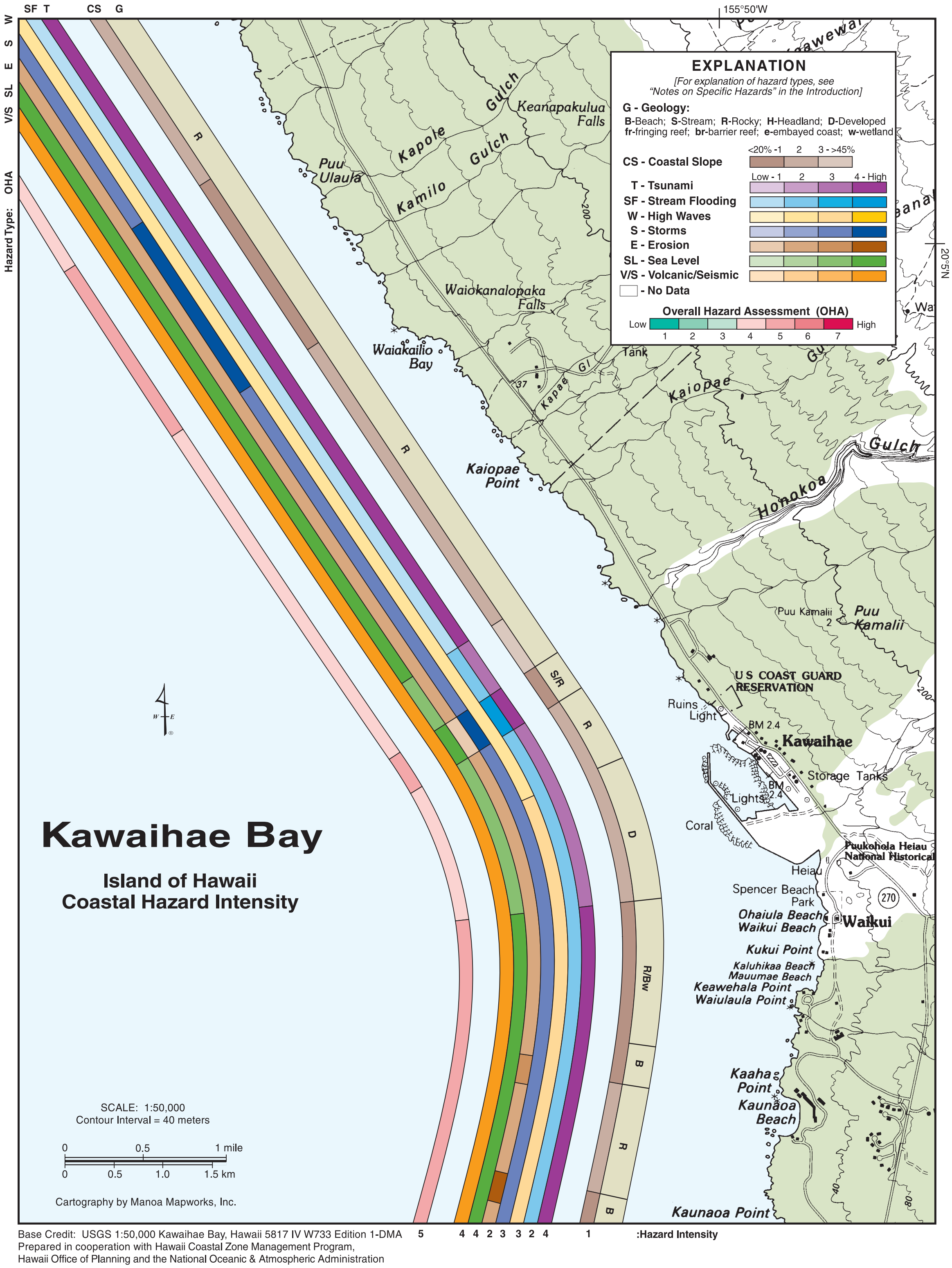


Figure 16. Coastal hazards map for Kawaihae Bay, Hawai'i (from Fletcher and others, 2002). The map shows the relative hazard intensity for seven natural hazards (tsunami, stream flooding, high waves, storms, erosion, sea level, and volcanic/seismic) and an overall hazard assessment based on a weighted ranking scheme [http://pubs.usgs.gov/imap/i2761/ (last accessed December 1, 2008)].

4. Hawai‘i is a seismically and volcanically active island. Lack of historic or Holocene lava flows within PUHE suggests that the volcanic hazard here is relatively low. The park is near the boundary between hazard Zones 8 and 9, which are the areas of least volcanic hazard (Mullineaux and others, 1987). Moderate earthquakes are common events on Hawai‘i. The recent October 15, 2006 Kīholo Bay earthquake caused severe damage to the older rock structures that consist of unreinforced fitted rock. Seismic safety design standards can be employed to minimize damage on any construction.
5. Landslides do not appear to be a problem within PUHE, although the steep sides of Makeāhua and Pohaukole Streams pose a potential threat.

Acknowledgments

The authors thank Rebecca Beavers, coastal geologist, and Bruce Heise, geologist, with the National Park Service (NPS) Geologic Resources Division who, together with Mike Field of the U.S. Geological Survey (USGS), were instrumental in initiating the cooperative study within the Pu‘ukoholā Heiau National Historic Site (PUHE). Cheryl Hapke, Tom Reiss, and Gerry Hatcher of the USGS Coastal and Marine Geology Team (CMG) assisted with GPS and GIS data collection in the field and postsurvey analysis. Josh Logan, USGS/CMG, assisted in the GIS data analysis and figure preparation. Staff of the USGS Hawaiian Volcano Observatory provided geospatial data, and in particular we would like to thank Frank Trusdell. PUHE park staff assisted with park logistics and provided background information on park resources. The manuscript benefited from reviews by Jane Reid and Mike Field, USGS/CMG. The cover photograph was generously provided by Brian Powers, Hawaiian Images Photography and Video, Kailua Kona, Hawai‘i.

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