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

Geologic Resource Evaluation of Pu‘uhonua O Hōnaunau National Historical Park, Hawai‘i; Part I, Geology and Coastal Landforms

Open-File Report 2008-1192

U.S. Department of the Interior
U.S. Geological Survey

This page intentionally left blank

Geologic Resource Evaluation of Pu‘uhonua O Hōnaunau National Historical Park, Hawai‘i; Part I, Geology and Coastal Landforms

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

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

Open-File Report 2008-1192

U.S. Department of the Interior
U.S. Geological Survey

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

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

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

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1-888-ASK-USGS

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Richmond, Bruce M., Cochran, Susan A., and Gibbs, Ann E., 2008, Geologic resource evaluation of Puʻuhonua O Hōnaunau National Historical Park, Hawaiʻi; part I, geology and coastal landforms: U.S. Geological Survey Open-File Report 2008-1192, 23 p. [http://pubs.usgs.gov/of/2008/1192/].

Front cover:
Oblique aerial photograph showing Puʻuhonua Point and the adjacent Puʻuhonua O Hōnaunau National Historical Park coast. The basalt platform, which extends along the coast between the waters edge and the white sand of the perched beaches, is mostly devoid of sediment cover. Photograph courtesy of Brian Powers, Hawaiian Images Photography and Video, Kailua Kona, Hawaiʻi.

Contents

Figures

This page intentionally left blank

Geologic Resource Evaluation of Pu‘uhonua O Hōnaunau National Historical Park, 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

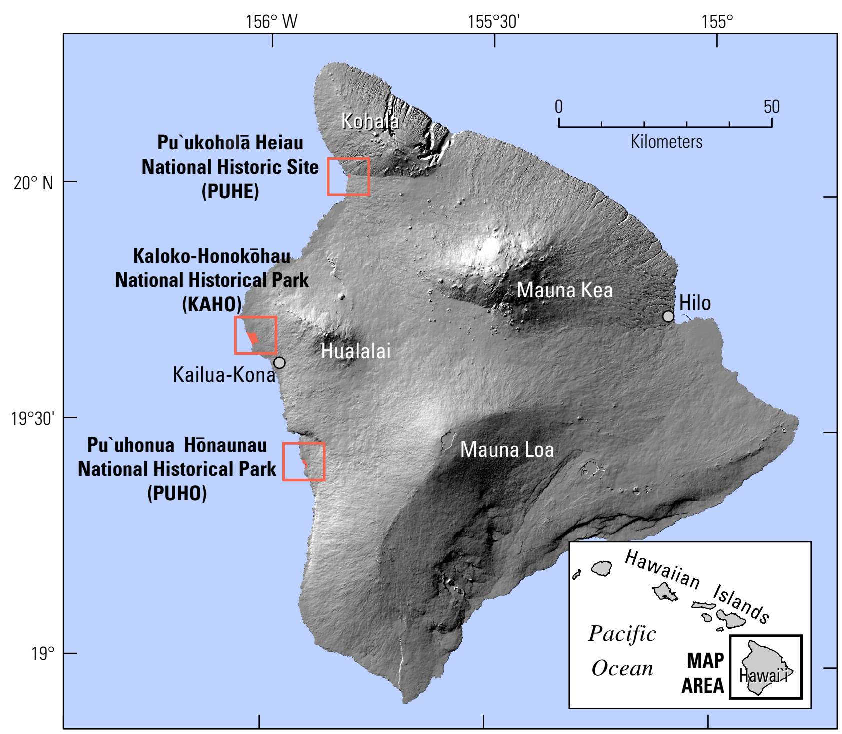

Figure 1. Index map of the Island of Hawai‘i showing the location of the three National Parks along the Kona coast. Volcano names are shown in white.

presents 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.

Puʻuhonua O Hōnaunau National Historical Park ("Place of Refuge of Hōnaunau") is the southernmost of the three National Parks located on the leeward Kona coast of the Island of Hawaiʻi (fig. 1). It is a relatively small park originally 73 ha (182 acres), and was expanded in 2006 with the acquisition of an additional 96 ha (238 acres). The park is probably best known for the puʻuhonua (place of refuge) native Hawaiian cultural site. In addition to the puʻuhonua, the park contains palace grounds, royal fishponds, burial sites, prehistoric trails, a royal canoe landing area, stone house platforms and associated temple structures. A massive basalt rock wall (300 m long, 3 m high, and 5 m wide) separates the puʻuhonua from the areas used by Hawaiian royalty and other grounds. Hōnaunau Bay is a popular marine resource area adjacent to the park.

The seaward-sloping lands of PUHO (fig. 2) lie at the base of Mauna Loa volcano, which forms a bench of low-lying pahoehoe lava flows at Puʻuhonua Point. The park coastline is approximately 1.6 km long and is mostly rocky with the exception of a small artificially nourished beach at Keoneʻele Cove at the northern boundary next to Hōnaunau Bay. The park is bounded to the south by Kiʻilae Bay and includes the coastal portions of three Hawaiian land divisions (ahupuaʻa): Hōnaunau, Kēōkea, and Kiʻilae. The western boundary is the high tide mark. The waters of Keoneʻele Cove, the ancient royal canoe landing at PUHO, while not formally under NPS jurisdiction, are managed by the park under an agreement with the State of Hawaiʻi. This small embayment is a known haven for sea turtles, which are often found sunning themselves on the nearshore volcanic platform. Impacts to this area include frequent visits by scuba divers and snorkelers to Hōnaunau Bay and a small boat ramp located just to the north of Keoneʻele Cove.

There is an accompanying report that presents the results of benthic habitat mapping of the offshore waters for PUHO (Cochran and others, 2006b). They mapped from the shoreline to depths of approximately 40 m, where the shelf drops off to a sand-covered bottom. PUHO park boundaries extend only to the mean high-tide level; however, landscape impacts created by development around the park are of concern to Park management.

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 Hawaiʻi 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 Loʻihi (the newest volcano forming on the sea floor), Mauna Loa, Hualālai, Māhukona (a submerged volcano), Kahoʻolawe, Lānaʻi, and West Molokaʻi (fig. 3). Age of the shield stages for the main Hawaiian Islands range from less than 1 Ma for the Island of Hawaiʻi to 5.8 – 3.9 Ma for the Island of Kauaʻi (Clague and Dalrymple, 1987). Hawaiʻi volcanic geology is thoroughly discussed in the two-volume U.S. Geological Survey Professional Paper 1350, Volcanism in Hawaiʻi, edited by Decker and others (1987).

The Island of Hawaiʻi 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 height, Hawaiʻi 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

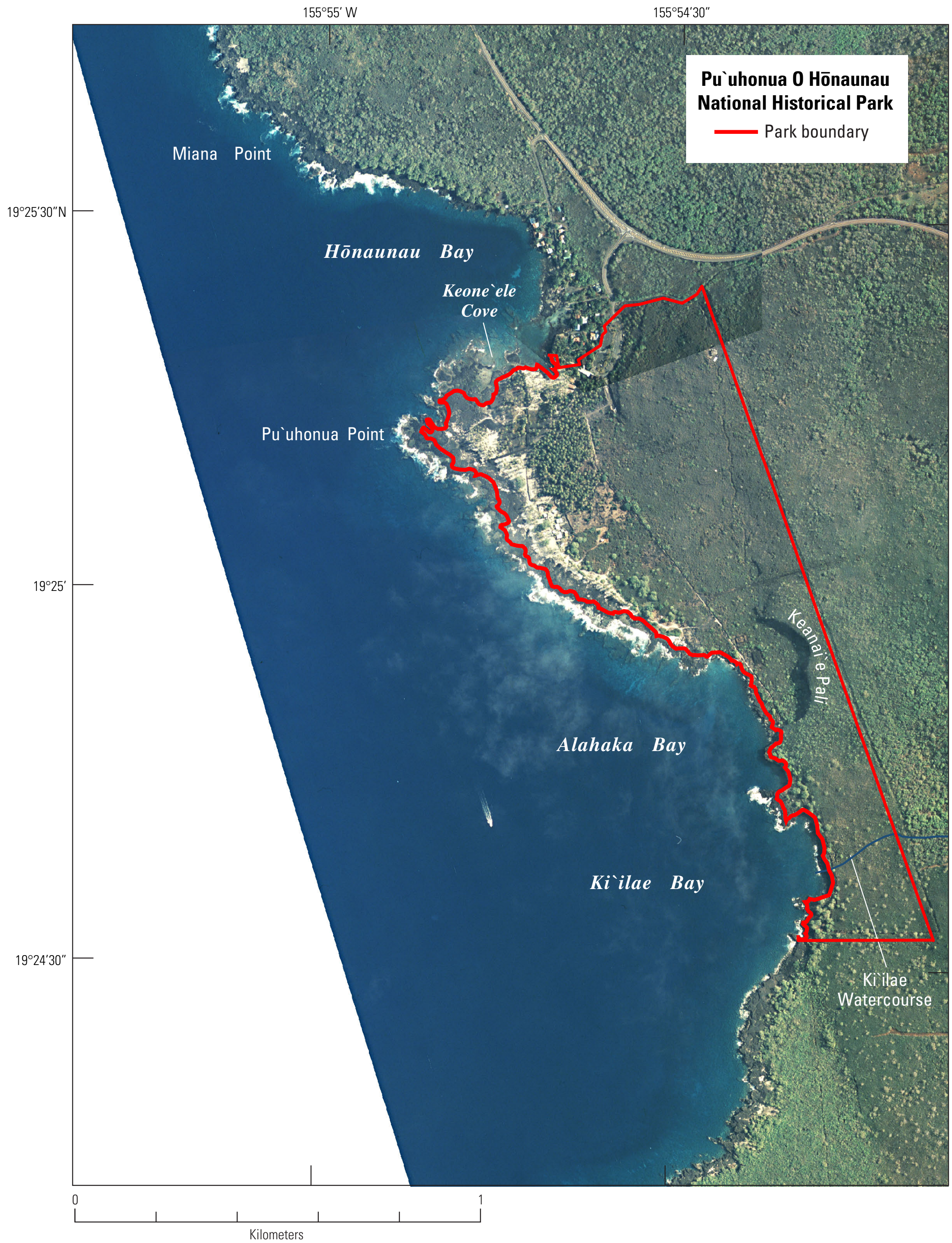

Figure 2. Aerial photomosaic of Pu'uhonua O Hōnaunau National Historical Park showing park boundaries and geographic locations.

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

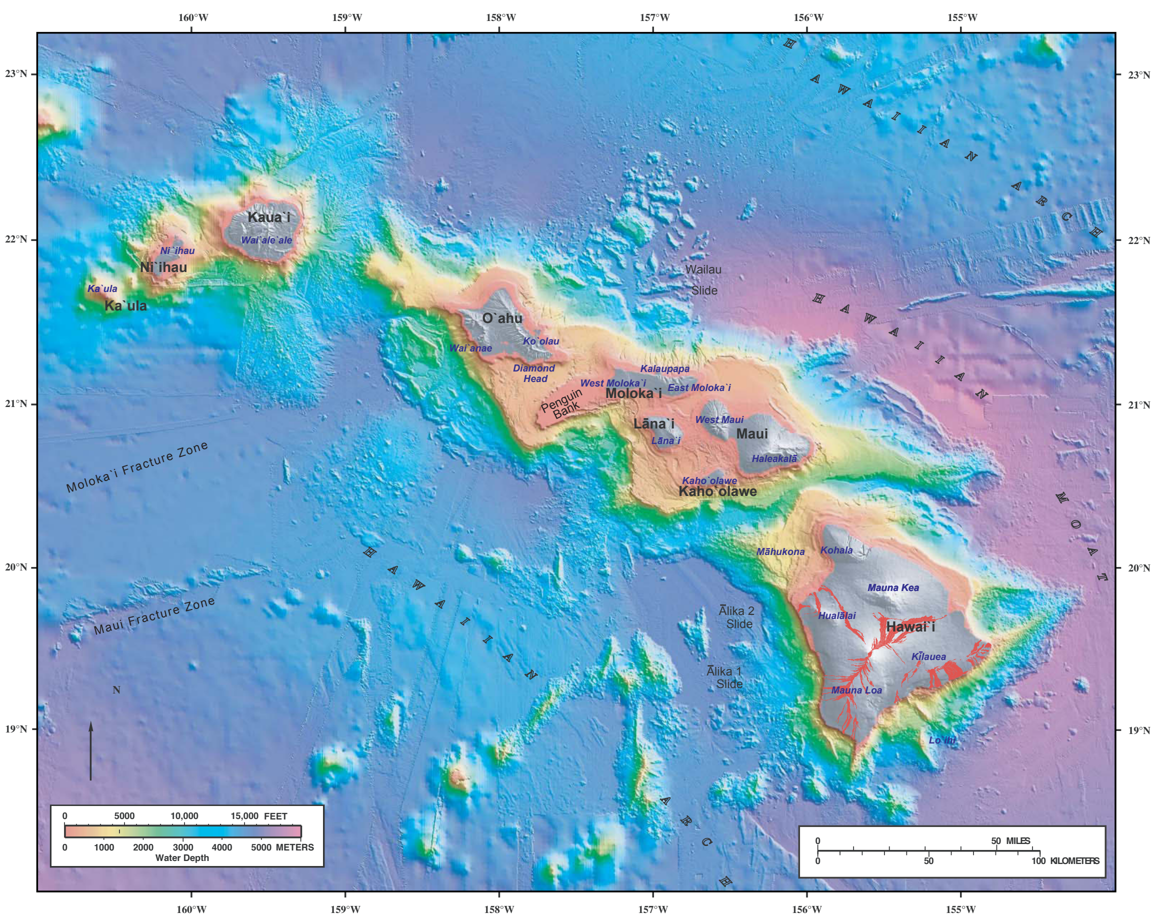

Figure 3. Topography and bathymetry of the main Hawaiian Islands (U.S. Geological Survey base image from Eakins and others, 2003). Island dissection and age increase towards the northwest. The red areas on the Island of Hawai‘i show the location of historical lava flows.

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.

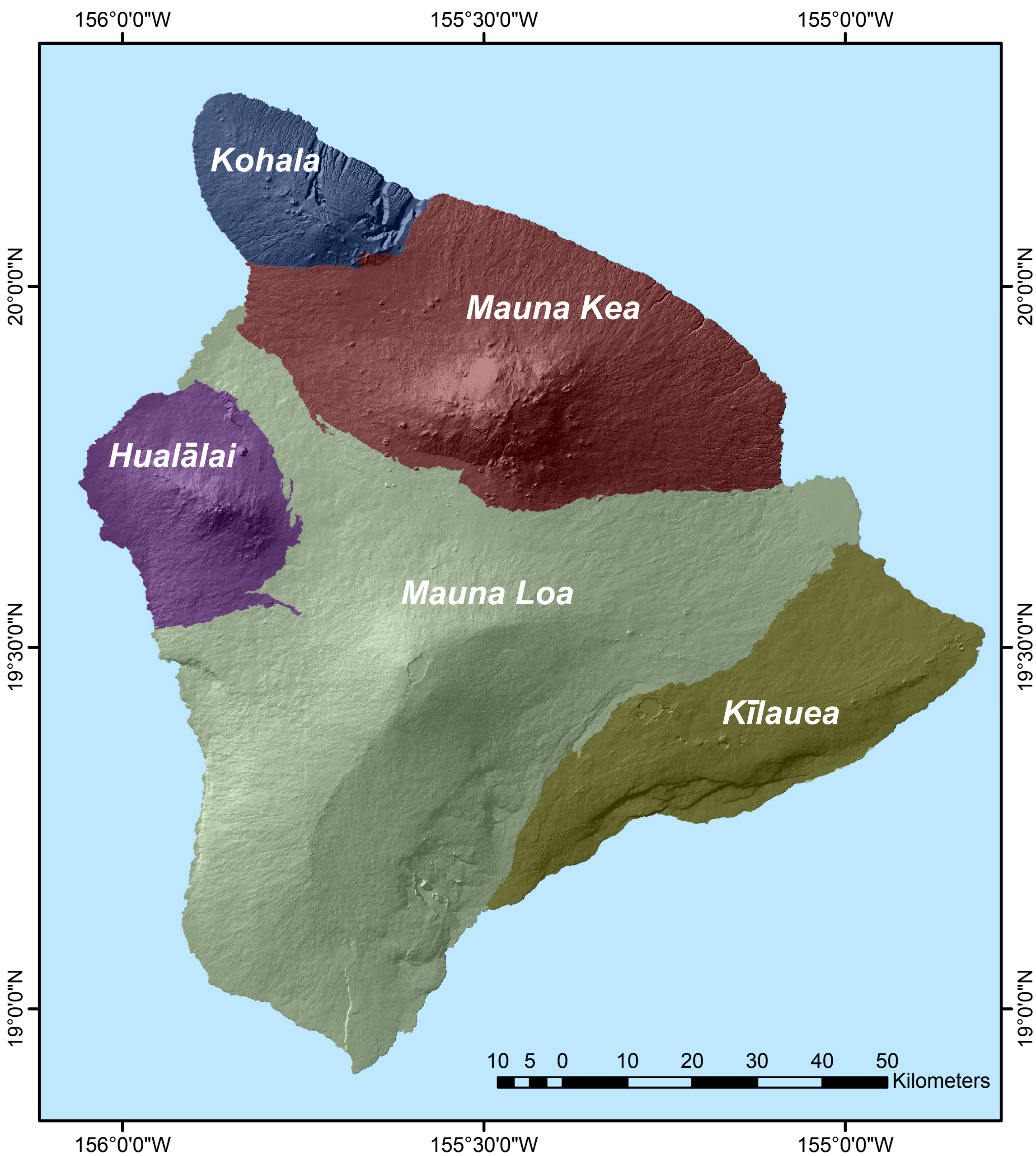

Figure 4. U.S. Geological Survey digital elevation model showing the five subaerial volcanoes that form the Island of Hawai‘i. The different colors show the approximate extent of the surface flows from each volcano. Geology data from Wolfe and Morris (1996) and Trusdell and others (2005).

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 in Hawaiʻi 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 Hawaiʻi 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 on-line 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 Hawaiʻi 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 Hawaiʻi 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, coastal erosion, and long-term relative sea-level rise (Richmond and others, 2001; Fletcher and others, 2002). Watersheds in Hawaiʻi 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 Hawaiʻi 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 Kauaʻi 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 Kauaʻi and leeward Oʻahu. The Island of Hawaiʻi 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 Hawaiʻi, erosion has caused beach loss or narrowing on nearly one-quarter of Oʻahu'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 Hawaiʻi 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

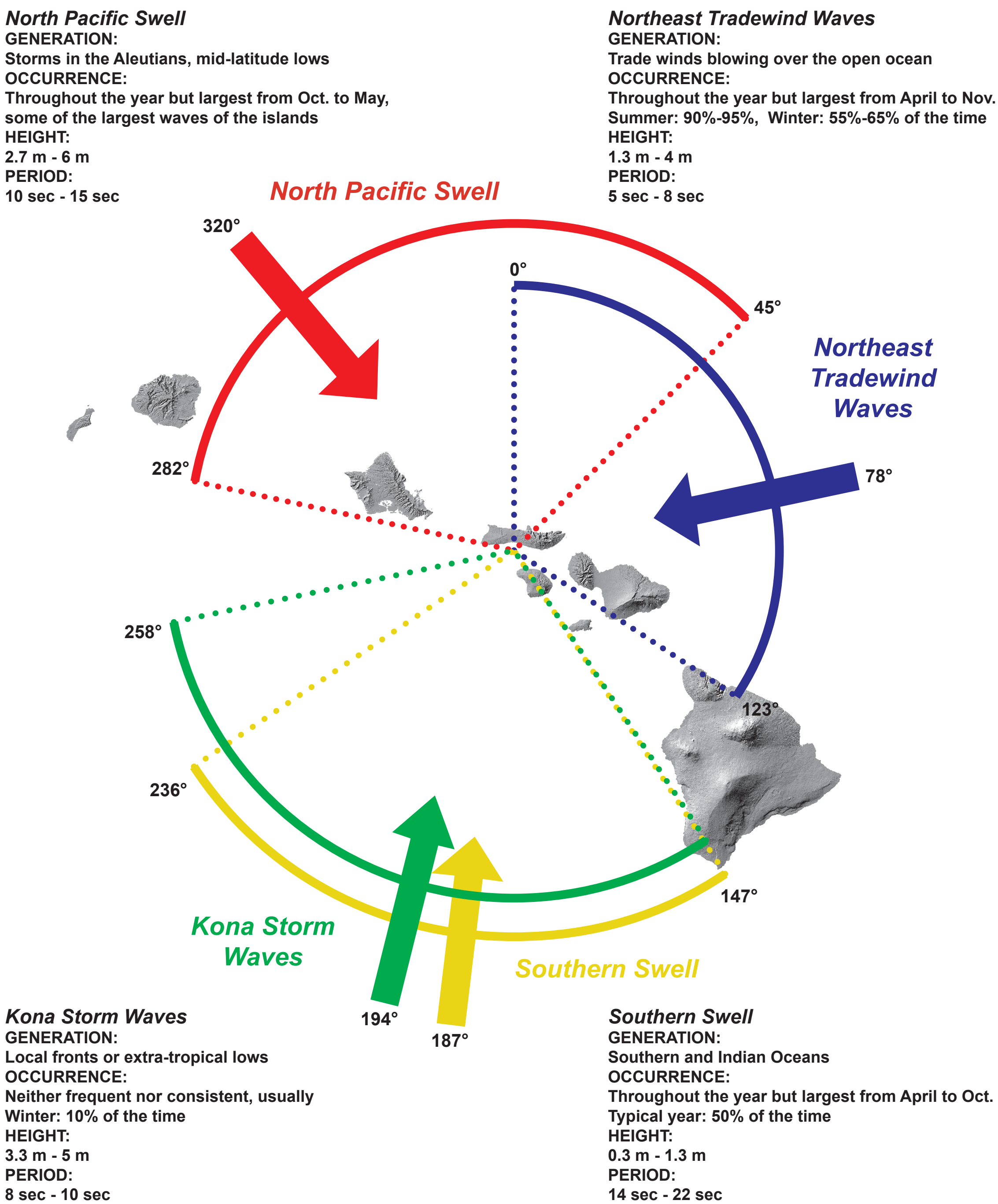

Figure 5. Diagram showing the wave-energy regime for the Island of Hawai‘i (modified from Moberly and Chamberlain, 1964). This figure summarizes the generation area, time of occurrence, and typical wave height and period for waves reaching the Hawaiian Islands.

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 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 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 the 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, 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.

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

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, 2006a).

Pu‘uhonua O Hōnaunau National Historical Park (PUHO)

Geology

Pu‘uhonua O Hōnaunau National Historical Park is underlain by Holocene basalt flows, named the Kau Basalt, that originated from Mauna Loa volcano (fig. 4). The Kau Basalt within the park consists mostly of pahoehoe type rocks that formed from elongated fissures on the volcano flank (Wolfe and Morris, 1996). Three different-aged flows are identified in the park and are shown on figure 7. The three periods of lava eruption, in years before present, are: 5,000 - 3,000, 3,000 - 1,500, and 1500, - 750. Figure 8 shows the surface of a pahoehoe flow exposed on the coastal bench near Pu‘uhonua Point. The bench is a natural depositional feature of the lava flow and is underlain by the younger rocks (1500 – 750 years BP) of the park. The smooth and ropy pahoehoe basalt is the dominant rock type within the park.

The Kau Basalt is a shield-stage lava consisting of tholeiitic basalt, olivine tholeiitic basalt and picritic tholeiitic basalt (Langenheim and Clague 1987). The young Kau Basalt overlies the Pāhala Ash and Kahuku Basalt. The Pāhala Ash is a17 – 10 ka regional tephra deposit that is up to 15 m thick, occurring on Mauna Loa and Kilauea Volcanoes (Hay and Jones, 1972). The Kahuku Basalt is a shield-stage tholeiitic basalt greater than 30 ka in age (Langenheim and Clague, 1987). The geologic map of the Island of Hawai’i (Wolfe and Morris, 1996) shows no major faults within PUHO, although there is a prominent cliff, named Keanai‘e Pali, preserved inland (fig. 9). The park occupies the gently-sloping lower flanks of Mauna Loa (fig. 10).

Hawai’i soil maps are available online (http://www.ctahr.hawaii.edu/soilsurvey/soils.htm, last accessed December 1, 2008) from the United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS). The soils of PUHO are generally very thin and poorly developed. The northern two-thirds of the park are mapped as pahoehoe lava flows (rLW) with little soil development. This soil is classified as a miscellaneous land type and commonly has little vegetation cover, although some plants may become rooted in the numerous cracks and crevices. The remainder of the park soils, mostly opposite Ki‘ilae Bay and within the Ki‘ilae watercourse, are mapped as rough broken land (RB). This soil is also classified as a miscellaneous land type and occurs in steep land crossed by channels. Vegetation varies with rainfall, which is typically low near the coast and increases with increasing elevation.

Coastal Landforms

Coastal landforms that occur within PUHO and discussed in this report include: a) beaches (perched, boulder, and intertidal), b) basalt shore platform, c) coastal cliffs, and, d) anchialine pools, wetlands, and fishponds. The coral reefs bordering PUHO are described in Cochran and others, 2006b.

Beaches

An extensive carbonate sand, perched beach system extends from Pu‘uhonua Point to the north end of Alahaka Bay. The perched beach is landward of the rocky shoreline and sits atop a gently seaward-sloping pahoehoe basalt coastal terrace that is largely free of sediment between the shoreline and the beach (cover photograph and fig. 11). The beach is landward of the shoreline, which is at the western edge of the basalt terrace, indicating that the beach is usually active only during large wave events. The wedge-shaped beach

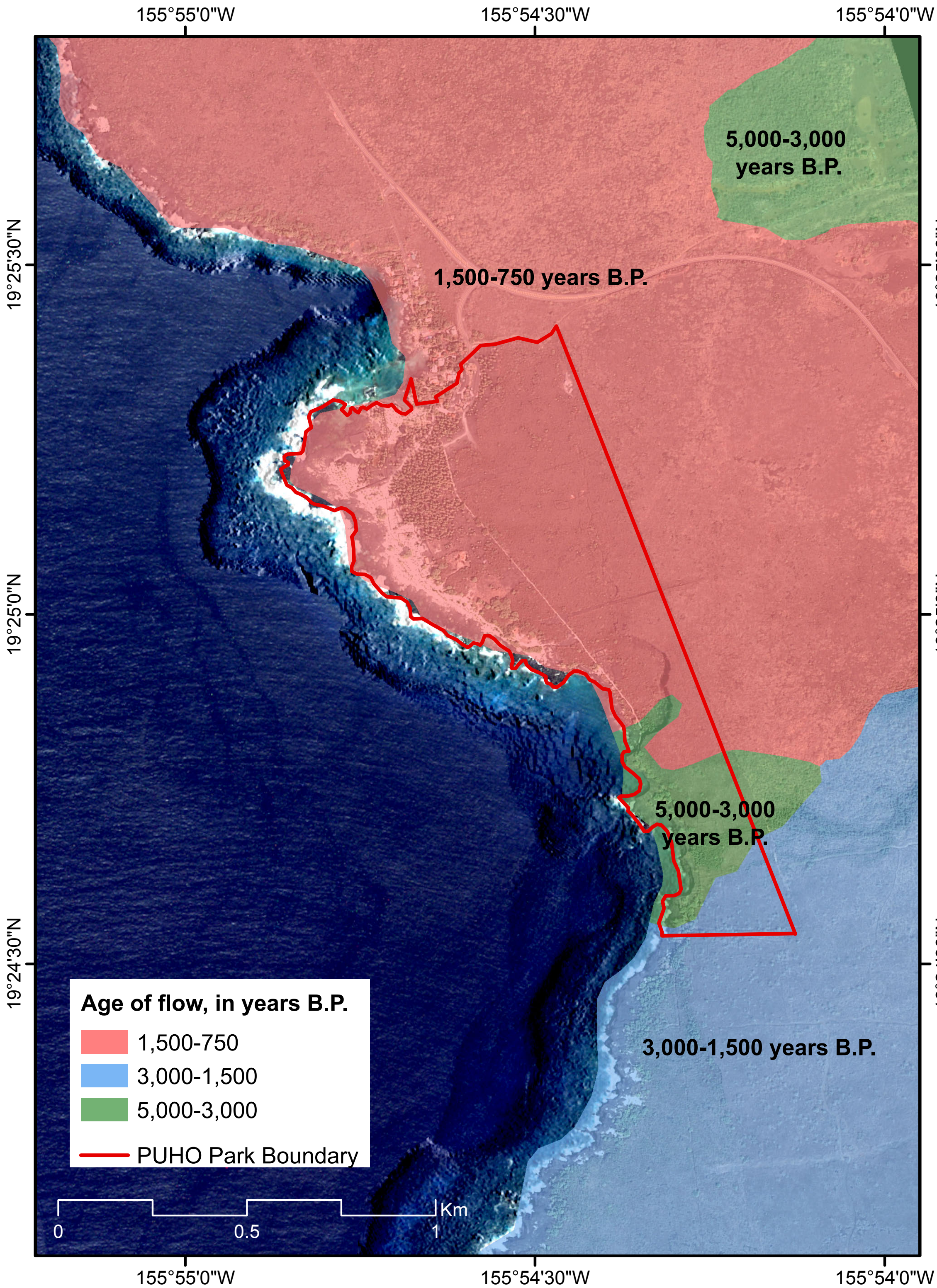

Figure 7. Aerial photomosaic showing bedrock geology, age of the Kau Basalt volcanic flows, and offshore morphology of PUHO (geology layer from Trusdell and others, 2005). In the offshore zone, Quickbird satellite imagery is overlain on 2000 U.S. Army Corps of Engineers SHOALS bathymetry. Park boundaries in red.

Figure 8. Photograph of the basalt platform exposure along the shore near Pu‘uhonua Point. The ropy texture of the pahoehoe flow is clearly visible in the foreground, and the white carbonate sands of the perched beach, which support the coastal vegetation, can be seen in the background. View towards the south.

deposits begin as a thin deposit on the basalt, and thicken landward where they become 1-2 m at their thickest. They thin again landwards of the crest and merge inland with the thin soils on the basalt flows. The width of the beach sand ridge varies from about 30 to 80 m. The beach is composed primarily of reef-derived carbonate sand with minor basalt fragments and varies from medium sand through gravel-sized material (fig. 12). Erosion on the seaward edge of the perched beach near the parking areas south of Pu‘uhonua Point has necessitated some artificial beach nourishment (Malia Laber, NPS, oral commun., 2004).

The shoreline along parts of Alahaka Bay is armored by a natural intertidal beach composed of basalt boulders (fig. 9). The boulders are rounded and fit together forming a few layers of a wave resistant structure. The boulder rounding suggests they move on occasion, most-likely during storms. The rocks are most-likely naturally quarried from nearby cliffs, probably by a combination of small landslides and high wave events. Boulder size ranges from 25 cm to a meter or more. Reef-derived carbonate sand and gravel form scattered pockets within the boulder deposits.

The beach at the head of Keone‘ele Cove is a small intertidal beach (fig. 13) that forms a barrier between the ocean and a royal fishpond complex (Hoover and Gold, 2006). The beach is protected from open-ocean waves by a combination Pu‘uhonua Point and its orientation towards the north and Hōnaunau Bay. The beach is composed of moderately well-sorted medium sand derived from the adjacent basalt and reef-derived material (fig 12c). The beach has also undergone artificial nourishment as a result of episodic erosion. The nourished sand is distinct from the native sand, both in color (gray) and being highly angular in shape (fig. 12d). The beach is gently-sloping and less than 1 m in height. Most of the back beach area has been modified by human activity, including the construction of stone walls and sand deposited to make pathways.

Basalt Shore Platform

Most of the shoreline of PUHO consists of pahoehoe basalt that forms a natural shore platform (cover image and fig. 8). The rocky intertidal zone is generally a bare rock surface with tide pools, associated flora and fauna, and little in the way of sediment accumulations. There are numerous culturally significant features within the basalt such as springs, net tanning tubs, and bait cups (Hoover and Gold, 2006). The submerged portion of the platform provides substrate for corals and other marine organisms. The platform is best developed around Pu‘uhonua Point where it is formed by one, or several related, lava flows between 1500 and 750 years ago. The distance between the edge of the platform and the perched beaches narrows both to the north and south of the point. The maximum width of exposed platform is about 140 m at Pu‘uhonua Point. Platform width varies between about 40 and 90 m from southern Pu‘uhonua Point to northern Alahaka Bay. The platform becomes more irregular, higher, and narrower in Alahaka Bay.

Figure 9. Photograph from the southern portion of the park opposite Alahaka Bay looking towards the southwest at Keanai‘e Pali. Rounded basalt boulders in the foreground are the primary beach sediment type at this location.

Coastal cliffs

The southern PUHO shoreline is characterized by basalt coastal cliffs fronted by a narrow shore zone. The basalt shore platform in northern Alahaka Bay narrows and increases in elevation towards the south, eventually merging with the inland cliffs of the Keanai‘e Pali and forming near-vertical cliffs about 10 m high. The shoreline of Ki‘ilae Bay alternates between coastal cliffs and a steeply seaward-dipping basalt platform. The older lava flows (5 – 3 ka) within the park occur along this segment of coast.

Anchialine Pools, Wetlands, and Fishponds

PUHO contains several anchialine pools that have recently been briefly described by Hoover and Gold (2006). The pools occupy low-lying depressions within the coastal basalt platform where there is access and mixing between fresh groundwater and seawater. Although not as well developed as other pools along the Kona coast, the PUHO anchialine pools are a valuable park resource because of the unique habitat they form. Occupying a similar environment to the anchialine pools are several man made fishponds, including a royal fishpond complex (Heleipalala). Man-made walls mark much of the fishpond boundaries, the construction of which probably took advantage of natural variations in surface elevation of the underlying basalt (for example, low areas for ponds and higher areas for wall construction). The two main fishponds are relatively small, in the 300-400 m^2 range, with the northern pond more stable in size than the southern pond, which fluctuates with varying water conditions (Hoover and Gold, 2006).

The wetlands in PUHO are associated with the fishponds and anchialine pools and consist primarily of marsh areas around the margins. Hoover and Gold (2006) report a relatively small area of wetlands (~ 2500 m^3) surrounding the Royal Fishponds.

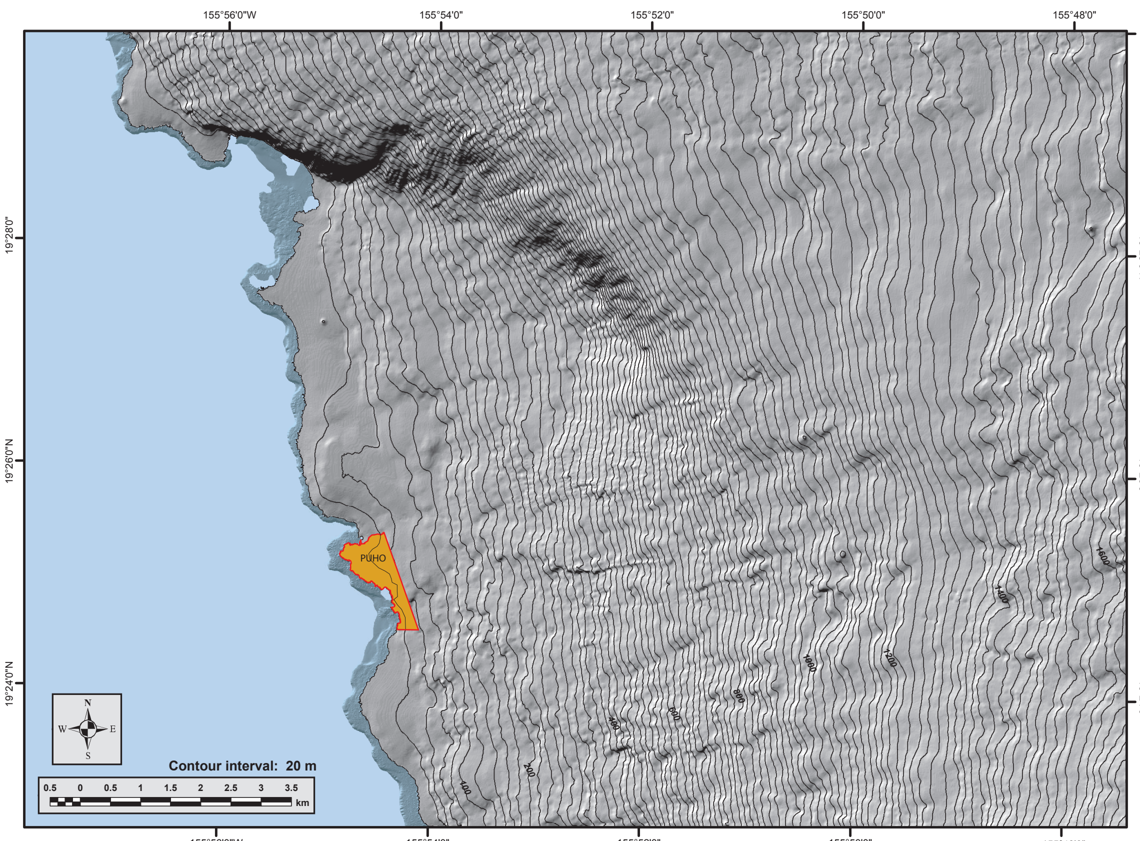

Figure 10. Shaded relief map showing the physiographic setting of PUHO on the gently-sloping lower flanks of Mauna Loa. The large escarpment north of PUHO forms the sea cliffs of Kealakekua Bay. Contour interval 20 m.

Coastal Sediments

The coastal sediment at PUHO is a combination of reef-derived carbonate detritus, volcanically-derived basaltic sediment, and artificial nourishment (fig. 12). Sediment size is largely controlled by local exposure to waves and availability of sediment. Grain size varies in both longshore and crosshore directions at PUHO. The coarsest beach sediment occurs in the south and consists of basalt boulders, coral gravel, and isolated carbonate sand patches. In general, the sediment fines and becomes more carbonate-rich towards

Figure 11. Photographs of perched beaches at PUHO. *A*, Photograph of the southern margin of the perched beach system in PUHO taken from the bluffs above Alahaka Bay. The light-colored sand of the perched beach is separated from the edge of basalt shoreline by a relatively sediment-free surface. View to the north. *B*, Photograph from south of Pu‘uhonua Point showing the perched beach and relatively sediment-free basalt platform. The beach grain size varies from medium sand through fine-gravel along the beach at this location. View to the north.

the north along the beach, although there are pockets of gravel-rich sediment scattered throughout the beach areas. In the cross-shore direction, the lower beach face is typically sand with scattered gravel and occasional gravel pockets. The upper beach face is often marked by a low gravel ridge that most likely represents a storm berm formed during periods of high wave activity. Landward of the storm berm the sediment is mostly sand with occasional gravel clasts. In the parking areas, pathways, and around buildings sand nourishment has occurred (Malia Laber, NPS, oral commun., 2004). The beach deposits are thickest near the crest of the beach and thin in both the seaward and landward directions with a maximum thickness of between 1-2 m.

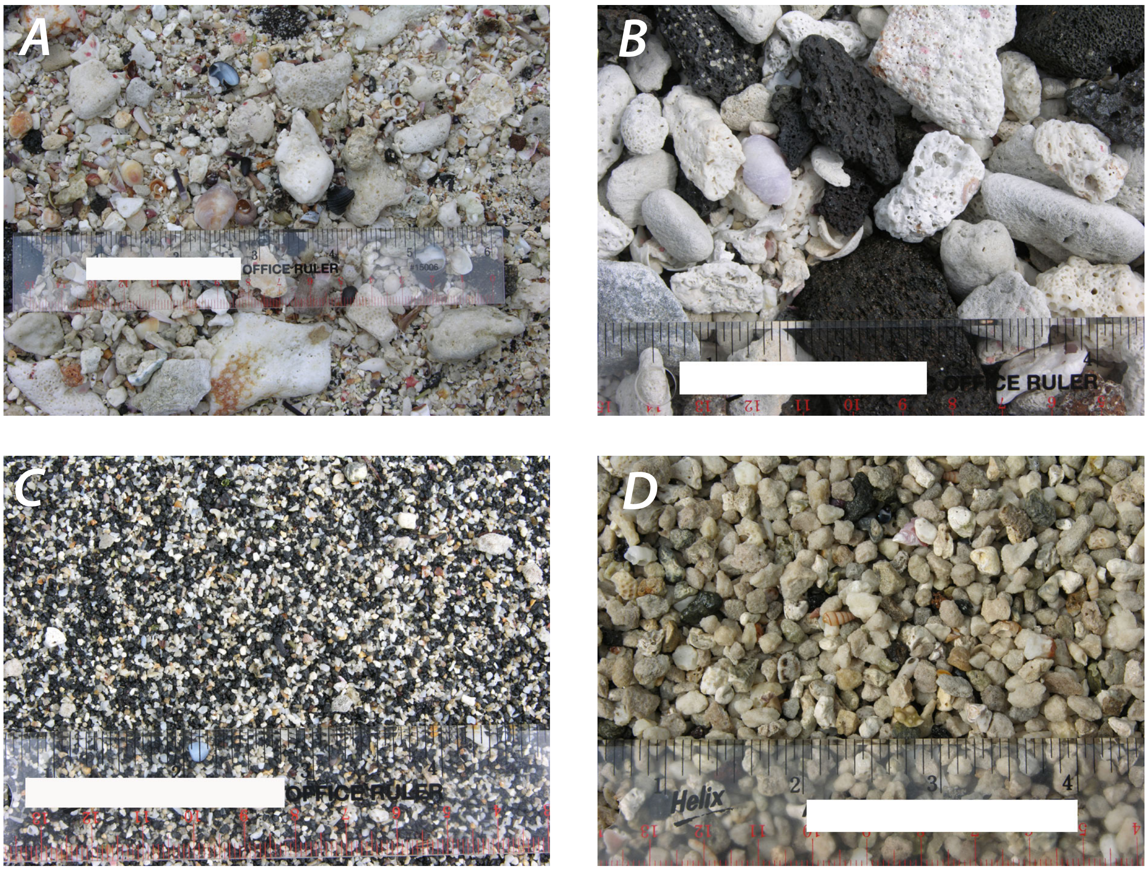

Figure 12. Close-up photographs of beach sediment from PUHO showing the variation in sediment type. *A*, Sediment from the southern segment of the perched beach showing a poorly-sorted sand and fine gravel with a mixture of clast types, including fragments of corals, mollusks, and a small percentage of basaltic rock. *B*, Coarse sediment from a section of beach north of Pu'uhonua Point consisting mostly of either rounded coral or basalt fragments. *C*, Mixed basalt and carbonate, well-sorted, medium sand from Keone‘ele Cove. *D*, Artificially nourished beach sand from Keone‘ele Cove. The introduced sand is gray in color and more angular than the native sand. The white bar in each photo is 5 cm long.

Natural Hazards

The natural hazards for the coastal area surrounding the park have been identified and mapped (fig.14, from Fletcher and others, 2002). Because of its coastal setting, PUHO is vulnerable to increased ocean-inundation from such events as tsunamis, storms, and sea-level rise. Lander and Lockridge (1989) identified six historical tsunamis that struck the coast near PUHO since 1896. The tsunamis ranged in height from 1.2 m to 4.9 m, with the largest runup originating from both a 1896 earthquake in Japan and the 1960 Chile earthquake. A tsunami of similar magnitude occurring today would most likely severely damage the

Figure 13. Photograph of the beach at Keone‘ele Cove showing recent erosion, as indicated by the exposed palm roots in the beach face and small erosional scarp. View towards the east, photograph taken in August 2004.

beaches, park infrastructure and historical sites near the coast. The basalt rock areas are stable and would undergo little change.

Hōnaunau Bay and the adjacent shallow reef areas partially protect the northern park coast from high waves and storms, whereas the remaining coast is exposed to Kona storm waves and swell originating from the southwest through northwest directions. Damaging high waves struck the southwest coast in 1969, 1985, and 1989 (Fletcher and others, 2002). Storm waves arriving on a direct approach to the park have the potential to impact the coastline, structures, and adjacent reefs. For example, a hurricane traveling 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 historical structures, beach parking facilities, fishponds, anchialine pools, and associated wetlands. Coastal erosion at present is episodic and related to the passage of seasonal storms and/or long-distant swell.

During periods of heavy rain, severe stream flooding culminating in flash floods could affect Ki‘ilae Stream, which is normally a dry channel (Hoover and Gold, 2006). An intense flooding event could result in erosion of parts of the stream channel and transport sediment to the coast where Ki‘ilae stream mouth

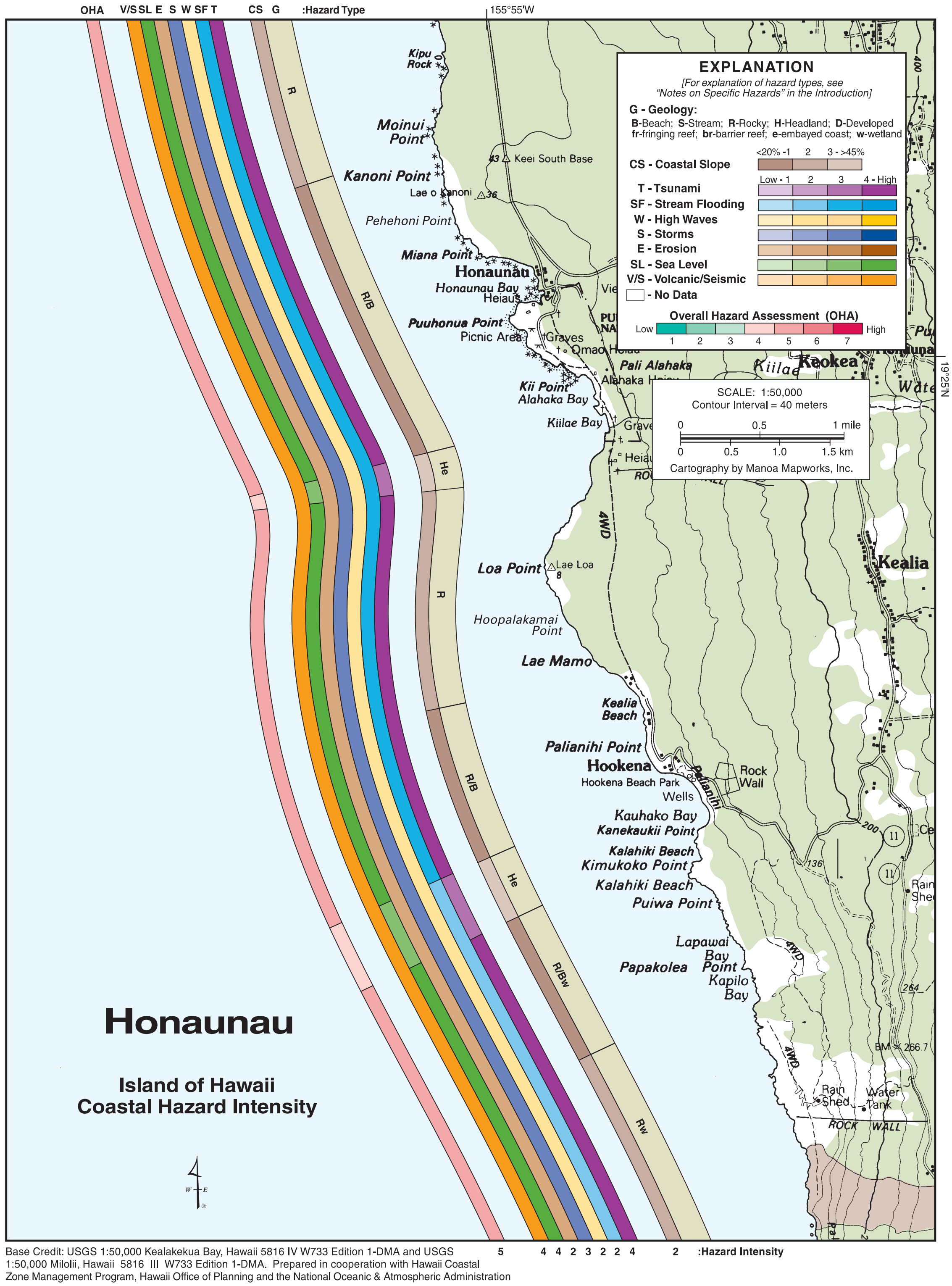

Figure 14. Coastal hazard map for Hōnaunau, Hawai‘i (from Fletcher and others, 2002). The maps show the relative hazard intensity for seven natural hazards (tsunami, stream flooding, high waves, storms, erosion, sea level, and volcanic/seismic) and an overall hazard assessment based on a weighted ranking scheme [http://pubs.usgs.gov/imap/i2761/ (last accessed December 1, 2008)].

terminates along low basalt cliffs. Heavy rains would also cause increased gullying and surface erosion in park uplands.

The entire park is subject to potential volcanic and seismic hazards and is mapped as Hazard Zone 2 (HZ 1 is the most hazardous) for lava flows (Mullineaux and others, 1987; updated online in 1997, http://pubs.usgs.gov/gip/hazards/maps.htm, last accessed on December 1, 2008). Eruptions of Mauna Loa in 1950 resulted in lava reaching the coast about 7 km south of PUHO. PUHO lies below the main southwest rift zone of Mauna Loa and therefore subject to potential lava flows during an eruption. Most of the park basalt at the surface is less than 1500 years old. The magnitude 6.7 October 15, 2006 earthquake caused some structural damage to archeological features within the park (Ben Barnette, NPS, written commun., 2008).

The overall hazard assessment for the park is relatively high (Fletcher and others, 2002), mostly due to the risk from volcanic and seismic hazards, and inundation from tsunamis, storms, and sea-level rise.

Hydrogeology

Ground water in Hawaiʻi provides most of the water consumed and is 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 PUHO, and the nearest stream monitoring station is located on Kiʻilae Stream at an elevation of 883 m, about 6 km upstream from the park. The stream was monitored from 1958 through 1982 by the U.S. Geological Survey, Water Resources Division, [http://waterdata.usgs.gov/hi/nwis/ (last accessed on December 1, 2008)]. Mean annual discharge varied from 0.057 to 0.387 cubic feet per second (cfs) with a peak stream flow of 85.0 cfs recorded during the monitoring period.

Water resources and watershed conditions for PUHO have been recently assessed by Hoover and Gold (2006). Most freshwater within the park occurs as brackish ground water that is mostly recharged in the high-rainfall areas above the park. Surface water within Kiʻilae Stream at the southern portion of the park is intermittent and flow is generally restricted to periods of high rainfall.

Resource Management Information

Puʻuhonua O Hōnaunau National Historical Park was established primarily to preserve native Hawaiian culture and cultural sites. In addition to the cultural sites, the park contains walking trails, beaches, and is adjacent to a variety of marine resources. In general, the park is relatively stable geologically; however some areas are of potential concern.

1. PUHO beaches are frequented by both tourists and local residents and represent a valuable park asset. Artificial beach nourishment that has occurred at Keoneʻele Cove and near the parking areas of the open ocean-facing beaches indicates there is a potential long-term shoreline erosion problem. The threats to the beach systems are primarily from high-wave events causing marine inundation during storms (relatively common) or tsunamis (rare), resulting in the removal of sediment from the beaches. However, these events also provide the mechanism to transport reef-derived sediment onshore for natural beach replenishment. Whether an event results in beach erosion or deposition depends upon the characteristics of the individual event. In some cases, erosion along one section of coast may be coupled with simultaneous deposition along another stretch of coast. Variation in the shoreline position of the beach is a natural process, and attempts to stabilize the shoreline by construction of engineering structures runs the risk of creating unforeseen adverse impacts. Artificial beach nourishment might have advantages over hard-engineering solutions in problem areas, in

which case carefully matching the native sediment, size, composition, and color results in a more pleasing environment.

2. Sea-level rise will most likely increase in the future and will affect the location, design, and protection of all coastal structures. Development near the coast might be affected by potential inundation and shoreline change. Sea-level rise will also have potential negative impacts on anchialine pools, wetlands, and groundwater resources within the park. Unfortunately, little can be done either to prevent sea-level rise, or protect these resources from the advancing sea.
3. The water-level elevation of the 1896 and 1960 tsunamis (4.9 m) that struck near PUHO, serve as an approximate guide for the potential elevation inundation zone as a result of rapid water-level rise because of tsunami impact. Clearly marked evacuation routes within the park will help protect lives in the event that a tsunami warning is issued.
4. Sediment delivered to the coast by streams probably contributes only small amounts to the overall sediment budget in the park, however, changes to the watershed surrounding the park could lead to changes in the sedimentation pattern. Increased sedimentation reaching the sea could have an adverse effect on nearby coral reefs. Monitoring the watershed surrounding PUHO for activities that would greatly change natural sedimentation patterns will help lessen those impacts.
5. The close proximity of the active volcano Mauna Loa, the location of PUHO below one of the main rift zones, and the presence of historic lava flows in the area are all causes for concern. Fortunately, volcano-monitoring activities should give ample warning of an impending eruption; however, in the event of a major eruption there is little that can be done to protect park resources. Moderate earthquakes are common events on Hawai‘i and seismic safety design considerations would be prudent.
6. Landslides do not appear to be a problem within PUHO, although the steep coastal cliffs and the Keanai‘e Pali pose a potential hazard to hikers.

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‘uhonua O Hōnaunau National Historical Park (PUHO). 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. Malia Laber of the National Park Service assisted with park logistics and provided background information on park resources. The manuscript benefited from reviews by Curt Storlazzi, USGS/CMG, and Malia Laber, NPS. The cover photograph was generously provided by Brian Powers, Hawaiian Images Photography and Video, Kailua-Kona, Hawai‘i.

References

Brock, R.E., and Kam, A.K.H., 1997, Biological and water characteristics of anchialine resources in Kaloko-Honokohau National Historical Park: University of Hawai‘i at Mānoa, Cooperative National Park Resources Study Unit, Technical Report 112, 110 p.

Brock, R.E., Norris, J.E., Ziemann, D.A., and Lee, M.T., 1987. Characteristics of water quality in anchialine ponds of the Kona, Hawaii Coast: Pacific Science, v. 41 p. 200-208.

Clague, D.A. and Dalrymple, G.B., 1987, The Hawaiian-Emperor volcanic chain; Part I, Geologic evolution, *in* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 5-54.

Cochran, S.A., Gibbs, A.E., and Logan, J.B., 2006a. Geologic resource evaluation of, Puʻukoholā Heiau National Historic Site, Hawaiʻi; Part II, Benthic habitat mapping: U.S. Geological Survey Scientific Investigations Report 2006-5254, 25 p. [http://pubs.usgs.gov/sir/2006/5254/, last accessed on December 1, 2008].

Cochran, S.A., Gibbs, A.E., and Logan, J.B., 2006b. Geologic resource evaluation of, Puʻuhonua O Hōnaunau National Historical Park, Hawaiʻi; Part II, Benthic habitat mapping: U.S. Geological Survey Scientific Investigations Report 2006-5258, 26 p. [http://pubs.usgs.gov/sir/2006/5258/, last accessed on December 1, 2008].

Coyne, M., Mullane, R., Fletcher, C., and Richmond, B., 1996, Losing Oahu, erosion on the Hawaiian Coast: Geotimes, v. 41, no. 12, p. 23-26.

Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., 1987, Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, 2 v., 1,667 p.

Dudley, W.C., and Lee, M., 1988, Tsunami!: Honolulu, University of Hawaiʻi Press, 132 p.

Eakins, B.W., Robinson, J.E., Kanamatsu, T., Naka, J., Smith, J.R., Takahashi, E., and Clague, D., 2003, Hawaii's volcanoes revealed: U.S. Geological Survey Geological Investigations Series I-2809 [http://geopubs.wr.usgs.gov/i-map/i2809/, last accessed on December 1, 2008].

Fletcher, C.H., Mullane, R.A., and Richmond, B.M., 1997, Beach loss along armored shorelines on Oahu, Hawaiian Islands: Journal of Coastal Research, v. 13, p. 209-215.

Fletcher, C.H., Richmond, B.M., Grossman, E.E., and Gibbs, A.E., 2002, Atlas of natural hazards in the Hawaiian coastal zone: U.S. Geological Survey Geologic Investigations Series I-2716, 186 p. [http://pubs.usgs.gov/imap/i2761/, last accessed on December 1, 2008].

Foulger, G.R., Natland, J.H., Presnall, D.C., and Anderson, D.L. eds., 2005, Plates, plumes and paradigms: Geological Society of America Special Paper 388, 881 p.

Gingerich, S.B., and Oki, D.S., 2000, Ground water in Hawaii: U.S. Geological Survey Fact Sheet 126-00, 6 p.

Goff, J., Dudley, W.C., deMaintenon, M.J., Cain, G., and Coney, J.P., 2006, The largest local tsunami in 20th century Hawaii: Marine Geology, v. 226, p. 65-79.

Greene, L.W., 1993, A cultural history of three traditional Hawaiian sites on the west coast of Hawaiʻi Island: United States Department of the Interior, National Park Service, Denver Service Center [http://www.cr.nps.gov/history/online_books/kona/history.htm, last accessed on December 1, 2008].

Hay, R.L., and Jones, B.F., 1972, Weathering of basaltic tephra on the Island of Hawaii: Geological Society of America Bulletin, v. 83 no. 2, p. 317-332.

Hapke, C.J., Gmirkin, R., and Richmond, B.M., 2005, Coastal change rates and patterns, Kaloko-Honokohau National Historical Park, Hawaiʻi: U.S. Geological Survey Open-File Report 2005-1069, 28 p. [http://pubs.usgs.gov/of/2005/1069/, (last accessed December 1, 2008)].

Hoover, D.J., and Gold, C., 2006, Assessment of coastal water resources and watershed conditions in Puʻuhonua O Hōnaunau National Historical Park, Hawaiʻi: National Park Service Technical Report NPS/NRWRD/NRTR-2006/352, 170 p.

Lander, J.F., and Lockridge, P.A., 1989, United States tsunamis (including United States possessions) 1690-1988: Boulder, Colorado, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, 265 p.

Langenheim, V.A.M., and Clague, D.A., 1987, The Hawaiian-Emperor volcanic chain; Part II, Stratigraphic framework of volcanic rocks of the Hawaiian Islands, *in* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 55-84.

Macdonald, G.A., Abbott, A.T., and Peterson, F.L., 1983, Volcanoes in the sea; the geology of Hawaii (2d ed.): Honolulu, University of Hawaii Press, 517 p.

McMurty, G.M., Fryer, G.J., Tappin, D.R., Wilkinson, I.P., Williams, M., Fietzke, J., Garbe-Schoenberg, D., and Watts, P., 2004, Megatsunami deposits on Kohala volcano, Hawaii, from flank collapse of Mauna Loa: Geology, v. 32, no. 9, p. 741-744.

Moberly, R., Jr. and Chamberlain, T., 1964, Hawaiian beach systems: Honolulu, University of Hawaiʻi, Hawaiʻi Institute of Geophysics, 95 p.

Moore, J.G., and Clague, D.A., 1992, Volcano growth and evolution of the island of Hawaii: Geological Society of American Bulletin, v. 104, p. 1471-1484.

Moore, J.G., Clague, D.A., Holcomb, R.T., Lipman, P.W., Normark, W.R., and Torresan, M.E., 1989, Prodigious submarine landslides on the Hawaiian Ridge: Journal of Geophysical Research, v. 94, p. 17465-17484.

Mullineaux, D.R., Peterson, D.W., and Crandell, D.R., 1987, Volcanic hazards in the Hawaiian Islands, *in* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 599-621.

Pendleton, E.A., Thieler, E.R., and Williams, S.J., 2005, Coastal vulnerability assessment of Kaloko-Honokohau National Historical Park to sea-level rise: U.S. Geological Survey Open-File Report 2005-1248, 25 p. [http://pubs.usgs.gov/of/2005/1248/, last accessed on December 1, 2008].

Peterson, F., 1996, Water resources, *in* Morgan, J.R., Hawai‘i, a unique geography: Honolulu, Hawai‘i, Bess Press, p. 51-60.

Presto, M.K., Storlazzi, C.D., Logan, J.B., and Grossman, E.E., 2007, Submarine groundwater discharge and fate along the coast of Kaloko-Honokōhau National Historical Park, Hawai‘i; Part I, Time-series measurements of currents, waves, salinity and temperature, November 2005 – July 2006: U.S. Geological Survey Open-File Report 2007-1310, 43 p. [http://pubs.usgs.gov/of/2007/1310/, last accessed on December 1, 2008].

Richmond, B.M., 2002, Overview of Pacific island carbonate beach systems, *in* Robbins, L.L., Magoon, O.T., and Ewing, L., eds., Carbonate beaches 2000: Dec. 5-8, Key Largo, Florida, American Society of Civil Engineers Conference Proceedings, p. 218-228.

Richmond, B.M., Fletcher, C.H., Grossman, E.E., and Gibbs, A.E., 2001, Islands at risk, coastal hazard assessment and mapping in the Hawaiian Islands: Environmental Geosciences, v. 8, no. 1, p. 21-37.

Storlazzi, C.D., and Presto, M.K., 2005, Coastal circulation and sediment dynamics along Kaloko-Honokōhau National Historical Park, Hawai‘i; Part I, Measurements of waves, currents, temperature, salinity and turbidity, April-October 2004: U.S. Geological Survey Open-File Report 2005-1161, 30 p. [http://pubs.usgs.gov/of/2005/1161/, last accessed on April 7, 2008].

Trusdell, F.A., Wolfe, E.W., and Morris, J., 2005. Digital database of the geologic map of the island of Hawai‘i: U.S. Geological Survey Data Series 144 [http://pubs.usgs.gov/ds/2005/144/, last accessed on December 1, 2008].

Wolfe, E.W., and Morris, J., compilers, 1996, Geologic map of the Island of Hawaii: U.S. Geologic Survey Miscellaneous Investigations Series Map I-2524-A, 3 sheets, scale 1:100,000.

Zhong, S., and Watts, A.B., 2002, Constraints on the dynamics of mantle plumes from uplift of the Hawaiian Islands: Earth and Planetary Science Letters, v. 203, p. 105-116.

USGS

Richmond and others—Puʻuhonua O Hōnaunau National Historic Site, Hawaiʻi Part I: Geology and Coastal Landforms—Open-File Report 2008-1192