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

Geologic Resource Evaluation of Kaloko-Honokōhau National Historical Park, Hawai‘i; Geology and Coastal Landforms

Open-File Report 2008-1191

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

Geologic Resource Evaluation of Kaloko-Honokōhau National Historical Park, Hawai‘i; Geology and Coastal Landforms

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

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

Open-File Report 2008-1191

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

Suggested citation:
Richmond, Bruce M., Gibbs, Ann E., 2008, and Cochran, Susan A., 2008, Geologic resource evaluation of Kaloko-Honokōhau National Historical Park, Hawai‘i; geology and coastal landforms: U.S. Geological Survey Open-File Report 2008-1191, 28 p. [http://pubs.usgs.gov/of/2008/1191/].

Front cover:
Oblique aerial photograph showing Kaloko Fishpond and a portion of the coastline of Kaloko-Honokōhau National Historical Park. Photograph courtesy of Brian Powers, Hawaiian Images Photography and Video, Kailua Kona, Hawai‘i

Contents

Figures

Geologic Resource Evaluation of Kaloko-Honokōhau National Historical Park, Hawaiʻi;
Geology and Coastal Landforms

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

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 that link the park geology and the resource manager.

The Kona coast National Parks of the Island of Hawaiʻi (fig. 1) are intended to preserve the natural beauty of the Kona coast and protect significant ancient structures and artifacts of the native Hawaiians. Puʻukoholā Heiau National Historic Site (PUHE), Kaloko-Honokōhau National Historical Park (KAHO), and Puʻuhonua O Honaunau 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

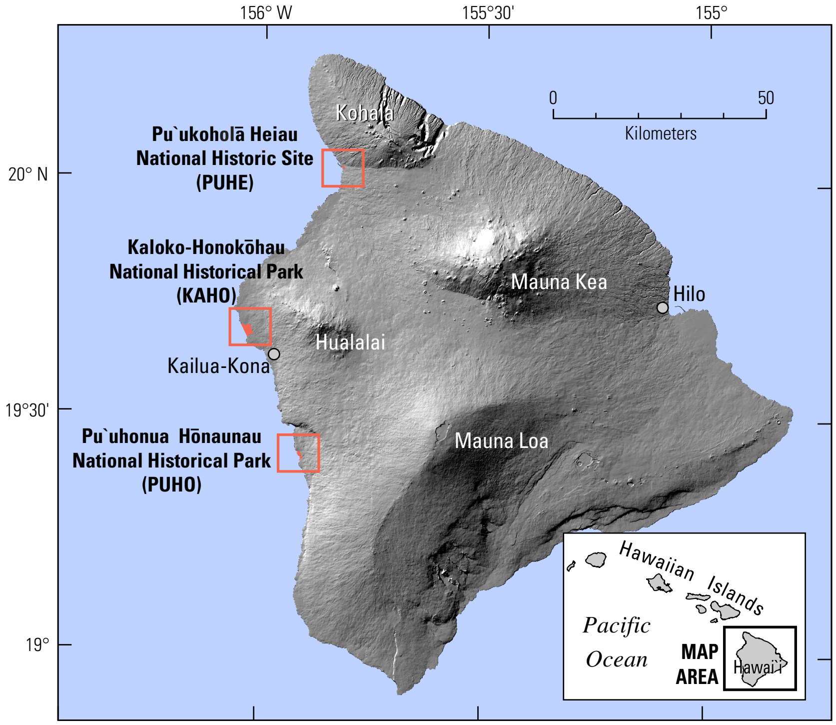


Figure 1. Index map of the Island of Hawaiʻi showing the location of the three National Parks along the Kona coast. Volcano names are shown in white.

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.

Kaloko-Honokōhau National Historical Park (KAHO) was established in 1978 in order to preserve and protect traditional native Hawaiian culture and cultural sites. The park (fig. 2) is the site of an ancient Hawaiian settlement, occupies 469 ha and is considered a locale of considerable cultural and historical significance (Greene, 1993). Cultural resources include fishponds, petroglyphs and a heiau (religious site). The fishponds are also recognized as exceptional birding areas and are important wetlands for migratory birds. The ocean and reef have been designated as a Marine Area Reserve, where green sea turtles commonly come ashore to rest. The park is also a valuable recreational resource, with approximately 4 km of coastline and a protective cove ideal for snorkeling and swimming. KAHO park boundaries extend beyond the mean high tide line and include the adjacent marine environment. An accompanying report for KAHO presents the results of benthic habitat mapping of the offshore waters, from the shoreline to approximately 40 m water depth (Gibbs and others, 2006). Ground-water quality and potential downslope 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 floor of the Pacific Ocean. 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). 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 the summit, Mauna Kea, and one of the world's most active volcanoes, Kilauea. Despite its great height, Hawaiʻi has subsided 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 Hawaiʻi is formed from five separate subaerial shield volcanoes—Kohala, Mauna Kea, Hualālai, Kilauea, and Mauna Loa (fig. 4)—and two submarine volcanoes, Loʻihi, 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 Hawaiʻi 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

Figure 2. Map of Kaloko-Honokōhau National Historical Park showing park boundaries and geographic locations. The legislated boundary was established by the U.S. Congress in 1978. The actual boundary includes only lands actually acquired by the National Park Service.

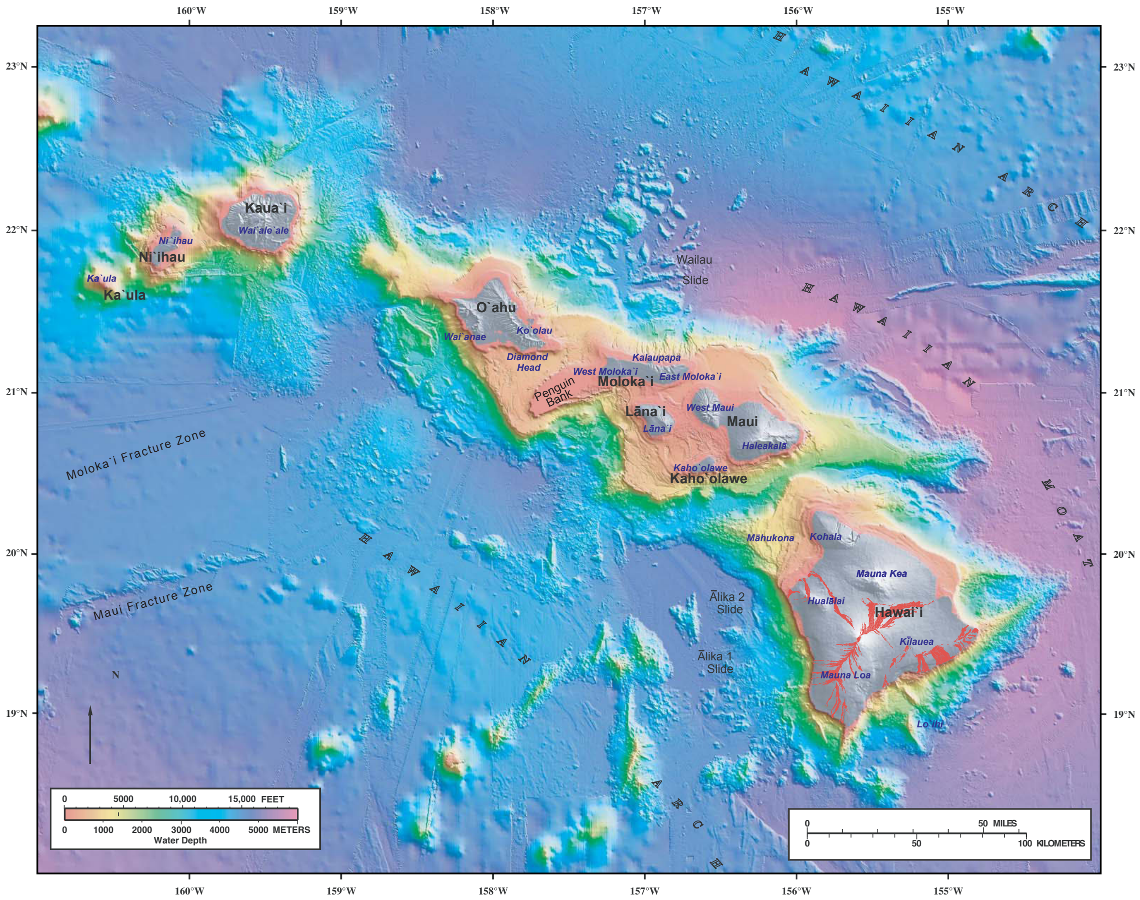


Figure 3. Topography and bathymetry of the main Hawaiian Islands (U.S. Geological Survey base image from Eakins and others, 2003). Island dissection and age increase towards the northwest. The red areas on the Island of Hawaiʻi show the location of historical lava flows.

Hawaiian shield volcanoes are the smooth ropy pahoehoe and the rough angular ʻaʻa. 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 ʻaʻa-type flow.

Modification of the volcanic landforms through erosion and weathering processes varies dramatically on the Island of Hawaiʻi, 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) slopes. Large canyons and surface gullies 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 Hawaiʻi 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 Hawaiʻi is unique in the Hawaiian Islands in that it is the only region to receive more rainfall in the summer than in the winter.

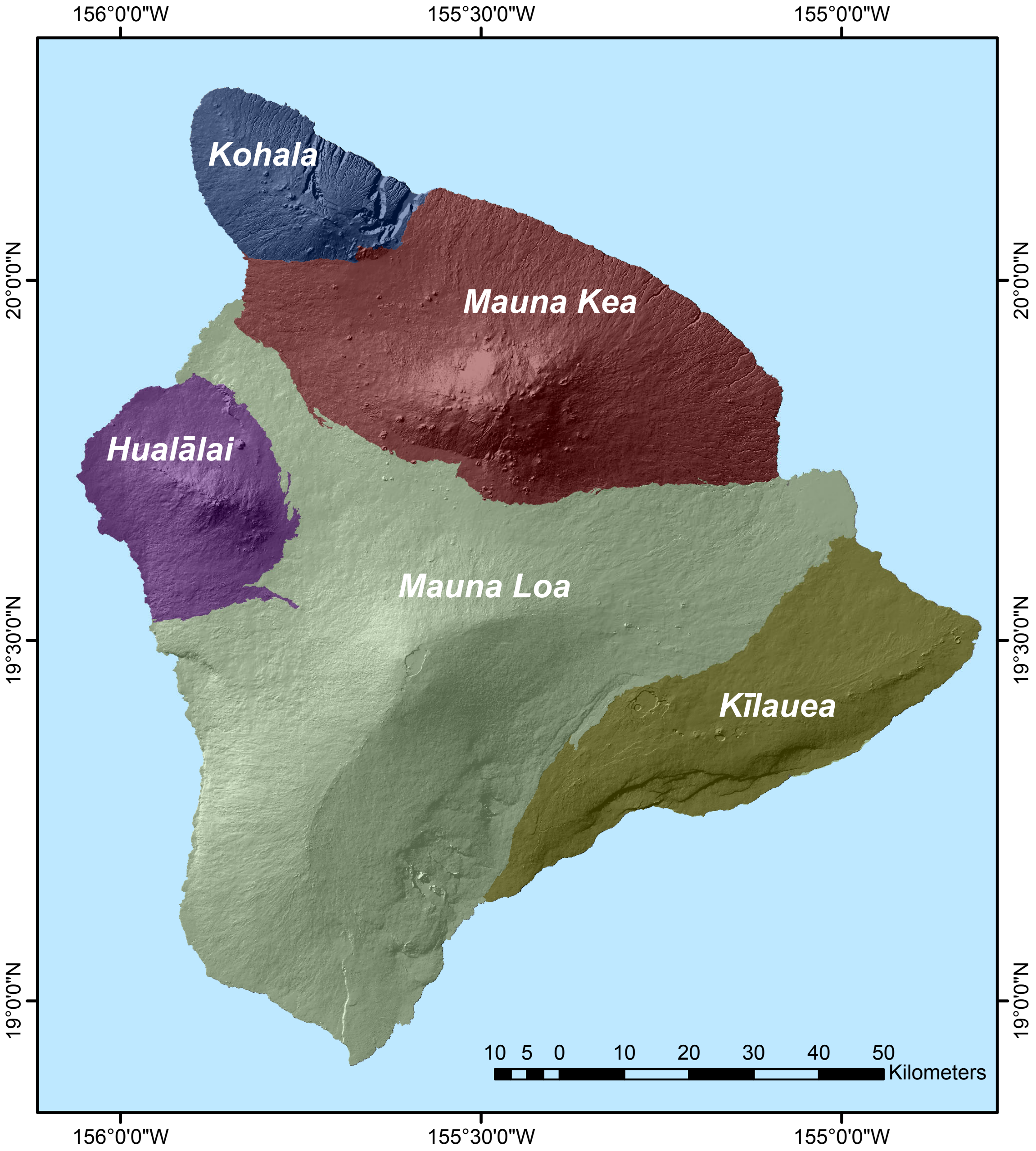


Figure 4. U.S. Geological Survey digital elevation model showing the five subaerial volcanoes that form the Island of Hawaiʻi. The different colors show the approximate extent of the surface flows from each volcano. Geology data from Wolfe and Morris (1996) and Trusdell and others (2005).

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 on the Island of 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. Recently, on October 15,0 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.

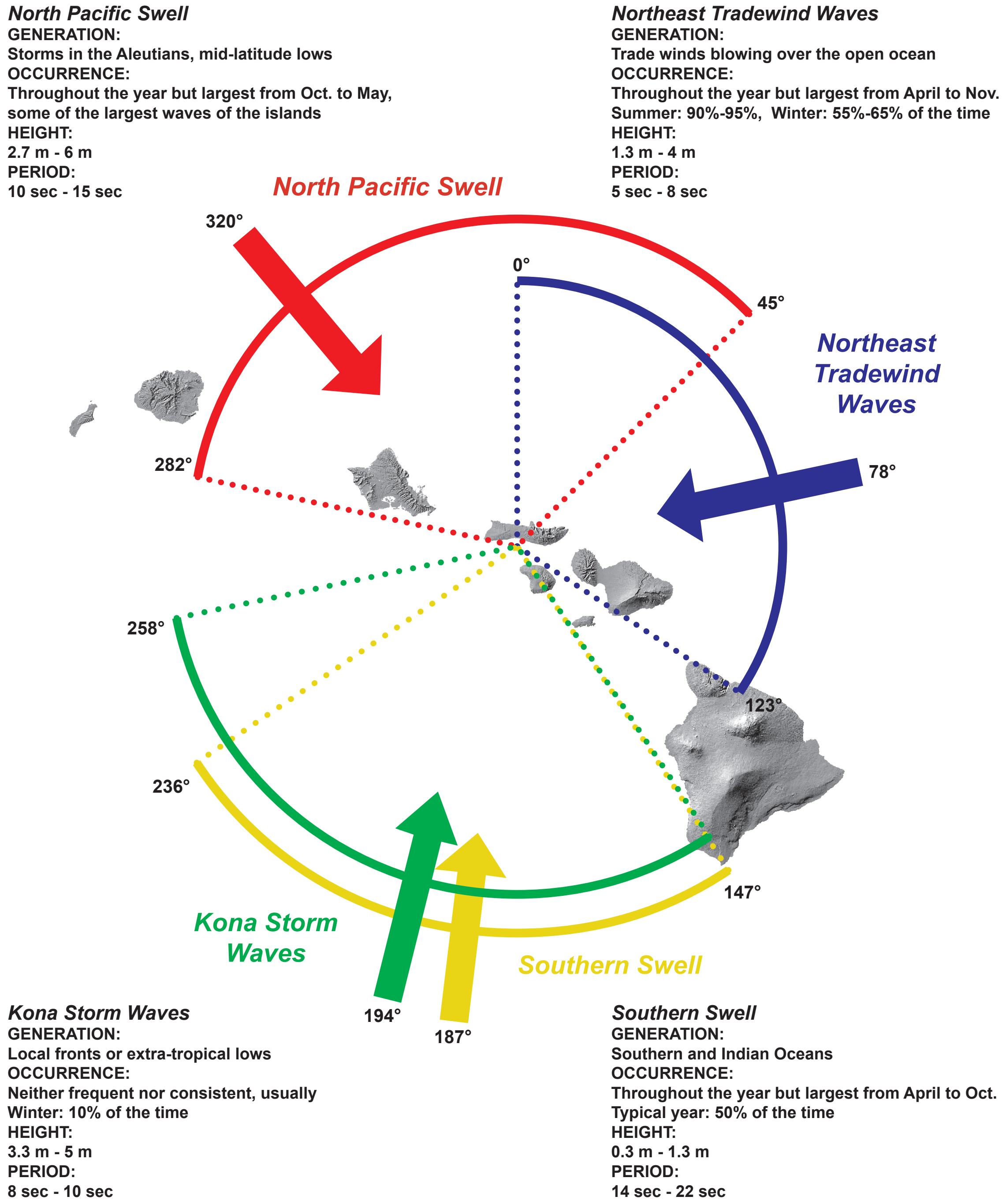
Occasional larger earthquakes, such as the magnitude 7.9 shock of 1868 located on the south flank of Mauna Loa, can cause more serious property damage and may generate local tsunamis when seawater is displaced by either fault movement or large landslides. For example, in November 1975, a locally generated tsunami with heights up to 14.6 m struck southeastern 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). In addition to locally generated events, tsunami hazards can also be caused by occurrences far away from the islands. 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). Since that last occurrence there has been widespread and intensive human development along the Hawaiian shoreline.

Fossiliferous marine conglomerates along the northwest coast of Kohala Volcano have been interpreted by geologists as megatsunami deposits generated by a flank-failure submarine landslide on western Mauna Loa (McMurty and others, 2004). According to McMurty and others (2006), 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 on the flanks of Kohala Volcano. 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 km2 (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

Puʻukoholā Heiau National Historic Site (PUHE), Kaloko-Honokōhau National Historical Park (KAHO), and Puʻuhonua O Hōnaunau National Historical Park (PUHO) are situated on the leeward west coast of the island of Hawaiʻi along the flanks of Kohala, Mauna Kea, Hualālai, and Mauna Loa Volcanoes (fig. 4). In addition to the seaward-sloping volcanic landscapes, coastal features of the parks include beaches, basalt shore platforms, ponds and wetlands, anchialine pools, coastal cliffs, and adjacent reef areas. These



North Pacific Swell

GENERATION:
Storms in the Aleutians, mid-latitude lows
OCCURRENCE:
Throughout the year but largest from Oct. to May, some of the largest waves of the islands
HEIGHT:
2.7 m - 6 m
PERIOD:
10 sec - 15 sec

Northeast Tradewind Waves

GENERATION:
Trade winds blowing over the open ocean
OCCURRENCE:
Throughout the year but largest from April to Nov.
Summer: 90%-95%, Winter: 55%-65% of the time
HEIGHT:
1.3 m - 4 m
PERIOD:
5 sec - 8 sec

Kona Storm Waves

GENERATION:
Local fronts or extra-tropical lows
OCCURRENCE:
Neither frequent nor consistent, usually
Winter: 10% of the time
HEIGHT:
3.3 m - 5 m
PERIOD:
8 sec - 10 sec

Southern Swell

GENERATION:
Southern and Indian Oceans
OCCURRENCE:
Throughout the year but largest from April to Oct.
Typical year: 50% of the time
HEIGHT:
0.3 m - 1.3 m
PERIOD:
14 sec - 22 sec

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.

features are described in more detail 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 animals such 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 m3 and a beach-sand volume of 3,000 m3/km of coastline (Moberly and Chamberlain, 1964). For comparison, the older island of Kaua‘i has 10,700,000 m3 and 59,000 m3/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 waters 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 and are influenced by daily water level variations caused by waves and tides. 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 northerly winter storm surf and occasional southern swell, as well as Kona storm waves (fig. 5), produce 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 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 m2 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 Hawaiʻi 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 Hawaiʻi 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 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 and 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. High-wave-energy settings tend to have coarser sediment 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 Hawaiʻi'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; Moberly and Chamberlain, 1964). 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 Hawaiʻi 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 (Pendleton 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

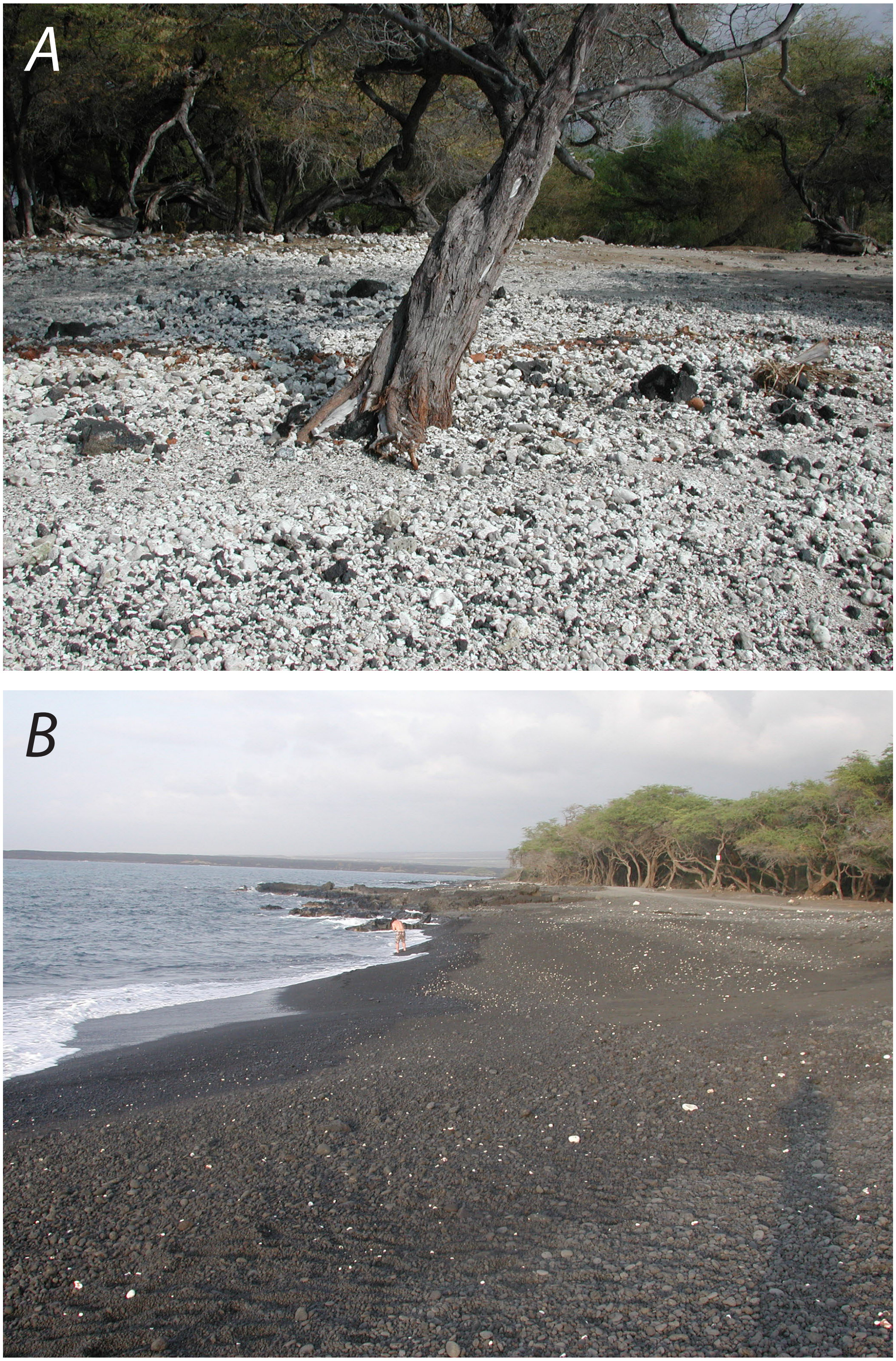


Figure 6. Photographs of coarse sediment beaches of the Kona coast. *A*, A predominantly coral pebble beach about 10 km south of PUHE. *B*, A basalt pebble beach about 30 km south of PUHE. Both beaches have minor components of the other's clast type.

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).

Kaloko-Honokōhau National Historic Park (KAHO)

Geology

Kaloko-Honokōhau National Historical Park is underlain by Holocene lava flows that originated from Hualālai Volcano (fig. 7). The Hualālai Volcanics have been described as transitional between alkalai basalt and trachyte (Wolfe and Morris, 1996). Both pahoehoe (fig. 8A) and ʻaʻa flows (fig. 8B) are present in the park. Flows of three different ages are identified in the park, and their periods of lava eruption, in years before present, are 10,000 to 5,000 years before present (BP), 5,000 to 3,000 BP, and 3,000 to 1,500 BP. The most recent eruption of Hualālai occurred in 1800-01 and deposited lava about 4 km north of the park.

Hualālai Volcano appeared above sea level about the same time as Mauna Loa (~300 ka) and ceased its shield-building phase at about 130 ka (Moore and Clague, 1992). Moore and Clague also noted a large submarine landslide on the flank of Hualālai that produced a concave scarp more than 40 km wide and up to 4 km high. The slump most likely occurred during the active shield-building phase of Hualālai (> 130 ka). Recent geologic mapping has identified no major faults in the vicinity of KAHO (Wolfe and Morris, 1996).

The topography within the park slopes gently seaward, and the highest elevation is about 25 m along the landward (east) border. Most of the park coast is low-lying and gently sloping (fig. 9) with low coastal basalt cliffs in the north and near the extreme southern boundary of the park.

Four soil types plus areas of water (primarily fishponds) have been mapped within KAHO by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS). These maps can be found online (http://www.ctahr.hawaii.edu/soilsurvey/soils.htm, last accessed on December 1, 2008). Because of the young age of the lava bedrock and the relatively dry climate, only thin, poorly developed soils occur within the park. Both ʻaʻa (rLV) and pahoehoe (rLW) lava-flow soil development is characterized by no soil to very thin soil with little vegetation cover, although some plants may become rooted in the numerous cracks and crevices. The soils developed on pahoehoe flows occur in the south and north portions of the park, and the ʻaʻa soil type occupies the central portion. The soils developed on bedrock closely follow the distribution of rock types shown in figure 7. Landward of Kaloko Fishpond is an area mapped as “Punaluu extremely rocky peat” (rPYD). This soil consists of a thin (~10 cm) layer of permeable organic peat overlying pahoehoe lava bedrock. Beaches are mapped as a soil type and are distributed as an uneven shore-parallel band along the KAHO coast.

Coastal Landforms

In a study of plant communities in KAHO, Canfield (1990) recognized eight major different coastal community types that are directly related to substrate type. These communities, substrates, and their approximate coverage within the park are as follows (after Canfield, 1990): barren lava rock (~25 percent); coastal strand (pahoehoe or sand substrate; ~10 percent); anchialine pools (pahoehoe substrate; <1 percent); marsh and mangrove forest (muddy sediment overlying pahoehoe; ~5 percent); grassland (pahoehoe substrate; ~20 percent); inland scrub (pahoehoe or ʻaʻa substrate; ~10 percent); savanna (pahoehoe or ʻaʻa substrate; ~25 percent); and forest (pahoehoe substrate; ~5 percent).

Coastal landforms that occur within KAHO and are discussed in this report include (1) beaches (perched, boulder, and intertidal), (2) basalt shore platform, (3) wetlands and fish ponds, and (4) anchialine pools.. The coral reefs bordering KAHO are described by Gibbs and others, 2006.

Beaches

Sand beaches within the park occur either as intertidal accumulations of sediment subjected regularly to wave interaction or as perched supratidal beaches that are typically active only during large-wave events. In addition to the above two types of sand beaches, there are smaller beach accumulations dominated by gravel-size material.

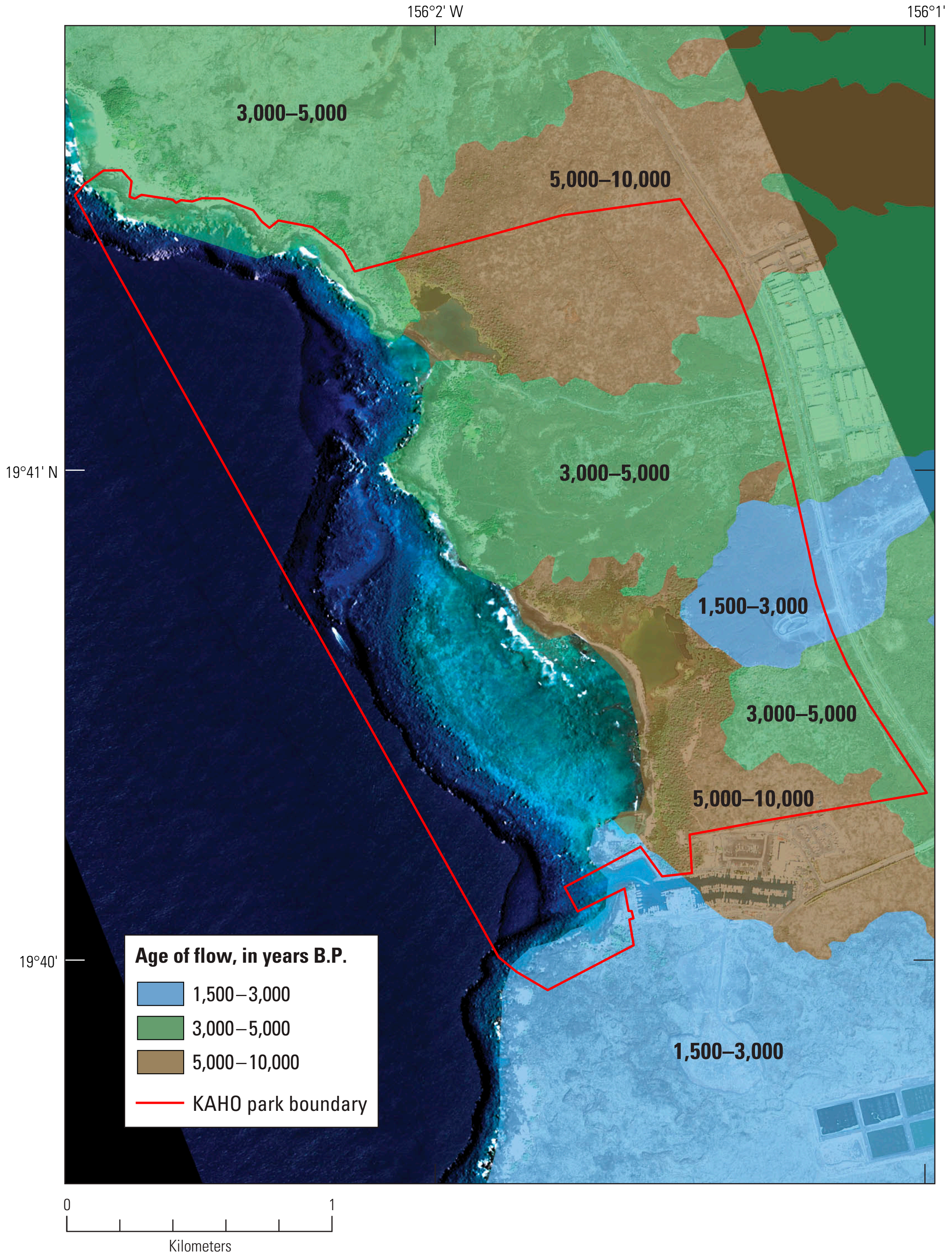


Figure 7. Aerial photomosaic showing bedrock geology, age of the Hualālai Volcanics, and offshore morphology of the Kaloko-Honokōhau National Historical Park area (geology layer from Trusdell and others, 2005). In the offshore zone, Quickbird satellite imagery is overlain on 2000 U.S. Army Corps of Engineers SHOALS bathymetry. Park boundaries are shown in red. ‘A‘a-type lava flows are mostly the 5,000-3,000 year old deposits in the center of the park (Wolfe and Morris, 1996).

The perched beaches make up approximately 60 percent of the beach area in the park (Hapke and others, 2005). They consist of a wedge-shaped veneer of marine-derived sand and gravel sediment deposited on the elevated basalt platform (fig. 8). Perched beaches are landward of the rocky shoreline and sit atop a gently seaward-sloping pahoehoe basalt coastal platform that is largely free of sediment between the shoreline and the beach. The landward position of the perched beaches indicates the beaches are active only during large wave events, when water levels are higher and reach further inland. The wedge-shaped perched beaches are thin at their seaward boundary and thicken landward to 1-2 m at the berm crest. Landward of the berm crest, the perched beaches tend to thin and merge inland with the thin soils on the basalt substrate. The landward extent of the perched beach deposits appears to be controlled by the elevation of the gradually sloping underlying rock platform and the maximum landward extent of storm-wave runup. Locally, basalt platform topography influences where perched beaches occur by creating an elevated surface periodically subjected to wave influence. Extensive perched carbonate sand beaches occur around Kaloko Point and from Kaloko Fishpond to the northern park boundary. Beach width of the perched beaches (the distance from the toe of the beach to the vegetation) varies considerably and ranges from a low of a few meters to nearly 17 m in the more exposed beaches north of Kaloko Fishpond.

A large intertidal beach borders Honokōhau Bay opposite ‘Aimakapa Fishpond. The offshore area is characterized by a submerged basalt platform and shallow fringing reef. The intertidal beach forms a barrier spit across the mouth of the fishpond (fig. 10), creating a barrier between the ocean and the ‘Aimakapa Fishpond complex. The beach, which is semiprotected from open-ocean waves by the broad, shallow reef fronting the bay, is composed of moderately well-sorted medium sand derived from a combination of weathering products from the basalt and adjacent reef. The slope and height of the beach vary alongshore. It is lower and flatter in the south, and increases in height and slope towards the north. The change in height and slope is accompanied by a concomitant increase in grain size towards the exposed northern segments. Beach width is fairly uniform along the barrier spit with a range from about 8 to 12 m. Width of the entire spit ranges from about 22 to 35 m.

The shoreline along the more exposed sections of the KAHO coast is typically armored by a natural beach composed of basalt (fig. 8B), and less commonly coral, gravel-sized clasts (fig 11). The gravel clasts are usually rounded and form a layer a few clasts thick, creating a wave-resistant structure. The clasts are eroded from the nearby basalt platform, presumably during high wave events, and their rounding suggests they are reworked by waves. Sediment ranges from 2-mm granules to large boulder blocks of a meter or more. Reef-derived carbonate sand and gravel form scattered pockets within the gravel deposits. Gravel beaches occur at Kaloko Point, in pockets north of Kaloko Fishpond, and on pocket beaches at the southern end of the park.

Beachrock (calcium-carbonate cemented beach sediment) is present in limited outcrops along the KAHO shoreline (figs. 11 and 12). On the intertidal beaches of Honokōhau Bay and north of Kaloko Fishpond the beach rock occurs as discontinuous sheets in the low intertidal to subtidal region. Beachrock outcrops on Kaloko Point occur mostly in the upper intertidal zone as isolated patches within the gravel beach deposits. Beachrock forms at a shallow depth within the beach system, and its exposure at the surface indicates there has been some erosion of the overlying beach sediment.

Long-term (>50 years) changes to the beach systems of KAHO were recently studied by Hapke and others (2005) using analysis of historical aerial photography taken in 1950, 1954, 1965, 1970, 1988, 1992, and 2002. The results of the 52-year linear-regression analysis of shoreline change shows a dominant erosional trend, with the net change of all the measurements taken yielding an average erosion rate of 0.3 m/yr for sand beaches in the park. There is a considerable alongshore variation in the rates (fig. 13), with several pronounced erosion hotspots and one location where the long-term signal is accretional. The rates are lowest overall north of Kaloko Fishpond and along the barrier spit across the mouth of ‘Aimakapa Fishpond (<0.1 m/yr). The highest erosion rates (>0.7 m/yr) were measured at Kaloko Point. The other main erosional areas occur north and south of ‘Aimakapa Fishpond (0.6 m/yr), and the beach at the south end of Honokōhau Bay (0.6 m/yr; fig. 13). Examination of time steps using photograph pairs shows that within the overall erosion signal are significant periods of beach accretion. During the periodic accretional events, the beach area increases from an average of around 46,000–50,000 m3 to as much as 80,000 m3. Based on

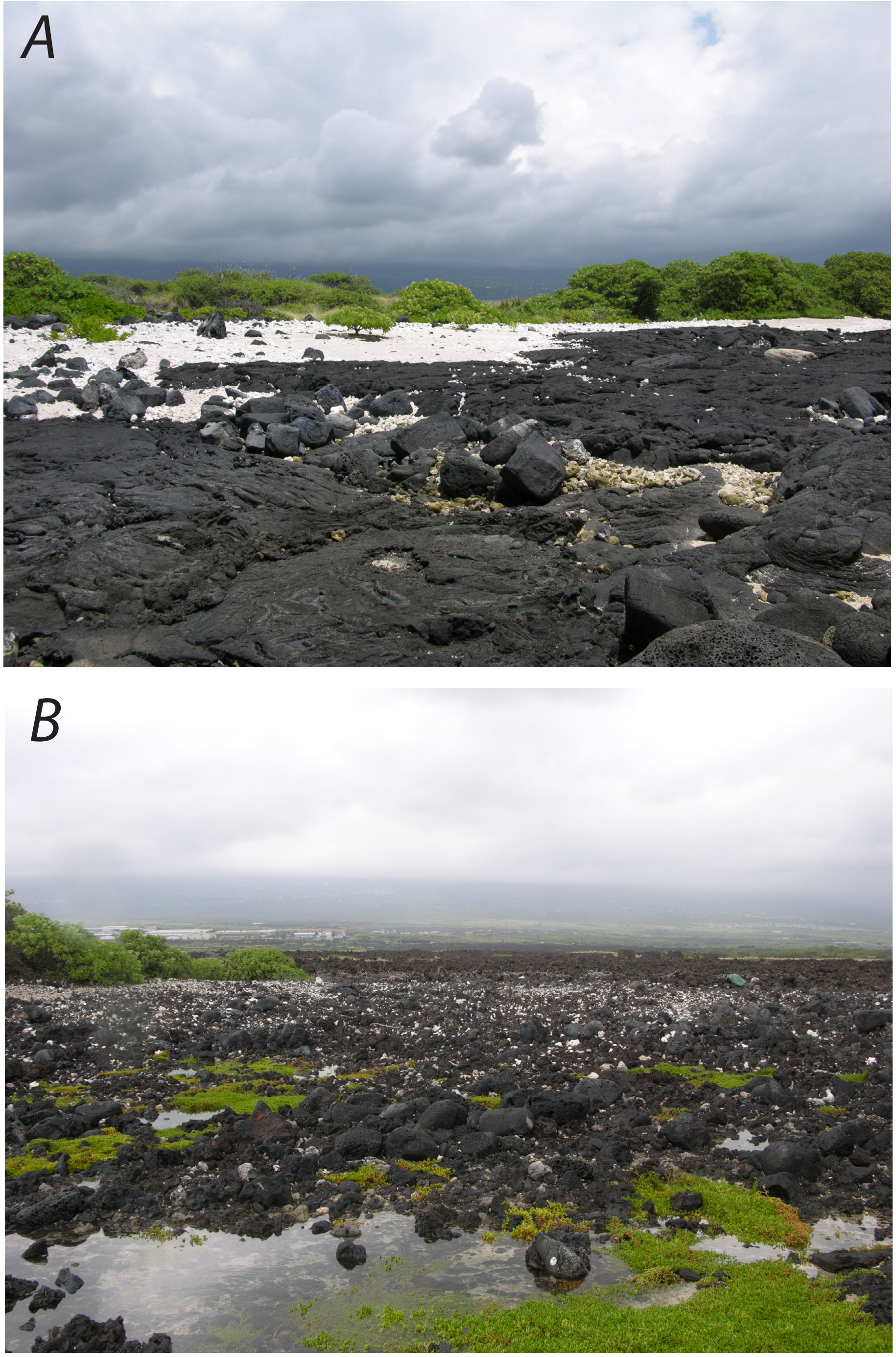


Figure 8. Photographs of different lava-flow types in Kaloko-Honokōhau National Historical Park. *A*, Basalt shore platform exposed at the coast south of Wawahiwa'a Point showing the characteristic pahoehoe surface texture. The seaward edge of the platform is mantled by rounded basalt boulders, and the landward margin supports a perched beach of mostly carbonate sand. Photograph taken in August 2004. View towards the south. *B*, An ‘a‘a flow (background) and overwash sediment (foreground) at the coast on the north side of Kaloko Point. The rough angular texture of the ‘a‘a flow is clearly visible, along with the sparse vegetation cover. The perched beach is composed of rounded coral and basalt gravel clasts that are most likely deposited by waves during storm overwash. Photograph taken in August 2004. View towards the east.

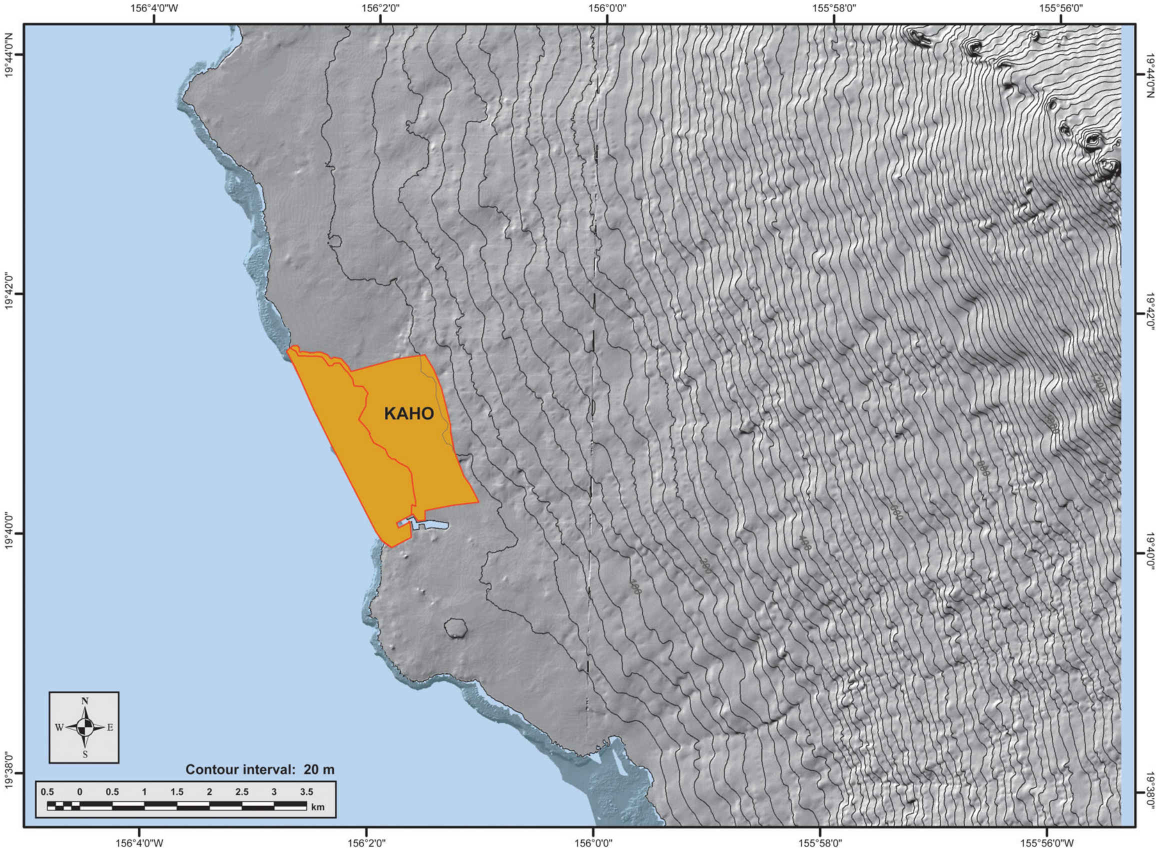


Figure 9. Shaded relief map showing the physiographic setting of KAHO near the base of Hualālai Volcano, where the park occupies the gently sloping lower flanks. In the upper right are several small cones that define a northwest-southeast-trending linear rift zone. U.S. Geological Survey 10-m digital elevation model used for the on-land base, and U.S. Army Corps of Engineers 2000 SHOALS data used for the immediate offshore physiography. Contour interval 20 m.

the photographs used for the analysis, the accretion events and subsequent erosion periods occur rapidly, as determined by comparing adjacent photo years.

The area of the beaches determined from each photographic survey was outlined as polygons in a Geographic Information System (GIS) (Hapke and others, 2005). The area of the polygons was analyzed at a 1-m grid spacing to determine the presence or absence of a beach. The most stable beach areas had beaches in all seven historical surveys, and the least stable beaches were present in only one survey. A beach stability diagram for KAHO is shown in figure 14 and depicts the relative stability of beach areas within the park.

Basalt Shore Platform

Most of the KAHO shoreline is fronted by a natural basalt shore platform (Parrish and others, 1990) that forms as lava cools at the coast. The character of the platform varies with the type of underlying basalt substrate, which is formed from either pahoehoe or ‘a‘a lava. The pahoehoe substrate is typically smoother and has a more undulating surface than the ‘a‘a type. The rocky intertidal zone is generally a bare rock surface with tide pools, various intertidal flora and fauna, and scattered pockets of accumulated sediment. The submerged portion of the platform provides a solid substrate for corals and other marine organisms (Gibbs and others, 2006).

Whether a shore platform is bare rock or buried by sand is primarily controlled by its elevation, exposure to waves, and availability of sand. The shore platform at KAHO is best developed at Kaloko Point, where it

Figure 10. Photograph of the well-developed intertidal beach system that separates Honokōhau Bay (left) from ʻAimakapā Fishpond (right). Berm height, beach-face slope, and grain size tend to increase from south to north along the beach indicating an increase in wave exposure. Photograph taken August 2004. View towards the north.

is about 125 m wide and extends from the perched beach to the seaward edge of the platform. The platform is exposed almost continuously from Wawahiwaʻa Point (known locally as "Pine Trees") to the north end of Kaloko Fishpond and from the south end of Kaloko Fishpond around Kaloko Point to the north end of ʻAimakapā Fishpond. Within Honokōhau Bay, platform exposure is intermittent and increases towards the south. With the exception of the entrance to Honokōhau Harbor, the platform is continuous but narrow around Maliu Point and towards Noio Point at the southern margin of the park. An ancient Hawaiian rock fishtrap (ʻAiʻōpio Fishtrap) rests on the submerged platform in southern Honokōhau Bay.

Wetlands and Fishponds

Two natural embayments within the park were used by ancient Hawaiians to create large fishponds. Kaloko Fishpond covers about 4.5 ha, and the slightly larger ʻAimakapā Fishpond is about 6 ha (Hoover and Gold, 2005). Kaloko Fishpond was formed by the construction of a mortarless rock wall, 230 m long, 2 m high, and 9-12 m wide, that enclosed a small natural embayment. The base of the wall is intertidal and is subject to damage by waves that strike the area. More than 50 percent of Kaloko Fishpond has depths less than 1 m, with a maximum depth of about 3.7 m (reported in Hoover and Gold, 2005; after Kikuchi and Belshe, 1971). ʻAimakapā Fishpond is an embayment in which a barrier beach has formed across the entrance, separating the pond from the adjacent shallow bay.

Brackish wetlands in KAHO border the two large fishponds. They consist primarily of alien marsh-plant species around the margins and, according to Canfield (1990), cover about 5 percent of the park area. The wetlands plants form a dense vegetation cover on pond margins and are developed over either sparse soil

Figure 11. Photograph of a pocket beach just north of Kaloko Fishpond showing and upper beach composed mostly of coral gravel and a lower beach armored by basalt boulders. The substrate underlying the green notebook in the left center portion of the photograph is exposed beachrock. Photograph taken August 2004. View towards the north.

or thin organic muck. The red mangrove was introduced to the Hawaiian Islands and at one time covered extensive areas to the north and northwest of Kaloko Fishpond. They were subsequently removed in 1991-1992 (Hoover and Gold, 2005).

Anchialine Pools

Brock and Kam (1997) identified 82 anchialine pools and pool complexes in KAHO and adjacent areas. More recent assessments in the park have identified around 120 pools (unpublished data provided by park personnel). The pools occupy low-lying depressions within the coastal basalt platform in areas where there is mixing between freshwater (ground water) and seawater. Within KAHO the pools are concentrated to the northwest of Kaloko Fishpond, landward of Maliu Point, and the coastal platform between Kaloko Point and ‘Aimakapā Fishpond. Most of the ponds are less than 100 m2 in area and less than 0.5 m in depth (Brock and Kam, 1997). Although not as well developed as some other pools along the Kona coast, the KAHO anchialine pools are a valuable park resource.

Coastal Sediments

The coastal sediment at KAHO is a combination of reef-derived carbonate detritus and volcanically derived basaltic sediment. Sediment size and deposit characteristics are largely controlled by local exposure to waves and availability of sediment. Grain size varies over short distances in both alongshore and cross-shore directions at KAHO. The coarsest beach sediment occurs in the north, where the coastline is more

Figure 12. Photograph of beachrock composed of basalt boulder clasts in a matrix of mostly carbonate material on the reef flat at Kaloko Point. GPS device in center of picture is approximately 15 cm long. Photograph taken August 2004.

exposed to incoming wave energy. This material consists of basalt boulders, coral gravel, and isolated carbonate sand patches (figs. 8, 11, and 15). In general, the sediment becomes finer and more carbonate rich towards the south (fig. 10). This is especially clear along the beach bordering Honokōhau Bay. Figure 16 illustrates the variation of beach sand composition, rounding, and sorting from north to south along Honokōhau Bay.

Throughout the park there are scattered pockets of gravel-rich sediment that occur where there is a local gravel source and where wave and current energy levels are sufficient to remove finer material. 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 that formed during periods of high wave activity. Landward of the storm berm the sediment is mostly sand with occasional gravel clasts. The beach deposits are thickest near the crest of the beach and thin in both the seaward and landward directions, with a maximum thickness between 1 and 2 m.

Natural Hazards

The natural hazards for the coastal area surrounding the park have been identified and mapped (fig. 17; from Fletcher and others, 2002). Because of its coastal setting, KAHO is vulnerable to hazards that increase ocean-inundation potential, such as tsunamis, storms, and sea-level rise. Lander and Lockridge (1989) identified seven historical tsunamis that have struck the coast near Kailua-Kona since 1896. The tsunami runup ranged in height from 0.6 m to 3.4 m, with the largest runup originating from a 1946 earthquake in the Aleutian Islands. A tsunami of similar magnitude occurring today would most likely cause damage

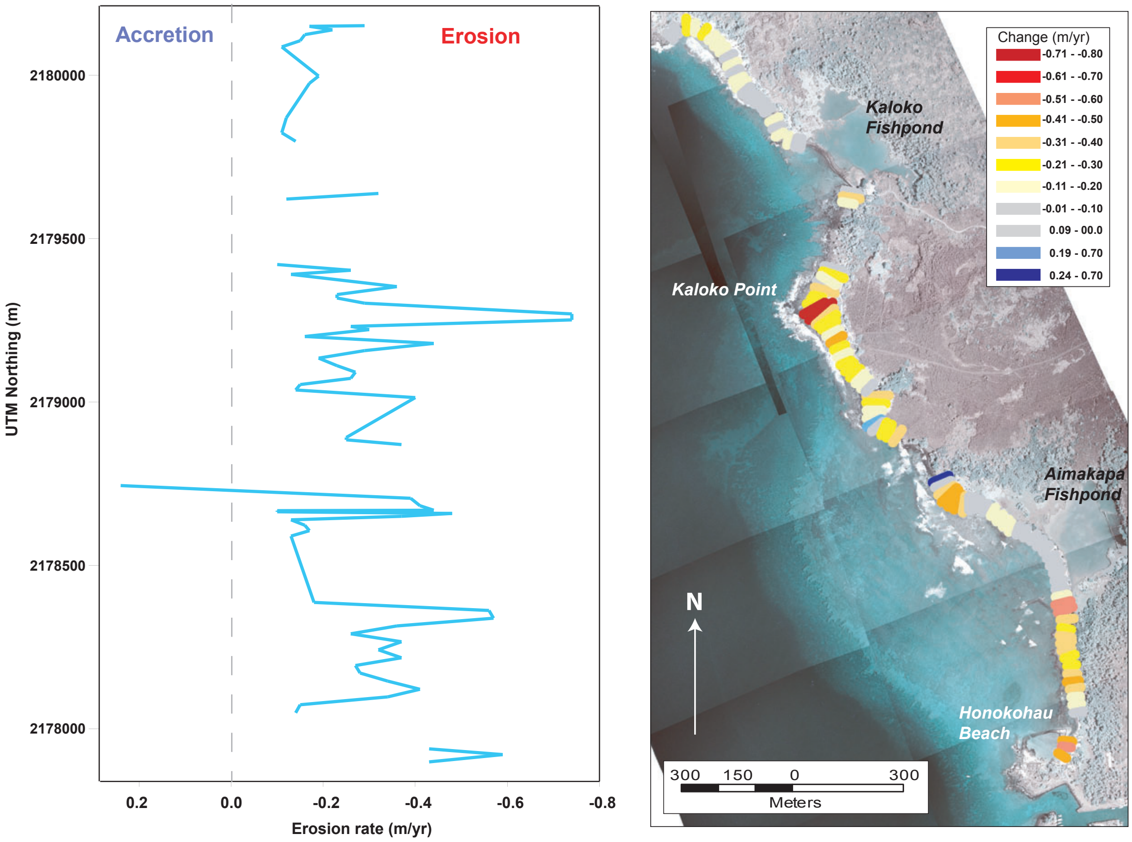


Figure 13. Diagram and map of shoreline change at Kaloko-Honokōhau National Historical Park (KAHO). Alongshore variation in the rate of change of shoreline position (diagram, left) using linear regression over a 52-year time span (from Hapke and others, 2005). The gray bands in the map (right) represent transects where the average rate of change is less than the rate that can be determined accurately by the methodology used.

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

The southwest exposure of KAHO partially protects it from high waves and storms approaching from the north. The park is more directly exposed to Kona storm waves and swell originating from southwest through northwest directions. Damaging high waves have struck the west coast of the Island of Hawai‘i more than a dozen times since 1956, with waves as high as 9 m reported (Fletcher and others, 2002). Storm waves arriving on a direct approach to the park have the potential to damage the coastline, structures, and adjacent reefs. For example, a hurricane traveling northward 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 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 Pendleton and others, 2005). This rate includes contributions from both eustatic and tectonic components at Hilo, which may be slightly different from the conditions at KAHO. 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, fishponds, anchialine pools, and associated wetlands. Coastal erosion at present is episodic and related to the passage of high surf from seasonal storms and/or long-distance swell. Over the long term the park has been undergoing net erosion of the beaches

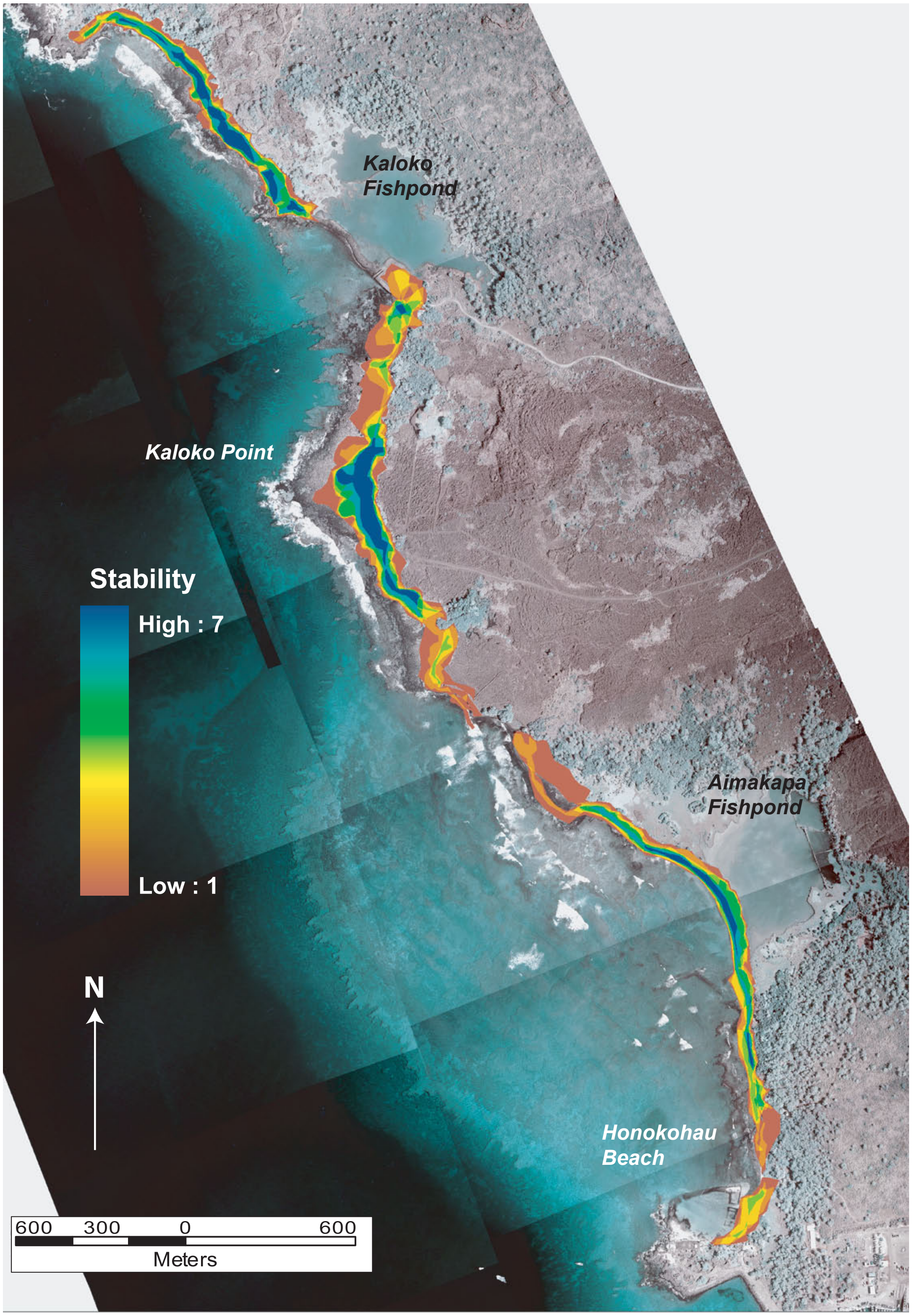


Figure 14. Beach stability map of KAHO based on the frequency of beach occurrence at 1-m grid spacing over the 52-year period of analysis (from Hapke and others, 2005). The stability is defined as the number of times a beach was detectable in the seven historical aerial photographic surveys used in this analysis. High stability indicates the frequent presence of a beach, and low stability indicates a beach was observed infrequently during the analysis.

Figure 15. Close-up photograph of poorly-sorted, angular, coarse sand from a pocket beach on the southern margin of Kaloko Point. The sand is a mixture of lithic basalt and carbonate fragments. Centimeter scale with millimeter ticks.

at an average rate of 0.3 m/yr (Hapke and others, 2005). A recent study by Pendleton and others (2005) examined the vulnerability of the park shoreline to sea-level rise and determined that approximately 45 percent of the KAHO shoreline is at very high (~20 percent) or high (~25 percent) risk to adverse impacts from rising sea level. The areas most at risk are the exposed beaches, which consist of unconsolidated sediment that can be easily eroded, and wetland areas prone to increased inundation.

During periods of heavy rain, severe stream flooding culminating in flash floods could affect upland areas above the park. An intense rainfall event could result in some erosion of surface sediment and soil. However, because of the low slopes and relatively porous nature of the substrate, stream flooding does not appear to be a major hazard within KAHO.

The entire park is subject to potential volcanic and seismic hazards and is mapped as Hazard Zone 4 (HZ 1 is the most hazardous) for lava flows (Mullineaux and others, 1987; http://pubs.usgs.gov/gip/hazards/maps.html, last accessed on December 1, 2008). Hualālai is older than Kilauea and Mauna Loa, and its eruptions occur much less frequently. Eruptions of Hualālai in 1800-01 resulted in lava reaching about 4 km north of KAHO. Other recent eruptions occurred about 300 and 700 years ago. Most of the basalt at the surface in the park is less than 10,000 years old. Although KAHO lies south and west of the main rift zones of Hualālai, the park is potentially subject to lava flows during an eruption.

The overall hazard assessment for coastal hazards of the park as mapped by Fletcher and others (2002) is moderate, mostly comprising risk from volcanic hazards, coastal erosion and inundation from tsunamis, storms, and sea-level rise.

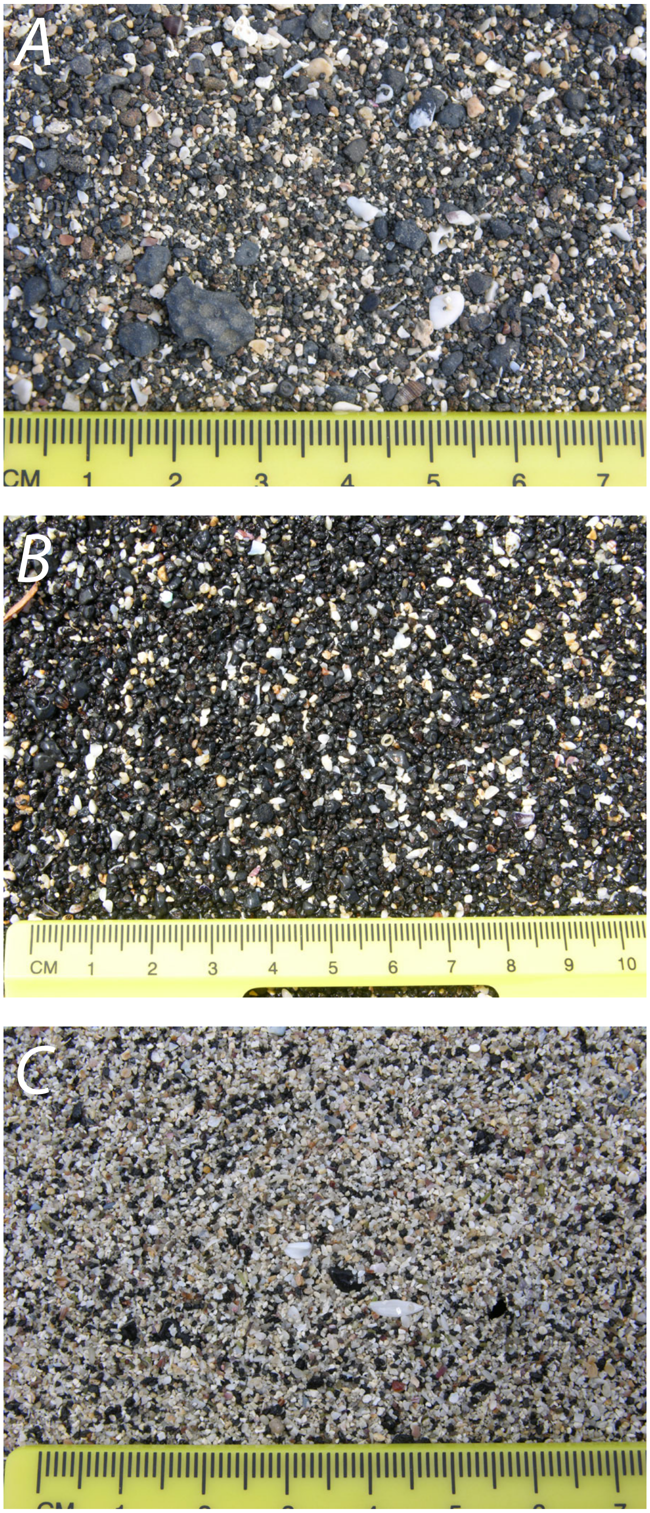
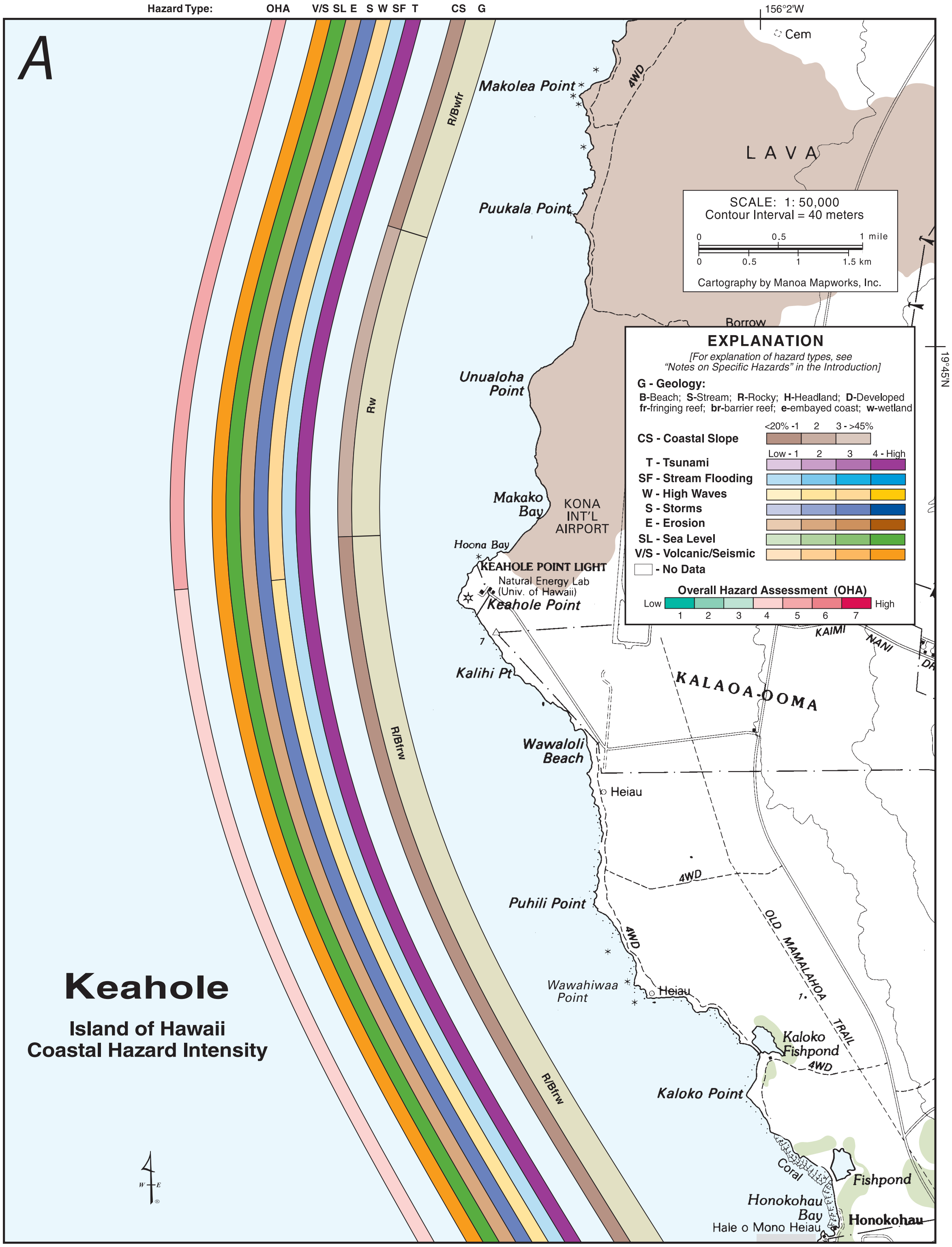
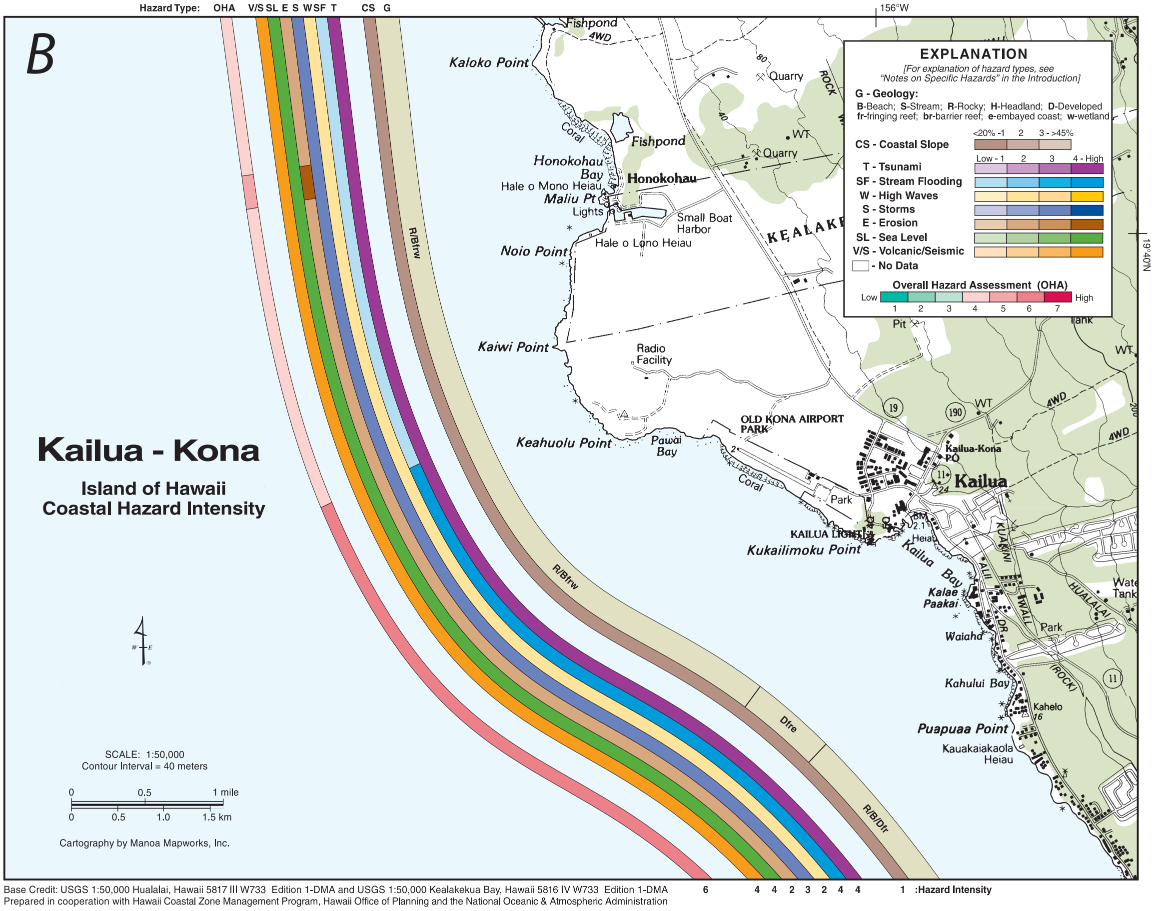


Figure 16. Close-up photographs of sediment from the beach at Honokōhau Bay showing the variation in sediment composition, rounding, and sorting from north to south along the beach. Centimeter scale with millimeter ticks. *A*, Poorly sorted coarse sand of mostly lithic fragments from the beach at the north end of the bay. *B*, Moderately well sorted, rounded, medium sand of mostly lithic fragments from the beach near the center of the bay. *C*, Moderately well sorted medium-fine sand of mostly carbonate fragments from the southern end of the bay.



Base Credit: USGS 1:50,000 Hualalai, Hawaii 5817 III W733 Edition 1-DMA
Prepared in cooperation with Hawaii Coastal Zone Management Program,
Hawaii Office of Planning and the National Oceanic & Atmospheric Administration



Base Credit: USGS 1:50,000 Hualalai, Hawaii 5817 III W733 Edition 1-DMA and USGS 1:50,000 Kealakekua Bay, Hawaii 5816 IV W733 Edition 1-DMA
Prepared in cooperation with Hawaii Coastal Zone Management Program, Hawaii Office of Planning and the National Oceanic & Atmospheric Administration

Figure 17. Coastal hazard intensity maps for Keāhole (*A*) and Kailua-Kona (*B*) 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 rise, 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)].

Hydrogeology

Ground water in Hawai‘i 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 volcano building stage (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 flows rapidly from the mountains to the sea. Recharge occurs through infiltration, primarily via precipitation, and by inflow from higher ground-water systems. Most freshwater within the park occurs as ground water that is mostly recharged in the high-rainfall areas above the park.

Surface water within the park streams is ephemeral and is generally restricted to periods of high rainfall. Water resources and watershed conditions for KAHO have been recently assessed by Hoover and Gold (2005). Ground water is an important park asset and near the coast consists primarily of a thin brackish layer overlying seawater. Ground water intersects the surface in the park's anchialine pools, and it contributes flow into the Kaloko and ‘Aimakapā fishponds.

Resource Management Information

Kaloko-Honokōhau 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 various marine resources. In general, the park is relatively stable geologically; however, some areas are of potential concern.

1. KAHO Beaches are frequented by both tourists and local residents and therefore represent a valuable park asset. Aerial photograph analysis indicates long-term erosion with an average park-wide beach retreat rate of at 0.3 m/yr (Hapke and others, 2005). The threats to the beach systems are primarily from high-wave events causing marine inundation during storms and the resulting movement of sediment away from the beach. However, big wave events also provide a mechanism to transport sand from deeper offshore regions that can be later redistributed by natural processes to facilitate beach replenishment. Whether a particular storm event results in beach erosion or deposition depends upon the characteristics of the individual storm. In some cases, erosion along one section of coast may be coupled with simultaneous deposition in another stretch. Continual variation in the shoreline position of the beach is a natural process, and any attempt to stabilize the shoreline by construction of engineering structures runs the risk of creating unforeseen adverse impacts. The park beach systems are variable and hazardous zones. Such hazards might affect the planning and construction of permanent structures.

2. Increased rates of sea-level rise also could affect the location and design of all coastal structures. Sea-level rise will also have potential negative impacts on anchialine pools, wetlands, and ground water resources within the park. Unfortunately, there is little that can be done either to prevent sea-level rise or protect these resources from the advancing sea.

3. Tsunamis are a real and potentially devastating hazard along Hawai‘i coastlines. The 3.4-m runup elevation of the 1946 tsunami serves as a guide for potential inundation-zone elevation as a result of rapid water-level rise during tsunamis. 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 via the streams probably contributes only small amounts of the overall sediment. However, changes to the watershed surrounding the park could lead to increased sedimentation, which would adversely affect nearby coral reefs. Protecting the KAHO watershed from activities that would greatly change natural sedimentation patterns would help protect the watersheds.

5. The close proximity of Hualälai Volcano and the presence historical lava flows in the area are causes for concern. Fortunately, volcano-monitoring activities at the USGS Hawaiian Volcano Observatory are such that there should be 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.

6. Moderate earthquakes are common events on Hawai‘i. The October 15, 2006, magnitude 6.7 earthquake caused widespread damage in western Hawai‘i. It was centered about 15 km north-northwest of Kailua-Kona and served as a stark reminder of the dynamic nature of the region. Seismic safety design standards can be employed on construction projects to help mitigate these events.

7. Because of the low relief and gently sloping topography within the park, landslides are not a hazard of concern at KAHO.

Acknowledgments

The authors thank Rebecca Beavers, coastal geologist, and Bruce Heise, geologist, with the National Park Service, Geologic Resources Division who, together with Mike Field of the U.S. Geological Survey (USGS), were instrumental in initiating the cooperative study within the Kaloko-Honokōhau National

Historical Park. 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. Sallie Beavers, Stanley Bond, and Richard Gmirkin of the National Park Service assisted with park logistics and provided background information on park resources. The manuscript benefited from reviews by Bruce Jaffe and Cheryl Hapke of the USGS. 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 and water quality in anchialine ponds of the Kona, Hawaii, Coast: Pacific Science, v. 41 p. 200-208.

Canfield, J.E., 1990, Description and map of the plant communities of Kaloko-Honokohau National Cultural Park: University of Hawai‘i at Mānoa, Cooperative National Park Resources Study Unit, Technical Report 73, 30 p.

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., 2006, Geologic resource evaluation of Pu‘ukoholā Heiau National Historic Site, Hawai‘i; 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].

Coyne, M., Mullane, R., Fletcher, C., and Richmond, B., 1996, Losing O’ahu; 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 Hawaii 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.

Gibbs, A.E., Cochran, S.A., Logan, J.B., and Grossman, E.E., 2006, Benthic habitats and offshore geological resources of Kaloko-Honokōhau National Historical Park: U.S. Geological Survey Scientific Investigations Report 2006-5256, 70 p. [http://pubs.usgs.gov/sir/2006/5256/, last accessed December 1, 2008].

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 Hawai‘i 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].

Hapke, C.J., Gmirkin, R., and Richmond, B.M., 2005, Coastal change rates and patterns, Kaloko-Honokohau National Historical Park, Hawai‘i: 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., 2005, Assessment of coastal water resources and watershed conditions in Kaloko-Honokohau National Historical Park, Hawai‘i: National Park Service Technical Report NPS/NRWRD/NRTR-2005/344, 139 p.

Kikuchi, W., and Belshe, J., 1971, Examination and evaluation of fishponds on the leeward coast of the island of Hawaii: Hilo, Hawai‘i, unpublished Hawai‘i County Planning Commission Report.

Lander, J.F., and Lockridge, P.A., 1989, United States tsunamis (including United States possessions) 1690-1988: Boulder, Colorado, 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 Hawai‘i, Hawai‘i 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.

Parrish, J.D., Smith, G.C., and Norris, J.E., 1990, Resources of the marine waters of Kaloko-Honokohau National Historic Park: University of Hawai‘i at Mānoa, Cooperative National Park Resources Study Unit, Technical Report 74, 115 p.

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, Hawaii, 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-Honokohau National Historical Park, Hawaii; 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-Honokohau 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 December 1, 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.

Richmond and others—Kaloko-Honokōhau National Historic Site, Hawaiʻi; Geology and Coastal Landforms—Open-File Report 2008-1191