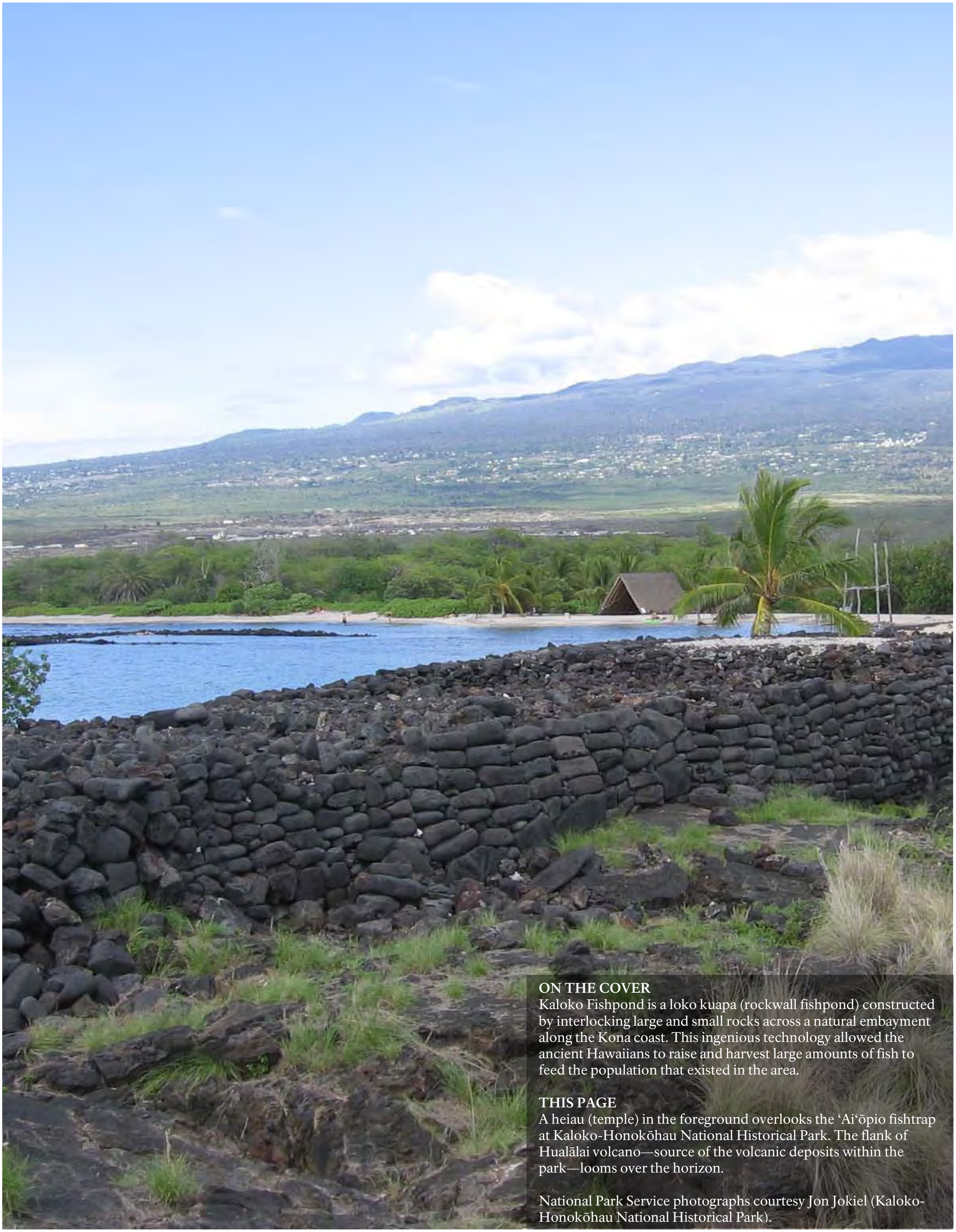
National Park Service
U.S. Department of the Interior

Natural Resource Program Center

Kaloko-Honokōhau National Historical Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2011/384



ON THE COVER
Kaloko Fishpond is a loko kuapa (rockwall fishpond) constructed by interlocking large and small rocks across a natural embayment along the Kona coast. This ingenious technology allowed the ancient Hawaiians to raise and harvest large amounts of fish to feed the population that existed in the area.

THIS PAGE
A heiau (temple) in the foreground overlooks the ‘Ai‘ōpio fishtrap at Kaloko-Honokōhau National Historical Park. The flank of Hualālai volcano—source of the volcanic deposits within the park—looms over the horizon.

National Park Service photographs courtesy Jon Jokiel (Kaloko-Honokōhau National Historical Park).

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National Park Service
Geologic Resources Division
PO Box 25287
Denver, CO 80225

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U.S. Department of the Interior
National Park Service
Natural Resource Program Center
Fort Collins, Colorado

The National Park Service, Natural Resource Program Center publishes a range of reports that address natural resource topics of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate high-priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

Printed copies of this report are produced in a limited quantity and they are only available as long as the supply lasts. This report is available from the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/).

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NPS 466/107491, April 2011

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Executive Summary

This report accompanies the digital geologic map data for Kaloko-Honokōhau National Historical Park in Hawaii, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork.

The landscape at Kaloko-Honokōhau National Historical Park sustained early Hawaiian settlements for many years prior to European discovery. Early settlement activities included raising crops, harvesting resources from the sea, and participating in a highly advanced religious society. The park strives to demonstrate the intimate balance and spiritual connections between the early Hawaiians and their surrounding natural environment, by preserving the remnants of their inhabitation, such as fishponds and fishtrap walls, stone walls, and religious structures.

Geology is fundamental to the management of the scenic and natural resources of the park. Geology influences groundwater flow, and it contributes to climate, weather, hydrology, and topography, which in turn affect coral reefs and other submarine habitats. Geology, in particular volcanism, volcanic deposits, and shoreline features, also strongly influenced the history of the park, affecting the ancient Hawaiian settlement there. Geologic issues of particular significance for resource management at Kaloko-Honokōhau National Historical Park include:

- Fishpond stability and shoreline change: the historic fishponds at the park changed the hydrogeologic system of the embayment at Kaloko, contributed to significant siltation of the seafloor, and are now important wetlands for migratory birds. Shoreline has shifted in an oscillatory manner, but the overall trend is erosional. North of the Kaloko fishpond wall, there is long-term net erosion; however, the highest erosion rates in the park occur at Kaloko Point, Honokōhau Beach, and ʻAimakapā Fishpond.
- Groundwater recharge and discharge: freshwater on the relatively dry, leeward Kona coast is a valuable natural resource. In Kaloko-Honokōhau National Historical Park, aquifers are unconfined, thin, brackish water lenses floating atop saline groundwater. This aquifer system supports anchialine ponds and coastal wetlands. Further saltwater intrusion is a possibility near coastal areas, and is among the factors limiting groundwater availability. Significant submarine groundwater discharge occurs all along the coast, through permeable lava flows from upslope recharge areas. This discharge provides nutrients for offshore benthic habitats.
- Anchialine ponds: these ponds are among the most threatened ecosystems in Hawaii. The ponds are home to unusual plants and animals, and several exist at Kaloko-Honokōhau National Historical Park; they are relatively small, inland sources of brackish water influenced by tides and springs. Water levels, temperatures, and salinity vary in the ponds constantly, because they are connected to the ocean via subterranean tunnels. It is unknown how sedimentation affects these anchialine ponds, or how exactly they can be restored from damage caused by invasive fish.
- Coral reef changes: the Kona coast of the Island of Hawaiʻi is relatively protected from high wave energy; coral reef development is relatively diverse, and it flourishes on mostly volcanic substrates. Heavy wave action, flooding, hurricanes, sea-level rise, climate change, or seismic events can disturb coral reef growth; the same is true of sedimentation and pollutants introduced by anthropogenic land clearing, agricultural development, dredging, overfishing, and heavy tourism. The U.S. Geological Survey produced a benthic habitat map for the park that notes coral cover percentage and species distribution.
- Geologic hazards: Kaloko-Honokōhau National Historical Park is underlain by relatively young volcanic flows from the Hualālai Volcano (still considered ʻactive'), and volcanism remains a possibility in the area. Due to its low-lying coastal location, Kaloko-Honokōhau National Historical Park is susceptible to inundation during tsunamis. Tsunami modeling takes into account seismic events, bathymetry, storm issues, and wind and rain conditions. Coastal erosion and relative sea-level rise affect some of the shoreline at the park, causing beach loss, saltwater inundation, damage to shallow coral reefs, and potential loss of cultural resources. Seismicity is a concern throughout the Pacific basin. Earthquakes occur frequently on the Island of Hawaiʻi, as a result of (1) magma movement accompanying volcanism; (2) crustal stresses arising from areas of structural weakness; and (3) crustal loading by the volcanic mass. Seismicity has caused fatalities, ground rupture, localized uplift and subsidence, liquefaction, ground settlement, and extensive damage to roads, buildings and homes; it has also triggered tsunamis.

The scenic and natural resources of the park are closely linked to geologic features and processes. Volcanism of Hualālai Volcano created lava flows that spread downslope to form the landscape features of the Kaloko-Honokōhau National Historical Park, including lava tubes, pāhoehoe and ʻaʻā basalt flows, and benches.

Active erosion modifies the shorelines. Active volcanism at Kīlauea creates hazy "vog", comprised of acidic aerosols, unreacted sulfur gases, volcanic ash, and other fine particulate matter. The geology at Kaloko-Honokōhau National Historical Park is a fundamental component of an ecosystem that hosts several indigenous species.

Knowledge of the physical properties of the different geologic units mapped at Kaloko-Honokōhau National Historical Park is vital to understanding and managing the varying ecosystems and natural resources in the park. The map unit properties table includes, for each mapped geologic unit, characteristics such as erosion resistance, suitability for infrastructure and recreation, geologic significance, and associated cultural and mineral resources. In addition to their physical properties, the rock units at Kaloko-Honokōhau National Historical Park (geologic map units Qh1o, Qh1y, and Qh2) contain information related to volcanic island evolution, and the geologic history of the Hawaiian-Emperor volcanic island and seamount chain in the Pacific Ocean basin.

The glossary contains explanations of many technical terms used in this report, including terms used in the Map Unit Properties Table. A geologic time scale is included as figures 18 and 19.

Acknowledgements

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The GRI is administered by the Geologic Resources Division of the Natural Resource Program Center.

The Geologic Resources Division relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

Special thanks to: Jon Jokiel (Kaloko-Honokōhau National Historical Park) provided photographs of the park. David Sherrod (U.S. Geological Survey) provided review comments on the Hawai'i Volcanoes National Park GRI report. Those comments were also included in this report as appropriate.

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Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Kaloko-Honokōhau National Historical Park.

Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The GRI, administered by the Geologic Resources Division of the Natural Resource Program Center, is designed to provide and enhance baseline information available to park managers. The GRI team relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

The goals of the GRI are to increase understanding of the geologic processes at work in parks and to provide sound geologic information for use in park decision making. Sound park stewardship requires an understanding of the natural resources and their role in the ecosystem. Park ecosystems are fundamentally shaped by geology. The compilation and use of natural resource information by park managers is called for in section 204 of the National Parks Omnibus Management Act of 1998 and in NPS-75, Natural Resources Inventory and Monitoring Guideline.

To realize these goals, the GRI team is systematically conducting a scoping meeting for each of the 270 identified natural area parks and providing a park-specific digital geologic map and geologic report. These products support the stewardship of park resources and are designed for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes.

The GRI mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their Geographic Information Systems (GIS) Data Model. These digital data sets bring an interactive dimension to traditional paper maps. The digital data sets provide geologic data for use in park GIS and facilitate the incorporation of geologic considerations into a wide range of resource management applications. The newest maps contain interactive help files. This geologic report assists park managers in the use of the map and provides an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and current GRI contact information, please refer to the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/).

Park Setting

Regional Information

Kaloko-Honokōhau National Historical Park covers 469.8 ha (1,160.91 ac) (249.2 ha [615.9 Federal ac]) on the Island of Hawai'i, approximately 5 km (3 mi) north of Kailua-Kona (figs. 1-2). The Island of Hawai'i covers an area of about 10,432 km^2 (4,028 mi^2) and is by far the largest of the eight main Hawaiian Islands. The Island of Hawai'i lies southeast of Maui, separated by the 48-km-wide (30-mi) 'Alenuihāhā Channel. It is currently the southernmost landmass of the Hawaiian island chain.

The Island of Hawai'i is geographically and ecologically divided into many sub-regions. The island is volcanically active; it contains three volcanoes that have erupted in the past 200 years: Kīlauea, Mauna Loa, and Hualālai. The highest point is the inactive volcano, Mauna Kea, at 4,205 m (13,796 ft) elevation (fig. 1).

Cultural History and Establishment of Kaloko-Honokōhau National Historical Park

The seemingly barren landscape at Kaloko-Honokōhau National Historical Park sustained early Hawaiian settlements for many years. These early inhabitants raised crops, harvested resources from the sea, and participated in a highly advanced religious society. Facets of this religion were defined in the "kapu" (laws of conduct). In old Hawaiian culture, kapu governed all aspects of society. Penalties were severe and quick. After the 1819 death of King Kamehameha I, Hawaiians discontinued the kapu system and old religions of Hawaii. Kaloko-Honokōhau National Historical Park preserves some of the few remaining religious sites from old Hawaii.

Kaloko-Honokōhau National Historical Park shows the intimate balance and spiritual connections between the early Hawaiians and their surrounding natural environment. Remnants of their inhabitation include aquaculture ponds (fishponds and fishtrap walls), stone walls and religious structures such as the ki'i pohaku (petroglyphs) and heiau (religious site).

Kaloko-Honokōhau National Historical Park provides approximately 4 km (2.5 mi) of protected coastline habitat for the endangered 'Ilio holo i ka (Hawaiian monk seal, *Monachus schauinslandi*), the Hawaiian coot (*Fulica americana alai*), and the Hawaiian stilt (*Himantopus mexicanus knedseni*), as well as several species of mammals, waterbirds, reptiles, fishes, and invertebrates endemic to Hawaii. Green sea turtles also nest there.

An act of Congress established Kaloko-Honokōhau National Historical Park on November 10, 1978 to "provide a center for the preservation, interpretation, and perpetuation of traditional native Hawaiian activities and culture, and to demonstrate historic land-use patterns as well as to provide a needed resource for the education, enjoyment, and appreciation of such traditional native Hawaiian activities and culture by local residents and visitors…" In addition to cultural and historic features, there are also notable natural resources. Preserving a precontact (e.g., prior to indigenous Hawaiians' contact with Europeans) historical context (including coastal areas, fishponds, a house site, and other archaeological remnants) complements natural resource management goals and helps to maintain a relatively pristine ecosystem.

Additional information may be found at http://www.nps.gov/kaho, the Kaloko-Honokōhau National Historical Park website.

Coastal and Upland Development

When the park was established, much of the surrounding lands were open space. However, since that time, extensive areas have been developed or zoned for urban use. Immediately inland and upslope of the park is an industrial complex, including a rock quarry, equipment storage area, and gasoline station (Hoover and Gold 2005). Honokōhau Harbor and its associated facilities border the park's southern edge. Construction of a resort and residential development began to the north of the park in 2005 (Hoover and Gold 2005). These surrounding areas have become local stressors that impact park resources (Ann Gibbs, geologist, U.S. Geological Survey, written communication, November 2010).

Geologic Setting

The Island of Hawai'i is just one volcanic mass among the many subaerial islands and submarine seamounts of the Hawaiian-Emperor volcanic chain. The chain stretches over 5,800 km (3,600 mi), from the Aleutian trench in the northwest Pacific basin to the Lō'ihi seamount, which is approximately 35 km (22 mi) to the southeast of the Island of Hawai'i. The chain formed due to the movement of the Pacific tectonic plate over an essentially stationary hotspot of volcanic activity. From southeast to northwest, the Hawaiian Islands increase in age, degree of erosion, and amount of subsidence into the sea. Many islands, such as Hawai'i, are composites of more than one volcano.

The land mass of the Island of Hawai'i contains 5 large volcanic centers: Kohala, Mauna Kea, Hualālai, Mauna Loa, and Kīlauea (fig. 1). The latter two are among the most active volcanoes in the world (see Hawai'i Volcanoes National Park report; Thornberry-Ehrlich 2009). Kaloko-Honokōhau National Historical Park is on the western slope of Hualālai Volcano, which looms over the park (see inside front cover). The majority of volcanic flows of the Hualālai volcanic center are older than much of Mauna Loa and Kīlauea, and they dominate the geology of the park. The basalts at Kaloko-Honokōhau National Historical Park are from three flows with age ranges from approximately 1,500 to 3,000 years before present (ybp) (geologic map unit Qh2), 3,000 to 5,000 ybp (geologic map unit Qh1y), and 5,000 to 10,000 ybp (geologic map unit Qh1o) (fig. 3) (Wolfe and Morris 1996). Other NPS areas along the Kona coast preserve lava flows from other volcanoes. Basalts from Mauna Loa are mapped within Pu'uhonua o Hōnaunau National Historical Park (Thornberry-Ehrlich 2011a). Basalts from Mauna Kea and Kohala are mapped within Pu'ukoholā Heiau National Historic Site (Thornberry-Ehrlich 2011b).

The landscape within Kaloko-Honokōhau National Historical Park consists of the relatively stark, rugged basalt flows that form broad benches or terraces along the shore, with limited carbonate sand and gravel beach areas (Richmond et al. 2008). Beach areas include normal intertidal to supertidal accumulations of perched storm sediments; however, beaches are relatively rare; most of the coast is rocky intertidal area, or short cliffs (Ann Gibbs, geologist, U.S. Geological Survey, written communication, November 2010). The lava has a gradual slope (5-10%) and undissected (relatively free of eroded channels) surface. Much of the area was originally covered in the pāhoehoe lava, but this was later covered in part by a later 'a'ā flow (Wolfe and Morris 1996; Richmond et al. 2008). Pāhoehoe lava has a characteristic "ropy" texture while 'a'ā lava is typically jagged or blocky.

Natural features in the park include anchialine ponds, wetlands, tidepools, and coral reefs. The Kaloko and 'Aimakapā fishponds form wetland areas within the park (fig. 4). Soil development is limited to low-lying pockets in the pāhoehoe lava, where eolian deposits of silt, volcanic ash and dust, and shoreline vegetation-derived organic humus accumulate. A small drainage empties into the 'Ai'ōpio fishtrap near the harbor of Honokōhau. Elevations range from sea level to about 25 m (80 ft) in elevation at the eastern boundary.

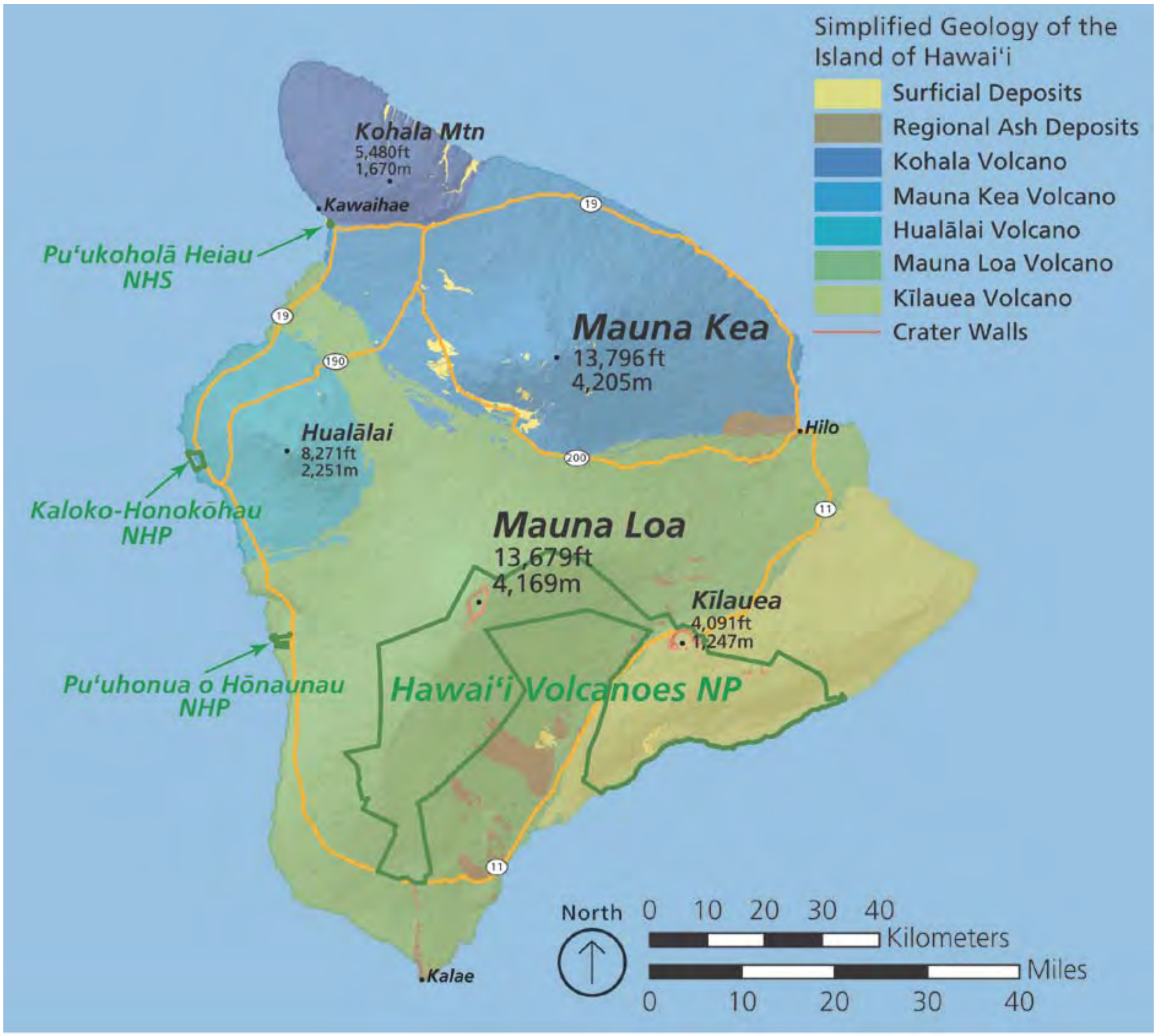


Figure 1. Shaded relief map of the Island of Hawai'i. Peaks of the island's five volcanoes are indicated. Different colors show the extent of volcanic deposits from the five volcanic centers. National Park Service areas are outlined in green. The Kona coast stretches from Kawaihae to Kalae on the west side of the island and is home to three NPS areas: Pu'ukoholā Heiau National Historic Site, Kaloko-Honokōhau National Historical Park and Pu'uhonua o Hōnaunau National Historical Park. Lava flows within Kaloko-Honokōhau National Historical Park originated from Hualālai. Graphic compiled by Phil Reiker and Jason Kenworthy (NPS Geologic Resources Division) using the GRI digital geologic data for Kaloko-Honokōhau National Historical Park (see Overview of Geologic Data section), ESRI ArcImage Service World Shaded Relief, and US Census data.

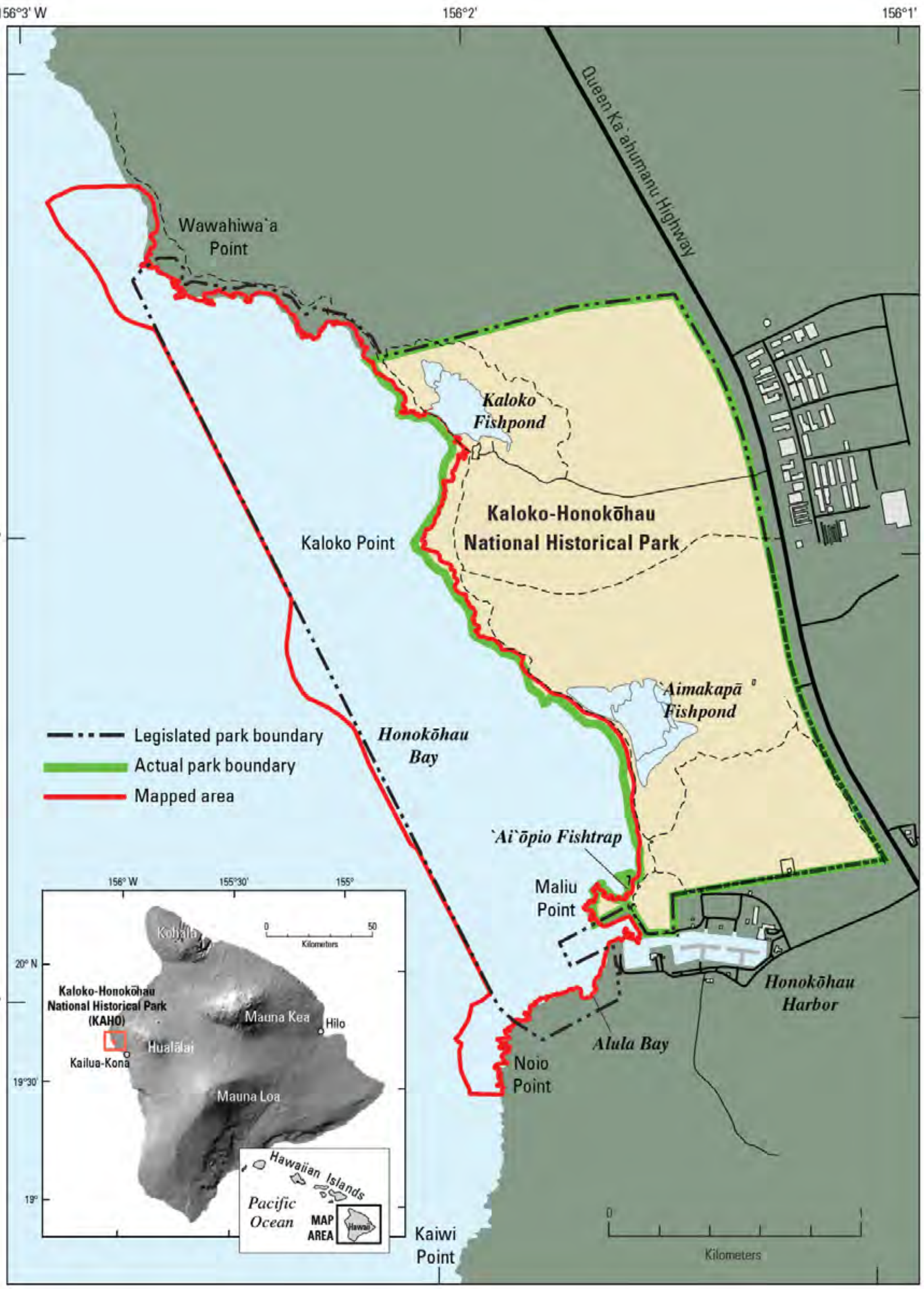


Figure 2. Map of Kaloko-Honokōhau National Historical Park and immediate surroundings. Congress established the legislated boundary in 1978; however, the actual boundary includes lands acquired by the National Park Service. "Mapped area" refers to the area encompassed by the benthic habitat map of Gibbs et al. (2007). U.S. Geological Survey graphic from Gibbs et al. (2007).

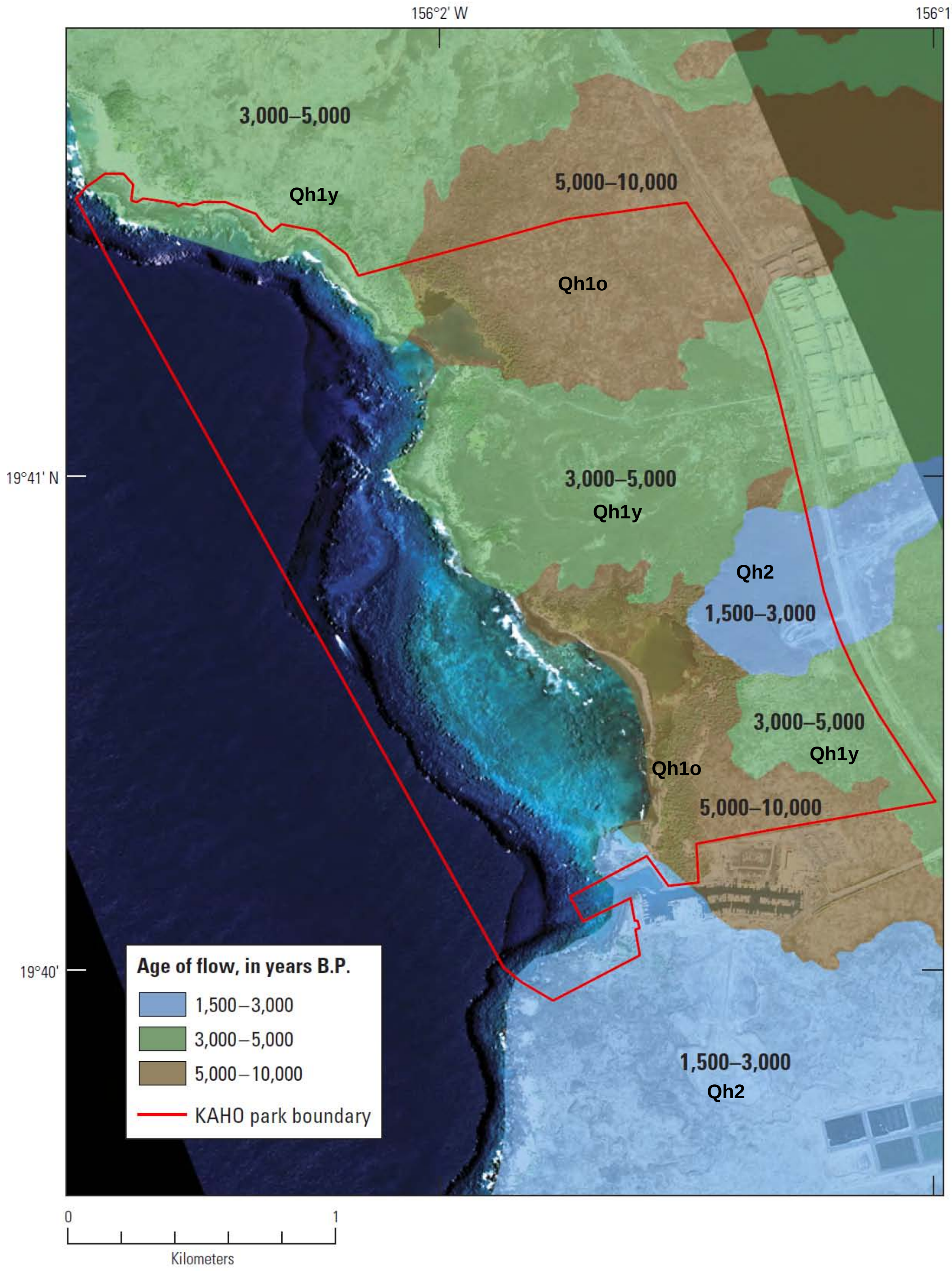


Figure 3. Map of Kaloko-Honokōhau National Historical Park showing flows of three distinct ages, between approximately 1,500 and 10,000 years old, from Hualālai Volcano. The different aged flows are differentiated on the geologic map GIS data, the map unit symbols are indicated on the above map. See Map Unit Properties Table and Overview of Geologic Data sections. KAHO is Kaloko-Honokōhau National Historical Park. U.S. Geological Survey graphic from Gibbs et al. (2007).

Figure 4. Aerial view of ‘Aimakapā fishpond within Kaloko-Honokōhau National Historical Park. The fishpond is one of the primary cultural features of the park. The view is to the south. Note the sand berm separating the fishpond from the ocean. Basalt benches are also visible along the coast to the south of the fishpond. Note the lava flow in the foreground of the image. Lava flows from Hualālai Volcano underlie the park. National Park Service photograph courtesy Jon Jokiel (Kaloko-Honokōhau National Historical Park)

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Kaloko-Honokōhau National Historical Park on March 20, 2003, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

Introduction

Three NPS units exist along the Kona coast of the Island of Hawaiʻi (fig. 1). In addition to Kaloko-Honokōhau National Historical Park are Puʻuhonua o Hōnaunau National Historical Park to the south (Thornberry-Ehrlich 2011a) and Puʻukoholā Heiau National Historic Site (Thornberry-Ehrlich 2011b) to the north. These three units have similar geologic issues, features, and processes.

The primary resource management emphasis at Kaloko-Honokōhau National Historical Park is preservation of the precontact historic setting. However, resource management objectives also take into account the inherent natural resources of the park. Natural resource management goals at Kaloko-Honokōhau National Historical Park include conducting and encouraging research to develop management strategies for preserving endemic island ecosystems while complementing the cultural landscape preservation. Hawaii is the only state in the U.S. that is subject to all of these hazards: earthquakes, volcanism, tsunamis, and hurricanes. Dynamic geomorphic processes sculpt the Hawaiian landscape through coastal erosion, rising sea level, seasonal high waves, and stream erosion (Richmond et al. 2001). Such processes emphasize the importance of a sound knowledge of the geologic framework underlying the tropical ecosystem. This section discusses management of natural resources, focusing on the most prevalent geologic issues at the park.

The U.S. Geological Survey, in cooperation with the National Park Service, prepared a report on the geology and coastal landforms for Kaloko-Honokōhau National Historical Park in the following reference:

Richmond, B. M., A. E. Gibbs, and S. A. Cochran. 2008. Geologic Resource Evaluation - Kaloko-Honokōhau National Historical Park, Part I: Geology and coastal landforms. Open-File Report 2008-1191. U.S. Geological Survey, Reston, Virginia, USA. (http://pubs.usgs.gov/of/2008/1191/)

A second part of this effort included benthic habitat mapping, in the following reference:

Gibbs, A. E., S. A. Cochran, J. B. Logan, and E. E. Grossman. 2007. Geologic resource evaluation of Kaloko-Honokōhau National Historical Park, Hawaii; Part II, Benthic habitat mapping. Scientific Investigations Report SIR 2006-5256. U.S. Geological Survey, Reston, Virginia, USA. (http://pubs.usgs.gov/sir/2006/5256/)

These reports are referenced throughout this document; however, readers are encouraged to read these sources for more detailed information related to resource management.

Fishpond Stability and Shoreline Change

The fishponds at Kaloko-Honokōhau National Historical Park are important cultural resources. Their presence changed the hydrogeologic system of the embayment at Kaloko, and has contributed to significant siltation of the seafloor; they are now important wetlands for migratory birds. The ʻAimakapā fishpond contains a valuable paleoenvironmental record in sediment cores containing pollen and gastropod remains (Athens et al. 2006; Hunt et al. 2007). However, a major goal of the National Park Service is to preserve the historic Hawaiian structures, which are in danger of degradation and erosion from rising seas and anthropogenic activities. Thus, the wall of Kaloko fishpond was restored in 2004 (front cover image) (Hoover and Gold 2005).

Brackish groundwater discharge affects Kaloko, ʻAimakapā, and ʻAiʻōpio pools (Hoover and Gold 2005). Stability of the Kaloloko and ʻAimakapā fishponds needs further evaluation. None of the major ponds within the park have been studied in detail to characterize ecosystem status, or link their current status to water quality, groundwater flow, groundwater residence times, or hydraulic connectivity (Hoover and Gold 2005).

Human activity, particularly the emission of greenhouse gases, very likely (more than 90% certain) contributes to global warming and thus accelerating the rate of climate change and global sea-level rise (IPCC 2007). Karl et al. (2009) summarize climate change impacts for Hawaii and other U.S.-affiliated islands. Along with increases in air and ocean surface temperatures, the number of heavy rain events is very likely to increase, particularly during the summer months (winter is the normal rainy season). Peak cyclone winds, precipitation, and associated storm surges are also projected to increase. Sea-level rise projections vary widely depending on location and future emissions scenarios. Globally, at least 0.18 m to 0.59 m (7 in. to 2 ft) of sea-level rise is projected by 2100 (Meehl et al. 2007). For coastal areas such as the Kona coast, sea-level rise may cause significant shoreline change, saltwater incursion into freshwater aquifers, and coastal inundation (Karl et al. 2009; Rutherford and Kaye 2006).

The U.S. Geological Survey, in a collaborative effort with the National Park Service, has conducted historical shoreline change and coastal landform mapping studies at Kaloko-Honokōhau National Historical Park. Aerial photographs, dating as far back as 1950, supplied consistent shoreline reference features that were digitized into a GIS to quantify shoreline change over time. The study showed that although the shoreline has shifted in an oscillatory manner, the overall shoreline change is erosional. North of the Kaloko fishpond wall, and along the barrier spit across the mouth of ʻAimakapā Fishpond, there is some net erosion, though at the lowest rates measured: <0.1 m/year (0.3 ft/year) (Hapke et al. 2005). The highest rates measured were at Kaloko Point [>0.7 m/year (2.3 ft/year)], ʻAimakapā Fishpond [0.6 m/year (2.0 ft/year)], and Honokōhau Beach [0.6 m/year (2.0 ft/year)] (Hapke et al. 2004; Hapke et al. 2005; Ann Gibbs, geologist, U.S. Geological Survey, written communication, November 2010). The dominant shoreline change signal at the park is erosional, with average rates of 0.3 m/year (1 ft/year) of loss for park beaches (Hapke et al. 2005). The nature of shoreline change is episodic, with periods of increased erosion or accretion that disrupt the system. The rate of change fluctuates on a nearly constant basis over time (Hapke et al. 2005). A resource management need persists at the national historical park to gain knowledge of the loss rate or stability of the area of the beaches.

Vitousek et al. (2009) further studied the shoreline changes at Kaloko-Honokōhau National Historical Park at two sections: 1) Maliu Point to just north of ʻAimakapā Fishpond (including Honokōhau Beach), and 2) the supratidal beach just north of Kaloko Fishpond. The thin carbonate beach between Maliu Point and the northern edge of the fishpond is experiencing long term erosion at rates averaging 0.2 m/year (0.8 ft/year) of loss. At the southern end of Honokōhau Beach, the ʻAiʻōpio Fishtrap, sand is migrating northward out to ʻAimakapā Fishpond and exposing several cultural sites to wave action. Erosion prevails here as well, at rates of about 0.2 m/year (0.7 ft/year) of loss. ʻAimakapā Fishpond, marked on the seaward side by Honokōhau Beach, has been moderately stable over the period of study, with an erosion rate of only 0.1 m/year (0.3 ft/year) of loss. The northern reaches of Kaloko-Honokōhau National Historical Park are active during storm and large swell events, but are relatively stable with regard to erosion. (Vitousek et al. 2009).

Bush and Young (2009) delineated the following methods and "vital signs" for monitoring coastal features and processes: 1) shoreline change; 2) coastal dune geomorphology; 3) coastal vegetation cover; 4) topography/elevation; 5) composition of beach material; 6) wetland position/acreage; and 7) coastal wetland accretion. The signs pertaining to dunes are probably not applicable to parks with limited sand supply; however, the remaining six signs are very relevant to the coastal parks of the Island of Hawaiʻi. This study includes detailed recommendations for resource managers, including expertise, personnel, and equipment needed, approximate cost, and labor intensity.

Also see the "Coastal Erosion and Relative Sea-Level Rise" section below.

Groundwater Recharge and Discharge

The availability of important, fresh groundwater resources on the Island of Hawaiʻi depends on the age and geologic structure of a given area. Most of the island's aquifers are unconfined, and range from thin, brackish water lenses to vertically extensive freshwater bodies floating atop saline groundwater (Takasaki 1978; Rutherford and Kaye 2006). Some groundwater systems are impounded by linear volcanic dikes. Hualālai has not been significantly dissected by erosion, and dikes are not exposed (Oki et al. 1999). Saltwater intrusion is a possibility near coastal areas, and is among the factors limiting freshwater groundwater availability at Kaloko-Honokōhau National Historical Park, where the groundwater flow system is composed of brackish water overlying saltwater (Oki et al. 1999).

Another factor limiting freshwater supply at the park is its location on the Kona coast, on the leeward side of the island, where it is blocked from trade winds by Mauna Kea and Mauna Loa. Thus, the amount of precipitation at the park is relatively low, at 25 to 75 cm/year (10-30 in/year), and arid conditions can prevail in the driest areas, north of Kailua-Kona in the Kaloko-Honokōhau National Historical Park area (Davis and Yamanaga 1968; Cordy et al. 1991; Oki et al. 1999). Locally, higher elevations can receive a mean annual rainfall of 102 cm (40 in) (Peterson et al. 2007). This precipitation serves to recharge aquifers downslope, but retention values may be low, given the high permeability of the lava flows.

Aquifer characteristics vary based on geologic features and structures (especially rock permeability) and recharge rates. Nearly all of the aquifers on the Island of Hawaiʻi are contained within volcanic rock. The permeability of volcanic rock is highly variable and can change over small geographic areas, depending on the mode of emplacement, degree of weathering, and overall rock thickness (Rutherford and Kaye 2006). The lava flows (geologic map units Qh1o, Qh1y, and Qh2) and scattered soils in the park are very porous, and infiltration levels are high, resulting in a lack of surface water features and saturation near sea level (Davis and Yamanaga 1968; National Park Service 2005). Groundwater levels within the park are in the range of 0.3 to 0.6 m (1-2 ft) above mean sea level, and fluctuate 0.2 to 0.5 m (0.5-1.5 ft) with the tides (Oki et al. 1999). Water quality data and a groundwater modeling study indicate that groundwater flows in the park have decreased significantly over the last 30 years, most likely as a result of surrounding development demands. This trend will probably increase as the human population in the local area continues to increase (Hoover and Gold 2005).

Most of the fresh groundwater supply is from subsurface flow, originating from areas that are upland and east of the park (Oki et al. 1999). Precipitation recharge events from lava flows (through tubes) along the Kona coast are observed in basal water discharge at sea level (fig. 5) (Davis and Yamanaga 1968). Upslope precipitation and fog drip flows seaward through dense, low-permeability dike complexes and geologically young, highly permeable lava flows of Hualālai Volcano (Cutillo 2006). Within the park itself, direct infiltration groundwater recharge rates are small, due to low rainfall and high evaporation rates along the coast (Oki et al. 1999).

Understanding the hydrogeologic system supports effective natural resource management. It is necessary to predict the hydrologic response to potential inputs, such as contaminants and other wastes as well as system response to diminished flow (Rutherford and Kaye 2006; Hoover and Gold 2005). Potential inputs include sources such as treated sewage pumped into an infiltration pit just south and upslope of the park, an adjacent development ("The Shores at Kohanaiki") along the northern park edge, the industrial area immediately inland of the park, and the Honokōhau small boat harbor. Failure to limit the amount of discharge loss may lead to loss of aquatic habitat, disruption of anchialine ponds (see below), wetlands, and fishponds, and saltwater intrusion into fresh groundwater lenses (Rutherford and Kaye 2006; Cutillo 2006). Surrounding industrial areas, including the Kaloko Industrial Park, a quarry and baseyard for heavy equipment, another industrial park, and Kealakehe Landfill (closed in 1989, now capped) are among the potential sources of groundwater contamination in the national historical park vicinity (Oki et al. 1999). Hoover and Gold (2005) conducted a watershed assessment, complete with recommendations for addressing watershed issues, that is a valuable resource management tool for understanding the current conditions at the park.

A significant hydrologic component to coastal systems, such as that off Kaloko-Honokōhau National Historical Park, is submarine groundwater discharge (SGD). Brackish water or fresh water flows out to sea via groundwater conduits, contributing terrestrially-derived input and creating a so-called subterranean estuary (Moore 2003; Paytan et al. 2006). SGD influences the brackish anchialine ponds, two 4.5-ha (11-ac) fishponds (with wetlands), and 241 ha (596 ac) of coral reef habitats at the park (fig. 6) (Presto et al. 2007). Profiling conductivity, temperature, and salinity, and using optical backscatter sensor surveys, revealed complex patterns of freshwater and subterranean groundwater discharge across the coral reef at Kaloko-Honokōhau National Historical Park (Gibbs et al. 2004). SGD can be an important source of nutrients (and contaminants) to coastal systems, and to coral reefs in particular (Paytan et al. 2006).

Between December 2003 and April 2006, U.S. Geological Survey scientists conducted seven surveys, incorporating depth profiles of surface water temperature and salinity, to characterize how nearshore water properties vary with seasonality and hydrodynamic forcing (tides, winds, and waves), as well as to determine the spatial and vertical extent of the influence of SGD plumes on the marine resources in the park (Grossman et al. 2010). Nearshore waters within the park are almost constantly influenced by plumes of SGD, which are colder, less saline, and more nutrient-rich than the surrounding seawater. The plumes are extensive, reaching as much as 1000 m (3,300 ft) offshore, and to depths between 1 and 5 m (3 and 16 ft). A single plume may contain several million to hundreds of millions of gallons of brackish water, creating a nearly estuarine nearshore environment (Grossman et al. 2010).

In a 2006 study, controlled radium isotope tracers and nutrient analyses along the Kona coast at Kaloko-Honokōhau National Historical Park determined in part the extent to which submarine groundwater discharge supplied terrestrial nutrients (including nitrogen) to the offshore environment. This study determined that nutrient loads associated with submarine groundwater discharge may be heavily influenced by land use within the greater watershed, and potentially threaten marine ecosystem and coral reef health, if nutrients and contaminants reach toxic levels (Paytan et al. 2006). From November 2005 to July 2006, the U.S. Geological Survey, in collaborative efforts with the National Park Service and other entities, collected high-resolution measurements of waves, currents, water levels, temperature, and salinity in the marine areas of the park to establish baseline information on the magnitude, frequency, rate, and variability of submarine groundwater discharge (Presto et al. 2007). This provides park resource managers with a valuable data set for future monitoring efforts.

As of 2003, Kaloko-Honokōhau National Historical Park had three wells and one upgradient within park boundaries. Using wells and hydrologic data, the U. S. Geological Survey estimates groundwater recharge, and has worked to develop groundwater flow models: (1) to quantify the hydrologic effects of groundwater withdrawal for human use; and (2) to address long term effects from such withdrawals on the Kona area of the Island of Hawai‘i (Oki et al. 1999). These models predict that upgradient withdrawals in excess of 1978 levels will drastically reduce the amount of freshwater coastal discharge within the park, in excess of 50% (Oki et al. 1999; Presto et al. 2007). Because this area of the Island of Hawai‘i has steadily increased in population since 1978, it seems safe to assume surrounding development is impacting the hydrologic system within the park.

Audiomagnetotelluric (AMT) methodology, used in conjunction with other geophysical methods such as aerial infrared scanning and low-level aeromagnetic surveys, can be used to estimate the depth of the seawater interface with fresh water, or analyze underground structures that may control the movement of groundwater (Adams et al. 1971; Lepley and Adams 1971). In 1971, a 50-km (30-mi) stretch of the Kona Coast was measured using the AMT method (Lepley and Adams 1971). The study revealed features in the substrate, such as horizontal isotropy, vertical dike swarms, freshwater aquifers atop saline water, and other geologic structures (fig. 5) (Lepley and Adams 1971).

In addition to interpretive studies on the quantity, quality, and dynamics of groundwater, the U.S. Geological Survey Water Resources Division-Hawaii District operates a network of monitoring stations that collect information on stream flow, suspended sediment, groundwater level, salinity, precipitation, and evapotranspiration. Baseline inventories and surveys of groundwater level, quality, and salinity exist for Kaloko-Honokōhau National Historical Park for 1969, 1980, 1985, and 1999 (Rutherford and Kaye 2006). These data are available from the USGS office in Honolulu (http://hi.water.usgs.gov/).

Anchialine Ponds

Anchialine ponds are among the most threatened ecosystems in Hawaii (Tetra Tech 2004). These pools are relatively small, inland sources of brackish water influenced by tides and springs. They are not connected at the surface to the ocean, but they connect hydrologically with the ocean and groundwater through a permeable aquifer system (Oki et al. 1999). Water levels and salinity in the ponds vary constantly, as they are connected to the ocean via subterranean tunnels (National Park Service 2005; Malama Kai Foundation 2008). Threats to anchialine pools include contamination of groundwater sources and addition of nutrients (The Nature Conservancy 2010; Ann Gibbs, geologist, U.S. Geological Survey, written communication, November 2010). Effects of contamination, exotic species, and upland changes, including modification or filling, are notoriously difficult to monitor (The Nature Conservancy 2010).

Anchialine ponds form where volcanic activity has created a depression with a connecting tunnel "plumbed" to the ocean. Anchialine ponds host unusual plants and animals, such as opae'ula shrimp (*Halocardinia* sp.). Some of these species only occur in the ponds. Over the last few decades, non-native fish species have been introduced and/or have invaded many of the anchialine pools, destroying the ecological balance and eliminating unique endemic species (Malama Kai Foundation 2008).

Because relatively little information on erosion or sediment transport is available for Hawaiian watersheds, it is unknown how sedimentation affects these anchialine ponds (Rutherford and Kaye 2006). It is also unknown whether upgradient groundwater withdrawals (increasing since the early 1990s) may affect groundwater flow, water levels, and salinity of the anchialine ponds and wetlands in the park. Anchialine pools are surface expressions of the local groundwater table, varying with both the degree of mixing between fresh and saltwater, and with local water quality factors; thus, the pools display a wide range of physical and chemical conditions within the park and merit a thorough inventory and monitoring program (Brock and Kam 1997; Hoover and Gold 2005).

Hawaii is the only location in the United States that contains anchialine pool habitat. Of the approximately 700 known Hawaiian anchialine pools, most are on the Island of Hawai'i. There are more than 120 anchialine pools and pool complexes within the park, occupying low-lying, natural depressions within the coastal, rough basalt platform (Brock and Kam 1997; Hoover and Gold 2005; Richmond et al. 2008).

At Kaloko-Honokōhau National Historical Park, water concerns regarding the anchialine ponds were studied in 1989 and 1998 (Rutherford and Kaye 2006). Refined mapping is a future resource management need at the national historical park. A project intended to restore specific anchialine ponds along the Island of Hawai'i's west coast was funded by a grant from the National Oceanic and Atmospheric Administration (NOAA); this grant was received by the Malama Kai Foundation in 1999. The University of Hawai'i Sea Grant Extension Service, students of West Hawai'i Explorations Academy, Department of Land and Natural Resources (DLNR) personnel, and community volunteers initiated this project. The restoration involved removing and controlling foreign species, and re-introducing native vegetation and aquatic species, such as opae'ula shrimp (*Halocardinia* sp.) and Makaloa reeds (*Cyperus laevigatus*) (Malama Kai Foundation 2008).

The project was suspended when the Department of Land and Natural Resources, Division of Aquatic Resources was unable to obtain permission from the State Department of Health to apply a chemical called "rotenone", which is used to kill foreign fish species in the ponds. The invasive species (mostly topminnows) eat the native red shrimp (opae'ula) that are vital to maintaining ecological balance in the anchialine ponds. When this balance is disturbed, excess algal growth occurs.

Coral Reef Changes

The boundary of Kaloko-Honokōhau National Historical Park extends beyond the mean high tide line, and includes significant submarine areas. Much of the coastal area is fringed with scattered reefs at several depths (fig. 7). Fletcher et al. (2008) offers a comprehensive look at the geology of Hawaiian reefs. A brief description is presented here; however, the reader is encouraged to consult the following web source for more information: (http://www.soest.hawaii.edu/coasts/publications/GeologyofHawaiiReefs.pdf).

Coral reefs are host to a high level of marine biodiversity. Coral reef ecosystems are also geologically productive, building islands such as atolls. The erosion of coral reefs by wave action can also create sand deposits and beaches. Typical reef growth within the coastal areas of the Hawaiian Islands consists of a thin, 1 to 2 m (3 to 6 ft) veneer of coral-algal growth (Grigg 1998). Substrate beneath reefs is either volcanic rock platforms or antecedent Pleistocene-age limestone (Grigg 1998; Richmond et al. 2001). However, at Kaloko-Honokōhau National Historical Park, there are no Pleistocene reef substrates; island subsidence has caused older reefs to be located in much deeper water (Bruce Richmond, geologist, U.S. Geological Survey, written communication, November 2010). Although substrates may be similar throughout the Island of Hawai'i, different morphologies and coral cover make each offshore environment unique (Gibbs et al. 2004).

Compared with other regions of the Island of Hawai'i, rich coral reef communities exist off the Kona coast. This coral richness can likely be attributed to the sheltered environment provided by the island in which corals can thrive (Dollar 1975). This 115-km (70-mi) long coast stretches from Kawaihae, south to Kalae (South Point), and is mostly protected from tradewind-generated wave energy. The island of Maui also serves to protect this stretch of shoreline from waves arriving from the northwest. However, the Kona coast is not immune to high wave energy, as seasonal storms, tsunami, and south (generated by winter storms in the southern Pacific Ocean, active from April to October) and west swells do occasionally create high wave energy conditions (Dollar 1975; Gibbs et al. 2006; Ann Gibbs, geologist, U.S. Geological Survey, written communication, November 2010). Still, the Keāhole region, of which Kaloko-Honokōhau National Historical Park is part, contains incredible marine biodiversity (Dollar 1975).

There are at least 21 species of hermatypic coral and one alcynarian soft coral off the Kona coast, with a total coral cover of approximately 48.3 percent (Dollar 1975). Field studies conducted along the Kona coast, consisting of coral counting along transects, cluster analyses on dendrographs, illumination measurements, rates of water movement, and transplant success, revealed a pattern of zonation of coral reef communities off the Kona coast; four clearly-defined zones were identified (Dollar 1975):

1. The nearshore zone extends out to 36 m (118 ft), with as much as 8 m (26 ft) of depth. This zone is dominated by *Pocillopora meandrina* coral, growing on an irregular bottom cover of basalt boulders.
2. The second zone extends another 35 m (115 ft), out to depths of 6-14 m (20-46 ft). *Porites lobata* coral dominate the coral species of this zone, growing on gently-sloping basalt and limestone substrates.
3. The third zone extends to 14-30 m (46-98 ft) depth (an additional 18-37 m [59-121 ft] downslope), and contains predominantly *Porites compressa* coral.
4. The last zone extends out to 50 m (164 ft) depth, with abundant coral rubble and fine sand substrates. Coral succession in this zone is limited by illumination levels and influxes of sand and rubble.

In the immediate vicinity of the Kaloko- Honokōhau embayment, the pāhoehoe lava intertidal platform descends to the inter-tidal shelf, where the local reef drops down to 12 m (40 ft) some 122 m (400 ft) offshore. Within this area, the high-surge platform/boulder subzone is dominated by the *Pocillopora meadrina* coral, and the deeper moderate-surge reef terrace zone is dominated by *Pocillopora lobata*. Below this inter-tidal shelf area, *Pocillopora compressa* (finger coral) dominate the deeper inshore zone (Cordy et al. 1991).

Natural processes, such as heavy wave action, flooding, hurricanes, sea-level rise, volcanism, climate change, and seismic events, disturb coral reef growth. Human practices of land clearing, agricultural development, dredging, overfishing, greenhouse gas emissions (climate change), and tourism negatively impact reefs in Hawaii. When natural reef-building processes are disturbed by human activities or extreme natural conditions, erosion of the reef will dominate and the reef ecosystem will deteriorate (Rutherford and Kaye 2006). Reefs previously dominated by coral may be dominated or replaced by algal habitats (Bruce Richmond, geologist, U.S. Geological Survey, written communication, November 2010).

In addition to labor-intensive hand transects and surveys, seismic-reflection profiling can yield a wealth of information about coral reef development. It provides an alternative to coring, which can be damaging to a reef, labor-intensive, and spatially limited (Barnhardt et al. 2005). However, seismic-reflection profiling may be limited to areas where there is vertical accretion of carbonate, such as Kawaihae (Ann Gibbs, geologist, U.S. Geological Survey, written communication, November 2010). Offshore sediment traps could be used to evaluate the frequency, cause, and relative intensity of sediment mobility and resuspension along fringing coral reefs, and to identify contributions of land-derived sediment, carbonate sediment, and storm-derived sediment that may impact coral reef development (Bothner et al. 2006). Other useful technologies for studying coral reef environments and monitoring change include aerial photography, bathymetric LiDAR, underwater video, and oceanographic measurements of currents, temperatures, salinities, waves, and turbidity (Gibbs et al. 2004).

A 2004 study measured water column temperature, salinity, and turbidity over several months at two locations off the Kaloko-Honokōhau National Historical Park coast. Temperature varied over 3 °C, salinity ranged more than 3 practical salinity units (PSU), and turbidity varied as much as 20 Nephelometric Turbidity Units (NTU) with tides and storm events (Storlazzi and Presto 2005). This kind of data will help park resource managers understand how currents, wave, tides, temperature, salinity, and turbidity vary temporally and spatially along the coast, and it will help them correlate these variables with coral reef change.

NOAA has established a standard for characterization of coral-reef environments that describes benthic habitats on the basis of sea floor geomorphology, geographic zonation, and biological cover. Expanding upon this theme, the U.S. Geological Survey created benthic habitat maps for Kaloko-Honokōhau National Historical Park, using data such as aerial photography, bathymetric lidar, underwater video, SCUBA, still photography, field checks and surveys, and GIS technology (Gibbs et al. 2004; Gibbs et al. 2007). Overall results of this mapping reveal that multiple flows coalesced within Kaloko-Honokōhau National Historical Park, and created a complex offshore morphology, including gently rolling pāhoehoe basalt flows, shear ledges, pinnacles and ridges. Each of these morphologies provides distinct habitats for the coral species *Porites lobata*, *Porites compressa* , and *Pocillopora meandrina* (Gibbs et al. 2007). This mapping will be useful as an inventory of baseline conditions, for any future monitoring projects off the coast of Kaloko-Honokōhau National Historical Park. It will help tounderstand responses of the coral reef communities to changes in the marine environment: relative sea-level rise, contamination, changing oceanic conditions (e.g. temperatures, wave energy and direction, changes in groundwater discharge and chemistry, etc.), and increased sediment and nutrient input from local development (Ann Gibbs, geologist, U.S. Geological Survey, written communication, November 2010).

Bush (2009) suggested five methods and "vital signs" for monitoring marine features and processes: 1) the general setting of the environment, of which water depth is the primary indicator; 2) the energy of the environment, waves, and currents; 3) barriers, including reefs and other offshore barriers, which block energy; 4) seafloor composition, or substrate; and 5) water column turbidity. Their study includes detailed recommendations and methodologies for resource managers.

Geologic Hazards

Many natural phenomena pose threats to coastal and near-coastal areas of the Hawaiian Islands. Among these hazards are volcanism, mass wasting, coastal erosion and sea-level rise (fig. 8), tsunami inundation, and seismic activity. Local slopes and geologic setting must be taken into account to accurately determine hazard potential for a specific area such as Kaloko-Honokōhau National Historical Park (figs. 9-11) (Richmond et al. 2001; Fletcher et al. 2002). Important tools in hazard assessment include historic records, including magnitudes and frequency of occurrence as determined from those records, coupled with accurate inventorying and regular monitoring of current conditions.

Vitousek et al. (2009) produced a coastal hazard analysis for Pu‘ukoholā Heiau National Historic Site and Kaloko-Honokōhau National Historical Park that includes coastal inundation (wave over-topping, sea-level rise, and tsunami) evaluations and maps, digital elevation models of shoreline morphology, historical shoreline change and coastal erosion maps, paleotsunami history, and recommendations for resource managers. This resource is available online: (http://www.soest.hawaii.edu/coasts/nps).

Volcanism

Kaloko-Honokōhau National Historical Park is underlain by lava flows from Hualālai Volcano, which last erupted in 1801 and is still considered to be active. Kīlauea, the Island of Hawai‘i's currently erupting volcano, and Mauna Loa are two of the most active volcanoes in the world. Mauna Loa last erupted in 1984. Since the active eruptions at Kīlauea started, in 1983, an additional 2.3 sq km (0.9 sq mi or 570 acres) have been added to the island. Several issues of concern associated with active volcanism are: lava eruption, destruction associated with flows, pyroclastic material ejection, lava tube collapse, corrosive volcanic gases, and subsurface thermal heating. Flows from Hawaiian volcanoes can reach distances of 50 km (30 mi) or more from the source vent. While lava generally flows slowly enough to allow people and animals to escape, anything in the path of a flow, such as rare rainforest, historical sites, or communities, can be damaged or destroyed by burial, crushing, or fire ignition (Rutherford and Kaye 2006). Similar impacts occur during the ejection of pyroclastic materials (cinder or spatter cones), but the spatial extent of such effects is limited to near-vent areas.

Eruptions are usually preceded and accompanied by seismic and volcanic unrest. This unrest manifests as earthquakes, and as variations in the geophysical and gas geochemical state of the volcanic system. The U.S. Geological Survey's Hawaiian Volcano Observatory (HVO) (http://hvo.wr.usgs.gov/) has an extensive monitoring system for the islands of Hawai‘i and Maui, covering lava flows, surface and subsurface deformation, seismicity and volcanic emissions. This is part of a cooperative effort with the Center for the Study of Active Volcanoes (CSAV) and other institutions, such as the University of Hawai‘i and Stanford University, to understand volcanic processes and attempt to lessen their potential threats to society (Rutherford and Kaye 2006).

Applicable to Kaloko-Honokōhau National Historical Park, the HVO performs periodic geodetic surveys (with GPS, electronic distance measurement [EDM], and dry tilt surveys) to precisely depict changes in ground deformation, as well as strain rates and velocities associated with potential volcanic activity; these are compared with previous measurements (Rutherford and Kaye 2006). Seismic refraction surveys can also yield valuable information leading to a fuller understanding of the volcanic and tectonic processes associated with the activity and growth of Hawaiian volcanoes (Zucca and Hill 1981; Zucca et al. 1982). Given the location of Kaloko-Honokōhau National Historical Park on the Kona Coast, far from the summit or rift zone of Hualālai, these surveys are indicative of volcanic unrest upslope that could potentially cause lava flow inundation in the park area. That potential was realized as recently as 1801, when the Ka‘ūpūlehu flow from Hualālai Volcano reached the coast near Kīholo Bay and just north of Keāhole Point (Cordy et al. 1991).

As lava flows and cools, inundation by lava and lava tube collapse are potential hazards. Lava tubes are hollow, cave-like spaces left void, or sometimes filled by subsequent flows, once the supply of molten lava is extinguished; they are located beneath the surface of solidified lava flows. Tube collapse can pose a threat to visitor safety and park infrastructure. According to archaeological studies in the Kaloko area, some caves may contain valuable artifacts and cultural resources that could be targets for protection (Cordy et al. 1991).

Another potential issue associated with active volcanism in the vicinity of Kaloko-Honokōhau National Historical Park is airborne volcanic emissions. According to the U.S. Geological Survey HVO, the volcano emits hundreds of tons of toxic sulfur dioxide gas (SO_2) each day, making it among the largest stationary sources of SO_2 in the United States. Sulfur dioxide, combined with acid aerosols, and fine particulates formed when volcanic and trace species react and become oxidized in the air, creates a hazy atmosphere known as "vog". The HVO maintains a website (http://volcanoes.usgs.gov/hvo/activity/kilaueastatus.php) posting daily updates for Kīlauea. Whether Kīlauean vog affects Kaloko-Honokōhau National Historical Park depends largely on the wind. The Island of Hawai'i's Kona coast is somewhat buffered from the prevailing Hawaiian tradewinds by Mauna Loa, Mauna Kea, and Hualālai mountains. The coast has diurnal sea and air circulation that drives winds downslope and offshore during the early evening and through the night, and upslope during the day. At times, this circulation is not enough to clear the air of vog trapped in the leeward Kona area of the south end of the island (National Park Service 2005). The air then appears very hazy. During particularly active eruptive periods, vog can cover the Island of Hawai'i's entire southern half. In the absence of prevailing winds, vog can stretch as far away as O'ahu, some 350 km (220 mi) northwest. Volcanic emissions can destroy surrounding vegetation by emitting large amounts of carbon dioxide, sulfur dioxide, and hydrochloric acid. These emissions are directly responsible for acidification of soils, and the enrichment of heavy metals in soils and surface water (Rutherford and Kaye 2006).

Smith et al. (2009) presented the following methods and "vital signs" for monitoring volcanoes: 1) earthquake activity; 2) ground deformation; 3) emissions at ground level; 4) emission of gas plume and ash clouds; 4) hydrologic activity; and 5) slope instability. Though some of these signs are not applicable to parks located at considerable distance from active volcanic centers, others, such as earthquake activity and ash clouds, are pertinent to resource managers at the park. Smith et al. (2009) also includes detailed recommendations and additional reference sources for resource managers.

Tsunamis

Inundation and destruction by tsunamis is a threat along nearly all Pacific Ocean coastlines. Hawaii, situated in the middle of the Pacific Ocean, has been struck by more tsunamis than any other place on earth (Dudley and Lee 1998). Since recordkeeping began in 1837, at least 33 tsunamis of have struck Hawaii. At least four of these were locally generated, when earthquakes beneath the islands caused submarine landslides (Walker 1999; Richmond et al. 2001). These locally-generated tsunamis are especially dangerous, due to short warning time (Richmond et al. 2001). Earthquakes from around the Pacific Basin (e.g., Alaska, Japan, etc.) generated the other tsunamis that struck the Hawaiian Islands. The Hawaiian Islands experience a tsunami on average every two years, with significant damage occurring every five years on average (Dudley and Lee 1998). Other estimates put the recurrence interval for locally-generated destructive tsunamis at 20 years (Walker 1999). Following a magnitude 7.1 earthquake in the Aleutian trench (Alaska) on April 1, 1946, a tsunami traveled across the Pacific basin and struck the Hawaiian Islands, causing 159 fatalities (Pacific Disaster Center 2008). On May 23, 1960, a magnitude 8.3 earthquake in Chile triggered a 11 m (35 ft) tsunami that caused serious damage to Hilo, Hawai'i and 61 deaths (Pacific Disaster Center 2008). A tsunami generated by a magnitude 9.0 earthquake off the coast of Japan struck Pu'uhonua o Hōnaunau and Kaloko Honokōhau national historical parks on March 11, 2011. At Kaloko-Honokōhau, the tsunami surges swept debris inland, covering the parking area and picnic facilities (fig. 12). Along the park's coastal trail, retaining walls collapsed, masonry walls were damaged, and the trail's "tread" was completely removed in some sections. The Kaloko Fishpond wall sustained damage from the tsunami at multiple points where the capping on top of the wall was damaged, portions of the edge of the wall collapsed, and the sand bank on the pond side of the wall was severely eroded (fig. 12) (National Park Service 2011).

In addition to loss of life and threats to infrastructure, tsunamis can cause erosion along the coastline, destroy shoreline cultural resources, damage coral reefs, and inundate nearshore habitats and aquifers with saltwater (Rutherford and Kaye 2006; Richmond et al. 2008). In November 1975, a locally-generated tsunami caused rapid coastal subsidence along the southeast coastal terrace, and transported washed debris as much as 320 m (1,050 ft) inland (Goff et. al., 2006). There has been widespread development along the Hawaiian shoreline since the 1960s which seems undeterred by the potential danger of inundation by tsunamis (Richmond et al. 2001).

The Pacific Tsunami Warning Center (PTWC) (http://www.weather.gov/ptwc/) in Ewa Beach (O'ahu) provides most countries in the Pacific Basin with tsunami warnings. This international program requires the cooperation of many seismic, tide, and communication facilities, operated by most of the nations bordering the Pacific Ocean. Their operational objective is to detect and locate significant seismic events in the Pacific region, determine whether a tsunami was generated by the event, and minimize risk to the population by providing warnings and tsunami information. Seismic activity and ocean surface levels of the Pacific Basin are constantly monitored (Rutherford and Kaye 2006).

According to the 2007 Tsunami Warning Center operations manual (based on the operations manual by the PTWC), a local tsunami warning is issued for any earthquake in the State of Hawaii of moment magnitude (Mw) greater than 6.8. This is the most severe local bulletin, during which the Hawaii State Civil Defense will sound the tsunami sirens. Depending on the location of the quake, only select counties in the state may be placed in a warning. Initially, only the county in which the earthquake occurred and bordering counties are placed in a warning. For example if the earthquake occurred on Maui, then Molokaʻi, Maui and Hawaiʻi counties would be placed in a warning. If the earthquake occurred on the Island of Hawaiʻi, then only Hawaiʻi and Maui counties would be placed in a warning. In a case where Mw is greater than 7.5, the entire state would be placed in a warning. Earthquakes originating from a distant source (outside of the Hawaiian Islands) with Mw greater than 7.5can also trigger tsunami advisories, watches, or warnings depending on the estimated time of arrival. For a summary refer to the PTWC messages webpage: http://ptwc.weather.gov/ptwc/about_messages.php?region=1.

The National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory has created a tsunami hazard assessment model, which is being used to create and update identified inundation zones. Tsunami modeling must factor in seismic events, which can be local or teleseismic (across the Pacific basin), in addition to bathymetry, and storm, wind and rain conditions (Rutherford and Kaye 2006). The University of Hawaiʻi SOEST Institute of Geophysics also developed a model, which may be more applicable to tsunamis caused by local seismic events. The low-lying coastal areas of Kaloko-Honokōhau National Historical Park would certainly be at risk for serious damage should a tsunami strike the western side of the Island of Hawaiʻi as illustrated by the damage from the March 11, 2011 teleseismic tsunami. During the GRI scoping meeting in 2003, the national historical park identified the need to create a tsunami hazard layer to incorporate into their GIS. This type of data could help target areas especially at risk of damage or destruction during a tsunami event, and model potential tsunami effects for the area.

Coastal Erosion and Relative Sea-Level Rise

Myriad factors are involved in coastal evolution and vulnerability to erosion, including coastal slope, geomorphology, historic rates of shoreline change, tidal range, wave height, and relative sea-level change. Average beach erosion rates in the Island of Hawaiʻi are approximately 15-30 cm/year (0.5-1 ft/year) (Richmond et al. 2001).

Coastal slope, or the steepness of the coastal region, directly determines the amount of land exposed to erosion processes (Richmond et al. 2001). Coastal slope is linked to inundation and to rates of shoreline advance or retreat.

Coastal geomorphology and geology, in particular the strength of the land materials, influences the relative erodibility of a specific section of shoreline. The coastline varies from gently-sloping, partially sand-covered lava benches, to low-lying rocky shorelines. Locally, coral reefs, embayments, anchialine ponds, and anthropogenic developments (e.g. fishponds) modify the Kona shoreline (Dollar 1975; Richmond et al. 2001). Two beach types—a tide-dominated intertidal beach, and a storm-dominated perched beach—exist within park boundaries (Hapke et al. 2005). Local beaches form a very dynamic and complex system. Beach morphological changes are difficult to model or predict. Erosion of the coast may cause beach loss, instability of lava benches, inundation, damage to shallow coral reefs, and increased sediment introduction to coastal waters.

Tidal range and wave height are linked to inundation hazards (Rutherford and Kaye 2006). Although not sheltered from south swell or hurricane waves, the Kona coast is relatively sheltered from the high wave energies found elsewhere in the state of Hawaii. However, deep-water ocean swells can rise to great heights when they encounter a shallow area, such as an island margin or seamount. In the Hawaiian Islands, this effect is exacerbated, because the contact between deep water and the shallow margins is especially abrupt. Surface waves can grow very tall, very rapidly over a short distance (City and County of Honolulu 2003). Sudden high waves and seasonal swells are among the most consistent and predictable coastal hazards in Hawaii (Richmond et al. 2001).

Relative sea level changes correspond to global (eustatic) sea level fluctuations and local vertical land motion (uplift or subsidence). As mentioned above under "Fishpond Stability and Shoreline Change" global climate change projections suggest a modeled sea-level rise of approximately 0.18 m to 0.59 m (7 in. to 2 ft) by 2100 (Meehl et al. 2007). For low-lying coastal areas, such as Kaloko-Honokōhau National Historical Park, with maximum elevations of less than 30 m (100 ft), any sea level rise will cause increased saltwater encroachment and coastal inundation (Rutherford and Kaye 2006). For additional information regarding climate change in the National Park System, access the National Park Service Climate Change Response Program online: (http://www.nature.nps.gov/climatechange/index.cfm). Schramm and Loehman (2011) discuss talking points regarding climate change impacts to the Pacific islands.

As volcanic material erupts onto the surface, its accumulated mass depresses the earth's crust causing a rise in relative sea level. This process is called "volcanic loading." Each island has a localized rate of relative sea-level rise, due to its response to volcanic loading (Rutherford and Kaye 2006). On average, the rate of relative sea-level rise is 3.9 mm/year (1.5 in/decade) for the Island of Hawaiʻi and the loading effect lessens with distance from the active volcanism (Richmond et al. 2001).

Because Kaloko-Honokōhau National Historical Park is near a volcanic center still considered active, crustal loading is a significant factor in local relative sea level rise.

Nearly one-quarter of the beaches throughout Hawaii have been significantly degraded over the last 50 years (Richmond et al. 2001). The causes of beach loss are generally not well understood or quantified. Possible causes include reduced sediment supply, major storms, and anthropogenic shoreline armoring structures, and other development (Richmond et al. 2001; Rutherford and Kaye 2006). Shoreline structures often exacerbate coastal erosion by changing a condition of shoreline erosion into one of beach loss (Richmond et al. 2001). At Kaloko-Honokōhau, the anthropogenic structures that have changed the shoreline include the fishpond walls and traps. These historic features are targets of preservation, but are naturally degrading and in danger of being inundated by rising seas (fig. 8). Shoreline change studies suggest the limited beach areas at the national historical park will be relatively stable over a 50-year period, but are in a state of short-term change (fig. 10) (Hapke et al. 2005).

High quality still photography by Brian Powers (available at http://www.hawaiianimages.net/) may aid in determining current conditions (Bruce Richmond, geologist, U.S. Geological Survey, written communication, November 2010). The U.S. Geological Survey created a map of relative vulnerability of the coast to future sea level rise within Kaloko-Honokōhau National Historical Park, using a coastal vulnerability index (CVI) that ranks a number of the physical factors listed above: e.g., regional coastal slope, geomorphology, mean tidal range, mean significant wave height, and historical shoreline change rates, among others (fig. 11). The CVI and the raw data used for the analysis emphasizes those regions where the impacts of sea level rise might be the greatest, and provides an evaluation tool and baseline information for park resource managers (Pendleton et al. 2005). Based on their analysis, the areas within the park that are most vulnerable to sea-level rise are areas of unconsolidated sediment and highest wave energy (Pendleton et al. 2005). Little can be done to prevent local sea-level rise, but careful inventory of existing features would be desirable before the sea advances.

According to Vitousek et al. (2009), specific features in the park that are at greatest risk of degradation from coastal flooding include the kuapā (seawall) at Kaloko Fishpond, the beach seaward of ʻAimakapā Fishpond, and the archaeological sites at the southern portion of the park, such as the ʻAiʻōpio Fishtrap and Puʻuoina Heiau. The Kaloko seawall experiences overwash and wave spray, and needs continual maintenance. The beach fronting ʻAimakapā Fishpond is eroding at an average of 0.08 to 0.15 m/year (0.25 to 0.5 ft/year) (fig. 4). At current rates of erosion and sea-level rise, the beach containing the fishpond will be breached by 2050. Sand migrating north along Honokōhau Beach is exposing sites en route to minor wave action.

Seismicity

Hawaii is the most seismically active place in the United States, with thousands of detectable tremors beneath the Island of Hawaiʻi each year. This frequency makes earthquake events a significant geologic hazard at Kaloko-Honokōhau National Historical Park (fig. 13) (Richmond et al. 2001). Hawaiian seismicity is closely linked with volcanism, as small earthquakes tend to accompany eruptions and subsurface magma movement within Kīlauea, Mauna Loa, Lōʻihi, and Hualālai volcanoes. Seismic refraction surveys can yield valuable insights into the locations and strengths of earthquakes occurring within active volcanoes, as well as the nature of the crust beneath volcanic masses (Zucca et al. 1982).

Though not as frequent, earthquakes can also occur due to tectonic processes. Non-volcanic seismicity is related to zones of structural weakness such as faults. Large earthquakes can occur on the Kona coast (magnitude 6.5 in 1929, and magnitude 6.9 in 1951) (Walker 1999). On October 15, 2006, a magnitude 6.7 earthquake occurred about 15 km (9 mi) north-northwest of Kailua Kona. The event damaged ancient Hawaiian structures protected by the Kona area parks (Richmond et al. 2008). Over the past 150 years, some of the larger Hawaiian earthquakes (magnitude 6 to 8) caused loss of life and extensively damaged buildings, roads, and homes (Rutherford and Kaye 2006). At Kaloko-Honokōhau National Historical Park, additional effects of earthquakes, such as ground rupture, uplift, subsidence, mudflows, liquefaction, and landslides could negatively impact the cultural resources at the park. A large earthquake could shift or damage historic structures and artifacts. Earthquakes are of particular importance, because of their role as tsunami triggers.

The USGS Hawaiian Volcano Observatory and National Strong Motion Program, as well as the NOAA Pacific Tsunami Warning Center, operate seismographic monitoring networks in the state of Hawaii. Data are generally shared between entities. Seismic monitoring at HVO began in 1912, and data from more than 60 remote stations are continuously monitored in real time to HVO on the Island of Hawaiʻi (Rutherford and Kaye 2006). Hualālai Volcano is among those active centers covered by the seismographic monitoring networks.

Braile (2009) highlights methods for seismic monitoring such as 1) monitoring earthquake activity, 2) analysis and statistics of earthquake activity, 3) analysis of historical and prehistoric earthquake activity, 4) earthquake risk estimation, and geomorphic, and 5) geologic indications of active tectonics. In addition, Braile (2009) provides a summary of seismic monitoring methods, including needed expertise, special equipment, cost, needed personnel, and labor intensity of each method.

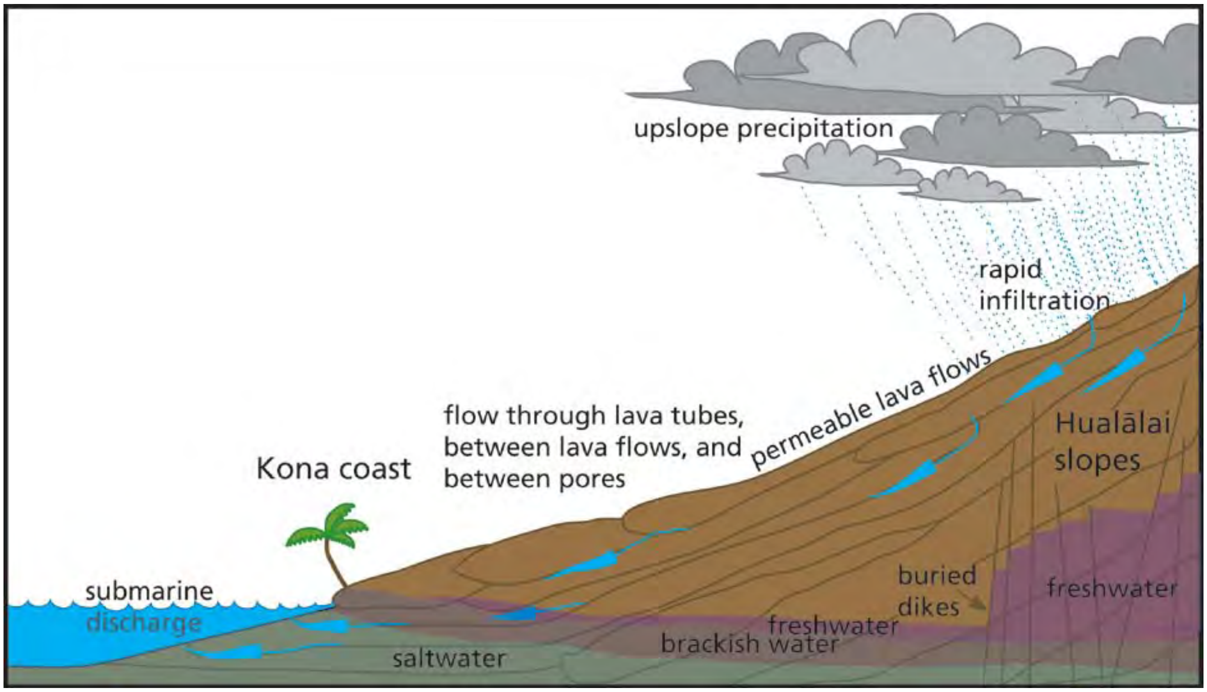


Figure 5. Diagrammatic model of precipitation-fueled submarine groundwater discharge along the Island of Hawai'i's Kona coast, and the regional groundwater flow system near Kaloko-Honokōhau National Historical Park. Graphic is not to scale, and is vertically exaggerated. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), based on information from figure 8 of Oki et al. (1999).

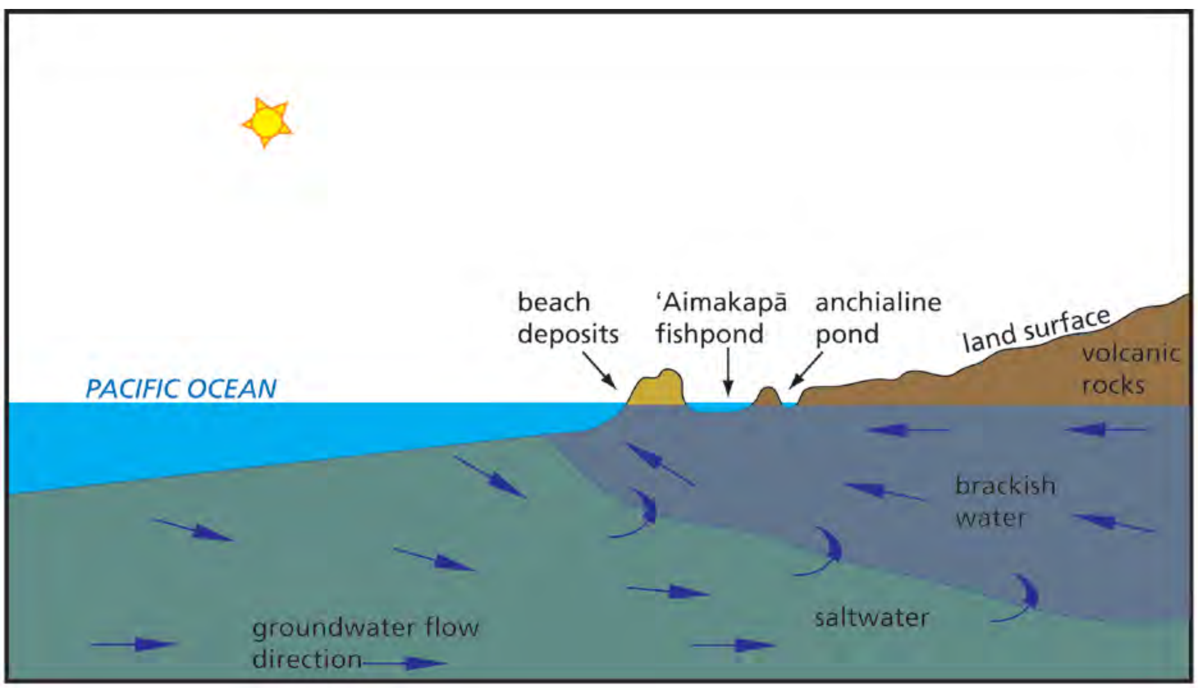


Figure 6. Schematic cross section of the groundwater flow system in Kaloko-Honokōhau National Historical Park, based on the model by Oki et al. (1999). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), adapted from figure 12 in Oki et al. (1999).

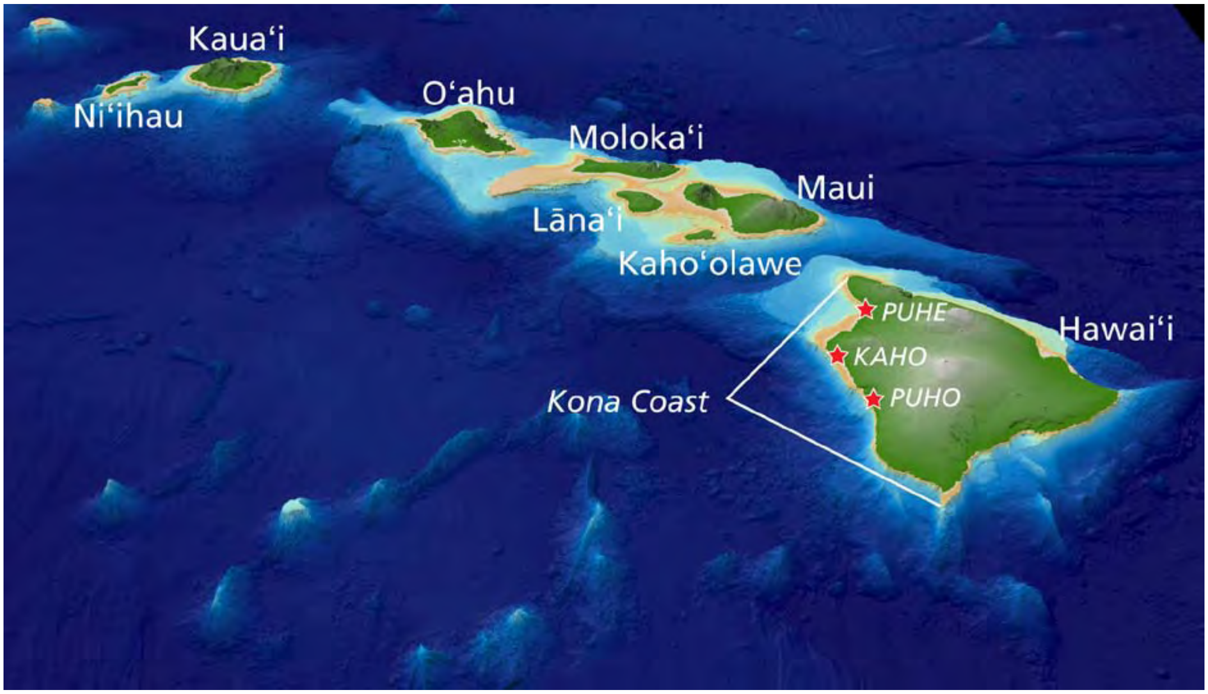


Figure 7. Bathymetry of the Hawaiian Islands. Note the relative lack of shallow, reef-sustaining substrate around the Island of Hawai'i compared to other islands such as O'ahu. Green areas are exposed land above sea level. Red stars are the location of the National Park Service areas along the Kona coast (PUHE: Pu'ukoholā Heiau National Historic Site; KAHO: Kaloko-Honokōhau National Historical Park; PUHO: Pu'uhonua o Hōnaunau National Historical Park). Graphic by Jason Kenworthy (NPS Geologic Resources Division). Base map created by the Hawaiian Multibeam Bathymetry Synthesis project, available online: http://www.soest.hawaii.edu/HMRG/Multibeam/index.php. Accessed 18 March 2011.

Figure 8. Photograph of walls of an ancient Hawaiian enclosure inundated by relative sea-level rise off the shore of Kaloko-Honokōhau National Historical Park. It is unclear whether the inundation is completely due to sea-level rise, deterioration of the historic structures, or a combination of the two (Ann Gibbs, geologist, U.S. Geological Survey, written communication, November 2010). National Park Service photograph by Rebecca Beavers (NPS Geologic Resources Division). Available online: http://www.nature.nps.gov/geology/cfprojects/photodb/Photo_Detail.cfm?PhotoID=672. Accessed 12 May 2011.

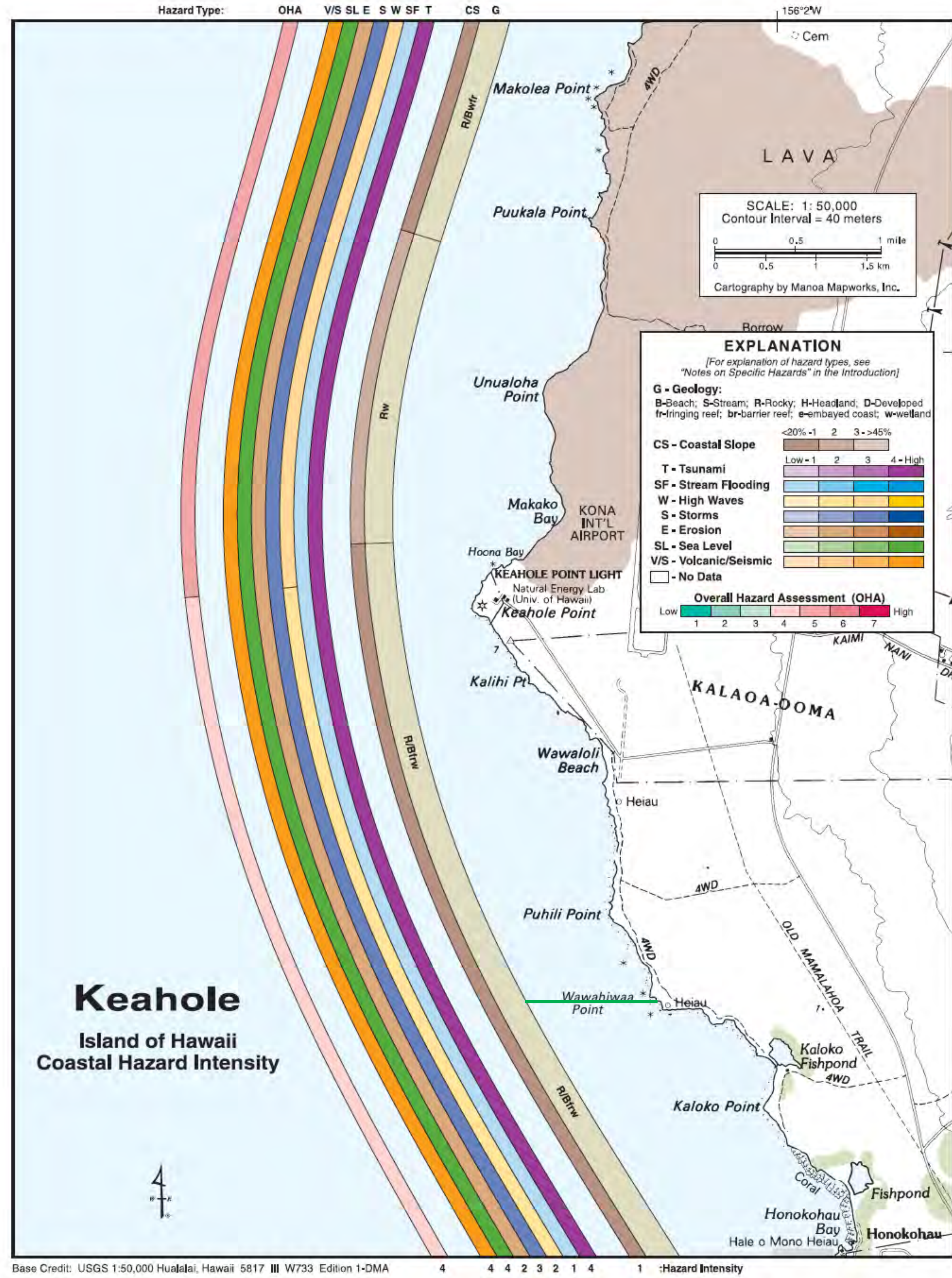


Figure 9. Coastal hazard intensity map for Kaloko-Honokōhau National Historical Park. The legislative boundary of the park extends south from the Wāwahiaʻa Point (green line) to the southern extent of the map. U.S. Geological Survey graphic from Fletcher et al. (2002).

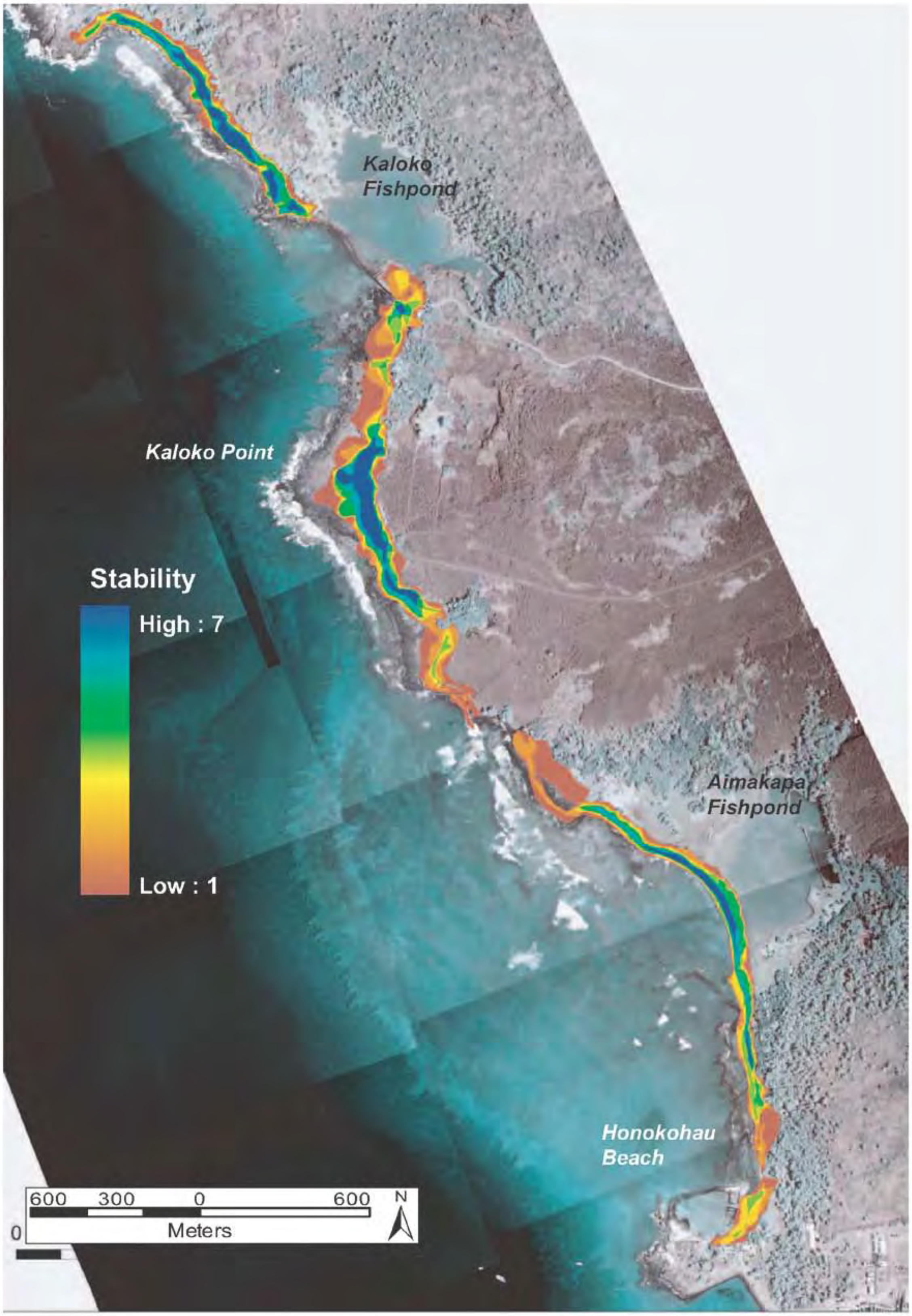


Figure 10. Beach stability map of the Kaloko-Honokōhau National Historical Park coastline. The index is based on the frequency of occurrence of a beach, as identified on aerial photographs, over 50 years. High stability measurements indicate the frequent presence of a beach for a particular area. U.S. Geological Survey graphic from Hapke et al. (2005).

Figure 11. Coastal vulnerability map of the Kaloko-Honokōhau National Historical Park coastline. The highest vulnerability area is along sand beach. U.S. Geological Survey graphic from Pendleton et al. (2005).

Figure 12. Damage from the March 11, 2011 tsunami within Kaloko-Honokōhau National Historical Park. Damaged walls and debris from Kaloko fishpond interior wall (top) and parking area (bottom). The tsunami caused considerable damage within Kaloko Honokōhau and Pu‘uhonua o Hōnaunau national historical parks. National Park Service photographs courtesy Jon Jokiel (Kaloko-Honokōhau National Historical Park).

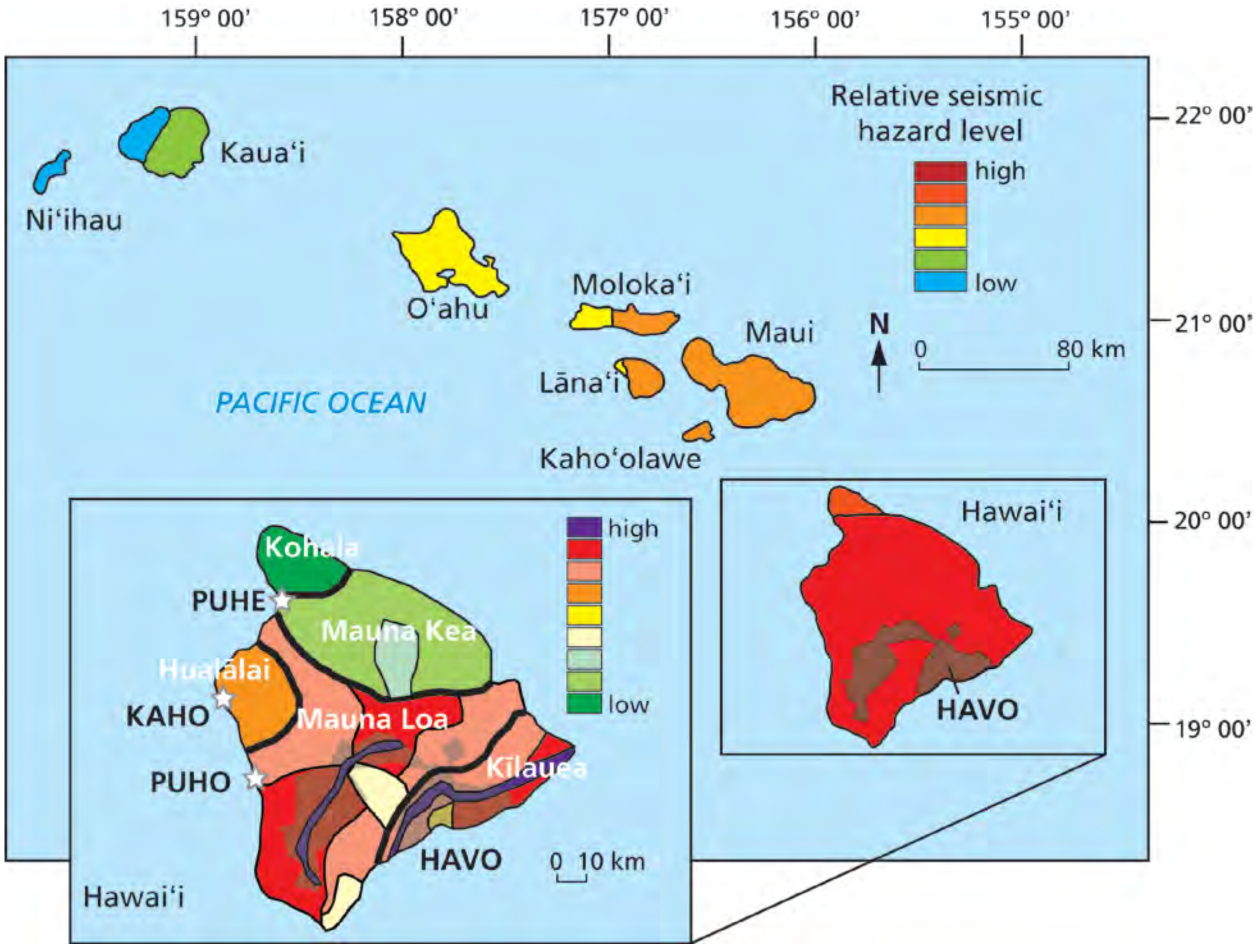


Figure 13. Earthquake hazard zones for the major Hawaiian Islands. White stars indicate park locations on the Island of Hawai'i enlargement (PUHE: Pu'ukoholā Heiau National Historic Site; KAHO: Kaloko-Honokōhau National Historical Park; PUHO: Pu'uhonua o Hōnaunau National Historical Park; HAVO: Hawai'i Volcanoes National Park). Volcanic centers on the Island of Hawai'i are labeled in white and separated by thick black lines. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) and Jason Kenworthy (NPS Geologic Resources Division), adapted from data provided by the U.S. Geological Survey (http://pubs.usgs.gov/imap/i-2724/).

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Kaloko-Honokōhau National Historical Park.

Volcanic Features and Processes

The dominant geologic features at Kaloko-Honokōhau National Historical Park are the volcanic flows that descended from the gently-sloped western flank of Hualālai Volcano (geologic map units Qh1o, Qh1y, and Qh2; see Overview of Geologic Data section).

Hualālai Volcano

Kaloko-Honokōhau National Historical Park lies along the western flank of Hualālai Volcano—the third youngest volcanic center on the Island of Hawai‘i, with flows ranging in age from Pleistocene to Holocene (geologic map units Qh5, Qh4, Qh3, Qh2, Qh1y, Qh1o, and Qh). The youngest rocks of the volcano are from 1801 (geologic map unit Qh5). Its summit is at an elevation of 2,521 km (8,271 ft) above sea level, 16 km (10 miles) east of the park boundary (fig. 1) (Moore and Clague 1991; Oki et al. 1999).

Several northwest and south-southeast trending rift zones coalesce near the volcano's summit, as well as a third, less-defined, north-trending rift (fig. 14) (Moore and Clague 1991). A linear series of cinder and spatter cones mark rift zones, as well as magnetic lows (probably related to hydrothermal fluid alteration) locally (Moore and Clague 1991; Oki et al. 1999). The youngest flow originated from the northwest rift zone (Moore and Clague 1991; Wolfe and Morris 1996a; Oki et al. 1999).

Lava and Lava Tubes

Both pāhoehoe and ‘a‘ā basaltic lava flow types exist within Kaloko-Honokōhau National Historical Park (geologic map units Qh1o, Qh1y, and Qh2). Pāhoehoe flows dominate much of the landscape, locally covered by a later ‘a‘ā flow. The surface of the pāhoehoe lava is generally smooth, but uneven. The flows have knolls, hummocks, and ridges as well as folds, depressions, and sinks. Domes can reach as high as 3-4.6 m (10-15 ft) higher than the surrounding terrain. A later pāhoehoe flow encroached from the north, and extends to the north end of the fishpond's wall at Kaloko, as a low ridge. A sand beach formed against this ridge. The southern coastal area of Kaloko is covered by very rough and blocky ‘a‘ā lava flows. ‘A‘ā is very sharp and uneven, making it difficult to cross on foot. Erosion of these ‘a‘ā flows created a marked, bluff-like drop near the seaward edge at about 4.6 m (15 ft) in elevation (Cordy et al. 1991).

When molten basaltic magma flows downhill, the upper surface cools faster than the underlying flow. This cooled upper surface often forms an insulating crust over the flowing lava. When the lava supply is extinguished, the flow leaves hollow spaces or tubes beneath the surface of the solidified lava flow. The HVO library (http://hvo.wr.usgs.gov/observatory/hvo_history_pubs.html) has more than 250 reports about lava tubes throughout the Hawaiian Islands, and the Hawaii Speleological Survey conducts explorations of larger tubes, including the famed Kaūmana lava tube near Hilo (Greeley 1974).

At Kaloko-Honokōhau National Historical Park, networks of lava tube caves underlie many areas. Caves may contain a number of unique geological formations, as well as cultural, paleontological, and biological resources. Potential paleontological resources include tree molds. Tree molds occur in similar lava flows at Pu‘uhonua o Hōnaunau National Historical Park (Hunt et al. 2007; Thornberry-Ehrlich 2011a). Caves form in the pāhoehoe lava flows. Some small tube caves, several of which measure 0.9-1.2 (3-4 ft) in height, 1.5-2.1 m (5-7 ft) in width and 1.8-4.3 m (6-14 ft) in length, occur within the park (Cordy et al. 1991). A formal cave inventory would be helpful for resource management (Rutherford and Kaye 2006).

Coastal Landforms

As described by Richmond et al. (2008), the coastal landforms that occur within the park include beaches, basalt shore platforms, wetlands, fish ponds, and anchialine pools. Sand beaches within the park are either intertidal accumulations or perched supratidal beaches. The former are subject to regular wave interaction and fluctuate daily, whereas the latter are active during large-wave events.

The intertidal sand beach at Honokōhau Bay forms a barrier spit across the mouth of the ‘Aimakapā Fishpond (figs. 4). The beach consists of well-sorted, medium-grained sands, derived from weathering of the adjacent, submerged basalt platform and fringing coral reef. Slope and height of the structure varies along shore; the sand spit varies in width from 22 to 25 m (72 to 82 ft) with the beach width ranging from 8 to 12 m (26 to 39 ft). Exposed calcium carbonate-cemented beach sand, or ‘beachrock’, exposed on the intertidal beaches of the park, indicates that there has been some erosion of the overlying beach sediment locally, because beachrock tends to form at a shallow depth within the beach system (Richmond et al. 2008).

The perched sand beaches are landward of the rocky shoreline, and consist of a wedge-shaped, marine-derived, sand and gravel sediment veneer, atop an elevated, gently-sloping basalt platform. At their berm crest, the sediments are 1-2 m (3-6 ft) thick. Their aerial extent appears limited by the elevation of the gradually sloping rock platform, and the maximum landward reach of storm-driven waves. Examples of perched, carbonate sand beaches within the park include those around Kaloko Point and from Kaloko Fishpond to the northern park boundary (Hapke et al. 2005; Richmond et al. 2008).

Most of the shoreline areas within the park contain beaches with natural, gravel-size, basalt- and less commonly coral-derived clasts. The clasts are generally rounded and form a wave-resistant barrier a few clasts thick. Individual clasts can reach boulders over 1 m (3 ft) in diameter. The larger clasts create pockets that accumulate finer sands and other debris. The coarsest sediments occur in the northern reaches of the park, where the coast is exposed to more wave energy (Richmond et al. 2008).

Fronting most of the shoreline at Kaloko-Honokōhau National Historical Park, and forming a substrate for beach sediment accumulation, are natural basalt platforms; these were formed as lava flows cooled at the coast (fig. 4). The nature of the platform varies with the type of basalt flow forming the substrate—pāhoehoe or ‘a‘ā. When exposed, the flows form a bare rock surface, with tide pools, intertidal habitats, and scattered pockets of accumulated sediment. The best exposures of bare rock platforms occur south of Honokōhau Harbor, and from the south end of Kaloko Fishpond around Kaloko Point to the north end of ‘Aimakapā Fishpond (Richmond et al. 2008; Ann Gibbs, geologist, U.S. Geological Survey, written communication, November 2010).

Submarine Habitats

Much of the area within park boundaries (240 ha; 596 acres) is under water. Submarine habitats are important natural resources for the Kaloko-Honokōhau National Historical Park (Gibbs et al. 2007). Archaeological, cultural, and recreational resources are also submerged offshore. Parrish et al. (1990) surveyed the marine resources of Kaloko-Honokōhau National Historical Park in detail, from the high intertidal mark to a depth of about 60 m (200 ft). General intertidal habitat types included exposed basalt bench (extensive), exposed low and nearly vertical cliffs, rock and rubble shore (largest habitat in the park), and sandy beach (smallest area). Subtidal habitat zones included an expansive, boulder-strewn basalt pavement area at 8 to 14 m (25 to 45 ft) deep, a coral-covered slope at 18 to 30 m (60 to 100 ft) deep, and an abrupt underwater cliff of 1.5 to 8 m (5 to 25 ft) along much of the shoreline (Parrish et al. 1990).

Kaloko has a large embayment that a shallow pāhoehoe sill separates into inner and outer areas. The wall of the Kaloko Fishpond crosses this sill. The inner bay is within the fishpond, covering 4.5 ha (11 ac). The bottom is covered with silt, probably the result of the ancient construction of the fishpond walls. Pāhoehoe lava flows fringe the outer bay, as an intertidal platform with basaltic boulders. Within the outer bay is a gradually descending coral reef, with some white sand areas (Cordy et al. 1991). As part of the Keāhole region, the embayment and adjacent intertidal platforms of pāhoehoe lava at Kaloko-Honokōhau host one of the most diverse and abundant reef fish populations in the main Hawaiian Islands (Cordy et al. 1991).

In 2003, the National Park Service and the U.S. Geological Survey embarked on a collaborative research effort to develop detailed benthic habitat classification maps for the marine lands within the park and adjacent areas to provide baseline information to resource managers prior to the expansion of surrounding development (figs. 15-16) (Gibbs et al. 2007). The data sources for the map included color aerial photography, Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) bathymetric measurements, georeferenced underwater video, and still photography. Attributes considered for individual habitat types included: 1) major structure or substrate, 2) dominant structure, 3) major biologic cover on the substrate, 4) percentage of major biological cover, and 5) geographic zone (Gibbs et al. 2007).

The aforementioned study determined that nearly 73 percent of the area of investigation consists of a hardbottom structure that could potentially support the 13 noted coral species within the park. The remaining 25 percent of the area includes unconsolidated sediment and anthropogenic features (Gibbs et al. 2007). With the exception of the Honokōhau Harbor mouth, the current status of the submarine habitats seems healthy, with little evidence of degradation, invasive macroalgae, or diseased coral observed (Gibbs et al. 2007). Researchers delineated twelve habitat zones comprising the study area: shallow cliff, deep cliff, dredged, shelf break, pinnacles/ridges, shoreline/intertidal, deep bench, shelf escarpment, shallow bench-narrow, intermediate bench, shallow bench-broad, and deep slope (fig. 16) (Gibbs et al. 2007).

Geology and Cultural Resources

Ancient Hawaiians were deeply reverent toward the landscape, and many of their traditions and cultural practices were directly related to geologic features and processes. Kaloko and Honokōhau are both prehistoric land units, or ahupua‘a, associated with a Hawaiian community. Another ahupua‘a, Kohanaiki, is north of Kaloko. The National Park Service boundary only includes the seaward side of the two ahupua‘as (Cordy et al. 1991). The concept of an ahupua‘a was the traditional native way to effectively manage the land and water in a particular area (Rutherford and Kaye 2006).

The park area, with its sheltered Kaloko Bay, and the presence of a large natural inlet (now Kaloko Pond) and a natural brackish pond (‘Aimakapā) made the site attractive for settlement, and application of aquaculture in the ponds (Hoover and Gold 2005). Early Hawaiians also recognized different marine zones, which correspond remarkably well with today’s classifications, such as lihikai, which means “rim of the sea”, ka kohola (“reef flats”), po‘ina kai (“wave breaking area”), ka uli (“deep blue sea”), moana (“ocean”), and ka popolohua mea a Kane (“the dark blue-purple sea of Kane”). They also likely sought to take advantage of the different plant communities, which are closely linked to the underlying substrate in the area. Canfield (1990) recognized eight major coastal plant community types at the park, including marsh and mangrove forest (muddy sediment overlying pāhoehoe substrate), grassland (pāhoehoe substrate), inland scrub (pāhoehoe or ʻaʻā substrate), savanna (pāhoehoe or ʻaʻā substrate), and forest (pāhoehoe substrate) (Canfield 1990; Richmond et al. 2008).

A summary by Cordy et al. (1991) contains a comprehensive description of the archaeological studies and results conducted at the Kaloko ahupuaʻa. Among the sites and complexes listed are brackish ponds, cairns, stone enclosures, trails, petroglyphs, pits, fishponds, stone walls, platforms, pavements, lava tube caves (cemeteries and temporary habitation sites), middens, and fire pits (fig. 17).

Cultural resources are threatened by geologic processes such as eustatic sea-level rise exacerbated by climate change-influenced sea-level rise, and relative sea-level rise (inundation) due to crustal loading by the ever-growing volcanic mass on the southern end of the Island of Hawaiʻi. Some features are already submerged, the shoreline is encroaching landward, and coastal processes will weather away features such as fishponds and seawalls.

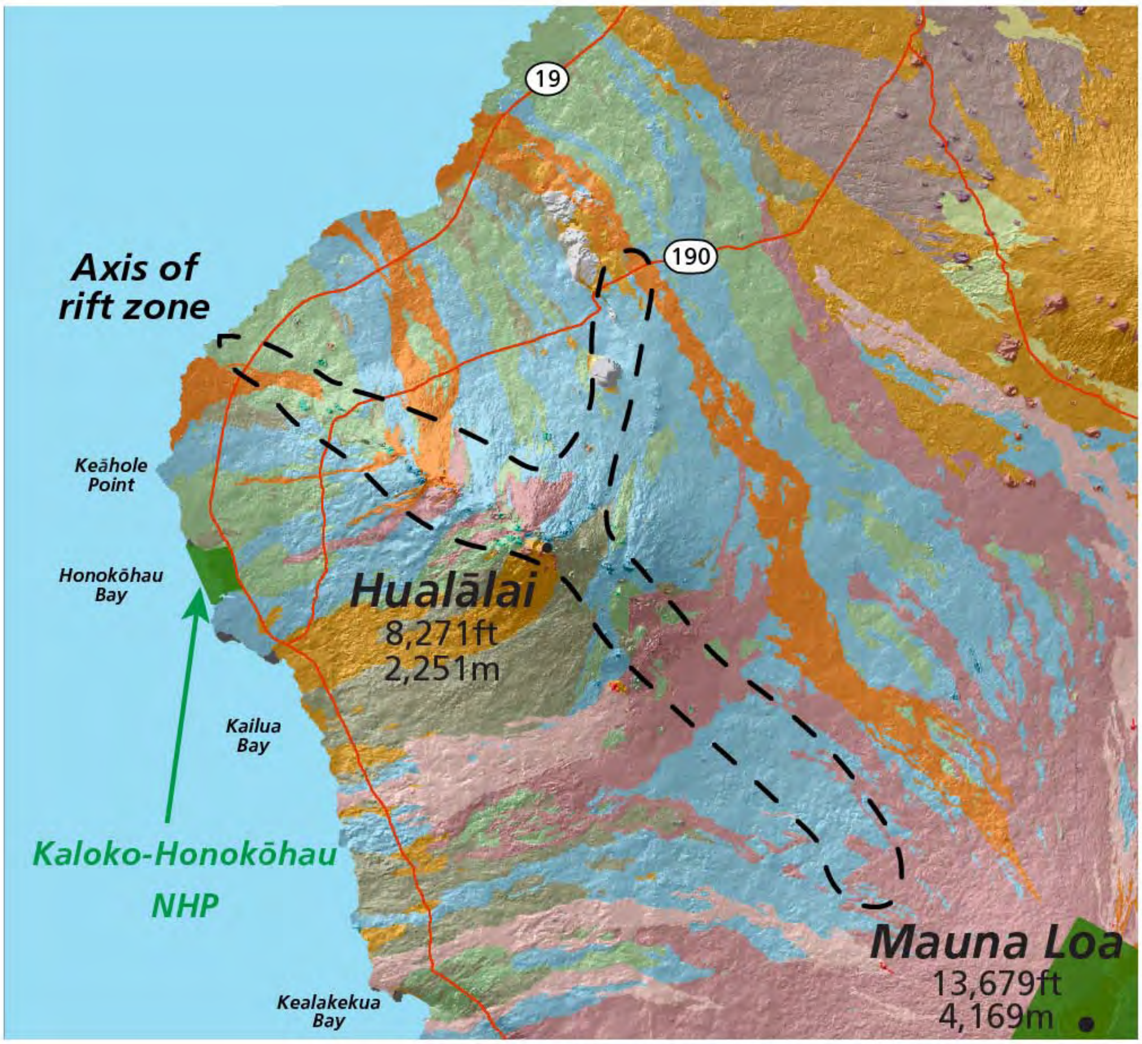


Figure 14. Map showing location of Hualālai rift zones, relative to Kaloko-Honokōhau National Historical Park on the Kona Coast. Different colors represent different lava flows as differentiated in the GRI digital geologic (GIS) data layers (see Overview of Geologic Data section). Note the lava flows originating from the rift zones and the cinder cones and spatter cones within the rift zone. Graphic by Phil Reiker (NPS Geologic Resources Division). Adapted from figure 1, Davis and Yamanaga (1968), with information from figure 5 in Oki et al. (1999).

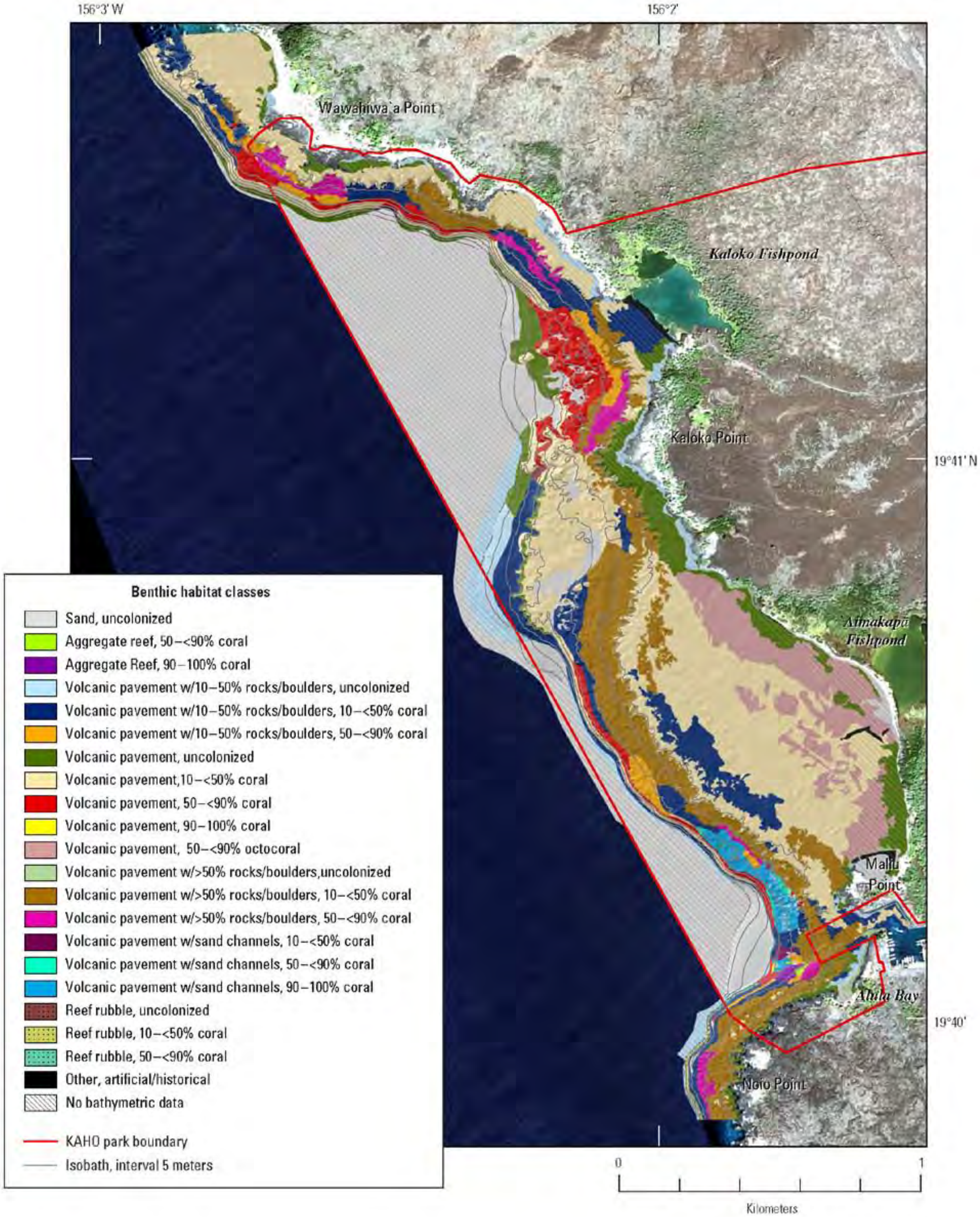


Figure 15. Benthic habitat map of Kaloko-Honokōhau National Historical Park and vicinity on the Kona Coast. U.S. Geological Survey graphic from Gibbs et al. (2007).

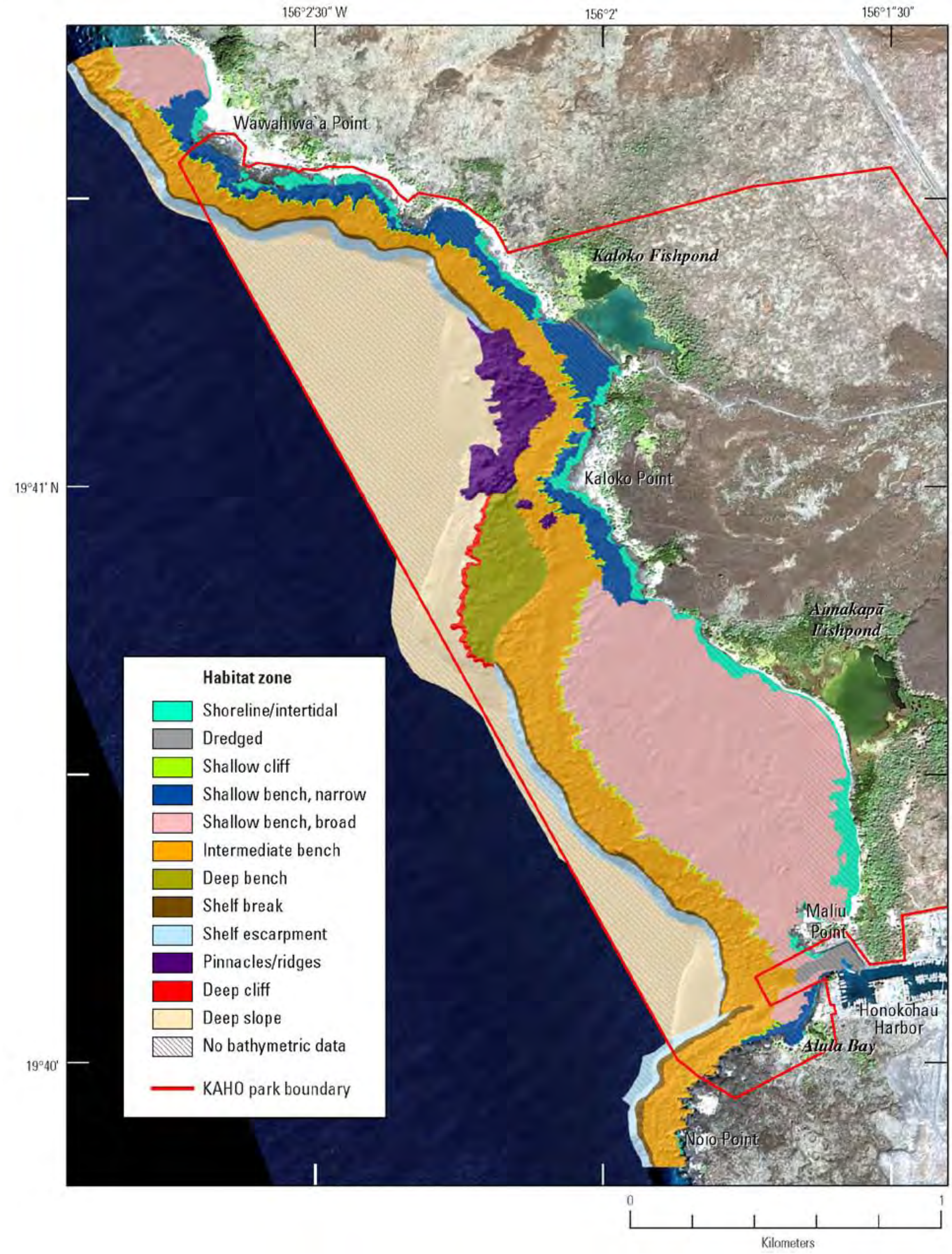


Figure 16. Map showing location of 12 benthic habitat zones overlaid on shaded relief bathymetry. U.S. Geological Survey graphic from Gibbs et al. (2007).

Figure 17. The cultural resources of Kaloko-Honokōhau National Historical Park are deeply connected to the park's geology. Māmalahoa trail (top) crosses lava flows in the park. A fishpond makaha (sluice gate; bottom)—constructed from basalt boulders—allows for water exchange with the pond and prevents larger fish from escaping. National Park Service photographs. Trail photograph courtesy Jon Jokiel (Kaloko-Honokohau National Historical Park). Makaha photograph by Rebecca Beavers (NPS Geologic Resources Division), available online: http://www.nature.nps.gov/geology/cfprojects/photodb/Photo_Detail.cfm?PhotoID=668. Accessed 13 May 2011.

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Kaloko-Honokōhau National Historical Park, the environment in which those units were deposited, and the timing of geologic events that created the present landscape.

In geologic terms, the rock units in Kaloko-Honokōhau National Historical Park are young (geologic map units Qh1o, Qh1y, and Qh2)—dating back approximately 10,000 years. Volcanism created the oldest of the rocks on the Island of Hawai‘i less than 1 million years ago, compared to more than 4 billion years of Earth's history (figs. 18-19) (Clague and Dalrymple 1987; Rubin 2005). Kīlauea Volcano, at nearby at Hawai‘i Volcanoes National Park, has been erupting lava since 1983 (Thornberry-Ehrlich 2009). The geologic evolution of the Pacific basin, including the Hawaiian Islands, is a key event in Earth's history. Knowledge of how the islands formed contributes to understanding the current landscape and to predicting potential future geologic events.

Pre-Quaternary History of the Pacific Basin (after Condie and Sloan 1998)

In the late Paleozoic, all continental landmasses joined to form one large supercontinent, Pangaea. During this time, mountain ranges formed by active continental collision. A huge water body, the Panthallassic Ocean, surrounded Pangaea. This water body had persisted in some form since the late Proterozoic Era (about 570 million years ago), when it appeared after a previous supercontinent, Rodinia, broke apart.

The supercontinent Pangaea began to break apart early in the Triassic Period. It split into a northern continent, Laurasia, and a southern continent, Gondwana. Further rifting divided Laurasia into the North American and Eurasian continents, while Gondwana eventually separated into the continents of South America, Africa, Australia, and Antarctica. Continental rifting opened new oceans, such as the Atlantic Ocean basin between the Americas, Europe, and Africa. The Indian Ocean basin formed between Africa, Antarctica, and Australia. Rifting continued throughout the Mesozoic. The oceanic crust of the Panthallassic Ocean basin was also evolving during this time.

At approximately 125 million years ago (early to middle Cretaceous), evidence suggests that a massive increase in volcanic activity in the western Pacific Ocean basin produced large volcanic plateaus above several large mantle plumes. This activity was concurrent with a rapid increase in rates of sea-floor spreading. Rates increased by 50%–100%, and remained high until the late Cretaceous. This volcanic event correlates with rising sea level, global climate change (warming), and several extinction events in the middle Cretaceous.

The Pacific plate currently encompasses most of the North Pacific Ocean basin, and is relatively young in geologic terms. In the Cretaceous, several plates existed within the basin, likely derived from the partitioning of the Panthalassic Ocean upon the breakup of Pangaea. During the Cretaceous, the Pacific plate was a small, central plate surrounded by the Aluk plate to the south, the Farallon plate to the east, and the Kula plate to the north (fig. 20) (University of California-Santa Barbara 2006). Separated by mid-ocean ridges, the plates surrounding the Pacific plate began moving away from it. The Kula plate plunged beneath the northeast Asian subduction zone, possibly coincident with the opening of the Sea of Japan. A remnant of this plate remains as an inactive area of the Bering Sea. Subduction of the Farallon plate beneath North and South America resulted in Rocky Mountain-building events, and the eventual formation of the San Andreas fault zone boundary. Remnants of this plate include the Juan de Fuca plate (off the coast of the Cascade volcanic chain in Oregon and Washington), the Cocos plate (in the eastern Pacific, off the coast of Central America), and the Nazca plate, which is subducting beneath South America (figs. 21-22).

During this time, the Pacific plate was enlarged by seafloor spreading to nearly fill the north Pacific basin. It now is moving slowly northward and westward—at 95 mm (3.7 in.) per year—away from the East Pacific Rise spreading center and toward the subduction zones bordering the Indo-Australian plate, Philippine plate, Eurasian plate and the Aleutian Islands of the North American plate (fig. 22).

Evolution of the Hawaiian-Emperor Seamount Chain

The Pacific plate now covers about 20% of the Earth's crust, and is the largest tectonic plate on the planet. There are linear chains of volcanic islands and seamounts (submerged volcanoes) throughout the Pacific basin. Many of these chains change in age from one end to the other, due to their formation on plates moving over hotspots.

Hotspots form in response to plumes of material rising at very high temperature from the lower mantle, just above the core-mantle interface. These plumes are thought to form as a result of localized thermal disturbances in the molten core of the Earth. A part of the core transfers heat to the overlying mantle, which then rises, owing to its decreased density. Once a plume reaches the shallow depths in the mantle ≈200 km (125 mi), the drop in pressure causes the material to melt. If this molten material (magma) finds a way to the outer crust it may erupt and produce a chain of volcanoes where the tectonic plate moved over the hotspot (Condie and Sloan 1998). The linear trend of the Hawaiian-Emperor islands and seamounts records the movement of the Pacific plate over such a stationary hotspot (fig. 23). Other such hotspots across the Pacific basin are the Caroline, Marquesas, Society, Pitcairn, Austral, and Easter hotspots (fig. 22) (Condie and Sloan 1998).

The Hawaiian Islands are part of the volcanic chain known as the Hawaiian-Emperor seamount chain. The seamount chain contains islands, seamounts, atolls, shallows, banks, and reefs, along a line trending southeast to northwest across the northern Pacific. This chain contains more than 80 undersea volcanoes and extends more than 5,800 km (3,600 mi)—from the Aleutian trench (a subduction zone) south and east to Lōʻihi, the submarine volcano off the coast of the Island of Hawaiʻi. The seamount chain is divided into two sections, the younger Hawaiian Ridge (Hawaiian Islands northwest to Kure Atoll) and the older Emperor Seamounts (fig. 22). The two components are divided at a distinctive bend in the chain, where the trend changes from a northerly to a more northwesterly direction. This bend corresponds to a change in direction of the Pacific tectonic plate movement, one that took place over a period of 8 million years, from 50 to 42 million years ago (fig. 22) (Sharp and Clague 2006).

Building Volcanoes

Each volcanic island in the Hawaiian chain evolved through four idealized eruptive stages: the preshield, shield, postshield, and rejuvenated stages (fig. 24) (Clague and Dalrymple 1987). These are also referred to as the "youthful stage," "mature stage," "old stage," and "rejuvenated stage" (Beeson 1976). Each stage corresponds to variations in the amount and rate of heat supplied to the lithosphere (Moore et al. 1982), as the Pacific tectonic plate drifts northwest over the Hawaiian hotspot at a rate of about 8.5–9.5 cm/year (3.3–3.7 in./year) (Eakins et al. 2003; Simkin et al. 2006). Preshield lava, erupted in the earliest stage of growth, is typically buried in the core of a large volcano. Shield volcanism produces vast amounts of tholeiitic basalt, chiefly as lava flows, and is the primary volcano growth stage. As the shield stage ends, the magma chamber evolves and the lavas become fractionated and more alkalic. Late-stage volcanic rocks, formed during rejuvenation stage, include cinder and spatter cones, and mixed lava flows over a localized area (Clague et al. 1982; Sherrod et al. 2007). Based on the rate of movement of the Pacific plate, and the average spacing of volcanic centers, it is calculated that each volcano requires about 600,000 years to grow from the ocean floor to the end of the volcanic shield-building phase, reaching the surface of the ocean midway through this period (Moore and Clague 1992).

Once the plate beneath a volcano moves away from the hotspot, volcanism ceases. The mass of the large shield volcano depresses the oceanic crust beneath it. On the Island of Hawaiʻi, Mauna Loa and its adjacent volcanoes have depressed the base of the crust about 9 km (6 mi) (Zucca et al. 1982). As each volcanic mass ages, the crust which it overlies cools and further subsides into the mantle. The combination of erosion, volcanic quiescence and subsidence cause the islands to reduce in size and eventually submerge below the ocean surface (Clauge and Dalrymple 1987; Rubin 2005).

Because the northernmost extinct volcanoes are subducting into the Aleutian trench, it is difficult to ascertain when the Hawaiian hotspot activity began. For the major Hawaiian Islands, their age increases with distance from the hotspot (currently beneath the Island of Hawaiʻi and Lōʻihi) (fig. 25) (Cross 1904). The oldest major island, Niʻihau, is the farthest distance away from Kīlauea; shield-stage lava age ranges for Niʻihau are 4.89±0.11 and 5.2 million years ago (oldest known age of 6 million years ago with large analytical error) (G. B. Dalrymple unpublished data 1982; Clague and Dalrymple 1987; Clague 1996; David Sherrod, geologist, U.S. Geological Survey, written communication, July 2009).

Kauaʻi is slightly younger and closer to Kīlauea and has shield lava ages of 5.14±0.20 and 5.77±0.28 million years ago (McDougall 1979; D. Sherrod, written communication, July 2009). The end of shield-building volcanism on Oʻahu dates between 2.6 and 3.0 million years ago (Clauge and Dalrymple 1987; Clague 1996). West Molokaʻi volcano has an age of 1.90±0.06 million years ago, whereas East Molokaʻi volcano has an age of 1.76±0.07 million years ago; however, these ages are uncertain due to potential issues associated with the dating methodology or laboratory procedures (Naughton et al. 1980; Clague and Dalrymple 1987; D. Sherrod, written communication, July 2009).

The neighboring islands of Kahoʻolawe and Lānaʻi have shield lava ages of 1.25±0.15 million years ago and 1.28±0.04 million years ago, respectively (Bonhommet et al. 1977; D. Sherrod, written communication, July 2009). The West Maui volcano erupted shield stage lava before Haleakalā on the Island of Maui, with ages of 2.15 million years ago. The oldest reported age for post-shield lava on Haleakalā is 1.12 million years ago (McDougall 1964; D. Sherrod, written communication, July 2009).

Ages of the Hawaiian volcanoes were primarily determined by measuring the ratio of potassium and argon isotopes.

The Island of Hawaiʻi's Volcanoes

Although some of the Hawaiian Islands were built by a single volcano, others are a composite of several. Today, the Island of Hawaiʻi is comprised of five volcanoes above sea level (fig. 1); a sixth, extinct volcano lies submerged north of Kailua. To the south of the island the active Lōʻihi volcano has grown to within 1 km (0.6 mi) of the ocean surface. Active volcanoes remain active over a long period of time (hundreds of thousands of years). Therefore, a significant overlap in age occurs between neighboring islands. Three volcanoes are considered active: Kīlauea (erupting since 1983), Mauna Loa (last erupted in 1984), and Lōʻihi (erupted in 1996). The currently active submarine volcano, Lōʻihi, is building layers of basaltic lava, and venting hydrothermal, mineral-laden water at the seafloor; in the future it may become the next Hawaiian island (Rubin 2005). Volcanoes that are considered dormant include Hualālai (last erupted in 1801), Haleakalā (last erupted in about 1790), and Mauna Kea (last erupted about 4,000 years ago) (Rubin 2005). Rift zones are often associated with hotspot volcanism. Seismic refraction profiles and gravity data collected along the Kona coast reveal the presence of an extinct, buried rift zone (possibly a buried rift of Hualālai volcano) parallel to the coast (Zucca 1981; Zucca and Hill 1981; Zucca et al. 1982). Geologists surmise that there may be many more buried rift zones around the Island of Hawaiʻi (Ann Gibbs, geologist, U.S. Geological Survey, written communication, November 2010).

Volcanic activity is still a possibility at Kaloko-Honokōhau National Historical Park. In 1801, the youngest flows from Hualālai reached the coast just north of the park boundary beyond Keāhole Point (geologic map unit Qh5). Recent flows from vents along the flanks of Mauna Loa are notoriously long, stretching from as far southeast as Hilo (1880-1881) to as far northwest as the west coast north of Hualālai (1859) (e.g. geologic map units Qk4 and Qk5) (Wolfe and Morris 1996). Volcanic flows from Hualālai Volcano that are from approximately 1,500 to 10,000 years old dominate the surface and subsurface rocks in and near Kaloko-Honokōhau National Historical Park (geologic map units Qh1y, Qh1o, and Qh2) (Oki et al. 1999). Units found within the park include alkalic and transitional basalt and minor hawaiite flows. This basalt is typically fine-grained, with some large phenocrysts of olivine, plagioclase, and/or clinopyroxene minerals. Both ropy pāhoehoe and blocky ʻaʻā flows are present within the park (Wolfe and Morris 1996a).

Not present within the park boundaries are the youngest flows (Kaʻūpūlehu flow, geologic map unit Qh5) from Hualālai Volcano, which reached the coast near Kīholo Bay and just north of Keāhole Point. This eruption was from 1800-01 (Cordy et al. 1991; Wolfe and Morris 1996a).

Modification of the Volcanic Landscape

Submarine mass wasting, landslides, and debris flows carry material from the shoreline, down the slopes of the islands, spreading it onto the deep sea floor. This process often creates steep lava benches, precipitous slopes, and cliffs on island shorelines (Keating et al. 2000). Mass movements have been an important, ongoing influence on the development of the overall volcanic complex of all the Hawaiian Islands (Keating et al. 2000; Moore and Clague 2002). Modern submarine surveys uncovered a history of instability along Mauna Loa's western flank; there is an active slump on the slopes of Kīlauea (Morgan and Clague 2003; Morgan et al. 2007).

During periods of volcanic quiescence, basalts, tuffs, breccias, cinder cones, and ash deposits of the Island of Hawaiʻi are affected by intense weathering. Resulting landforms include steep-sided stream valleys, dissected volcanic plateaus, alternating valley and ridge topography, small-scale gullies, isolated plateau remnants, talus slope deposits, levee deposits, sea cliffs, and benches (Ollier 1998). Ocean waves continuously modify the shorelines, carrying away sands and gravels deposited near the shore by the islands' rivers. Coral reefs fringe certain areas of the islands, and contribute carbonate sediments to the island's beaches as well as younger dune deposits (Sherrod et al. 2007). During the last major glaciation ("ice age") of the late Pleistocene, 21,000 years ago, sea level was 130 m (430 ft) lower than present. This and other sea level lows carved basalt benches and created carbonate platforms around many of the Hawaiian Islands. A carbonate reef substrate formed on the northwest coast of the Island of Hawaiʻi. A lack of this reef substrate elsewhere is due to active subsidence accompanying volcanism (Barnhardt et al. 2005; Bruce Richmond, geologist, U.S. Geological Survey, written communication, November 2010; Ann Gibbs, geologist, U.S. Geological Survey, written communication, November 2010).

Weathering of volcanic units and coral reefs by wind, water, and slope processes produced the bulk of the unconsolidated geologic units on the Island of Hawaiʻi (See Map Unit Properties Table). Modern low-lying areas across the Island of Hawaiʻi collect Holocene-age alluvium, colluvium, eolian deposits, and slope deposits.

Coastal deposits along the west coast of the Island of Hawaiʻi are generally poorly-developed. In the park, the shoreline is mostly rocky and irregular, with some beach areas near Honokōhau Bay. Several old (about 13,000 years old) drowned carbonate reefs exist off the west coast of Hawaiʻi at 150 m (500 ft) below sea level (Oki et al. 1999). These may have once contributed carbonate sediments to sheltered areas along the coast (Oki et al. 1999), though they are likely too deep to be a significant source of modern sediments (Ann Gibbs, geologist, U.S. Geological Survey, written communication, November 2010).

Humans also impact the geologic processes on the Island of Hawaiʻi. Shoreline armoring, piers, and harbor breakwaters along the coast interrupt natural sediment transport to and from the shores of the island.

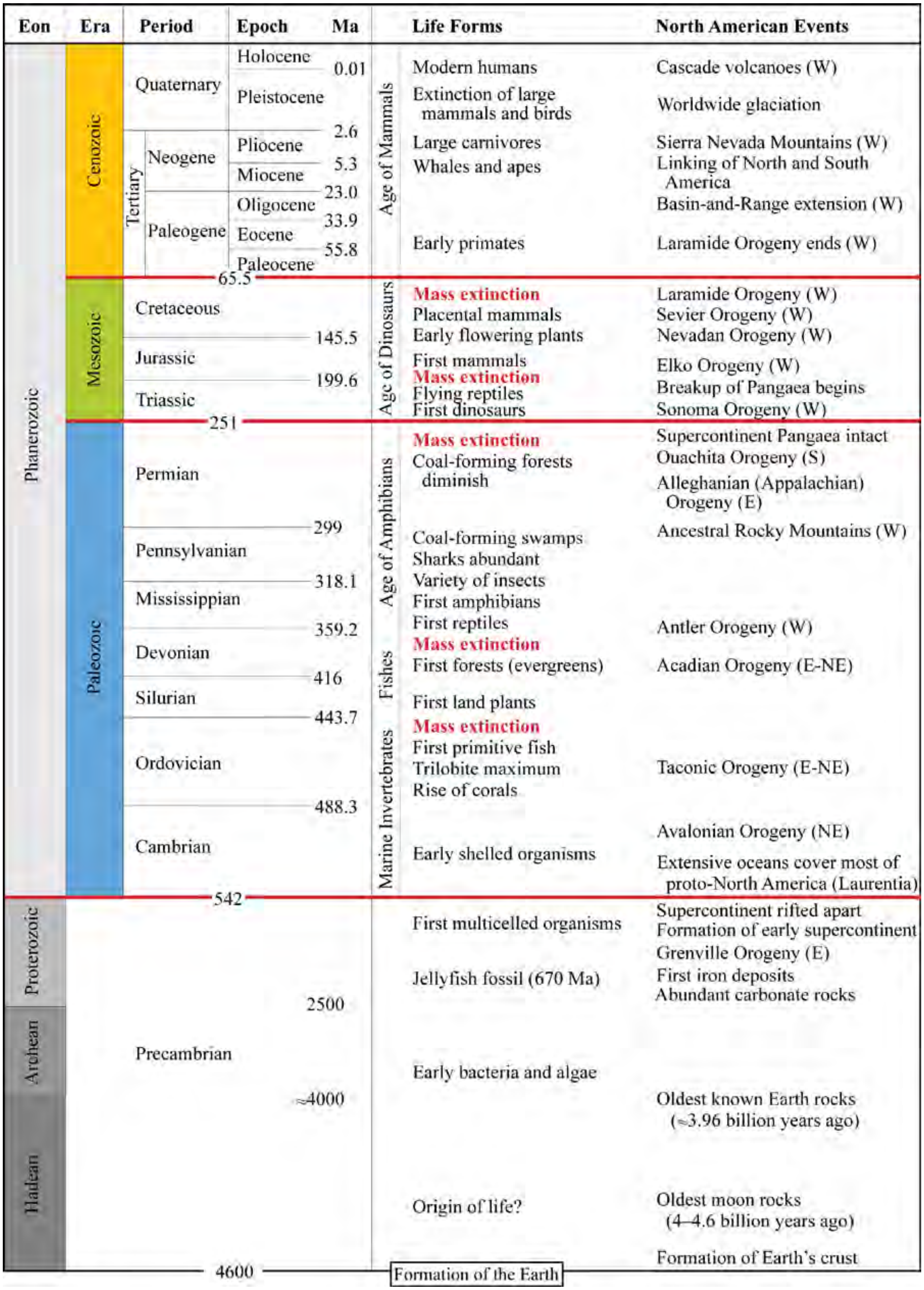


Figure 18. Geologic timescale. Included are major life history and tectonic events occurring in the Pacific region. Red lines indicate major unconformities between eras. Isotopic ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Adapted from the U.S. Geological Survey (http://pubs.usgs.gov/fs/2007/3015/) with additional information from the International Commission on Stratigraphy (http://www.stratigraphy.org/view.php?id=25), and Condie and Sloan (1998).

Era	Period		Epoch	Ma	Hawaiian Events	Volcanic Deposition
Cenozoic	Quaternary		Holocene	0.01	Active volcanism of Kīlauea and Mauna Loa	Puna Basalt, and Ka‘ū Basalt deposition ongoing Laupāhoehoe Volcanics, and Hualālai Volcanics (Basalt Member) deposited
			Pleistocene	2.6	Shield stage volcanism on Mauna Kea Shield stage volcanism on Kohala	Pāhala Ash deposited Hilina Basalt, and Kahuku Basalt deposited Hualālai Volcanics (Wa‘awa‘a Trachyte Member) deposited Hāwī Volcanics, Hāmākua Volcanics, and Nīnole Basalt deposited
					Shield stage volcanism on Haleakalā Shield stage volcanism on Kaho‘olawe Shield stage volcanism on West Maui Shield stage volcanism on Lāna‘i Shield stage volcanism on East Moloka‘i Shield stage volcanism on West Moloka‘i	Pololū Volcanics deposited
	Tertiary	Neogene	Pliocene	5.3		
			Miocene	23.0	Shield stage volcanism on Ni‘ihau Shield stage volcanism on Kaua‘i Gardner Pinnacles volcanism	
		Paleogene	Oligocene	33.9	Midway Island volcanism	
			Eocene	55.8	Pacific plate changes motion, causing bend in seamount chain	
			Paleocene	65.5	Hotspot volcanism along Hawaiian-Emperor seamount chain ongoing throughout the Cenozoic	

Figure 19. Geologic time scale of events affecting the Hawaiian Islands throughout the Cenozoic Era; adapted from U.S. Geological Survey (http://pubs.usgs.gov/fs/2007/3015/ using information from Clague and Dalrymple (1987), written communication from D. Sherrod (2009), and the GRI digital geologic map for Hawai‘i Volcanoes National Park. Ages of volcanic flows are generally relative and overlap considerably. Absolute ages in millions of years (Ma, or mega-annum).

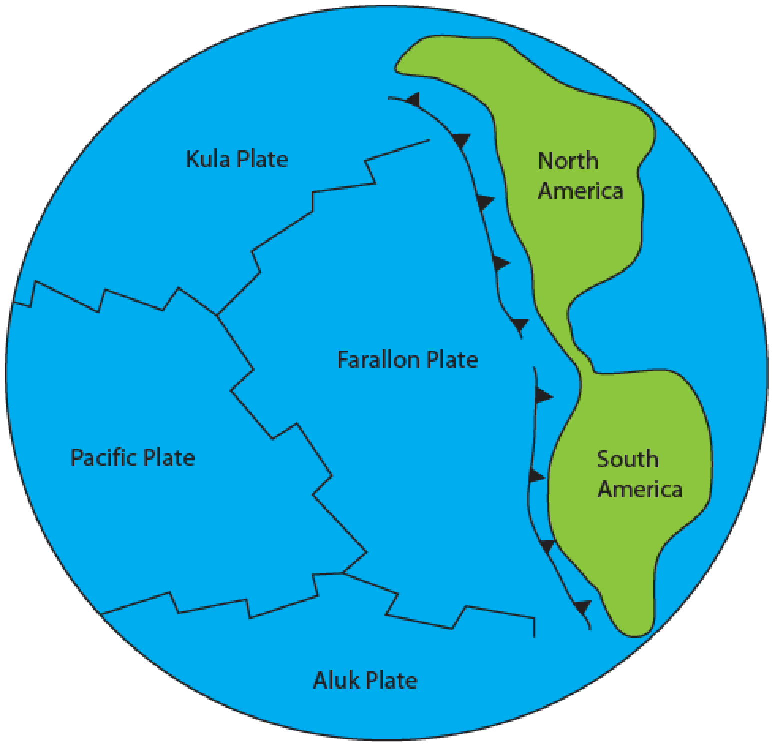


Figure 20. Generalized arrangement of plates in the Pacific Ocean basin during the middle Cretaceous. Lines with "teeth" represent convergent boundaries (subduction zones) where plates are coming together. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

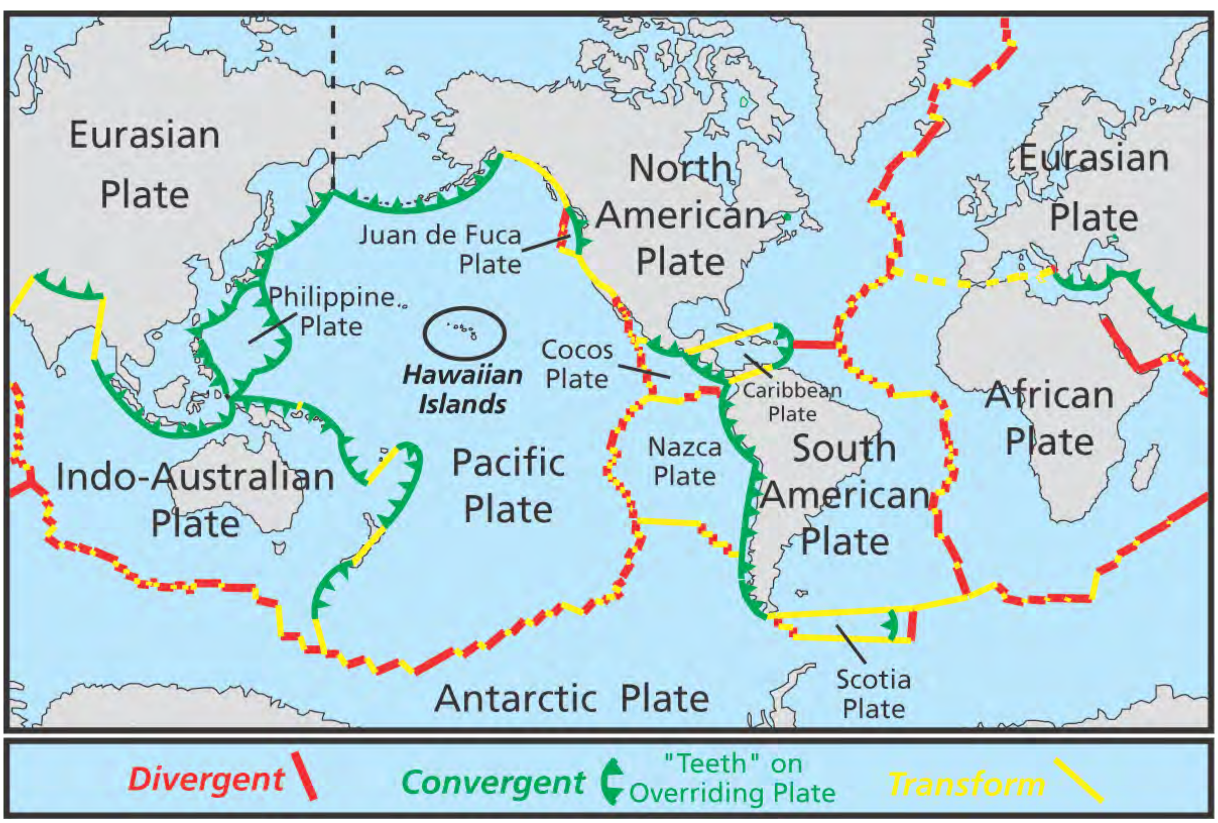


Figure 21. Map of the current tectonic plates. The Hawaiian Islands are circled. Divergent boundaries are where plates are pulling apart. Plates come together at convergent boundaries, and slide past one another at transform boundaries. Graphic courtesy Robert J. Lillie (Oregon State University), modified from Lillie (2005).

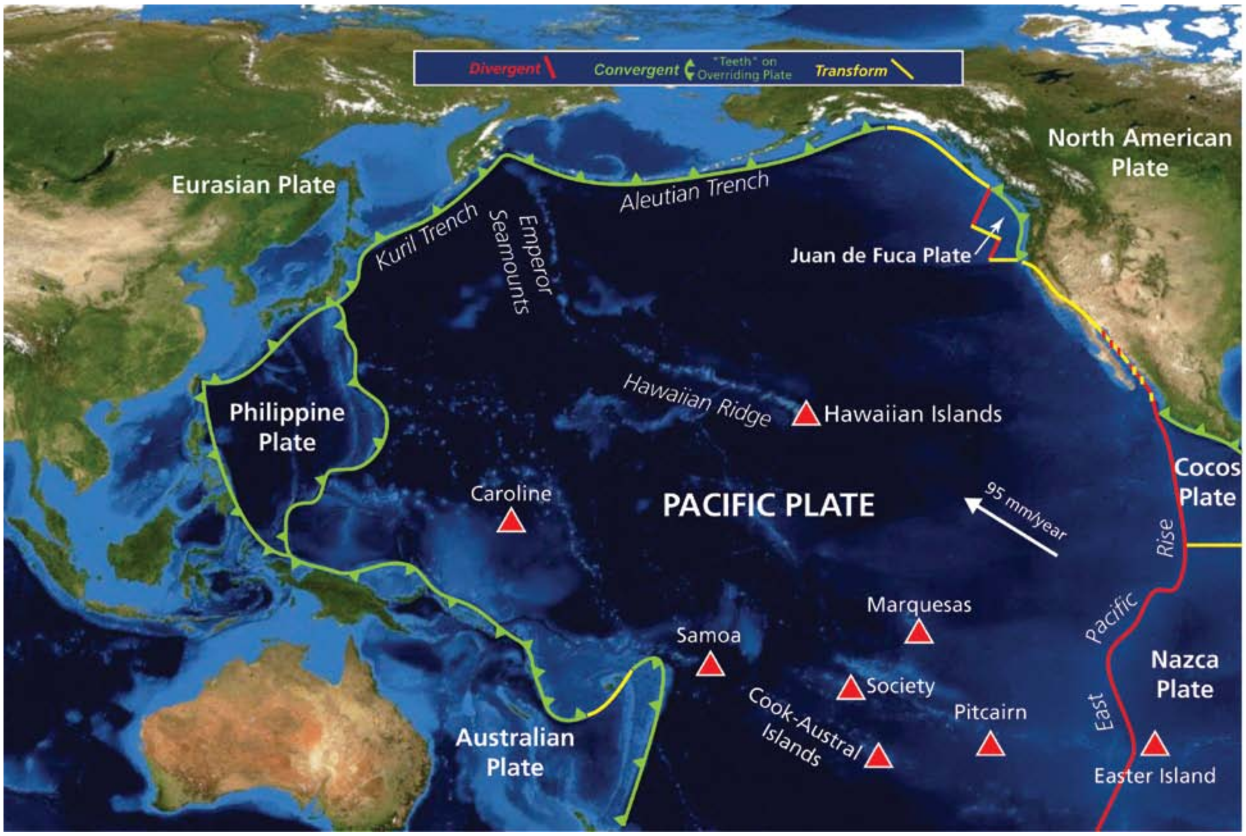


Figure 22. Tectonic setting of the Pacific Plate. This figure illustrates many of the features described in the Geologic History section. Note the extent of the Emperor Seamounts and Hawaiian Islands. Currently the Pacific Plate is moving to the northwest at about 95 mm (3.7 in.) per year. The "kink" between the Emperor Seamounts and Hawaiian Islands chain shows how the direction of motion changed while the Hawaiian hotspot remained stationary (see figs. 23, 24, and 25). Selected hotspots across the Pacific Ocean are indicated by red triangles. Boundaries between plates are color coded. Divergent boundaries (red) are where plates are pulling apart. Plates come together at convergent boundaries (green; green triangles indicate overriding plate at subduction zone), and slide past one another at transform boundaries (yellow). Compiled by Jason Kenworthy (NPS Geologic Resources Division from ESRI Arc Image Service Imagery Prime World 2D, with information from figure 2 in Clouard and Bonneville (2001).

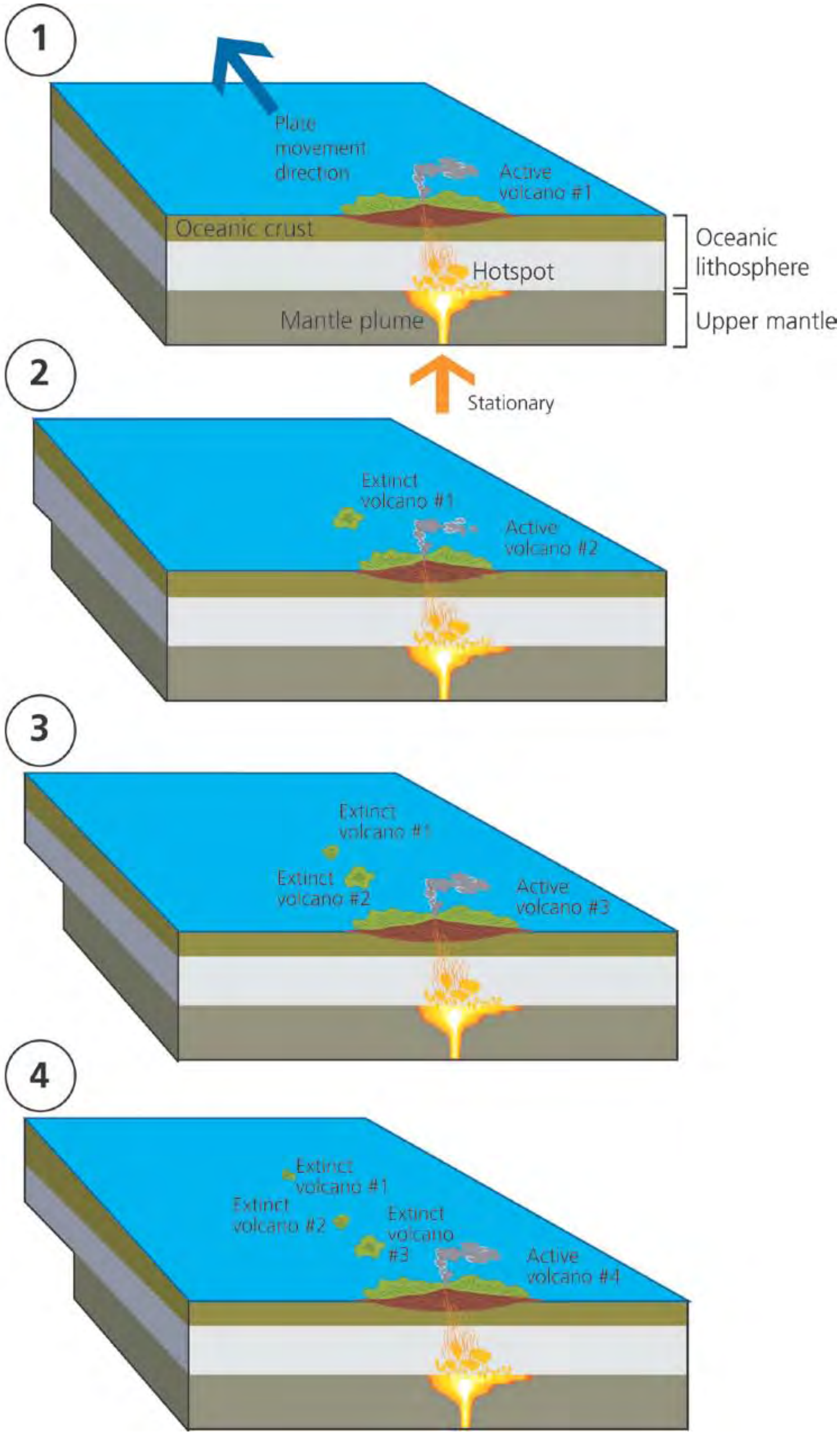


Figure 23. Evolution of a chain of islands over a stationary hotspot in Earth's crust. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

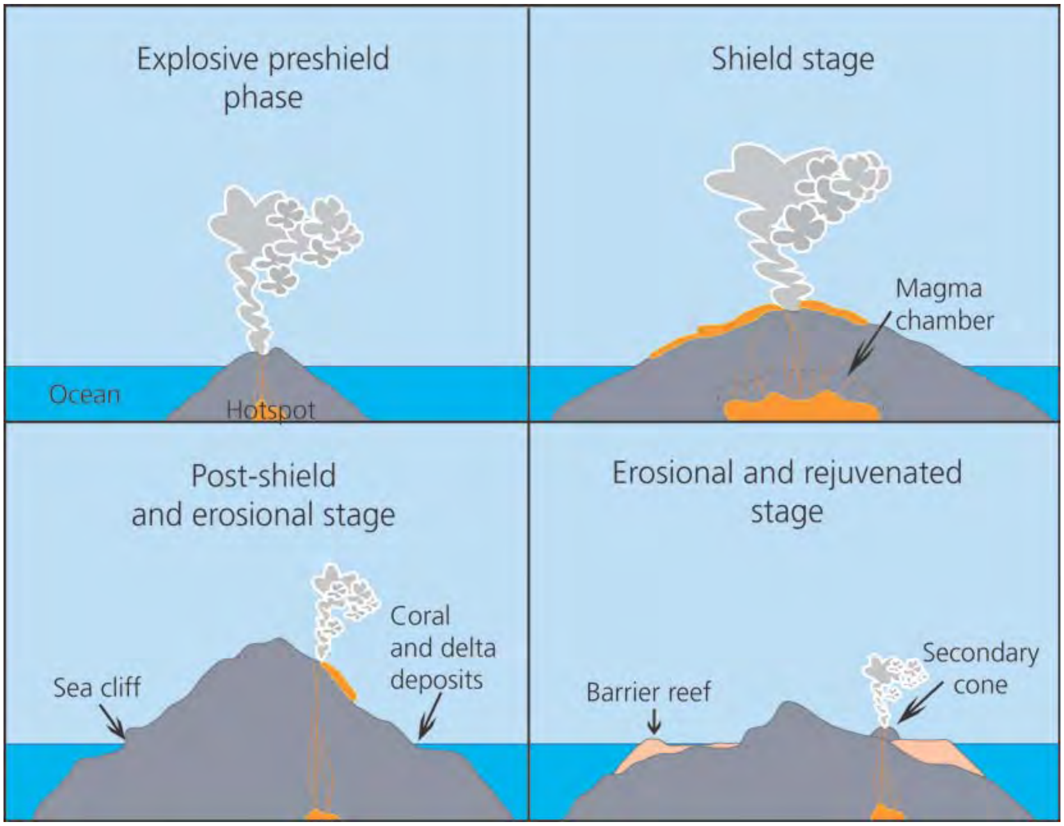


Figure 24. Simplified stages of Hawaiian hotspot island volcanism. After volcanism ceases, erosion and subsidence slowly reduce the island to a smaller subaerial remnant. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), after Keating (1992, fig. 29).

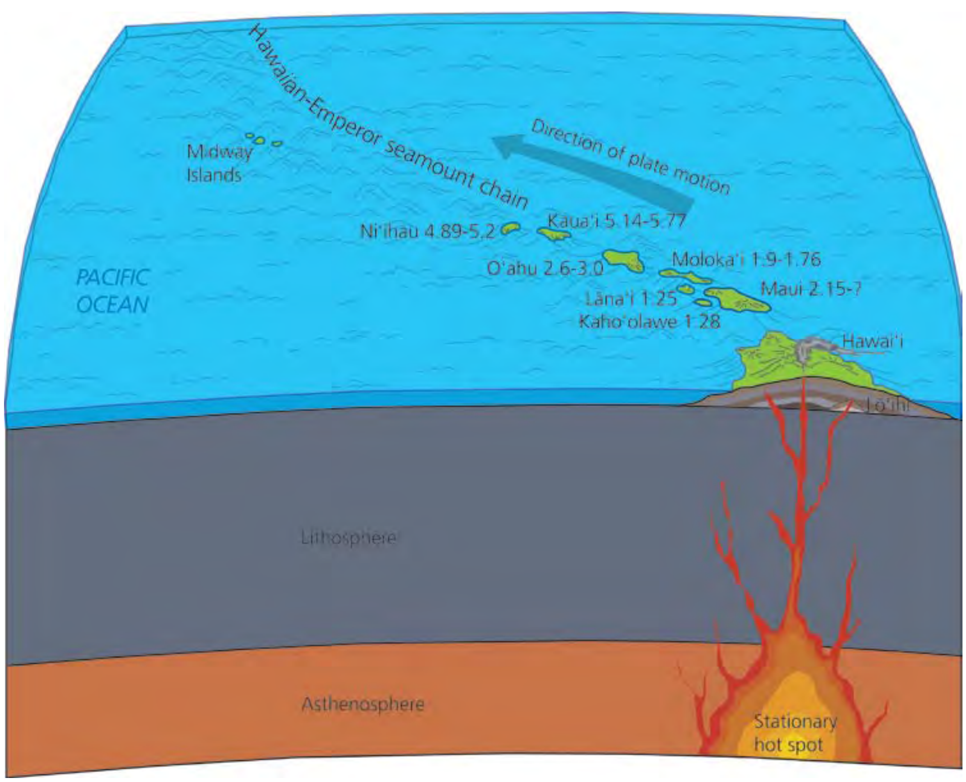


Figure 25. Evolution of the Hawaiian-Emperor seamount chain showing ages of shield-stage volcanism for the major Hawaiian Islands (ages are in millions of years). The specific type of age, error, and source are detailed in the text. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), after http://geology.uprm.edu/Morelock/1_image/seamt.jpg. Accessed 16 November 2010.

Overview of Geologic Data

This section summarizes the digital geologic data available for Kaloko-Honokōhau National Historical Park. It includes an overview graphic of the GIS data and a summary table that lists each map unit displayed on the digital geologic map for the park. Complete GIS data are included on the accompanying CD and are also available at the Geologic Resources Inventory (GRI) publications website: (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. Geologic maps also may show geomorphic features, structural interpretations, and locations of past geologic hazards that may be prone to future activity. Additionally, anthropogenic features such as mines and quarries may be indicated on geologic maps.

Source Maps

The Geologic Resources Inventory (GRI) team converts digital and/or paper source maps into the GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps including unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source maps to create the digital geologic data for Kaloko-Honokōhau National Historical Park:

Trusdell, F. A., E. W. Wolfe, and J. Morris. 2006. Digital database of the geologic map of the Island of Hawai'i (scale 1:100,000). Data Series 144. U.S. Geological Survey, Reston, Virginia, USA.

Wolfe, E. W., and J. Morris. 1996a. Geologic map of the Island of Hawaii (scale 1:100,000). Geologic Investigations Series Map I-2524-A. U.S. Geological Survey, Reston, Virginia, USA.

Wolfe, E. W., and J. Morris. 1996b. Sample data for the geologic map of the Island of Hawaii (scale 1:100,000). Miscellaneous Investigations Series Map I-2524-B. U.S. Geological Survey, Reston, Virginia, USA.

An additional source was unpublished data from the U.S. Geological Survey, Hawaiian Volcano Observatory, of the distribution of the Pu'u 'Ō'ō–Kupaianaha lava flow field (David Sherrod, geologist, U.S. Geological Survey, written communication, July 2009).

These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Kaloko-Honokōhau National Historical Park using data model version 1.4.

GRI digital geologic data for Kaloko-Honokōhau National Historical Park are included on the attached CD and are available through the NPS Natural Resource Information Portal (https://nrinfo.nps.gov/Reference.mvc/Search). Enter "GRI" as the search text and select Kaloko-Honokōhau National Historical Park from the unit list. The following components and geology data layers are part of the data set:

- Data in ESRI geodatabase, shapefile, and coverage GIS formats
- Layer files with feature symbology
- Federal Geographic Data Committee (FGDC)–compliant metadata
- A help file (.hlp) document that contains all of the ancillary map information and graphics, including geologic unit correlation tables and map unit descriptions, legends, and other information captured from source maps.
- An ESRI map document file (.mxd) that displays the digital geologic data

Geology data layers in the Kaloko-Honokōhau National Historical Park GIS data

Data Layer	*Code*	*On Overview?*
Faults	*FLT*	*Yes*
Geologic Contacts	*GLGA*	*Yes*
Geologic Units	*GLG*	*Yes*
Fault Map Symbology	*SYM*	*Yes*
Ash Contacts	*ASH*	*No*
Ash Units	*ASHA*	*No*
Deformation Area Contacts	*DEFA*	*No*
Deformation Areas	*DEF*	*No*
Geologic Sample Localities	*GSL*	*No*
Observation, Observed Extent, and Trend Lines	*LIN*	*No*
Volcanic Line Features	*VLF*	*No*
Volcanic Point Features	*VPF*	*No*

Note: All data layers may not be visible on the overview graphic.

Overview Graphic of Digital Geologic Data

The overview graphic displays the GRI digital geologic data draped over a shaded relief image of Kaloko-Honokōhau National Historical Park and includes basic geographic information. Digital geologic data for the entire Island of Hawaii is provided to each of the island's parks. For graphic clarity and legibility, not all GIS feature classes are visible on the overview graphic. The digital elevation data and geographic information are not included with the GRI digital geologic GIS data for Kaloko- Honokōhau National Historical Park, but are available online from a variety of sources.

Map Unit Properties Table and Correlation Table

The geologic units listed in the map unit properties table correspond to the accompanying digital geologic data. Following overall structure of the report, the table highlights the geologic issues, features, and processes associated with each map unit. The units in the map unit properties table are arranged by volcano and then by origin (e.g. spatter cone deposit). The subsequent map units correlation table is also arranged by volcano and illustrates the temporal relationships between units. The units, their relationships, and the series of events the created them are highlighted in the "Geologic History" section. Please refer to the geologic timescale (figs. 19 and 20) for the geologic period and age associated with each unit.

Use Constraints

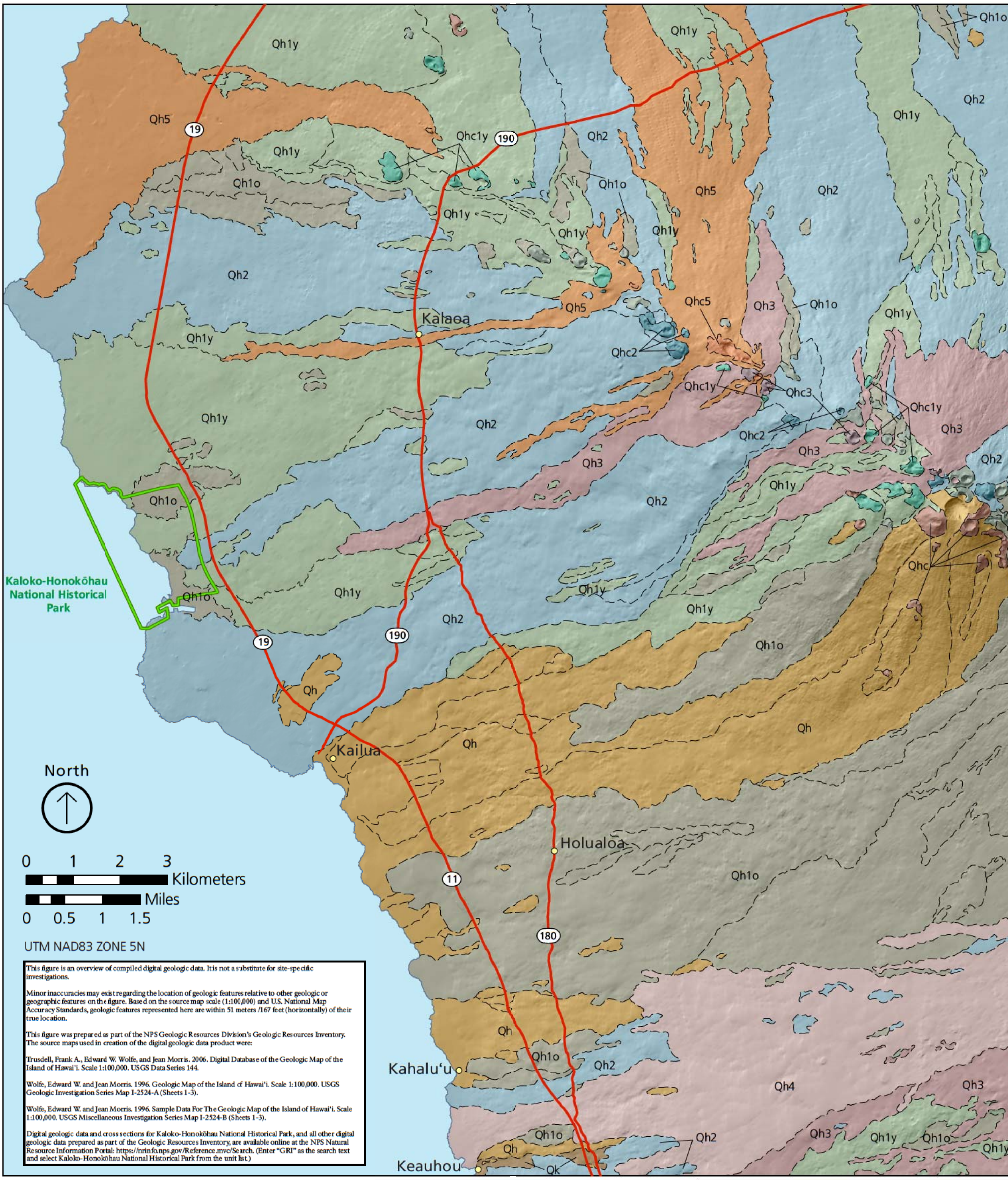
Graphic and written information provided in this section is not a substitute for site-specific investigations, and ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the overview graphic. Based on the source map scale (1:100,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 51 meters /167 feet (horizontally) of their true location.

Please contact GRI with any questions.

Kaloko-Honokōhau National Historical Park
Hawaii

National Park Service
U.S. Department of the Interior

Overview of Digital Geologic Data for Kaloko-Honokōhau NHP



This figure is an overview of compiled digital geologic data. It is not a substitute for site-specific investigations.

Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the figure. Based on the source map scale (1:100,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 51 meters /167 feet (horizontally) of their true location.

This figure was prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source maps used in creation of the digital geologic data product were:

Trusdell, Frank A., Edward W. Wolfe, and Jean Morris. 2006. Digital Database of the Geologic Map of the Island of Hawai'i. Scale 1:100,000. USGS Data Series 144.

Wolfe, Edward W. and Jean Morris. 1996. Geologic Map of the Island of Hawai'i. Scale 1:100,000. USGS Geologic Investigation Series Map I-2524-A (Sheets 1-3).

Wolfe, Edward W. and Jean Morris. 1996. Sample Data For The Geologic Map of the Island of Hawai'i. Scale 1:100,000. USGS Miscellaneous Investigation Series Map I-2524-B (Sheets 1-3).

Digital geologic data and cross sections for Kaloko-Honokōhau National Historical Park, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Natural Resource Information Portal: https://nrinfo.nps.gov/Reference.mvc/Search. (Enter "GRI" as the search text and select Kaloko-Honokōhau National Historical Park from the unit list.)

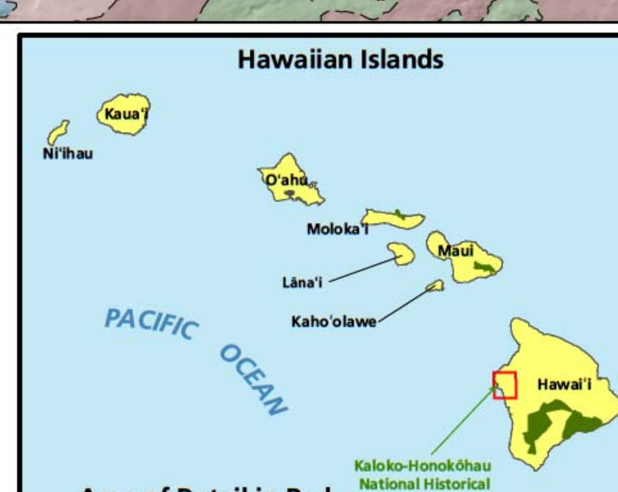
NPS Boundary

Geologic Contacts

- approximate
- water or shoreline

Geologic Units

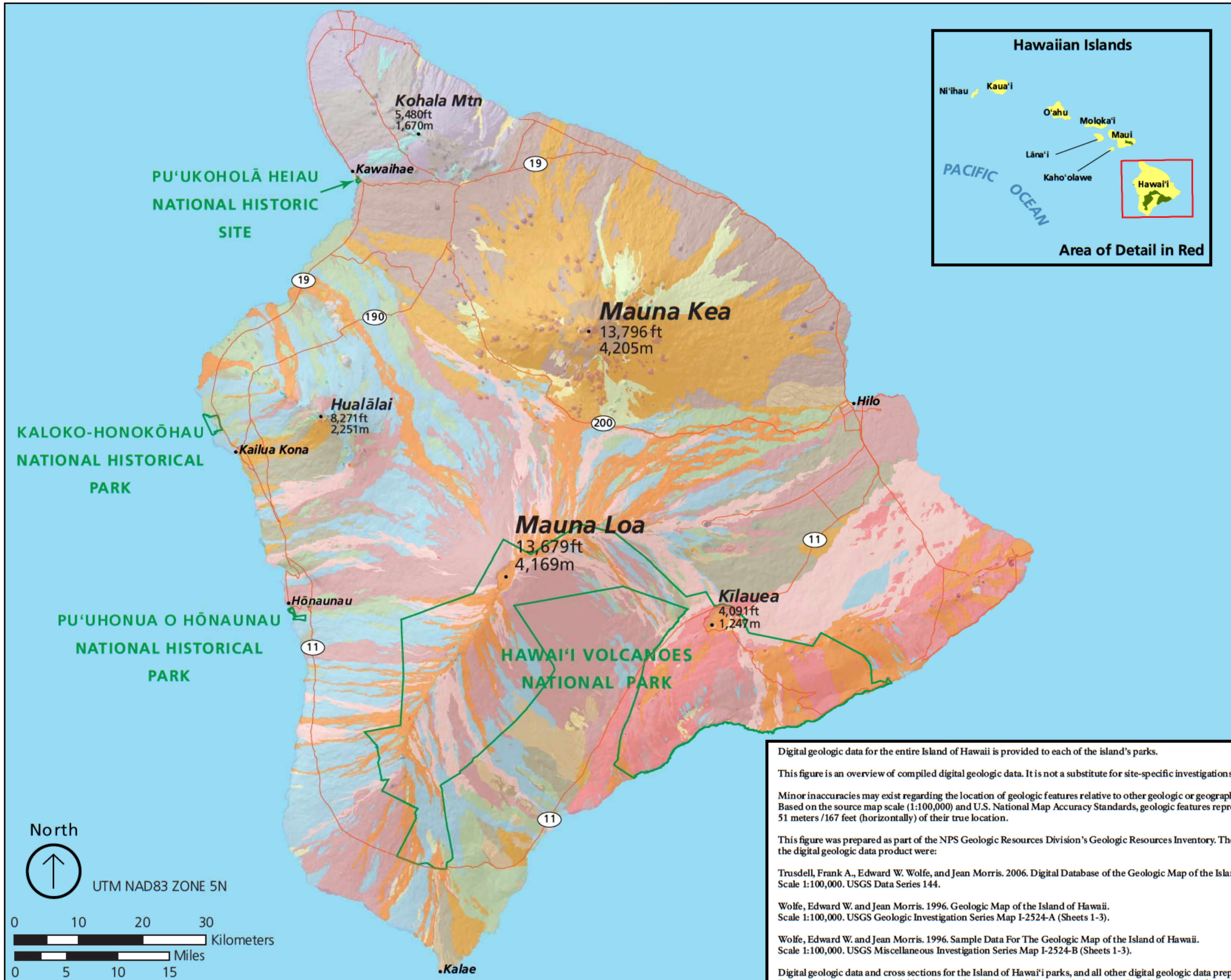
- Qac - alluvium and colluvium
- Qk - Kau Basalt, lava flow
- Qhc5 - Haualalai Volcanics, basalt, cone
- Qh5 - Haualalai Volcanics, basalt, lava flow
- Qh4 - Haualalai Volcanics, basalt, lava flow
- Qhc3 - Haualalai Volcanics, basalt, cone
- Qh3 - Haualalai Volcanics, basalt, lava flow
- Qh2 - Haualalai Volcanics, basalt, lava flow
- Qhc2 - Haualalai Volcanics, basalt, cone
- Qhc1y - Haualalai Volcanics, basalt, cone
- Qh1y - Haualalai Volcanics, basalt, lava flow
- Qh1o - Haualalai Volcanics, basalt, lava flow
- Qhc1o - Haualalai Volcanics, basalt, cone
- Qhc - Haualalai Volcanics, basalt, cone
- Qh - Haualalai Volcanics, basalt, lava flow



Produced by the Geologic Resources Inventory

April 2011

Overview of Digital Geologic Data for the Island of Hawai‘i



Digital geologic data for the entire Island of Hawaii is provided to each of the island's parks.

This figure is an overview of compiled digital geologic data. It is not a substitute for site-specific investigations.

Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the figure. Based on the source map scale (1:100,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 51 meters /167 feet (horizontally) of their true location.

This figure was prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source maps used in creation of the digital geologic data product were:

Trusdell, Frank A., Edward W. Wolfe, and Jean Morris. 2006. Digital Database of the Geologic Map of the Island of Hawai‘i. Scale 1:100,000. USGS Data Series 144.

Wolfe, Edward W. and Jean Morris. 1996. Geologic Map of the Island of Hawaii. Scale 1:100,000. USGS Geologic Investigation Series Map I-2524-A (Sheets 1-3).

Wolfe, Edward W. and Jean Morris. 1996. Sample Data For The Geologic Map of the Island of Hawaii. Scale 1:100,000. USGS Miscellaneous Investigation Series Map I-2524-B (Sheets 1-3).

Digital geologic data and cross sections for the Island of Hawai‘i parks, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Natural Resource Information Portal: https://irma.nps.gov/Reference.mvc/Search. (Enter “GRI” as the search text and select the park name from the unit list.)

Map Unit Properties Table: Kaloko-Honokōhau National Historical Park

Colored rows indicate geologic units mapped within Kaloko-Honokōhau National Historical Park.

Age		Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure and Recreation	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Geologic Significance
QUATERNARY (Pleistocene and/or Holocene)	Surficial Deposits	*caldera:* Qcal *fill:* Qf *landslide deposits:* Qls *alluvium and colluvium:* Qac *eolian deposits:* Qe *slope deposits:* Qsd	Unit Qcal encompasses caldera wall rocks, where several formations may be exposed, but are too thin to show in plan view at common map scales. Unit Qf contains man-made breakwater structures along coastlines. Unit Qls includes blocks of soil, basalt, and vegetation that slid from steep valley walls. Unit contains angular breccia and shattered basalt blocks as much as 1 m (3 ft) in diameter in a muddy orange matrix locally. Unit Qac contains sand and gravel derived from lava flows and pyroclastic flows distributed by seasonal streams and mass wasting; some eolian and coralline beach sand present locally. Unit Qe includes very fine-grained to fine-grained dune sand of dark-gray, unconsolidated, crossbedded, reworked ash deposits. Unit Qsd contains interlayered fluvial, eolian, debris-flow, and tephra-fall (volcanic) deposits.	Low	With exception of unit Qcal, deposits are unconsolidated, and units Qcal, Qls, Qac, and Qsd are associated with steep slopes, and should be avoided for heavy infrastructure, wastewater treatment facilities, and recreation infrastructure.	Units are prone to mass wasting and erosion, especially where present on a slope. Seismicity of magnitude greater than 4 or 5 may trigger mass movements in these units.	Sedimentary units may contain recent plant and animal remains.	Unit may contain ancient Hawaiian artifacts. Unit Qls contains a landslide from 1868 (Wood Valley) that buried a village and killed 31 people.	Sand, ash, gravel	Units form substrate for many habitats throughout the mapped area.	Units record landscape evolution following volcanic eruptions, as well as anthropogenic alterations to the landscape.
	Regional Ash Deposits	Pāhala Ash Qpha	Unit is widespread, and contains deeply weathered ash deposits that are commonly altered to yellowish-orange to reddish-brown clay minerals and hydrated oxide residues. Unit commonly crops out in k īpukassurrounded by younger lava flows and interlayered ashes. Unit ranges in thickness from a few centimeters to as much as 15 m (45 ft).	Moderately low	Easily weathered ash material may form clays that pose infrastructure challenges, especially if shrink-and-swell clays are present. Avoid areas close to active flows. Clays may provide slippery recreational base.	Ash horizons weathered to clay may pose rockfall hazard, if overlain by intact rock and exposed on even moderate slopes.	None documented	Weathered clay may have provided materials for domestic use. Thick ash units may have provided abrasive material.	Clay, hydrated oxides.	Unit contributes to fertile volcanic soils.	Origin is likely reworked and primary tephra-fall deposits; distribution is linked to prevailing wind direction. Age dates range from 31,000 to 23,000 years old. Important marker unit.
	Kīlauea Volcano	Puna Basalt *spatter or tuff cones:* Qpc5, Qpc4y*, Qpc4o, Qpc3*, Qpc2* *lava flows:* Qp5, Qp4, Qp3, Qp2, Qp1y, Qp1o, Qp4y, Qp4o *littoral cones:* Qpld5, Qpld4o, Qpld3 *tephra deposits:* Qpa5,Qpa4o, Qpa2	Various subunits contain spatter or tuff cones (Qpc5, Qpc4y, Qpc4o, Qpc3, Qpc2), lava flows (Qp5, Qp4, Qp3, Qp2, Qp1y, Qp1o), littoral deposits in cones (Qpld5, Qpld4o, Qpld3), and tholeiitic basalt tephra deposits (Qpa5, Qpa4o, Qpa2). Compositions vary between tholeiite and transitional alkalic basalt. Cones consist of spatter and scoria deposited during brief explosive eruptions. Lava flows vary from vesicular p āhoehoe to blocky ʻaʻā. Littoral deposits are localized along the coast where lava flows entered the water and fragmented during explosive cooling. Deposits include ash, lapilli, and bombs of dense, gray basalt. Tephra deposits include widespread ash and lapilli.	Moderately low to moderate	Avoid areas of active volcanism for all major infrastructure and recreation.	Unit is strongly associated with potentially dangerous, active volcanism (lava flows and pyroclastic events). Recently emplaced lava may still be hot, causing burns. Unit also subject to lava tube collapse and steam explosions. Noxious fumes may still issue from these units.	Tree molds and other casts from recent lava flows and ash falls.	A party of Hawaiian warriors was killed during a pyroclastic surge-steam explosion southwest along Kīlauea Crater. Human footprints are preserved in the Keanakākoʻi Ash.	Olivine, plagioclase, pyroxene, basalt, ash, cinders	Very recent volcanic activity provides habitat for early, opportunistic species on Kīlauea Volcano.	These units record accurately dated, recent volcanic activity around Kīlauea Volcano.
	Kīlauea Volcano	Hilina Basalt *lava flows:* Qhi	This unit crops out in kīpukas surrounded by younger units, and contains lava flows and intercalated ash deposits. Approximately 95% of the exposed unit is pāhoehoe and ʻaʻā lava flows at least 300 m (1,000 ft) thick. Compositions are mostly tholeiite. Ash layers can reach 4 m (13 ft) in thickness, with vitric to lithic textures. Unit weathers to reddish-brown clays.	Moderately low to moderate	Suitable for most infrastructure, unless close to active flows of Kīlauea Volcano. ʻAʻā can be a suitable trail base if trail is properly constructed.	Ash horizons weathered to clay may pose rockfall hazard if overlain by intact rock and exposed on even moderate slopes.	None documented	Thick ash units may have provided abrasive material.	Olivine, plagioclase, pyroxene, ash, basalt.	Weathered areas of this unit support soil and palagonite horizons.	Unit predates unit Qpha and is older than 23,000 years old.
	Mauna Loa Volcano	Kaʻū Basalt *spatter or tuff cones:* Qkc5, Qkc4, Qkc3, Qkc2, Qkc1, Qkc, Qkc1y, Qkc1o *lava flows:* Qk5, Qk4, Qk3*, Qk2*, Qk1, Qk, Qk1y*, Qk1o *littoral cones:* Qkld5, Qkld4, Qkld3, Qkld2, Qkld1 *tephra deposits:* Qka3	Unit comprises various subunits, including spatter or scoria cones, lava flows, littoral cone deposits, and tephra deposits. Spatter cones (Qkc5, Qkc4, Qkc3, Qkc2, Qkc1, Qkc, Qkc1y, Qkc1o) contain spatter and minor scoria in steep-sided mounds as large as tens to hundreds of meters in diameter. Lava flows consist of pāhoehoe and ʻaʻā (Qk5, Qk4, Qk3, Qk2, Qk1, Qk, Qk1y, Qk1o). Pāhoehoe flows contain vesicular basalt, in long, narrow flows confined by self-made levees. Cone-building littoral deposits (Qkld5, Qkld4, Qkld3, Qkld2, Qkld1) formed during steam explosions, as lava reached the ocean and violently cooled. These deposits contain dense glassy basalt as ash, lapilli, and bombs. Tephra deposits (Qka3) contain ash and lapilli that were blown chiefly toward the southwest by prevailing winds.	Moderately low to moderate.	Unit is associated with recent volcanism on an active volcano, and should be avoided for major infrastructure. Avoid unstable areas and areas with sharp substrates for recreation infrastructure.	Unconsolidated cinder cones may be unstable on slopes. Lava tubes may collapse in lava flows within this unit. Sharp fragments are present throughout these units.	Tree molds and other casts from recent lava flows and ash falls.	Formation of these units was witnessed and revered by ancient Hawaiians.	Olivine, plagioclase, pyroxene, ash, basalt, cinders	Very recent volcanic activity provides habitat for early, opportunistic species on Mauna Loa volcano.	Deposits and flows are historically datable from Mauna Loa volcano, and formed during brief eruptive spurts. Ash and pyroclastic deposits can record prevailing wind and current directions. Radiocarbon ages from unit Qk range from 31,000 to 10,000 years old.

Colored rows indicate geologic units mapped within Kaloko-Honokōhau National Historical Park.

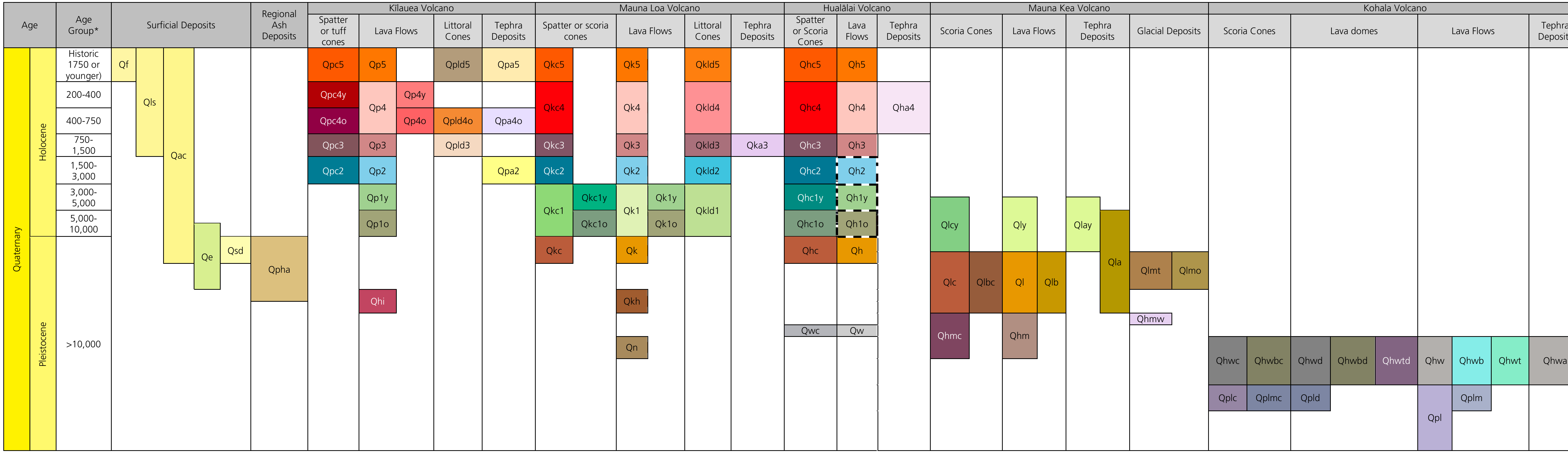
Age		Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure and Recreation	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Geologic Significance
QUATERNARY (Pleistocene and/or Holocene)	Mauna Loa Volcano	Kahuku Basalt *lava flows:* Qkh Nīnole Basalt *lava flows:* Qn	Unit Qkh contains tholeiitic basalt flows from Mauna Loa that resemble Ka'ū basalt but underlie unit Qpha. Unit Qn contains lava flows of tholeiitic basalt that crop out as erosional remnants. Unit contains deep lava flow canyons partially filled by ash and younger lava flows. Flows of this unit are thin pāhoehoe and 'a'ā, interlayered with some basaltic tuff, dikes, and ash beds.	Moderate	Heterogeneous nature of this unit may render it unstable on slopes; canyons should be avoided for infrastructure and recreation. 'A'ā can be a suitable trail base if trail is properly constructed.	Unit Qn is associated with steep canyon slopes and landslides, which may have contributed to canyon growth.	Tree molds and other casts from recent lava flows and ash falls.	Canyons may have been preferred travel routes.	Olivine, plagioclase, ash, basalt.	None documented	Unit Qkh is useful in relative age dating, predates unit Qpha and the 31,000 year old part of unit Qk. Unit Qn is 300,000 to 100,000 years old, as determined by Potassium-Argon radiometric dating.
	Hual	Hualālai Volcanics basalt member *spatter or scoria cones:* Qhc5, Qhc4, Qhc3, Qhc2, Qhc1y, Qhc1o, Qhc *lava flows:* Qh5, Qh4, Qh3, Qh2*, Qh1y*, Qh1o*, Qh *tephra deposits:* Qha4	Units include spatter or scoria cones (Qhc5, Qhc4, Qhc3, Qhc2, Qhc1y, Qhc1o, Qhc), lava flows (Qh5, Qh4, Qh3, Qh2, Qh1y, Qh1o, Qh), and tephra deposits (Qha4). Compositions range from alkalic and transitional basalt to hawaiite. Vent deposits comprise small spatter cones with larger scoria and spatter cones deposited locally by short extrusive events. Flows are pāhoehoe and/or 'a'ā. Unit Qha4 contains weakly consolidated light-gray tuff, with lapilli and large alkalic basalt, tholeiitic basalt, and trachyte blocks. *Qh1o, Qh1y, and Qh2 are mapped within Kaloko-Honokōhau National Historical Park.	Moderately low to moderate.	Unconsolidated tephra and cinders should be avoided for major infrastructure. Suitable for most recreation unless fresh and sharp fragments exist.	Unconsolidated units may fail on even moderate slopes during heavy precipitation or seismic events. Recent flows may pose hazard for lava tube collapse.	Tree molds and other casts from recent lava flows and ash falls.	Formation of younger units may have been viewed by ancient Hawaiians.	Olivine, pyroxene, plagioclase, basalt, ash, cinders, trachyte, hawaiite	Unit provides substrate for upland, scrubby vegetation locally.	Unit Qha4 records steam-driven explosive events at 700 years before present. Flows are at least as old as 13,000 years, but historic activity was as recent as A.D. 1800–1801.
		Hualālai Volcanics Wa'awa'a Trachyte Member *spatter or scoria cones:* Qwc *lava flows:* Qw	Units consist of a scoria cone (Qwc) and a lava flow (Qw). Unit Qwc contains loose fragments of pumice, obsidian, some sheared trachyte flows, and altered volcanic rocks. Unit Qw contains sheared flows of trachyte, now slightly altered and appearing light brown.	Moderately low to moderate	Friable nature of this unit renders it relatively unsuitable for major infrastructure, especially if exposed on steep slopes. Suitable for most recreation unless sharp fragments exist.	Unit may be extensively altered locally and unstable on steep slopes.	Tree molds and other casts from recent lava flows and ash falls.	Obsidian and pumice may have provided tool and trade material.	Biotite, plagioclase, pyroxene (phenocrysts are rare), trachyte, obsidian, pumice.	Unit provides substrate for upland, scrubby vegetation locally.	Unit is Potassium-Argon radiometric age-dated to approximately 105,000–100,000 years old. Unit is present as xenoliths elsewhere on Hualālai.
	Mauna Kea Volcano	Laupāhoehoe Volcanics younger volcanic rocks member *scoria cones:* Qlcy *lava flows:* Qly *tephra deposits:* Qlay Laupāhoehoe Volcanics older volcanic rock member *scoria cones:* Qlc, Qlbc *lava flows:* Ql, Qlb *tephra deposits:* Qla	The younger volcanic rocks member contains scoria cones (Qlcy), lava flows (Qly), and tephra deposits (Qlay). Unit Qlcy consists of scoria cones, containing vesicular lapilli and lesser amounts of ash and bombs with local agglutinated spatter. Fresh exposures are dark gray to red. Unit Qly deposits are predominantly 'a'ā and blocky 'a'ā, with some localized pāhoehoe flows. Flow surfaces are brown to gray with dense, massive, gray interiors. Surfaces are relatively fresh. Unit Qlay contains lapilli and ash distributed by pyroclastic flow. Exposures are black where fresh, and yellowish-brown where weathered. The older volcanic rock member contains scoria cones (Qlc, Qlbc), lava flows (Ql, Qlb), and tephra deposits (Qla). Compositions range from hawaiite and mugearite to benmoreite. Units are more weathered than their younger counterparts and may be mantled by eolian, tephra-fall or colluvial deposits.	Moderately low to moderate.	Unconsolidated areas of these units should be avoided for major infrastructure. Blocky 'a'ā flows can be suitable trail bases if properly constructed; avoid young flows for recreation infrastructure.	Younger units contain sharp 'a'ā lava flows. Weathered units may contain clay that can cause unsafe conditions, and slip surfaces if overlain by intact rock, posing landslide hazards.	Tree molds and other casts from recent lava flows and ash falls.	None documented	Hawaiite, mugearite, benmoreite, ash, basalt, cinders	Weathered units contribute to fertile, clayey soil in localized areas.	Potassium-Argon radiometric ages for older Laupāhoehoe Volcanics range from 65,000 to 14,000 years old.
QUATERNARY (Pleistocene)		Laupāhoehoe Volcanics Mākanaka Glacial Member *glacial deposits:* Qlmt, Qlmo	Glacial till unit (Qlmt) contains massive, poorly consolidated diamict, with angular to subrounded cobbles and boulders. Some individual clasts may be larger than 2 m (7 ft) in diameter and consist of dense, light- to medium-gray hawaiite or mugearite. The matrix is gray to light yellowish brown, fine grained, and unsorted. Unit Qlmo contains unconsolidated gravel, with subrounded to rounded cobbles, and boulders of similar composition to those in unit Qlmt.	Low	Due to poor consolidation and heterogeneous nature of this unit, avoid for most major infrastructure. Jumbled nature of unit makes it an unstable trail base.	Poorly consolidated or unconsolidated parts of these units are prone to mass wasting and erosion, especially if exposed on slopes.	Some remains may be present in glacial member.	Unconsolidated parts may have provided construction material for early Hawaiians.	Cobbles, boulders.	None documented	Relative age dating of nearby flows suggests that the age of these units is between 40,000 and 14,000 years old, during the Mākanaka glaciation.

Colored rows indicate geologic units mapped within Kaloko-Honokōhau National Historical Park.

Age	Unit Name (Symbol)		Features and Description	Erosion Resistance	Suitability for Infrastructure and Recreation	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Geologic Significance
QUATERNARY (Pleistocene)	Mauna Kea Volcano	Hāmākua Volcanics basalt member *spatter or scoria cones:* Qhmc *lava flows:* Qhm Hāmākua Volcanics Waihū Glacial Member *glacial deposits:* Qhmw	The basalt member is divided into scoria cones (Qhmc) and lava flows (Qhm). Compositions range from alkalic and transitional basalt, to minor hawaiite, tholeiitic, and strongly undersaturated basalt. Unit Qhmc contains vesicular lapilli, ash, and bombs with surfaces locally mantled by tephra-fall and eolian deposits. Unit Qhm contains ‘a‘ā and pāhoehoe with fresh dark-gray exposures and weathered yellowish-brown to brown exposures. Flows are locally mantled by eolian, tephra-fall, and colluvial deposits. Unit Qhmw contains glacial drift of diamict and gravel. Much of the unit is massive to crudely layered with subangular to subrounded cobbles and boulders of Hāmākua lava flow remnants encased in an indurated, gray to yellowish-reddish-brown, unsorted matrix. Layered, sorted gravel lenses and tongues are present locally.	Moderately low to moderate	Avoid weathered and/or unconsolidated units for heavy infrastructure. ‘A‘ā can be a suitable trail base if trail is properly constructed.	Intense erosion and mass wasting associated with these units. Areas exposed on slopes are vulnerable to fail during moderate seismic events.	Some remains may be present in glacial member.	Unconsolidated parts may have provided construction material for early Hawaiians.	Olivine, plagioclase, clinopyroxene, basalt, cinders, ash.	Weathered areas contribute to primitive, fertile soils when combined with mantling younger deposits.	Unit includes an unmapped glacial till of the Pōhakuloa Glacial Member on the flanks of Mauna Kea. Potassium-Argon radiometric age dates range from 250,000–200,000 years to 70,000–65,000 years. Unit Qhmw is poorly constrained by Potassium-Argon radiometric age-dating at 150,000–70,000 years old.
QUATERNARY (Pleistocene)	Kohala Volcano	Hāwī Volcanics *scoria cones:* Qhwc, Qhwbc *lava flows:* Qhw, Qhwb, Qhwt *lava domes:* Qhwd, Qhwbd, Qhwtd *tephra deposits:* Qhwa	Unit is divided into scoria cones (Qhwc, Qhwbc), lava domes (Qhwd, Qhwbd, Qhwtd), lava flows (Qhw, Qhwb, and Qhwt), and tephra deposits (Qhwa). Compositions range from hawaiite, mugearite, and benmoreite to trachyte. Flows are light to medium-gray and blocky. Flows may be as much as 30 m (100 ft) thick. Tephra-fall deposits flank cinder cones with ash and lapilli clasts. Most of this unit is mantled by younger tephra-fall and eolian deposits.	Moderately low to moderate	Suitable for most infrastructure and recreation except where steep slopes are present.	Units are prone to rockfall if undercut and/or exposed on steep slopes. Areas exposed on slopes are vulnerable to failure during moderate seismic events.	None documented	Unconsolidated parts may have provided construction material for early Hawaiians. Hāwī is an ancient royal site.	Trachyte with strongly aligned plagioclase crystals in a finer matrix, benmoreite, hawaiite, mugearite.	Unit supports a wide variety of vegetation and associated animal habitat. Weathering contributes material to fertile soils.	Potassium-Argon radiometric ages for lava flows range from 230,000 to 120,000 years old.
QUATERNARY (Pleistocene)	Kohala Volcano	Pololū Volcanics *scoria cones:* Qplc, Qplmc *lava flows:* Qpl, Qplm *lava domes:* Qpld	Unit contains basalt scoria cones (Qplc), lava flows (Qpl), and a lava dome (Qpld), as well as mugearite scoria cones (Qplmc) and lava flows (Qplm). Basalt ranges in composition from tholeiitic, through transitional, to alkalic (hawaiite) with textures varying from porphyritic to aphyric. Flows are mostly ‘a‘ā, but most surface expression has been muted by weathering and erosion. Most surfaces are mantled by eolian and younger tephra-fall deposits.	Moderately low to moderate	Avoid areas especially rich in clay or weathered on slopes for major infrastructure. ‘A‘ā can be dangerous trail base if trail is not properly constructed, but weathering has dulled the sharpness of many areas.	Weathered ash horizons may pose rockfall hazard if overlain by intact rock and exposed on even moderate slopes.	None documented	None documented	Olivine, plagioclase, clinopyroxene, mugearite, basalt, cinders.	Extensively weathered, this unit provides material for fertile volcanic soils locally. Unit supports forests on the windward side of the island.	Potassium-Argon radiometric age dating suggests the magma evolved from tholeiitic basalt to transitional and alkalic basalt 400,000 years ago and erupted until at least 250,000 years ago. Older lava flows are as old as 700,000 years and are the oldest exposed rocks on Hawai‘i. All exposed Pololū Volcanics strata were emplaced during the Brunhes Normal-Polarity Chron (they are younger than 780,000 years old).

Map Unit Correlation Table: Kaloko-Honokōhau National Historical Park

Geologic units mapped within Kaloko-Honokōhau National Historical Park are indicated with a dashed outline. Colors match those on the Overview of Digital Geologic Data. Modified from U.S. Geological Survey Data Series 144 (Trusdell et al. 2006).



* = Ages in "Age Group" are in radiocarbon years and have not been calibrated to calendar years (Wolfe and Morris 1996a). Ages in calendar years are older than radiocarbon years.
The discrepancy increases as ages increase. For example, radiocarbon ages of a few hundred or few thousand years may only differ by tens or hundreds of years, respectively. Ages of tens of thousands of years can differ by a few thousand years.

The Map Unit Properties Table contains additional information regarding the age of geologic units.

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005).

ʻaʻā. Hawaiian term for lava flows characterized by a rough, jagged, "clinkery" surface.

alcyonarian. Describes coral of the subclass Alcyonaria, colonial forms with eight pinnate tentacles, and endoskeleton, and eight complete septa.

alkalic. Describing a rock that contains more sodium and potassium than is average for the group of rocks to which it belongs.

alluvium. Stream-deposited sediment.

aquifer. A rock or sedimentary unit that is sufficiently porous to hold water, sufficiently permeable to allow water to move through it, and currently saturated to some level.

ash (volcanic). Fine pyroclastic material ejected from a volcano (also see "tuff").

basalt. A dark-colored, often low-viscosity, extrusive igneous rock.

basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.

basin (sedimentary). Any depression, on a scale ranging from continental to local, into which sediments are deposited.

basinite. A very fine-grained basalt.

beach. A gently-sloping shoreline covered with sediment, commonly formed by action of waves and tides.

bedrock geology. The geology of underlying solid rock, as it would appear with the sediment, soil, and vegetative cover stripped away.

benmoreite. A silica-saturated igneous rock intermediate between mugearite and trachyte.

bioherm. A mound-like, dome-like, lens-like, or reef-like mass of rock built up by sedentary organisms, composed almost exclusively of their calcareous remains, and enclosed or surrounded by rock of different lithology.

block. A pyroclast ejected in a solid state, having a diameter greater than 64 mm (2.5 in.).

bomb. A pyroclast ejected while viscous, and shaped while in flight, greater than 64 mm (2.5 in.) in diameter and usually hollow or vesicular inside.

breccia (volcanic). A coarse-grained, generally unsorted volcanic rock, consisting of partially-welded, angular fragments of ejecta, such as tuff or ash.

buried rift zone. An area of extension and volcanic vents subsequently buried and obscured by later lava flows.

calcareous. Describing rock or sediment that contains calcium carbonate.

caldera. A large bowl- or cone-shaped summit depression in a volcano, formed by explosion or collapse.

cinder. A glassy pyroclastic fragment that falls to the ground in an essentially solid condition.

cinder cone. A conical hill formed by the accumulation of cinders and other pyroclasts, normally of basaltic or andesitic composition.

clastic. Describing rock or sediment made of fragments of pre-existing rocks.

clinopyroxene. A group name for pyroxene minerals crystallizing in the monoclinic system. Important rock-forming minerals; common in igneous and metamorphic rocks.

colluvium. A general term applied to any loose, heterogeneous, and incoherent mass of rock fragments deposited by unconcentrated surface runoff or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides.

conglomerate. A coarse-grained, generally unsorted sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).

continental crust. The crustal rocks rich in silica and alumina that underlie the continents; ranging in thickness from 35 km (22 mi) to 60 km (37 mi) under mountain ranges.

continental drift. The concept that continents have shifted in position over the Earth (see and use "plate tectonics").

convergent margin. An active boundary where two tectonic plates are colliding.

continental rifting. Process by which a region of crust undergoes extension (pulling apart), resulting in the formation of many related normal faults, and often associated with volcanic activity.

coralline. Pertaining to, composed of, or having the structure of corals.

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes, depicted in an oriented vertical plane.

crust. The Earth's outermost compositional shell, 10–40 km (6–25 mi) thick, consisting predominantly of silicate minerals of relatively low density (also see "oceanic crust" and "continental crust").

debris flow. A moving mass of rock fragments, soil, and mud, more than half the particles of which are larger than sand size.

deformation. A general term for the process of faulting, folding, and shearing of rocks as a result of various Earth forces, such as compression (pushing together) and extension (pulling apart).

dike. A tabular, discordant igneous intrusion.

dike swarms. A group of dikes in radial, parallel, or en echelon ("stepped") arrangement.

dip. The angle between a bed or other geologic surface and the horizontal.

dip-slip fault. A fault having measurable offset where the relative movement is parallel to the dip of the fault.

divergent boundary. An active boundary where tectonic plates are moving apart (e.g., a spreading ridge or continental rift zone).

driblet. Volcanic spatter.

dripstone. A general term for a mineral deposit formed in caves by dripping water.

eolian. Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "Aeolian."

eustatic. Relates to simultaneous worldwide rise or fall of sea level.

fault. A break in rock along which the two sides have moved relative to one another.

felsic. Describes an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite. Compare to "mafic."

fracture. Irregular breakage of a mineral. Any break in a rock (e.g., crack, joint, fault).

glaze. A fired, glassy surface on lava features.

hawaiite. A type of volcanic rock with a potash:soda value of less than 1:2, a moderate to high color index, and a modal composition that includes essential andesine and accessory olivine.

hermatypic. A type of reef-building coral, incapable of adjusting to aphotic conditions.

highstand. The interval of time during one or more cycles of relative change of sea level when sea level is above the shelf edge in a given local area.

hornito. A small mound of spatter built on the back of a lava flow, formed by the gradual accumulation of clots of lava ejected through an opening in the roof of an underlying lava tube.

hydrothermal alteration. Alteration of rocks or minerals by the reaction of hydrothermal water.

hot spot. A volcanic center, 100–200 km (62–124 mi) across and persistent for at least a few tens of millions of years, that is thought to be the surface expression of a rising plume of hot mantle material.

igneous. Describing a rock or mineral that originated from molten material. One of the three main classes of rock: igneous, metamorphic, and sedimentary.

inflation. Process by which a local area or flow field of pāhoehoe lava swells, as a result of injection of lava beneath its crust.

intrusion. A body of igneous rock that invades (pushes into) older rock. The invading rock may be a plastic solid or magma.

island arc. A line or arc of volcanic islands formed over, and parallel to, a subduction zone.

isostatic. Describes the condition of equilibrium, comparable to floating, of the units of the lithosphere above the asthenosphere. Crustal loading (commonly by large ice sheets or volcanoes) leads to isostatic depression or downwarping; removal of the load leads to isostatic uplift or upwarping.

isostatic response. The adjustment of the lithosphere of the Earth to maintain equilibrium among units of varying mass and density; excess mass above is balanced by a deficit of density below, and vice versa.

isotopic age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products; "absolute age" and "radiometric age" are often used in place of isotopic age but are less precise terms.

isotropy. The condition of having uniform properties in all directions.

jameo. A large collapse sink formed by structural failure of the roof of more than one level of a multi-level, lava-tube cave.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

lapilli. Pyroclastics in the general size range of 2–64 mm (0.08–2.5 in.).

lava. Still-molten or solidified magma that has been extruded onto the Earth's surface though a volcano or fissure.

lavacicle. A general term applied to nearly anything that protrudes into a lava tube.

lava tumulus. A doming or small mound on the crust of a lava flow, caused by pressure that results from the difference in the rate of flow between the cooler crust and the more fluid lava below.

lineament. Any relatively straight surface feature that can be identified via observation, mapping, or remote sensing, often reflecting crustal structure.

lithology. The physical description or classification of a rock or rock unit, based on characteristics such as its color, mineralogic composition, and grain size.

lithosphere. The relatively rigid outermost shell of the Earth's structure, 50–100 km (31–62 mi) thick, that encompasses the crust and uppermost mantle.

littoral. Pertaining to the benthic ocean environment, or depth zone between high water and low water.

lowstand. The interval of time during one or more cycles of relative change of sea level when sea level is below the shelf edge.

mafic. Describes dark-colored rock, magma, or minerals rich in magnesium and iron. Compare to "felsic."

magma. Molten rock capable of intrusion and extrusion.

magma reservoir. A chamber in the shallow part of the lithosphere from which volcanic materials are derived; the magma has ascended from a deeper source.

magnetic low. Magnetic anomaly of having particularly localized, low resistivity.

mantle. The zone of the Earth's interior between crust and core.

mantle plume. A rising pipe-shaped volume of mantle that is either abnormally hot or wet or both, such that during decompression it partially melts more than normal mantle material.

mass wasting. A general term for the downslope movement of soil and rock material under the direct influence of gravity.

mugearite. An extrusive igneous rock of the alkali basalt suite, containing oligoclase, alkali feldspar, and mafic minerals.

normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall.

oceanic crust. The Earth's crust, formed at spreading ridges that underlie the ocean basins. Oceanic crust is 6–7 km (about 4 mi) thick and generally of basaltic composition.

olivine. An olive-green mineral rich in iron, magnesium, and manganese that is commonly found in low-silica (basaltic) igneous rocks.

outer trench swell. A subtle ridge on the seafloor near an oceanic trench formed where a subducting plate begins to flex and fault into the trench.

pāhoehoe. Hawaiian term for basaltic lava characterized by a smooth, billowy, or ropy texture.

Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic periods.

patch reef. A mound-like or flat-topped organic reef, generally less than a kilometer across, isolated from other bioherms, less extensive than a platform reef, and frequently forming a part of a larger reef complex.

pendant. A solutional remnant hanging from the ceiling or wall of a cave.

permeability. A measure of the relative ease with which fluids move through the pore spaces of rocks or sediments.

phenocryst. A coarse (large) crystal in a porphyritic igneous rock.

phreatic explosion. A volcanic eruption, or explosion of steam, mud, or other material that is not incandescent; it is caused by the heating and consequent expansion of ground water by an underlying igneous heat source.

picrite. Olivine-rich basalt.

plagioclase. An important rock-forming group of feldspar minerals.

plate tectonics. The concept that the lithosphere is composed of a series of rigid plates that move over the Earth's surface above a more fluid asthenosphere.

plume. A persistent, pipelike body of hot material moving upward from the Earth's mantle into the crust.

pluton. A body of intrusive igneous rock.

plutonic. Describing igneous rock intruded and crystallized at some depth in the Earth.

porphyritic. Describing an igneous rock wherein the rock contains conspicuously large crystals in a fine-grained groundmass.

pyroclastic. Pertaining to clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent; also pertaining to rock texture of explosive origin. In the plural, the term is used as a noun.

recharge. Infiltration processes that replenish ground water.

rejuvenation. The renewal of any geologic process, such as the reactivation of a volcanic fissure.

reverse fault. A contractional, high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall (also see "thrust fault").

rift. A region of crust where extension results in formation of an array of related normal faults, commonly associated with volcanic activity.

rilles. A trenchlike or cracklike valley, commonly occurring on planetary surfaces subjected to plains volcanism; they may be irregular, with meandering courses, (sinuous rilles) or relatively straight (normal rilles).

runup. The advance of water up the foreshore of a beach or structure, following the breaking of the wave.

scoria cone. A conical volcanic feature formed by the accumulation of cinders and other pyroclasts, normally of basaltic or andesitic composition.

seafloor spreading. The process by which tectonic plates pull apart and new lithosphere is created at oceanic ridges.

seamount. An elevated portion of the sea floor, 1,000 m (3,300 ft) or higher, either flat-topped or peaked.

shield volcano. A volcano in the shape of a flattened dome, broad and low, built by flows of very fluid basaltic lava.

slump. A generally large, coherent mass having a concave-up failure surface and subsequent backward rotation relative to the slope.

spatter. An accumulation of initially very fluid pyroclasts, usually stuck together, coating the surface around a volcanic vent.

spatter cone. A low, steep-sided cone of spatter built up on a fissure or vent, usually composed of basaltic material.

speleothem. Any secondary mineral deposit that forms in a cave.

spring. A site where water issues from the surface due to the intersection of the water table with the ground surface.

squeeze-ups. A small extrusion of viscous lava from a fracture or opening on the solidified surface of a flow; caused by pressure, it may be marked by vertical grooves.

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

strike-slip fault. A fault having measurable offset, where the relative movement is parallel to the strike of the fault.

subaerial. Describes conditions and processes that exist or operate in the open air on or immediately adjacent to the land surface.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

subsidence. The gradual sinking or depression of part of the Earth's surface.

supertidal. Describes features or processes at elevations higher than normal tidal range on a give shoreface.

talus. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they are derived.

tectonics. The geological study of the broad structural architecture and deformational processes of the lithosphere and asthenosphere.

tephra. A collective term used for all pyroclastic material, regardless of size, shape, or origin, ejected during an explosive volcanic eruption.

tholeiite. A basalt characterized by the presence of orthopyroxene and/or pigeonite, in addition to clinopyroxene and calcic plagioclase.

thrust fault. A contractional dip-slip fault, having a shallow-dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall.

topography. The general morphology of the Earth's surface, including relief and locations of natural and anthropogenic features.

trace. The exposed intersection of a fault or lineation with the Earth's surface.

trachyte. A group of fine-grained, generally porphyritic, extrusive rocks containing alkali feldspar and minor mafic minerals.

transgression. Landward migration of the sea as a result of a relative rise in sea level.

trend. The direction, or azimuth, of elongation of a linear geological feature.

tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time.

vent. An opening at the surface of the Earth where volcanic materials emerge.

volcanic. Related to volcanoes. Igneous rock crystallized at or near the Earth's surface (e. g., lava).

water table. The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.

weathering. The set of physical, chemical, and biological processes by which rock is broken down.

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are current as of April 2011.

Geology of National Park Service Areas

NPS Geologic Resources Division (Lakewood, Colorado): http://nature.nps.gov/geology/

NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm

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NPS Geoscientist-in-the-parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm

Resource Management/Legislation Documents

NPS 2006 Management Policies (Chapter 4—Natural Resource Management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

NPS-75: Natural Resource Inventory and Monitoring Guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural Resource Management Reference Manual #77: http://www.nature.nps.gov/Rm77/

Geologic Monitoring Manual
R. Young, R., and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/index.cfm.

NPS Technical Information Center (Denver; repository for technical (TIC) documents): http://etic.nps.gov/

Geological Survey Websites

Hawaiian Volcano Observatory (U.S. Geological Survey): http://hvo.wr.usgs.gov/

Pacific Tsunami Warning Center (PTWC) in Ewa Beach, Hawaii (http://www.weather.gov/ptwc/)

U.S. Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geological Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

Other Geology/Resource Management Tools

Neuendorf, K. K. E., J. P. Mehl Jr., and J. A. Jackson. 2005. Glossary of geology. Fifth edition. American Geological Institute, Alexandria, Virginia, USA.

Bates, R. L., and J. A. Jackson, editors. Dictionary of geological terms. Third edition. Bantam Doubleday Dell Publishing Group, New York, New York, USA.

U.S. Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

U.S. Geological Survey Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

U.S. Geological Survey Geographic Names Information System (GNIS; search for place names and geographic features, and plot them on topographic maps or aerial photos): http://gnis.usgs.gov/

U.S. Geological Survey GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on “Map Locator”)

U.S. Geological Survey Publications Warehouse (many USGS publications are available online): http://pubs.usgs.gov

U.S. Geological Survey, Tapestry of Time (description of physiographic provinces): http://tapestry.usgs.gov/Default.html

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