National Park Service
U.S. Department of the Interior

Natural Resource Program Center

Pu‘ukoholā Heiau National Historic Site

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2011/386

ON THE COVER
Pu‘ukoholā Heiau at sunset with Mauna Kea in background (right) and Pelekane Bay in foreground. National Park Service photograph by Greg Cunningham.

THIS PAGE
Aerial View of Pu‘ukoholā Heiau and Mailekini Heiau (left) looking north towards Kawaihae Harbor and the North Kohala Coast. The gently-sloping flank of Kohala Volcano looms over the landscape. National Park Service photograph by Pierre Lesage.

National Park Service photographs courtesy Greg Cunningham (Pu‘ukoholā Heiau National Historic Site).

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

April 2011

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

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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/).

Please cite this publication as:

Thornberry-Ehrlich, T. 2011. Pu‘ukoholā Heiau National Historic Site: geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2011/386. National Park Service, Ft. Collins, Colorado.

NPS 454/107502, April 2011

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Executive Summary

This report accompanies the digital geologic map data for Pu'ukoholā Heiau National Historic Site 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 Pu'ukoholā Heiau National Historic Site inspired King Kamehameha the Great to establish a religious center there. The geology provided an ideal setting for the construction of a great "heiau" (temple) atop a prominent lava dome where the park is today. Pu'ukoholā Heiau National Historic Site strives to restore and preserve the cultural heritage permeating the heiau area, including several historic structures, a royal courtyard, and an early western-style homestead.

Geology is fundamental to the management of the scenic, cultural, and natural resources of the park. Geology influences groundwater flow, contributes to climate, weather, hydrology, and topography, which in turn affect coral reefs and other submarine habitats. In particular volcanism, volcanic deposits, and shoreline features have also strongly influenced the history of the park.

Geologic issues of particular significance for resource management at Pu'ukoholā Heiau National Historic Site include:

- Wind erosion and increased sediment load: changes in native vegetation and increased upslope development increase the amount of fine-grained, unconsolidated sediment available to prevailing winds. Fine particles, transported by the winds, are often deposited in the coastal waters near the park. This causes increased sedimentation and turbidity, affecting the submarine environment.
- Reestablishing historic landscape: the primary management goal at Pu'ukoholā Heiau National Historic Site is the restoration of the historic landscape of the time of Kamehameha the Great. To this end, park managers strive to understand how the removal of modern features, such as roads and facilities, will affect the natural environment, which is intimately tied to the historic preservation.
- Groundwater recharge: fresh water on the relatively dry leeward western coast of the Island of Hawai'i is a valuable natural resource. Within the Pu'ukoholā Heiau National Historic Site, the Waimea aquifer is brackish water. This aquifer is part of the larger West Mauna Kea aquifer system. Potable water is not available at the coast, it is only found some miles inland, where freshwater recharge can keep pace with downslope filtration. Further saltwater incursion is a possibility near coastal areas, and is among the factors limiting groundwater availability.
- Anchialine ponds: these ponds are among the most threatened ecosystems in Hawaii. The ponds are home to unusual plants and animals; at least one brackish pool exists at Pu'ukoholā Heiau National Historic Site. Water levels, temperatures, and salinity constantly vary in the anchialine ponds, because the ponds are connected to the ocean via subterranean tunnels. It is unknown how sedimentation affects the ponds.
- Coastal erosion and relative sea-level rise: coastal erosion and relative sea level rise affect parts of the shoreline at the park, potentially causing loss of cultural resources. Anthropogenic features, such as breakwaters and harbors, often exacerbate coastal erosion.
- Geologic hazards: Pu'ukoholā Heiau National Historic Site is underlain by weathered volcanic flows from the dormant Mauna Kea and Kohola volcanoes (e.g. geologic map units Qhm, Qhw, and Qpl), but volcanism remains a distant possibility in the area. Due to its low-lying coastal location, Pu'ukoholā Heiau National Historic Site is susceptible to inundation during tsunamis. Tsunami modeling takes into account seismic events, bathymetry, storm issues, and wind and rain conditions. Seismicity is a concern throughout the Pacific basin. Earthquakes occur frequently on the Island of Hawai'i, 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 cultural resources of the park are closely linked to geologic features and processes. This theme is a potential interpretive topic. The process of active volcanism at Kīlauea creates hazy "vog", comprised of acidic aerosols, unreacted sulfur gases, volcanic ash, and other fine particulate matter. On certain days, this vog obscures the landscape at the park. The offshore marine environment in the park area hosts important benthic habitats, which onshore activities may negatively impact.

Knowledge of the physical properties of the different geologic units mapped at Pu'ukoholā Heiau National Historic Site contributes to understanding and managing the natural and cultural 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 Pu‘ukoholā Heiau National Historic Site (geologic map units Qf, Qhm, Qhwb, and Qpl) 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 13 and 14.

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: Greg Cunningham (Pu‘ukoholā Heiau National Historic Site) for providing photographs and reviewing a draft of the report. 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 U.S. Geological Survey.

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 web site (http://www.nature.nps.gov/geology/inventory/).

Park Setting

Regional Information

Puʻukoholā Heiau National Historic Site covers 34.90 ha (86.24 ac) (24.67 ha [60.95 ac] of which are Federal) on the relatively undeveloped northwestern shore of the Island of Hawaiʻi, approximately 56 km (35 mi) north of Kailua-Kona in the district of south Kohala (figs. 1-4). A major development, Kawaihae Harbor, is adjacent to the north of the park to, and the popular Samuel M. Spencer Beach Park is at the southern boundary. Along the western boundary, off the western coast of the Island of Hawai'i, there is a broad, submerged reef. The eastern boundary is just east of highway 270. The Island of Hawaiʻi 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 Hawaiʻi lies southeast of Maui, separated by the 48-km-wide (30-mi) ʻAlenuihāhā Channel. It is currently the southernmost landmass of the Hawaiian island chain.

The Island of Hawaiʻi 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 Puʻukoholā Heiau National Historic Site

The seemingly barren landscape at Puʻukoholā Heiau National Historic Site sustained an early Hawaiian religious settlement, hosting the "Temple on the Hill of the Whale" (see front cover and inside cover) during the rise to power of King Kamehameha the Great. The Puʻukoholā Heiau was a "luakini" (used for human sacrifice) and was dedicated to the king's personal war god, Kūkāʻilimoku.

Around 1790, these early inhabitants built large heiau (the temples of Puʻukoholā and Mailekini onshore, and one offshore) at the site, for ceremonies related to war. Facets of their religion were defined in the "kapu" (laws of conduct). In old Hawaii, 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. Puʻukoholā Heiau National Historic Site preserves some of the few remaining religious sites from old Hawaii.

Also preserved at the national historic site are the remains of John Young's homestead—the first western style structure in Hawaii. Young was a stranded British sailor who advised King Kamehameha during the King's quest to extend his royal reign over all Hawaiian Islands.

The founding of the unified Hawaiian kingdom is directly associated with the Puʻukoholā Heiau structure.

Puʻukoholā Heiau National Historic Site illustrates the balance and spiritual connections between the early Hawaiians and their surrounding natural environment, as well as the history of the Hawaiian Islands. Remnants of early inhabitation include a massive stone heiau (Puʻukoholā) built in 1790-91, two other smaller heiau (Mailekini and the submerged Hale o Kapuni), a rumored smaller fourth structure, and a royal courtyard area known as Pelekane.

Puʻukoholā Heiau National Historic Site also protects scenic shore areas along the Kohola coast. Pelekane, the small bay at the park, is known for black-tipped reef shark sightings. Offshore from Pelekane Bay is the larger Kawaihe Bay. This bay area provides habitat for a variety of marine life, including an extensive coral reef system, sea turtles, monk seals, and migratory birds such as the Pacific golden plover (kōlea, *Pluvialis fulva*). Within nearby Kawaihae Harbor is a coral reef area; other coral reefs fringe the shore in the park vicinity. The area is also near the Hawaiian Islands Humpback Whale National Marine Sanctuary waters.

The establishment of Puʻukoholā Heiau National Historic Site on August 17, 1972 was intended to preserve "... the historically significant temple associated with Kamehameha the Great and the property of John Young who fought for Kamehameha the Great during the period of his ascendancy to power." In addition to cultural and historic features, there are also notable natural resources that are priorities for resource managers at the park. Preserving precontact (e.g., prior to indigenous Hawaiians' contact with Europeans) historical contexts (including the viewshed, heiaus, homestead 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/puhe, the Puʻukoholā Heiau National Historic Site website.

Geologic Setting

The Island of Hawaiʻi 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 Lōʻihi seamount, which is approximately 35 km (22 mi) to the southeast of the Island of Hawaiʻi. 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 Hawaiʻi, are composites of more than one volcano.

The landmass of the Island of Hawaiʻi contains five large volcanic centers: Mauna Kea, Kohala, Hualālai, Mauna Loa, and Kīlauea (fig. 1). The latter two are among the most active volcanoes in the world (see Hawaiʻi Volcanoes National Park report; Thornberry-Ehrlich 2009). Puʻukoholā Heiau National Historic Site is located at a junction of the slopes of Mauna Kea, Kohala Mountain, on lava flows from both volcanoes (geologic map units Qhm, Qhwb, and Qpl; see Overview of Geologic Data). Mauna Kea last erupted about 3,600 years ago, forming the Laupāhoehoe Volcanics (Qlmt and Qlmo), which overlie the shield and postshield Hāmākua Volcanics (Qhmc, Qhm, Qhmw). Kohala is the oldest volcano on the Island of Hawaiʻi. Kohala lava flows within the park are at least 120,000 years old.

Other NPS areas along the Kona coast preserve lava flows from other volcanoes. Basalts from Hualālai are mapped within Kaloko-Honokōhau National Historical Park (Thornberry-Ehrlich 2011a). Basalts from Mauna Loa are mapped within Puʻuhonua o Hōnaunau National Historical Park (Thornberry-Ehrlich 2011b).

The landscape within Puʻukoholā Heiau National Historic Site consists of the relatively stark, rugged basalt flows that form broad, sloping benches or terraces along the shore. The large heiau caps a highpoint (a lava dome rise of approximately 15 m, or 50 ft) within park boundaries and dominates the view from the shore landward (see front cover and fig. 3). This site was presumably chosen because of its elevated position on Puʻukoholā, and the visual alignment with the Kona Coast and neighboring island of Maui. The park overlooks Kawaihae Bay and Pelekane Beach (see inside front cover).

Sparse beach areas include intertidal to supertidal accumulations of perched coralline sediments, from storms and repeated marine highstands throughout the Holocene. Weathered pāhoehoe lava stretches and narrow mud flats separate sandy beach areas. Natural features include ephemeral streams, brackish anchialine ponds, tidepools, and coral reefs. Soil development is limited.

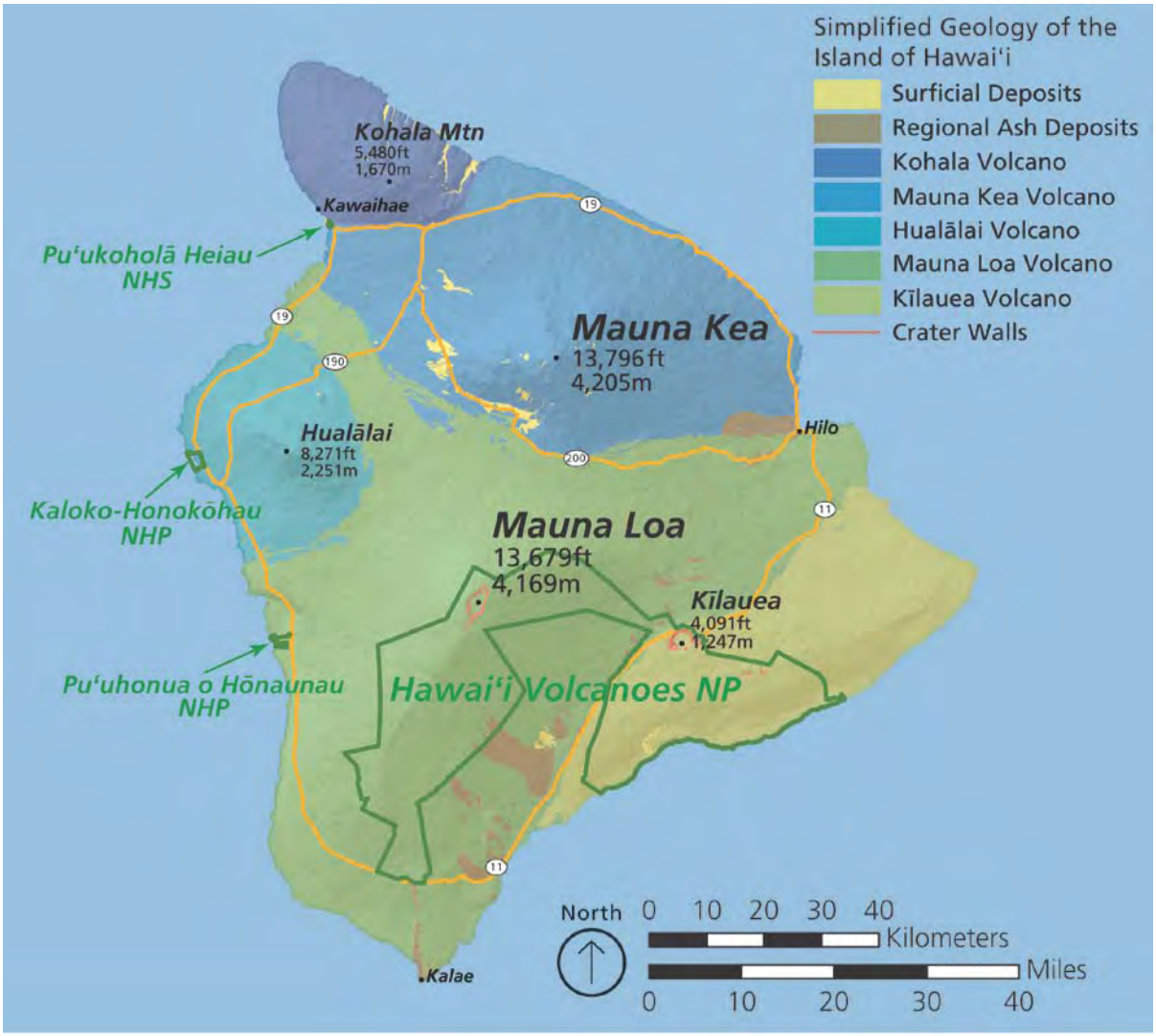


Figure 1. Shaded relief map of the Island of Hawai'i. Peaks of the island's five volcanoes are indicated. Different colors show the extent of volcanic deposits from the five volcanic centers. National Park Service areas are outlined in green. The Kona coast stretches from Kawaihae to Kalae on the west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

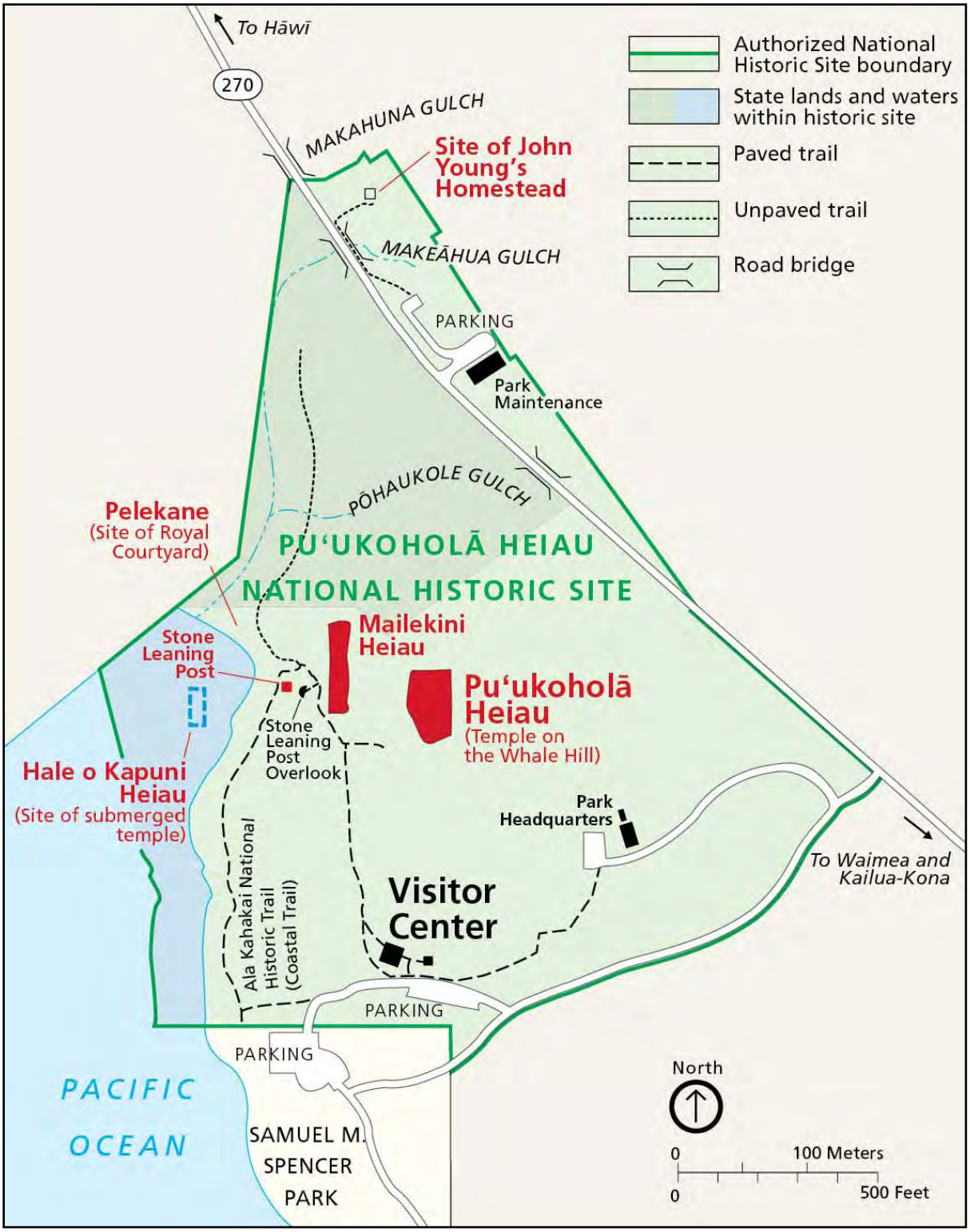


Figure 2. Map of Pu'ukoholā Heiau National Historic Site. National Park Service map.

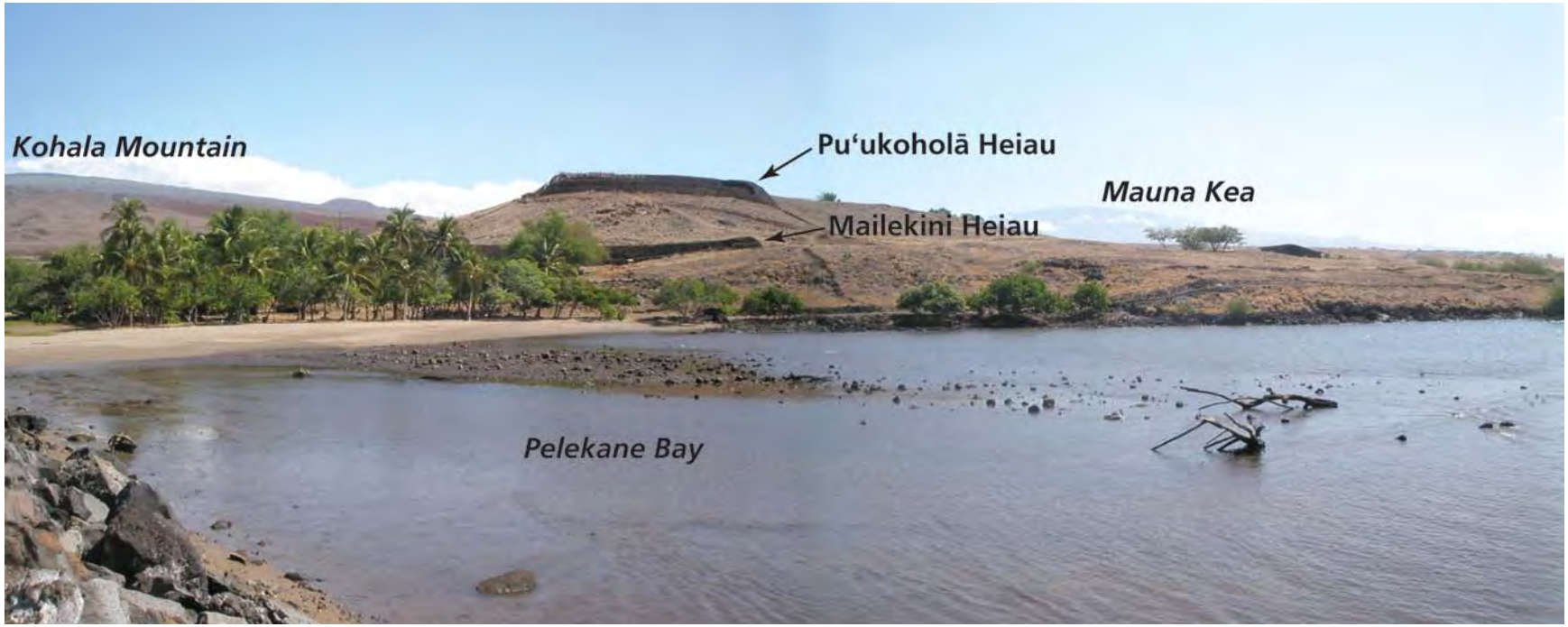


Figure 3. Panoramic view of Pu'ukoholā Heiau with Pelekane Bay in foreground and Mauna Kea in right background (about 46 km [29 mi.]) southeast of the park. Kohala Mountain looms over the left background. National Park Service photograph courtesy of Greg Cunningham (Pu'ukohol Historic Site)

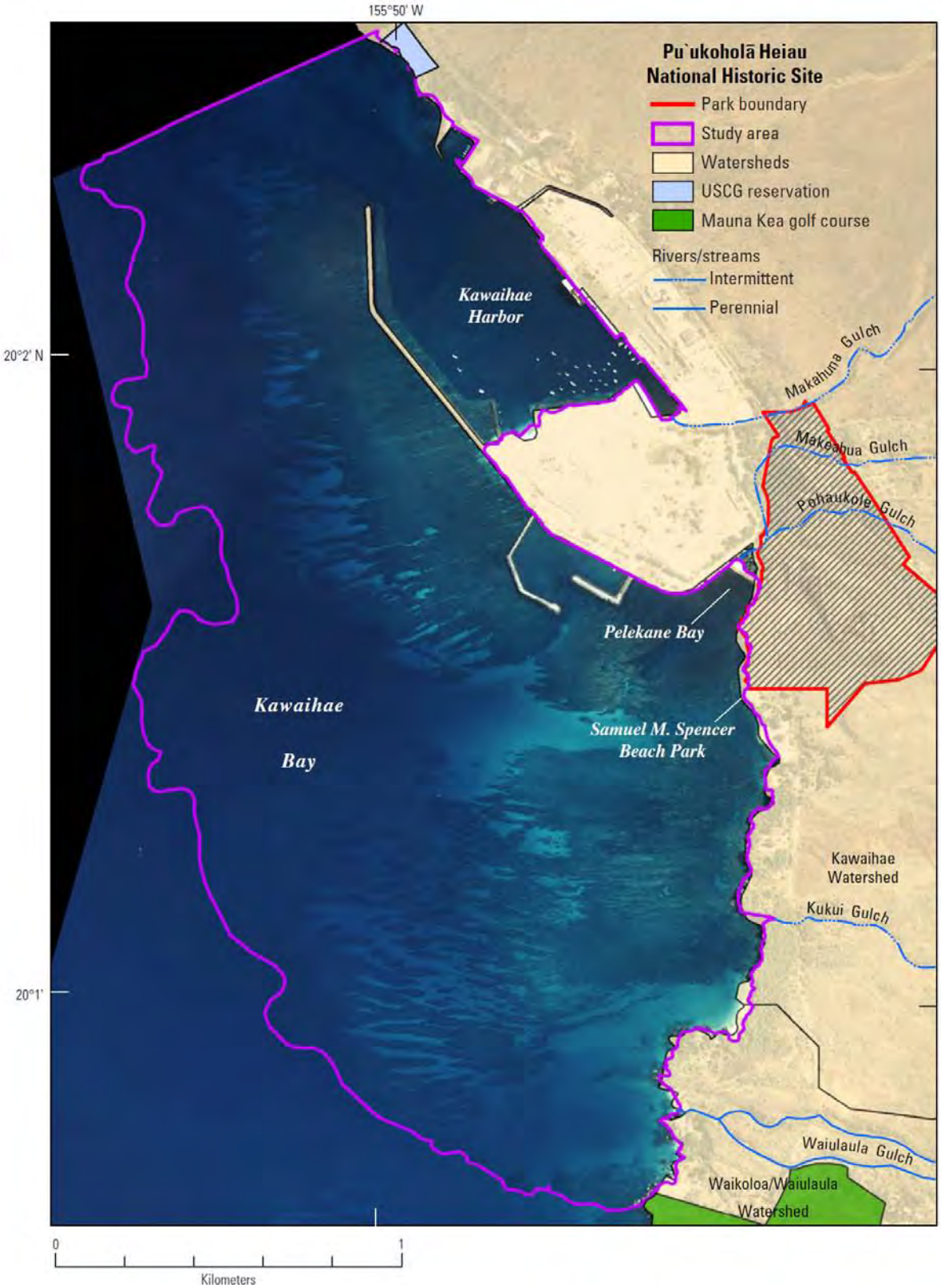


Figure 4. Aerial photomosaic of Pu'ukoholā Heiau National Historic Site and surrounding geographic features. U.S. Geological Survey graphic from Cochran et al. (2006).

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Pu'ukoholā Heiau National Historic Site 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 Hawai'i (fig. 1). In addition to Pu'ukoholā Heiau National Historic Site are Kaloko-Honokōhau National Historical Park (Thornberry-Ehrlich 2011a) and Pu'uhonua o Hōnaunau National Historical Park (Thornberry-Ehrlich 2011b). These three units have similar geologic issues, features, and processes.

The primary resource management emphasis at Pu'ukoholā Heiau National Historic Site is restoration and preservation of the historic heiau setting established during the time of King Kamehameha the Great. However, resource management objectives also take into account the inherent natural resources of the park. Natural resource management goals at Pu'ukoholā Heiau National Historic Site include reducing the impact of park activities on the offshore environment while complementing the cultural landscape preservation (Cochran et al. 2007). 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 Pu'ukoholā Heiau National Historic Site in the following reference:

Richmond, B. M., S. A. Cochran, and A. E. Gibbs. 2008. Geologic Resource Evaluation of Pu'ukoholā Heiau National Historic Site, Hawai'i; Part I, Geology and coastal landforms. Open-File Report 2008-1190. U.S. Geological Survey, Reston, Virginia, USA. (http://pubs.usgs.gov/of/2008/1190/).

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

Cochran, S. A., A. E. Gibbs, and J. B. Logan. 2007. Geologic resource evaluation of Pu'ukoholā Heiau National Historic Site, Hawai'i; Part II: Benthic habitat mapping. Scientific Investigations Report SIR 2006-5254. U.S. Geological Survey, Reston, Virginia, USA. (http://pubs.usgs.gov/sir/2006/5254/).

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

Wind Erosion and Increased Sediment Load

In the arid environment of the park area, changes to existing native vegetation can increase the amount of unconsolidated material available to prevailing winds. Cattle grazing upslope of the park disturbs vegetation (Hoover and Gold 2006). Once disturbed, stabilizing vegetation is slow to reestablish. Increased upslope development has disturbed vegetation causing exposure of bare sediment and soil. In this way, the developments facilitate wind erosion—a major resource management concern at Pu'ukoholā Heiau National Historic Site. Lancaster (2009) describes aeolian features and processes in addition to providing guidance and methodology for monitoring the following vital signs: 1) frequency and magnitude of dust storms, 2) rate of dust deposition, and 3) rate of sand transport.

An increase in erosion onshore leads to increased sedimentation and turbidity in the submarine habitat offshore (Rutherford and Kaye 2006). Coastal waters adjacent to the site are impacted heavily by sediment trapped in Pelekane Bay (Kawaihae harbor); however, the offshore area of the park is one of the best-developed shallow-water coral reef systems along the west coast of the Island of Hawai'i (Hoover and Gold 2006). In the Pu'ukoholā Heiau National Historic Site area, sediments typically travel downslope only during infrequent seasonal rainstorms and flash floods, but if prevailing winds can entrain fine sedimentary material, wind erosion becomes a consistent source of fine-grained sediment. Increased sedimentation and turbidity can negatively impact marine environments, such as coral reefs. Sediment can mantle the living reef, blocking sunlight and inhibiting photosynthesis, in addition to causing other problems (Susan Cochran, geologist, U.S. Geological Survey, written communication, November 2010).

Reestablishing Historic Landscape

The main management goal of Pu‘ukoholā Heiau National Historic Site is the restoration of the historic scene of the park back to the time of Kamehameha the Great, with as little impact to the historic sites as possible (National Park Service 2006). In 1997, geophysical methods such as magnetic, electromagnetic, and ground-penetrating radar surveys were employed at Pu‘ukoholā Heiau National Historic Site to determine potential locations of possible buried heiau, both on and offshore. These techniques measure the differences in geophysical properties in the substrate and are preferable to invasive excavating and core hole boring; they could be used in the future to determine locations of other cultural resources. Magnetic surveys measure local disturbances in the earth's magnetic field. Electromagnetic surveys measure differences in terrain conductivitiy, which is affected by substrate porosity, water content, and groundwater chemistry. Ground-penetrating radar measures reflections caused by materials having contrasting electrical properties (Llopis and Sharp 1997). Many times, lava rocks have different geophysical signatures than surrounding sediments, and since the ancient Hawaiians built many of their structures using lava rocks, these techniques delineate potential areas where ancient artifacts may be found (Llopis and Sharp 1997).

In a 2004 environmental assessment (Tetra Tech 2004), the National Park Service explored the possibility of removing, to the greatest extent possible, modern structures; these include visitor contact and administrative facilities, which obscure the historic scene and viewscape of the large heiau on the "Hill of the Whale," at Pu‘ukoholā Heiau National Historic Site. Such restoration strikes a balance among visitor use, cultural access (for native Hawaiians), and historic landscape integrity.

The environmental assessment also identified geologic resources among the potential impact topics. Geologic features at Pu‘ukoholā Heiau National Historic Site include topography, sediments, stratigraphy, seismic hazards, earthworks, slope stability, mineral resources, unique landforms, and hydrogeology (Tetra Tech 2004). These geologic features would be impacted by the restoration plans, which include constructing a new visitor center, access road, and parking lot (north of the new Spencer Beach Road), as well as new interpretive trails. In addition, the plans include burial of utility lines (water pipes, power lines, telephone lines, etc.) and removal of existing trails and structures.

Hale o Kapuni Heiau, an ancient offshore structure used for shark feeding and worship, was buried by flood deposits resulting from active fluvial processes during periods of high rainfall (Clark 1985; Richmond et al. 2008). Two intermittent streams, Makeāhua and Pohuakole, converge near the park's northern boundary. The first stream originally entered the ocean further north, but was rerouted for the construction of Kawaihae Harbor (Greene 1993; Richmond et al. 2008). As evidenced by the presence of slightly rounded boulders in their channels, these streams are capable of delivering coarse sediment to the coast during intense flooding events (Richmond et al. 2008). Active streams can lead to increased gullying and surface erosion of the park uplands. In addition to further obscuring the heiau, increased sedimentation could have adverse effects on nearby coral reefs(Richmond et al. 2008). It is unknown if the submerged and buried structure could be uncovered permanently for interpretive purposes.

Groundwater Recharge

The availability of important, fresh groundwater resources on the Island of Hawai‘i 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.

Aquifer characteristics vary, based on geologic features and structures (especially rock permeability), as well as recharge rates. Nearly all the aquifers on the Island of Hawai‘i 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; Hoover and Gold 2006). Pu‘ukoholā Heiau National Historic Site is above the Waimea Aquifer. This aquifer is part of the larger West Mauna Kea aquifer system. Significant amounts of groundwater discharge along the coastline within the park (fig. 5); however, groundwater flows have declined significantly over at least the last 16 years (Hoover and Gold 2006).

The basal aquifer in the Hāmākua geologic unit (geologic map units Qhmc and Qhm, see map unit properties table) contains brackish water more than 6 km (4 mi) inland of the coast. At higher elevations, withdrawal of potable water is possible due to increased levels of freshwater recharge from precipitation. Further saltwater intrusion is a possibility near coastal areas, and is among the factors limiting freshwater groundwater availability at Pu‘ukoholā Heiau National Historic Site. Within the park, water levels vary between 0.4 to 1.4 m (1.4 to 4.5 ft) above mean sea level. Discharge is always brackish and non-potable (Tetra Tech 2004).

Another factor limiting freshwater supply at the park is its location on the leeward side of the island, which 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 (Davis and Yamanaga 1968; 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 weathered pāhoehoe lava flows in the park area.

Within the park area, only ephemeral gulches carry runoff after heavy seasonal storms (Tetra Tech 2004).

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 2006). Failure to limit the amount of discharge loss may lead to loss of aquatic habitat, disruption of anchialine ponds (see below), and saltwater intrusion into fresh groundwater lenses (Rutherford and Kaye 2006). Hoover and Gold (2006) 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.

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 the Pu‘ukoholā Heiau National Historic Site, for 1968, 1969, 1971, 1977, 1986, and 1995. Wells were drilled within and near the park in 1961 and 1963 (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 to the ocean at the surface, but are connected hydrologically with the ocean through a permeable aquifer system (Oki et al. 1999). Water levels and salinity in the ponds vary constantly. (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).

Excess sediment (due to enhanced erosion in the watershed) may be the most significant threat to anchialine pools within the park (Hoover and Gold 2006). Because relatively little information is available for Hawaiian watersheds on water quality within the pools, or on erosion and sediment transport, it is unknown how sedimentation affects these anchialine ponds (Rutherford and Kaye 2006; Hoover and Gold 2006). It is also unknown whether upslope development and upgradient groundwater withdrawals (increasing since the early 1990s) may affect groundwater flow, water levels, and salinity of the anchialine ponds (Hoover and Gold 2006).

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. Though nearly destroyed by developers along the leeward coasts, a few brackish pools remain in the park area. One such pool is located in the northern end of the park and may contain sensitive species, as well as exotic fish (Tetra Tech 2004; Hoover and Gold 2006). Two major pools within the park are in ephemeral stream channels and thus are unusual in that they experience occasional flushing by high runoff events. There are rare wetlands associated with the large anchialine pool/estuarine pool in Makeāhua Stream that are threatened by the same potential for sediment loading, as well as accumulation of metals and toxic compounds (Hoover and Gold 2006).

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.

The recent installment of a septic leach field at the park may provide a source of nutrients to the groundwater, which may in turn introduce toxic contaminants to the anchialine pools (Hoover and Gold 2006). Inventory of the anchialine pools at Pu‘ukoholā Heiau National Historic Site would help determine the extent to which protection and restoration of the resources is necessary.

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, tsunami inundation, sea-level rise, and seismic activity (Richmond et al. 2008). Local slopes and geologic setting must be taken into account, to accurately determine hazard potential for a specific area such as Pu‘ukoholā Heiau National Historic Site (fig. 6) (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

Pu‘ukoholā Heiau National Historic Site is underlain by lava flows from Kohola and Mauna Kea volcanoes, both of which are considered dormant (see Map Unit Properties Table and Overview of Geologic Data). According to Mullineaux et al. (1987), the risk of volcanic eruption or lava inundation at the park is low. However, Hualālai Volcano, which last erupted in 1801, is still considered to be active and flows from this volcano could impact the park.

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).

Another potential issue associated with active volcanism in the vicinity of Pu‘ukoholā Heiau National Historic Site 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 western Kohala coast of the Island of Hawai‘i is somewhat buffered from prevailing tradewinds by Mauna Loa, Mauna Kea, Kohala, 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.

Coastal Erosion and Relative Sea-Level Rise

Myriad factors are involved in coastal evolution and erosion, including coastal slope, geomorphology, rates of shoreline change, tidal range, wave height, and relative sea-level change. Average beach erosion rates in Hawaii

are approximately 15-30 cm/year (0.5-1 ft/year) (Richmond et al. 2001).

Erosion of the coast may cause cultural resource loss, instability of lava benches, inundation, damage to shallow coral reefs, and increased sediment load. Coastal slope 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. The coastline at the park varies from gently sloping, partially sand-covered lava benches, to higher lava domes.

Coastal geomorphology and geology, in particular the strength of the land materials, influences the relative erodibility of a specific section of shoreline. Locally, coral reefs, embayments, anchialine ponds, and anthropogenic development (e.g. harbors and breakwaters) modify the shoreline (Richmond et al. 2001; Cochran et al. 2007). Shoreline structures often exacerbate coastal erosion by changing a condition of shoreline erosion into one of beach loss (Richmond et al. 2001). In Pu‘ukoholā Heiau National Historic Site, some of the anthropogenic structures that have changed the shoreline include the harbor at Kawaihae, breakwaters, causeways, and shoreline roads. Geologic map unit Qf, mapped within the park, is artificial fill used to alter the shoreline. Construction of the harbor may also have contributed to the submergence of Hale o Kapuni Heiau (National Park Service 2009b).

Tidal range and wave height are linked to inundation hazards (Rutherford and Kaye 2006). Although not sheltered from south swell or hurricane waves, the Island of Hawai‘i’s western coast is relatively sheltered from the high wave energies found elsewhere in the state. 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 (fig. 7). 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 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 Hawai‘i and the loading effect lessens with distance from the active volcanism (Richmond et al. 2001).

Because Pu‘ukoholā Heiau National Historic Site is relatively distant from volcanic centers that are still considered active, crustal loading is a less significant factor in local relative sea level rise.

Human activity, particularly related to 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). For low-lying coastal areas such as Pu‘ukoholā Heiau National Historic Site, with maximum elevations of less than 15 m (50 ft), sea level rise will cause increased saltwater encroachment and coastal inundation (Rutherford and Kaye 2006) and could will eventually threaten many of the park’s historical structures, parking facilities, fishponds, associated wetlands, and other coastal features (Richmond et al. 2008). 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 risk of degradation from coastal flooding include the Ala Kahakai National Historic Trail. At Pelekane, the trail currently is subject to wave spray and overwash. Visible erosion occurs along stretches of the trail with root exposures on the seaward side. Coastal hazards also threaten Pelekane Bay and the remaining archaeological sites. Models predict nearly complete submersion of the beach at high tide, if current erosion and sea level rise continue. Pelekane Beach, created from carbonate spoil from reef dredging during the construction of the harbor, is accreting at an average rate of 0.4 m/year (1.4 ft/year) (Vitousek et al. 2009).

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.

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 Hawaii. This study includes detailed recommendations for resource managers, including expertise, personnel, and equipment needed, approximate cost, and labor intensity.

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, Hawaiʻi and 61 deaths (Pacific Disaster Center 2008). A tsunami generated by a magnitude 9.0 earthquake off the coast of Japan struck Puʻuhonua o Hōnaunau and Kaloko Honokōhau national historical parks on March 11, 2011. This tsunami caused extensive damage to both parks (National Park Service 2011; Thornberry-Ehrlich 2011a, 2011b).

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 (Oʻahu) 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.

Although undamaged by the March 11, 2011 tsunami, Puʻukoholā Heiau National Historic Site could be at risk for serious damage should another tsunami strike the western side of Hawaiʻi. Tsunami damage may also have contributed to the submergence of Hale o Kapuni Heiau (National Park Service 2009b).The park has a camera installed for monitoring tsunami activity. The park is attempting to film tsunami events, after receiving a warning from the PTWC or civil defense (Rutherford and Kaye 2006).

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 Puʻukoholā Heiau National Historic Site (fig. 8) (Richmond et al. 2001). Hawaiian seismicity is closely linked with volcanism, as small earthquakes tend to

accompany eruptions and subsurface magma movement within the currently active volcanoes.

Though not as frequent, earthquakes can also arise due to plate tectonic processes. This non-volcanic seismicity corresponds to areas of structural weakness, often deep within Earth's crust, such as faults. Large earthquakes have occurred locally (magnitude 6.5 in 1929, and magnitude 6.9 in 1951) (Walker 1999). On October 15, 2006, the Kīholo Bay earthquake, with an epicenter less than 50 km (30 mi) away, caused severe damage to the heiaus within the park; the earthquake manifested as partial collapse and bulging of the unmortared rock structures (Medley and Zekkos 2007; Richmond et al. 2008). Over the past 150 years, some of the larger Hawaiian earthquakes (magnitudes from 6 to 8) have caused loss of life and extensive damage to buildings, roads, and homes (Rutherford and Kaye 2006). Earthquakes are of particular importance, because of their role as tsunami triggers.

At Pu'ukoholā Heiau National Historic Site, additional effects of earthquakes, such as ground rupture, uplift, subsidence, mudflows, liquefaction, and landslides could negatively impact the park's cultural resources and setting. As experienced in 2006, large earthquakes could shift or damage historic structures and artifacts. The 2006 earthquake caused liquefaction and lateral spreading to Kawaihae Harbor (Richmond et al. 2008).

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 Hawai'i (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.

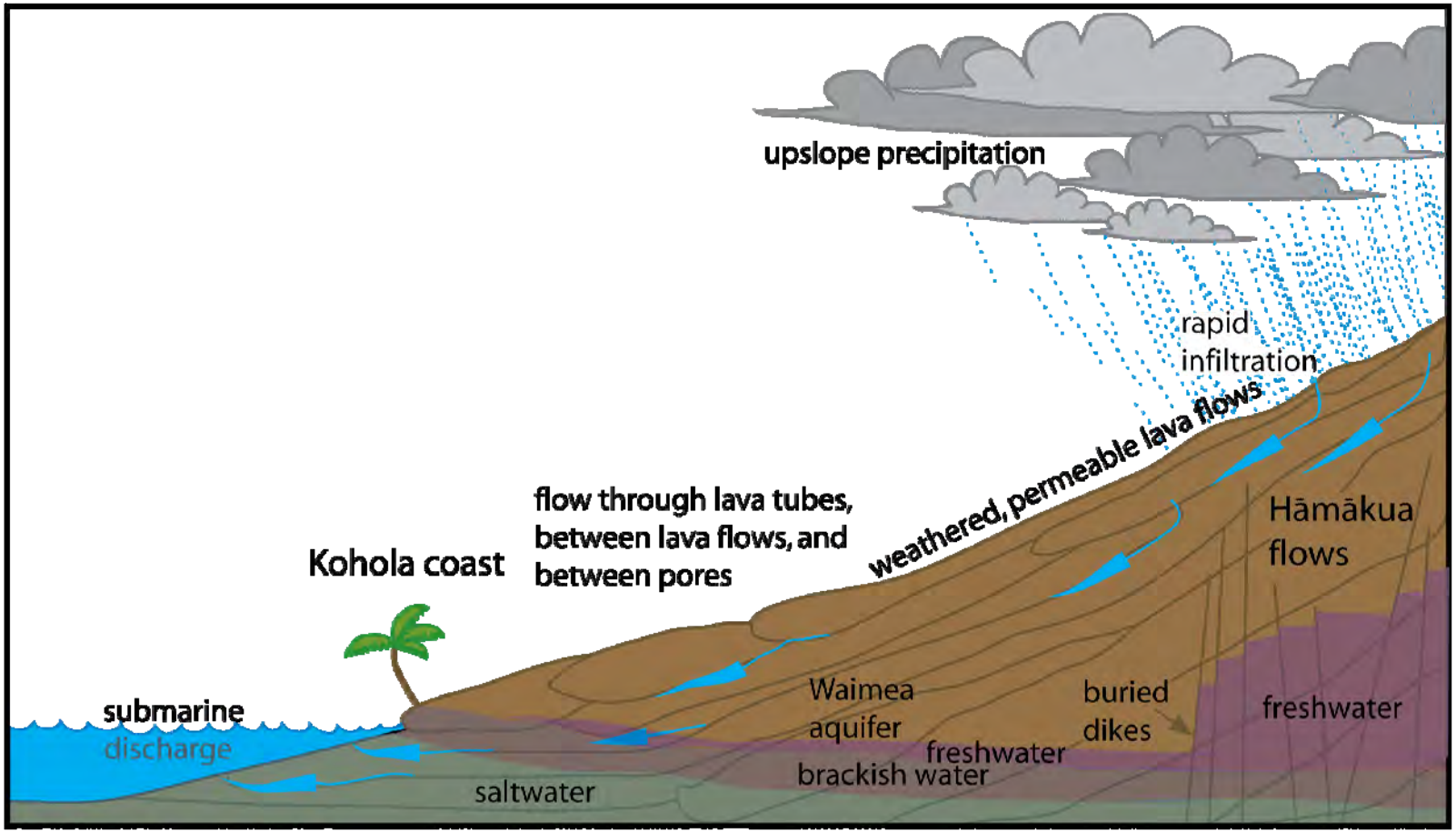


Figure 5. Diagrammatic model of precipitation-fueled submarine groundwater discharge along the Kohola coast in Hawai'i, and the regional groundwater flow system near Pu'ukoholā Heiau National Historic Site. Graphic is not to scale, and is vertically exaggerated. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), based on information from figure 8 of Oki et al. (1999).

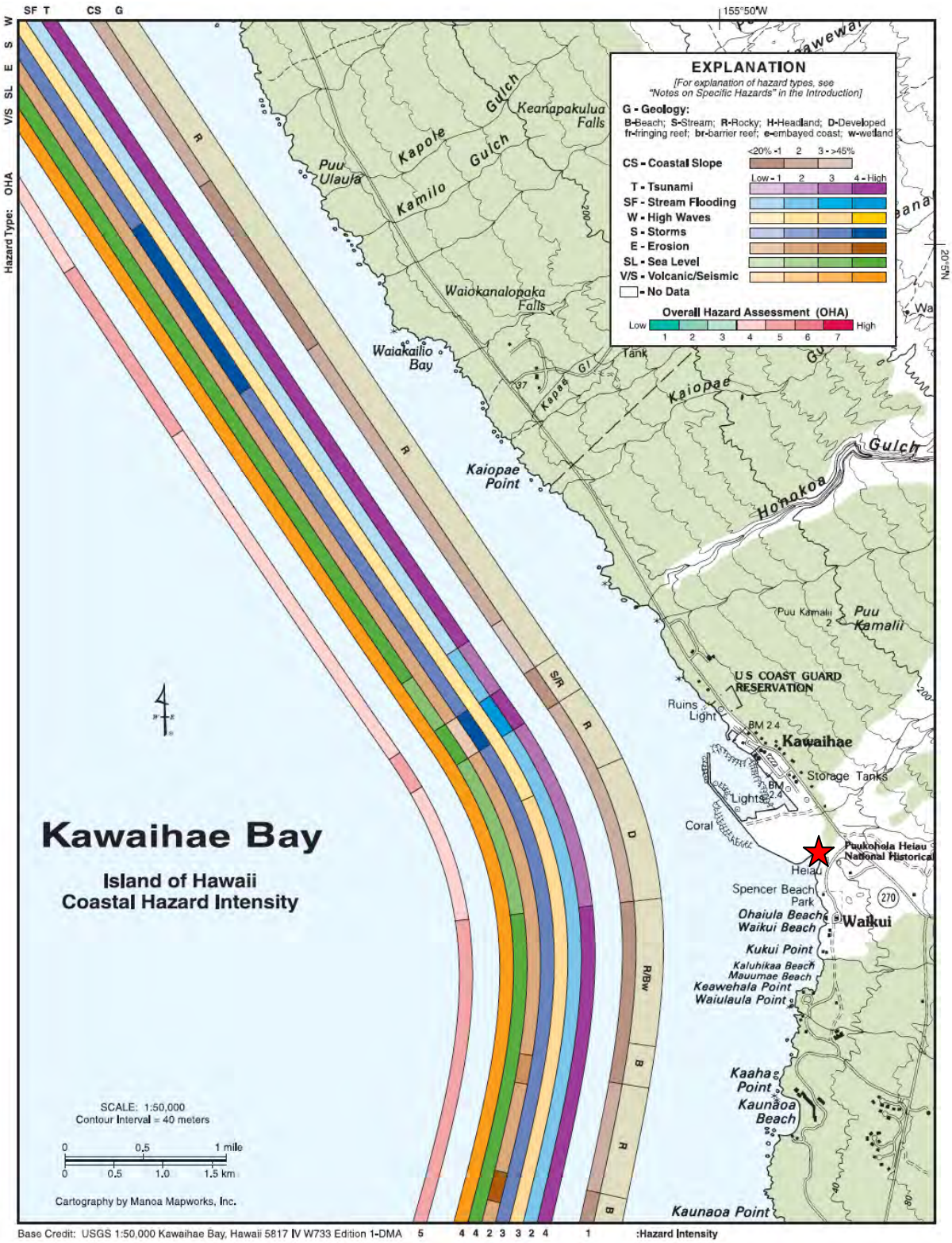


Figure 6. Coastal hazard intensity map for Puʻukoholā Heiau National Historic Site (red star). U.S. Geological Survey graphic from Fletcher et al. (2002).

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.

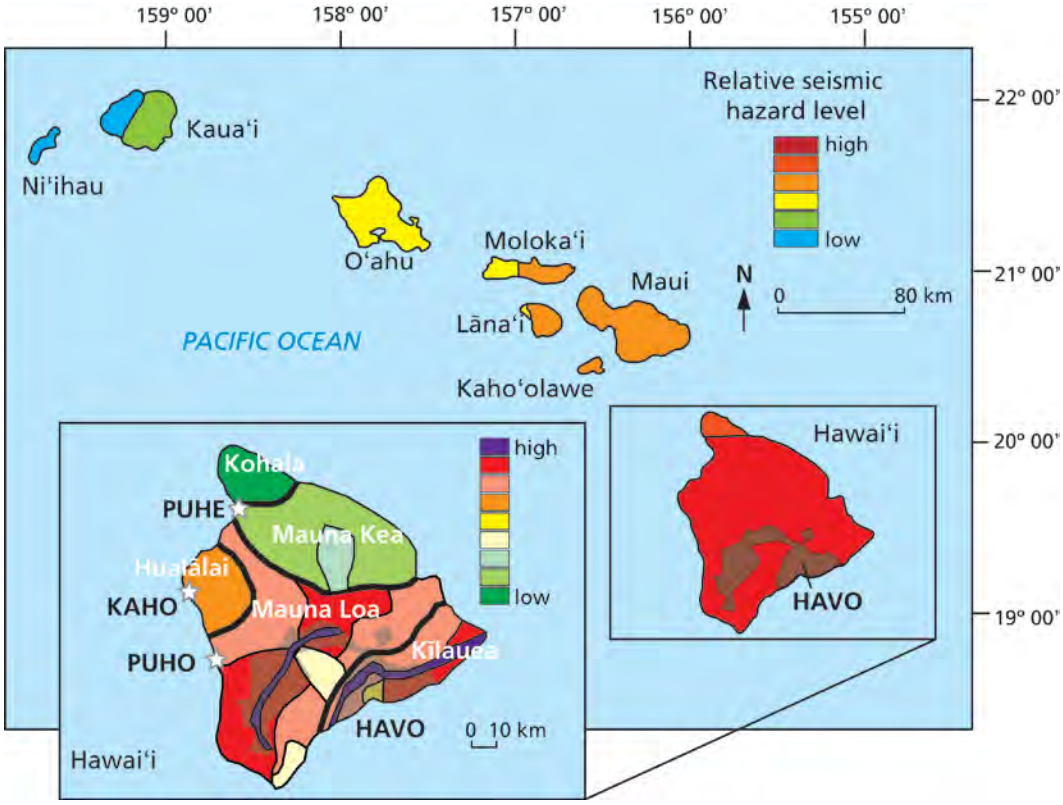


Figure 8. Earthquake hazard zones for the major Hawaiian Islands. White stars indicate park locations on the Island of Hawai‘i enlargement (PUHE: Pu‘ukoholā Heiau National Historic Site; KAHO: Kaloko-Honokōhau National Historical Park; PUHO: Pu‘uhonua o Hōnaunau National Historical Park; HAVO: Hawai‘i 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 Pu'ukoholā Heiau National Historic Site.

Coastal Landforms

According to Richmond et al. (2008), two types of shoreline exist at Pu'ukoholā Heiau National Historic Site: rocky shoreline and beach. The rocky shoreline at the park exhibits low-lying basalt, scattered boulders, and assorted debris. The surface is mostly bare, unvegetated basalt.

Pelekane Beach, a small, intertidal barrier beach, occurs at the north park boundary (figs. 4 and 9). This beach is approximately 1 to 2 m (3 to 6 ft) high and forms the seaward margin of a small coastal plain. On the other side of the beach is a broad, gently sloping reef flat that is largely covered with sediments. The beach formed where two ephemeral streams, Makeāhua and Pohaukole, converge. Landward of the beach, a semi-permanent pond has developed along the northern park boundary, occupying the streambed (Richmond et al. 2008).

Construction of Kawaihae Boat Harbor in the late 1950s modified the coastline north of the park, and changed the drainage pattern of Makeāhua and Pohuakole streams (Greene 1993; Hoover and Gold 2006; Richmond et al. 2008). The beach sediment supply was likely disturbed upon construction of the harbor (Richmond et al. 2008), and that may contribute to beach habitat destruction. Makeāhua Stream was redirected around the harbor to the south, to its current discharge point at Pelekane Beach; sediments discharged from the stream have caused accretion of beach sediments and shoaling of Pelekane Bay (Hoover and Gold 2006). The original breakwater construction included dredging of an area of pristine reef in Kawaihae Bay, and construction of an extensive breakwater system (Hoover and Gold 2006). The harbor includes a breakwater, jetty, and riprap.

Submarine Habitats

The U.S. Geological Survey mapped the underwater environment adjacent to Pu'ukoholā Heiau National Historic Site and beneath Kawaihae Bay, using color aerial photography, Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) bathymetric data, georeferenced underwater video, and still photography (Gibbs et al. 2004; Cochran et al. 2007). The National Oceanic and Atmospheric Administration (NOAA) established benthic habitat standards used by the mappers. This scheme uses the following basic attributes to delineate 29 different habitats at Pu'ukoholā Heiau National Historic Site: 1) the major structure or substrate, 2) dominant structure, 3) biological cover, 4) percentage of biological cover on the substrate, and 5) the geographic zone of the habitat location (figs. 10 and 11).

Submarine habitats offshore of Pu'ukoholā Heiau National Historic Site include a nearshore, coralline, algae-covered reef platform, a distinct series of spurs and grooves normal to the shoreline, and an extensive aggregate reef. Some individual and aggregated patch reefs exist between the shore and the fore reef. The spur and groove morphology, supporting a diverse assemblage of coral species, results in a relatively unique environment along the Kona Coast (Gibbs et al. 2004). Nearly half of the submarine area offshore of Pu'ukoholā Heiau National Historic Site consists of live, accreting coral structures. The dominant coral species is *Porites lobate*, which can thrive in high wave environments. Coral diversity increases behind the main harbor breakwater, due to its buffering effect (Cochran et al. 2007).

The park boundaries do not extend into the marine environment; however, of concern to park management are the potential downslope impacts of onshore activities (Cochran et al. 2007). Anthropogenic activities, such as dredging in the 1950s to create Kawaihae Harbor, construction of the surrounding causeways and revetment wall (using coral rubble), and blasting of the reef near Pelekane to create a smaller harbor have caused damage to the submarine environment. Changes in water circulation patterns cause increased turbidity (Cochran et al. 2007).

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. The study includes detailed recommendations and methodologies for resource managers.

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. Historic structures within the park were constructed utilizing a plentiful building stone on a volcanic island—boulders of basalt originally erupted from Mauna Kea or Kohala Volcano. There are three primary temples within Pu'ukoholā Heiau National Historic Site: Pu'ukoholā Heiau, Mailekini Heiau, and Hale o Kapuni Heiau.

The eponymous cultural feature of the park, Pu'ukoholā Heiau, was constructed in 1791 atop the park's primary topographic feature, the "hill of the whale" (see front and inside cover and fig. 12). The site is underlain by lava

flows from Mauna Kea volcano (geologic map unit Qhm). Tetra Tech (2004) suggests the elevated topography results from a coastal lava dome. The visual alignment of the site with the Kona Coast and Maui as well as its elevated topography made it an ideal location for the temple (Tetra Tech 2004). King Kamehameha constructed the heiau in response to a priest's prophecy that Kamehameha would be able to conquer all the Hawaiian islands if the temple was built on the site and dedicated to his family war god.

While the temple site is underlain by lava flows from Mauna Kea, the temple is likely constructed of basalt rocks that were lava flows from Kohala Volcano. The massive amount of water-worn basalt stones used to construct the temple were obtained from as far away as the Pololū Valley on the north flank of Kohala Mountain (Tetra Tech 2004). According to some stories, the laborers formed a human chain approximately 30 km (20 mi) long, passing the stones from one to another (National Park Service 2009a). Lava flows mapped in Pololū Valley are from the Kohala Volcano (geologic map units Qpl [also mapped in the park] and Qhw) are a potential source of the boulders used in the construction of Puʻukoholā Heiau. Lava flows of unit Qpl are the oldest on the Island of Hawaiʻi—some erupted 700,000 years ago.

Mailekini Heiau, just below Puʻukoholā Heiau (see inside front cover and fig. 12), also took advantage of the elevated topography of the site. The fort was originally built between 1400 and 1580 (National Park Service 2010). In the early 1800s, Kamehameha converted the site to a fort with mounted guns, offering firepower to protect the local port (National Park Service 2010).

Ruins of the third temple, Hale o Kapuni Heiau, are now submerged offshore and not readily visible (figs. 9 and 12). Hale o Kapuni was constructed as a temple to the shark gods and was last visible at low tides in the 1950s (National Park Service 2009b). A variety of factors may have lead to the submergence of the site including siltation related to construction of Kawaihae Harbor and tsunamis. The basalt stone leaning post (kikiakoʻi) overlooks the site of Hale o Kapuni Heiau.

Figure 9. Offshore view from the trail to Puʻukoholā Heiau. Figures 10 and 11 show the benthic habitats of the offshore areas surrounding the park and Pelekane Bay. The elevated vantage point of Puʻukoholā made it a desirable location for heiaus. 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=698 Accessed 17 May 2011.

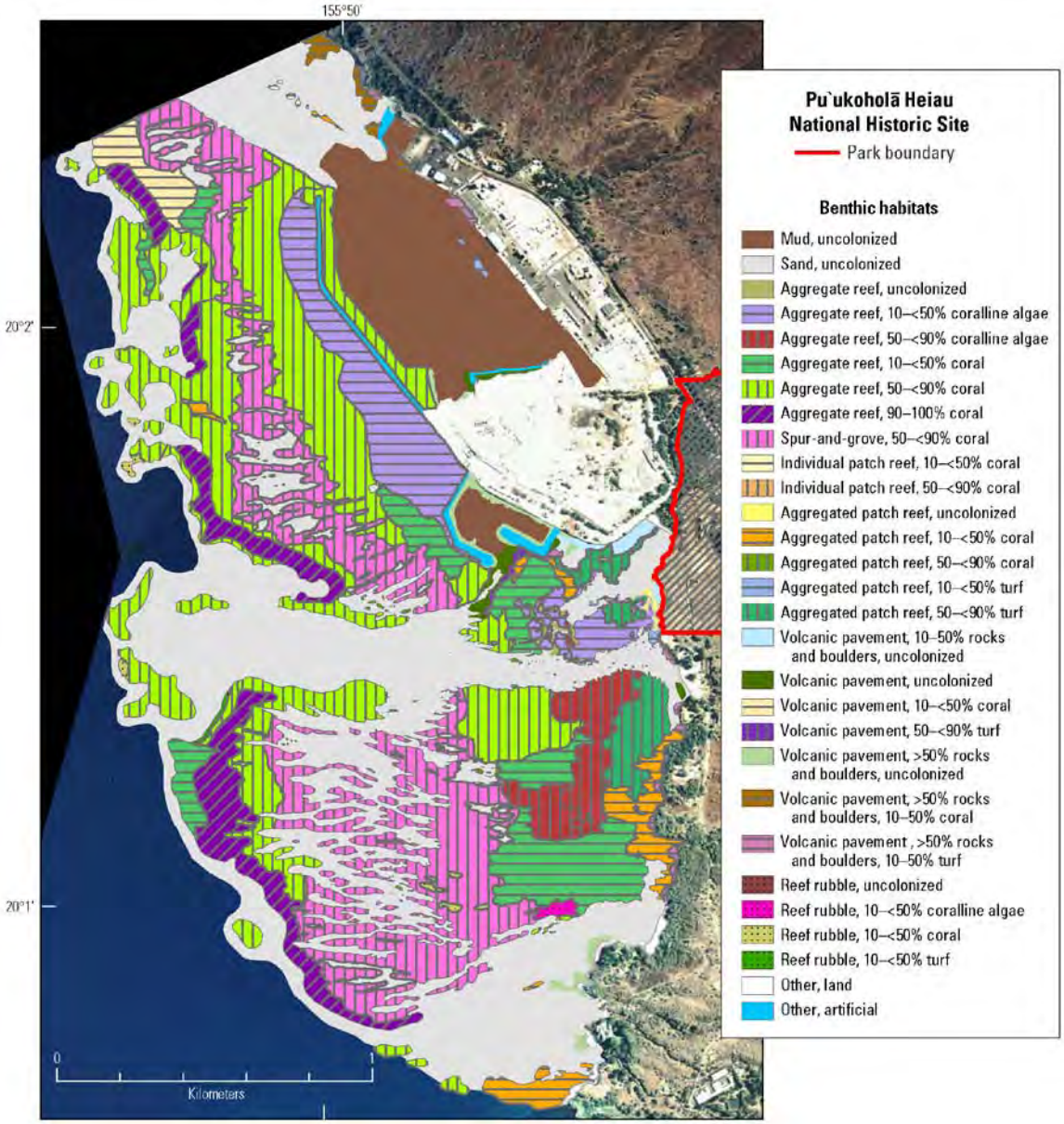


Figure 10. Map of the 29 benthic habitats offshore of Pu'ukoholā Heiau National Historic Site. U.S. Geological Survey graphic from Cochran et al. (2007).

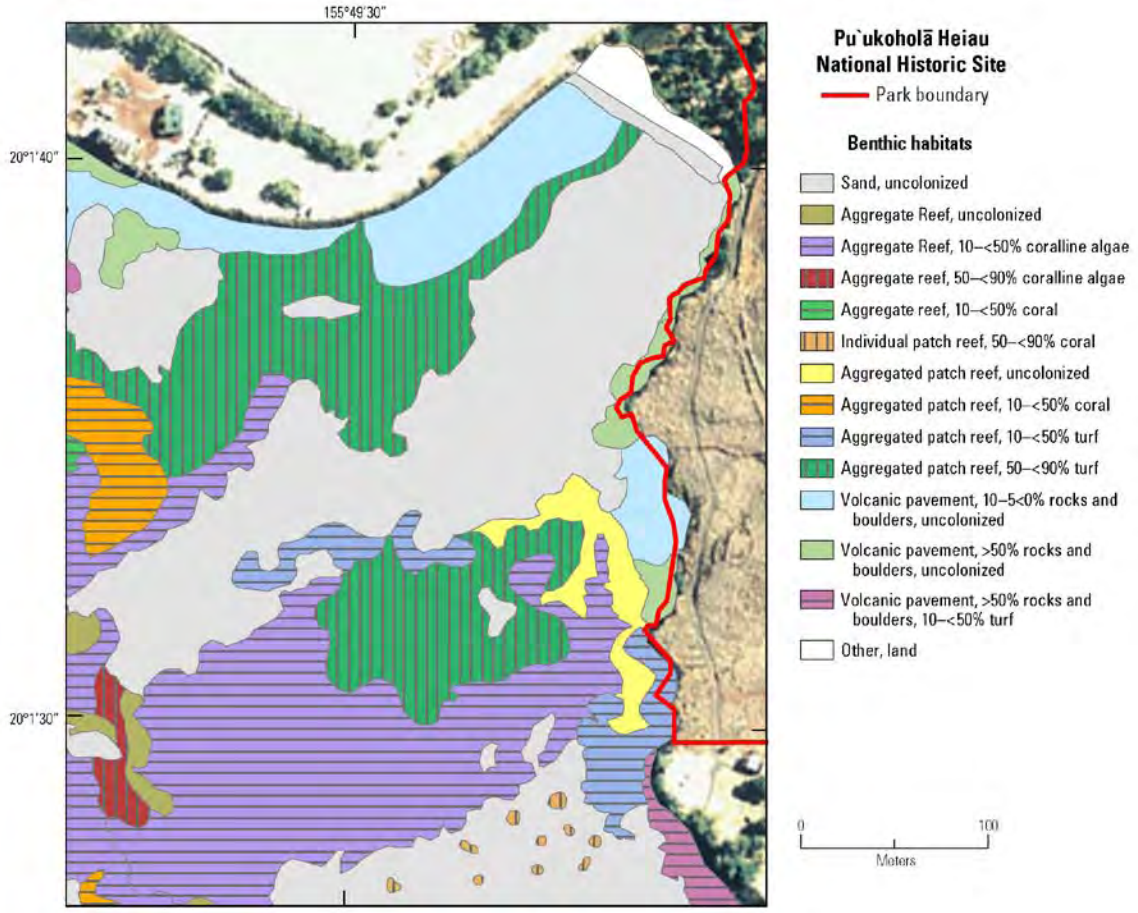


Figure 11. Detail map of the benthic habitats immediately offshore of Pu‘ukoholā Heiau National Historic Site, showing Pelekane Bay. U.S. Geological Survey graphic from Cochran et al. (2007).

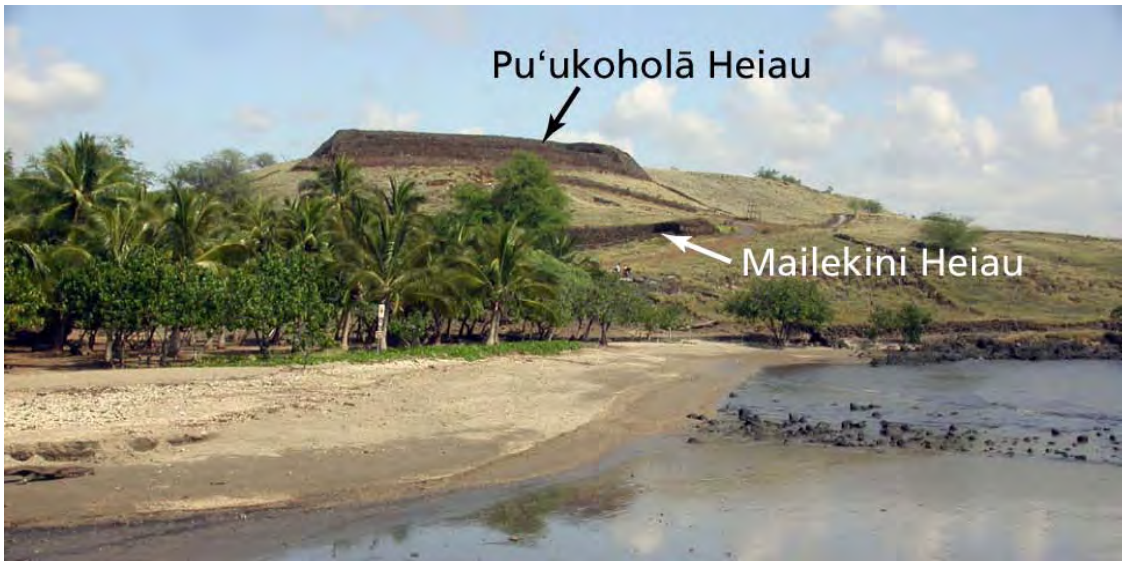


Figure 12. Photograph of Pu‘ukoholā, "Hill of the Whale." Pu‘ukoholā Heiau (constructed 1790-1791) tops the topographic feature. Mailekini Heiau also utilized the high topography. Hale o Kapuni Heiau is submerged just offshore. The rocks in the right foreground of the photograph may be building stones from Hale o Kapuni Heiau. 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=699. Accessed 17 May 2011.

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Pu'ukoholā Heiau National Historic Site, 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 Pu'ukoholā Heiau National Historic Site are young (geologic map units Qpl, Qhm and Qhwb)—dating back as many as 700,000 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. 13-14) (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. 15) (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. 16-17).

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. 17).

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. 18). Other such hotspots across the Pacific basin are the Caroline, Marquesas, Society, Pitcairn, Austral, and Easter hotspots (fig. 17) (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. 17). 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. 17) (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. 19) (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. 20) (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 remote possibility at Puʻukoholā Heiau National Historic Site. The youngest flows from the nearby Hualālai Volcano (geologic map unit Qh5) reached the coast south of the park boundary, near Keāhole Point, in 1801. Mauna Kea is considered dormant, not extinct. 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 1996a, 1996b). The rocks exposed within Puʻukoholā Heiau National Historic Site demonstrate the overlapping nature of volcanic growth within the Hawaiian Islands. The park straddles the stratigraphic boundary between Pleistocene volcanic lava flows from Kohala and Mauna Kea volcanoes (Richmond et al. 2008).

Volcanic flows from Kohala Volcano from at least 400,000 years ago to 250,000 dominate the surface and subsurface rocks in and near Puʻukoholā Heiau National Historic Site (Wolfe and Morris 1996a). Units found within the park include transitional and alkalic and transitional basalt ʻaʻā flows of the Pololū Volcanics of Kohala (geologic map units Qpl). These flows are thoroughly weathered and eroded, and are locally covered by a mantle of eolian and tephra-fall deposits (Wolfe and Morris 1996a). They are among the oldest rocks exposed on the Island of Hawaiʻi. Benmoreite lava flows from the Hāwī Volcanics of the Kohala Volcano are also present in the park (Qhwb). This flow originated from vents on the topographic crest and flanks of the volcano to the northeast (Wolfe and Morris 1996a).

Younger ʻaʻā and pāhoehoe flows from vents on Mauna Kea (Hāmākua Volcanics, geologic map unit Qhm) are younger than the more dissected, gullied, and weathered Kohala basalts (Wolfe and Morris 1996a; Richmond et al. 2008). In outcrop, these units are dark gray to yellowish brown and frequently eroded and mantled by unmapped and unconsolidated eolian, tephra-fall, and colluvial deposits (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.

Humans are impacting the geologic processes on the Island of Hawaiʻi. Shoreline armoring, piers, and harbor breakwaters such as that at Kawaihae Harbor near the park interrupt natural sediment transport to and from the shores of the island. Extensive artificial fill deposits are mapped as Qf in the GRI digital geologic map data (see Overview of Geologic Data section). Scant beach deposits and other unconsolidated sediments are not mapped seperately on the digital geologic map of the park.

Eon	Era	Period	Epoch	Ma		Life Forms	North American Events
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01	Age of Mammals	Modern humans	Cascade volcanoes (W)
			Pleistocene	2.6		Extinction of large mammals and birds	Worldwide glaciation
		Tertiary – Neogene	Pliocene	5.3		Large carnivores	Sierra Nevada Mountains (W)
			Miocene	23.0		Whales and apes	Linking of North and South America
		Tertiary – Paleogene	Oligocene	33.9			Basin-and-Range extension (W)
			Eocene	55.8		Early primates	Laramide Orogeny ends (W)
			Paleocene	65.5			
	Mesozoic	Cretaceous		145.5	Age of Dinosaurs	**Mass extinction** Placental mammals Early flowering plants	Laramide Orogeny (W) Sevier Orogeny (W) Nevadan Orogeny (W)
		Jurassic		199.6		First mammals **Mass extinction** Flying reptiles	Elko Orogeny (W) Breakup of Pangaea begins
		Triassic		251		First dinosaurs	Sonoma Orogeny (W)
	Paleozoic	Permian		299	Age of Amphibians	**Mass extinction** Coal-forming forests diminish	Supercontinent Pangaea intact Ouachita Orogeny (S) Alleghanian (Appalachian) Orogeny (E)
		Pennsylvanian		318.1		Coal-forming swamps Sharks abundant Variety of insects	Ancestral Rocky Mountains (W)
		Mississippian		359.2		First amphibians First reptiles	Antler Orogeny (W)
		Devonian		416	Fishes	**Mass extinction** First forests (evergreens)	Acadian Orogeny (E-NE)
		Silurian		443.7		First land plants	
		Ordovician		488.3	Marine Invertebrates	**Mass extinction** First primitive fish Trilobite maximum Rise of corals	Taconic Orogeny (E-NE)
		Cambrian		542		Early shelled organisms	Avalonian Orogeny (NE) Extensive oceans cover most of proto-North America (Laurentia)
Proterozoic		Precambrian		2500		First multicelled organisms Jellyfish fossil (670 Ma)	Supercontinent rifted apart Formation of early supercontinent Grenville Orogeny (E) First iron deposits Abundant carbonate rocks
Archean				≈4000		Early bacteria and algae	Oldest known Earth rocks (≈3.96 billion years ago)
Hadean				4600		Origin of life?	Oldest moon rocks (4–4.6 billion years ago) Formation of Earth's crust
						Formation of the Earth	

Figure 13. 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).

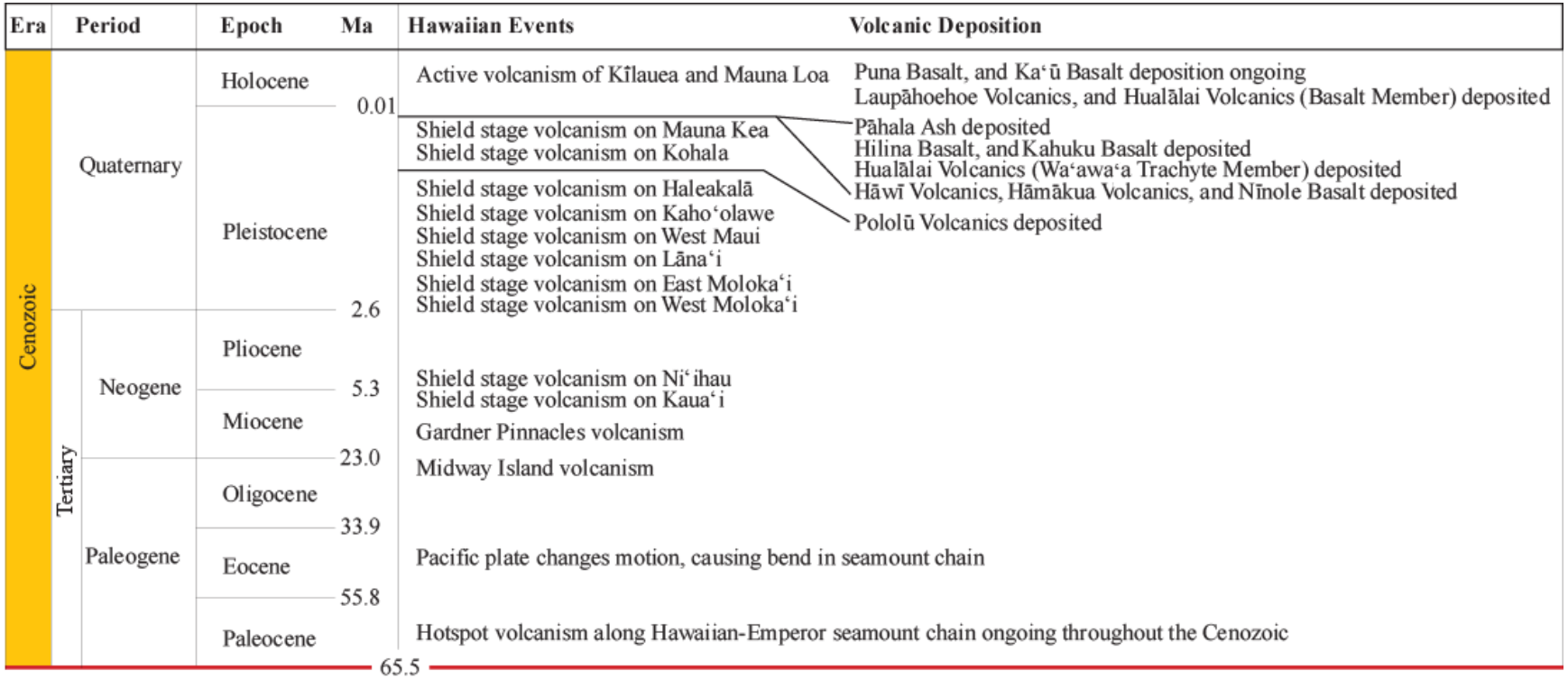


Figure 14. Geologic time scale of events affecting the Hawaiian Islands throughout the Cenozoic Era; adapted from U.S. Geological Survey (http://www.usgs.gov) using information from Clague and Dalrymple (1987), written communication from D. Sherrod (2009), and the GRI digital geologic map for Hawaiʻi Volcanoes National Park. Ages of volcanic flows are generally relative and overlap considerably. Absolute ages in millions of years (Ma, or mega-annum).

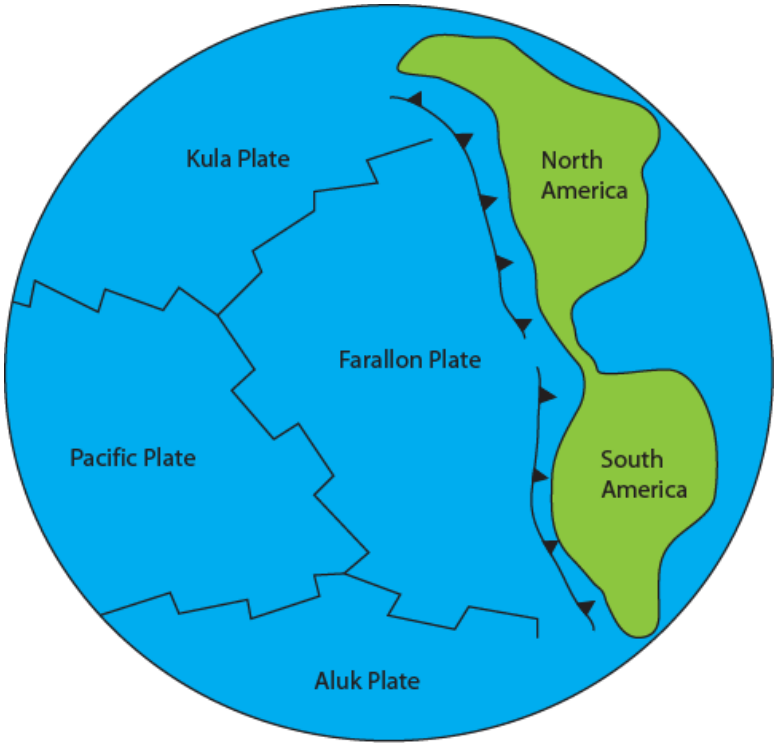


Figure 15. Generalized arrangement of plates in the Pacific Ocean basin during the middle Cretaceous. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

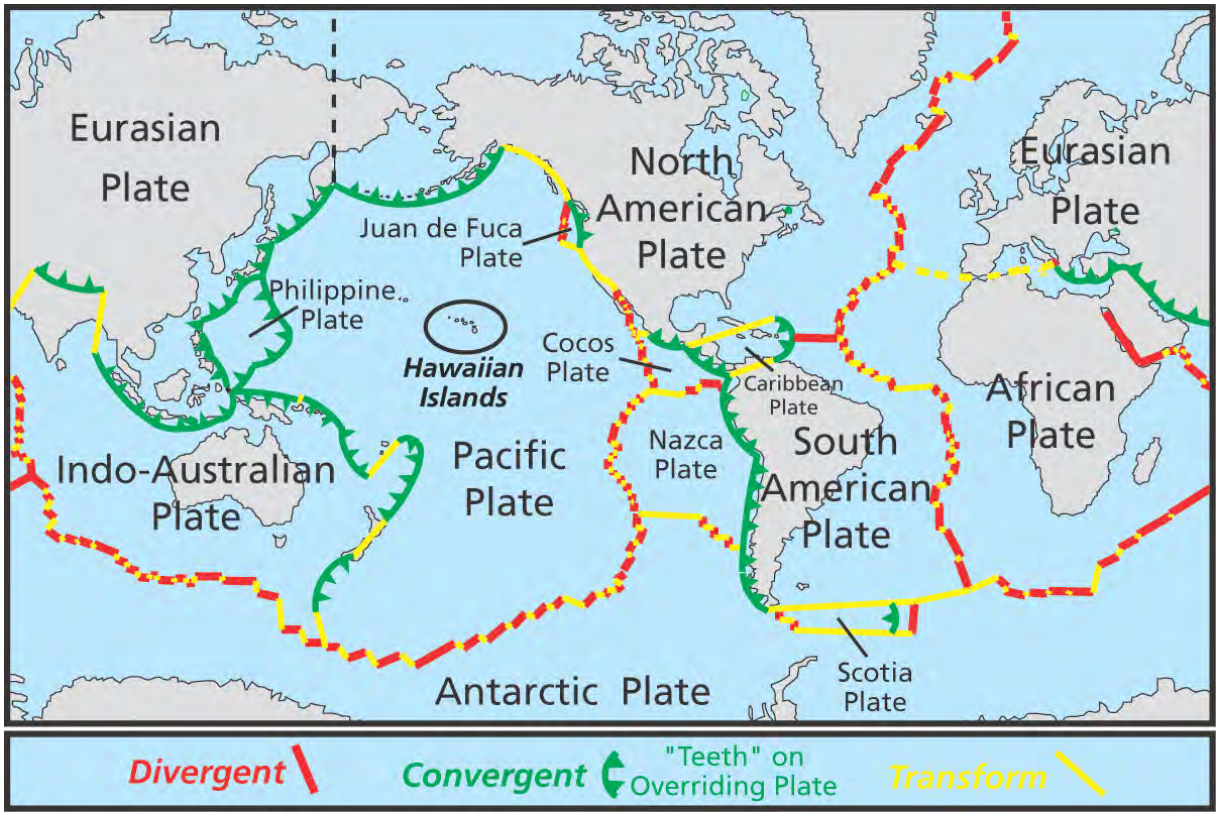


Figure 16. Map of the current tectonic plates. The Hawaiian Islands are circled. Divergent boundaries are where plates are pulling apart. Plates come together at convergent boundaries and slide past one another at transform boundaries. Graphic courtesy Robert J. Lillie (Oregon State University), modified from Lillie (2005).

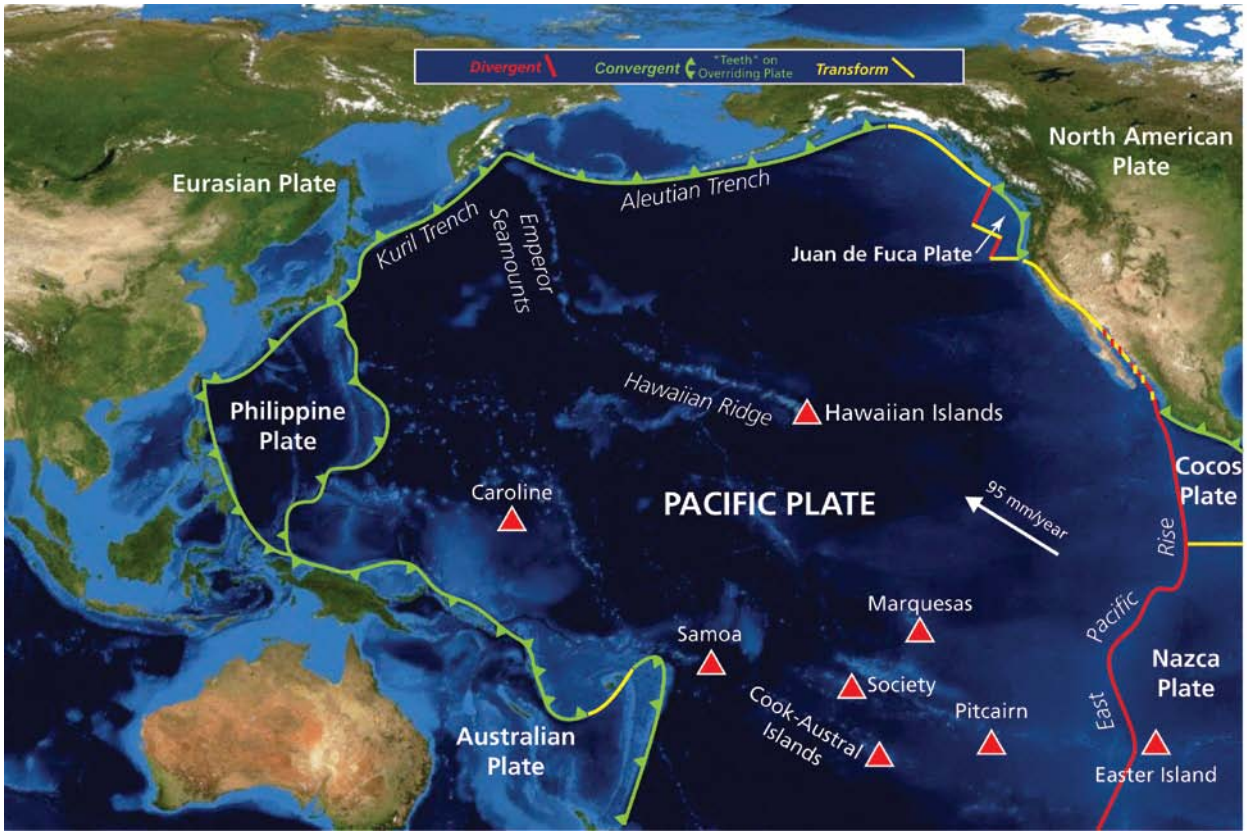


Figure 17. Tectonic setting of the Pacific Plate. This figure illustrates many of the features described in the Geologic History section. Note the extent of the Emperor Seamounts and Hawaiian Islands. Currently the Pacific Plate is moving to the northwest at about 95 mm (3.7 in.) per year. The "kink" between the Emperor Seamounts and Hawaiian Islands chain shows how the direction of motion changed while the Hawaiian hotspot remained stationary (see figs. 18 and 20). 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).

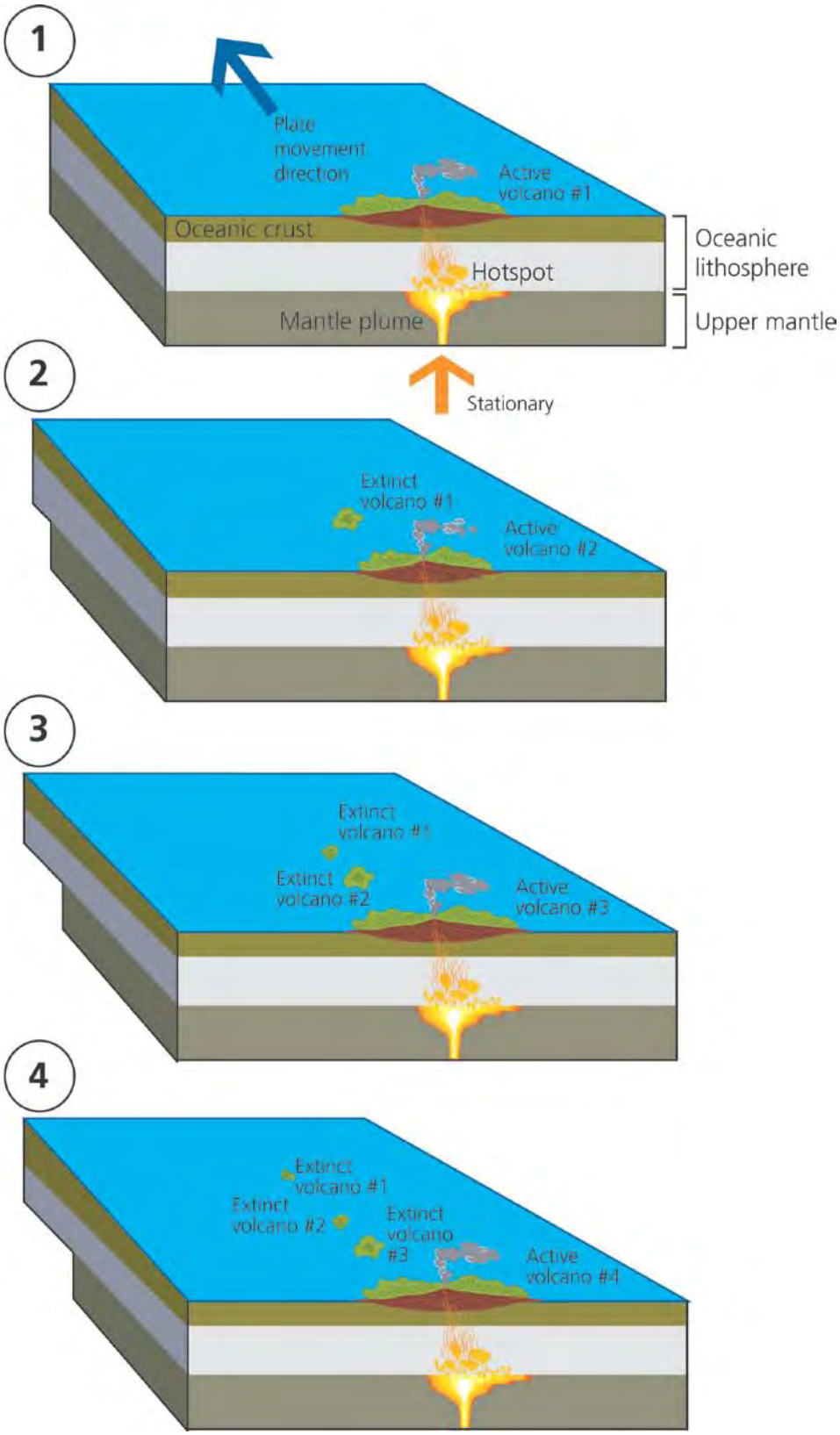


Figure 18. Evolution of a chain of islands over a stationary hotspot in Earth's crust. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

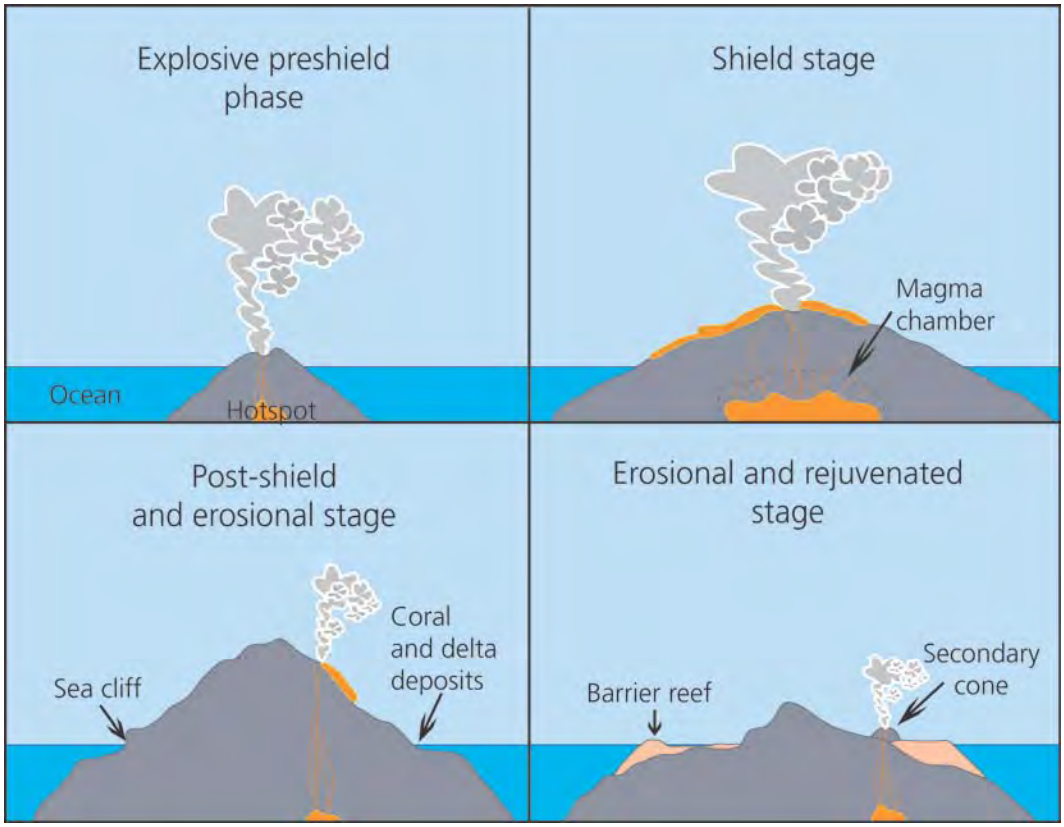


Figure 19. Simplified stages of Hawaiian hotspot island volcanism. After volcanism ceases, erosion and subsidence slowly reduce the island to a smaller subaerial remnant. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), after Keating (1992, fig. 29).

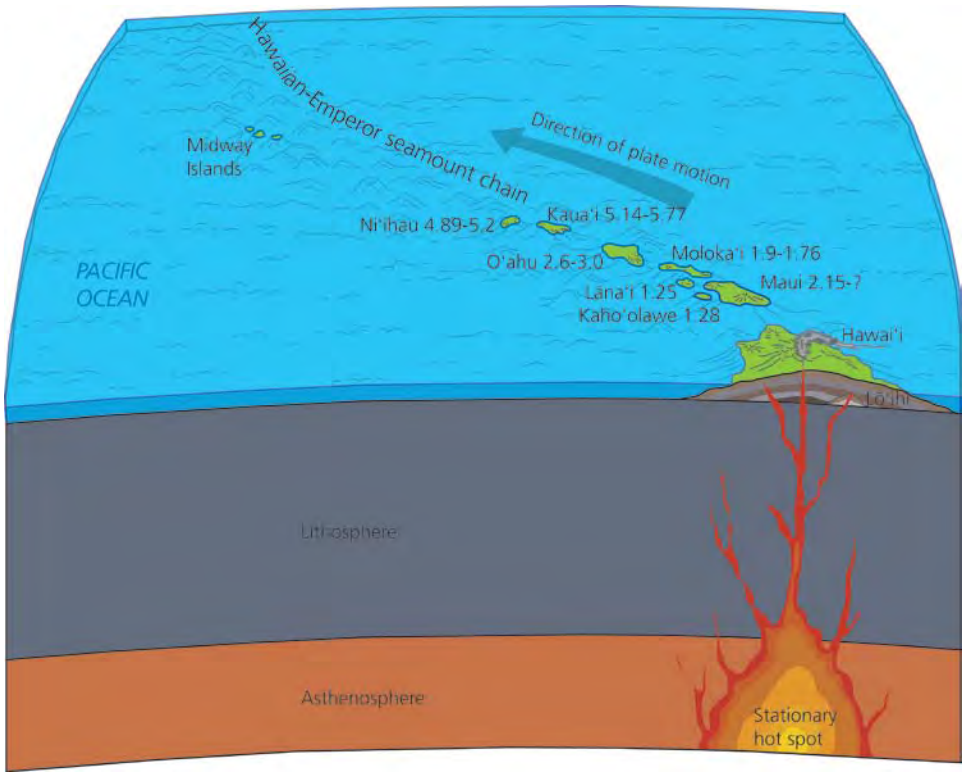


Figure 20. Evolution of the Hawaiian-Emperor seamount chain showing ages of shield-stage volcanism for the major Hawaiian Islands (ages are in millions of years). The specific type of age, error, and source are detailed in the text. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), 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 Pu'ukoholā Heiau National Historic Site. 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 Pu'ukoholā Heiau National Historic Site:

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 Pu'ukoholā Heiau National Historic Site using data model version 1.4.

GRI digital geologic data for Pu'ukoholā Heiau National Historic Site 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 Pu'ukoholā Heiau National Historic Site 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 Pu‘ukoholā Heiau National Historic Site 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 Pu‘ukoholā Heiau National Historic Site 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 Pu‘ukoholā Heiau National Historic Site, but are available online from a variety of sources.

Map Unit Properties Table and Correlation Table

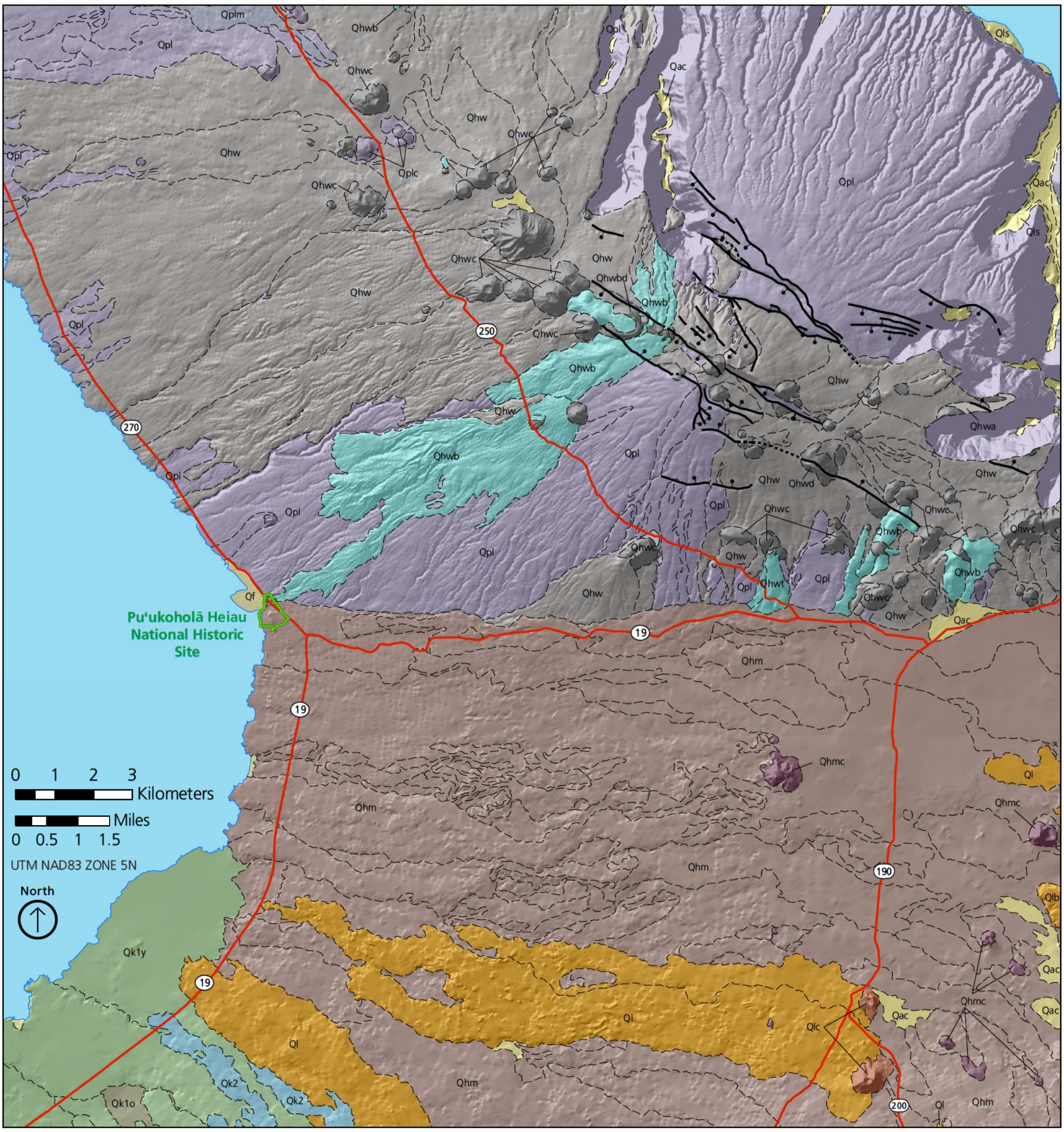
The geologic units listed in the map unit properties table correspond to the accompanying digital geologic data. Following overall structure of the report, the table highlights the geologic issues, features, and processes associated with each map unit. The units in the map unit properties table are arranged 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. 13 and 14) 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 50.8 meters /166.667 feet (horizontally) of their true location.

Please contact GRI with any questions.

Overview of Digital Geologic Data for Pu'ukoholā Heiau National Historic Site



NPS Boundary

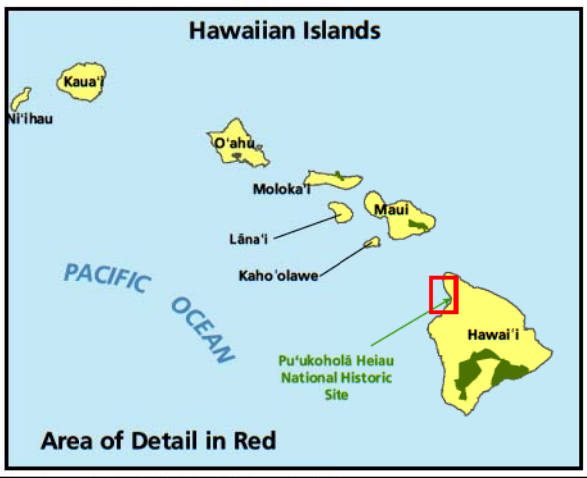
Faults
- normal fault, known or certain
- normal fault, approximate
- normal fault, concealed

Ash Contacts
- known or certain
- approximate

Ash Units
- Qhwa - Hawi Volcanics

Geologic Contacts
- known or certain
- approximate
- water or shoreline

Geologic Units
- Qf - fill
- Qls - landslide deposits
- Qac - alluvium and colluvium
- Qk2 - Kau Basalt, lava flow
- Qk1y - Kau Basalt, lava flow
- Qk1o - Kau Basalt, lava flow
- Qk - Kau Basalt, lava flow
- Qlc - Laupahoehoe Volcanics, older volcanic rocks member, cone
- Ql - Laupahoehoe Volcanics, older volcanic rocks member, lava flow
- Qlb - Laupahoehoe Volcanics, older volcanic rocks member, lava flow
- Qhmc - Hamakua Volcanics, basalt, cone
- Qhm - Hamakua Volcanics, basalt, lava flow
- Qhwc - Hawi Volcanics, scoria cone
- Qhwd - Hawi Volcanics, lava dome
- Qhw - Hawi Volcanics, lava flow
- Qhwa - Hawi Volcanics, tephra deposit
- Qhwbc - Hawi Volcanics, scoria cone
- Qhwbd - Hawi Volcanics, lava dome
- Qhwb - Hawi Volcanics, lava flow
- Qhwtd - Hawi Volcanics, lava dome
- Qhwt - Hawi Volcanics, lava flow
- Qplc - Pololu Volcanics, scoria cone
- Qpl - Pololu Volcanics, lava flow
- Qplm - Pololu Volcanics, lava flow



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:

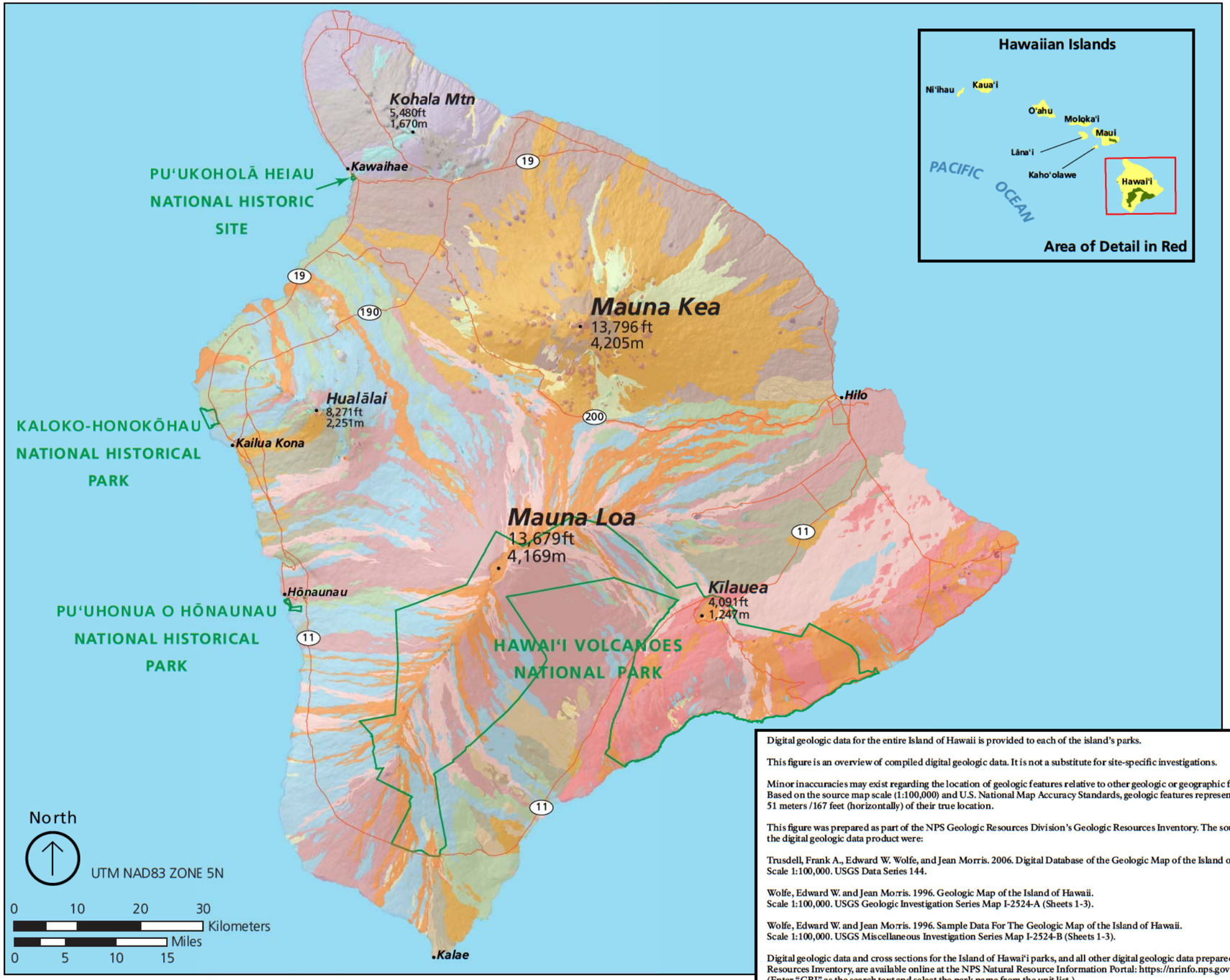
Trusdell, Frank A., Edward W. Wolfe, and Jean Morris. 2006. Digital Database of the Geologic Map of the Island of Hawai'i. Scale 1:100,000. USGS Data Series 144.

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 Pu'ukoholā Heiau National Historic Site, 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 Pu'ukoholā Heiau National Historic Site from the unit list.)

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://nrinfo.nps.gov/Reference.mvc/Search. (Enter "GRI" as the search text and select the park name from the unit list.)

NPS Boundary

Geologic Units

- Qf - fill
- Qls - landslide deposits
- Qac - alluvium and colluvium
- Qe - eolian deposits
- Qsd - slope deposits
- Qpha - Pahala Ash
- Qpc5 - Puna Basalt, cone
- Qp5 - Puna Basalt, lava flow
- Qpld5 - Puna Basalt, littoral cone
- Qpa5 - Puna Basalt, tephra deposit
- Qpc4y - Puna Basalt,cone
- Qpc4o - Puna Basalt, cone
- Qp4 - Puna Basalt, lava flow
- Qp4y - Puna Basalt, lava flow
- Qp4o - Puna Basalt, lava flow
- Qpld4o - Puna Basalt, littoral cone
- Qpa4o - Puna Basalt, tephra deposit
- Qpc3 - Puna Basalt, cone
- Qp3 - Puna Basalt, lava flow
- Qpld3 - Puna Basalt, littoral cone
- Qpc2 - Puna Basalt, cone
- Qp2 - Puna Basalt, lava flow
- Qpa2 - Puna Basalt, tephra deposit
- Qp1y - Puna Basalt, lava flow
- Qp1o - Puna Basalt, lava flow
- Qhi - Hilina Basalt, lava flow
- Qkc5 - Kau Basalt, cone
- Qk5 - Kau Basalt, lava flow
- Qkld5 - Kau Basalt, littoral cone
- Qko4 - Kau Basalt, cone
- Qk4 - Kau Basalt, lava flow
- Qkld4 - Kau Basalt, littoral cone
- Qkc3 - Kau Basalt, cone
- Qk3 - Kau Basalt, lava flow
- Qkld3 - Kau Basalt, littoral cone
- Qka3 - Kau Basalt, tephra deposit
- Qkc2 - Kau Basalt, cone
- Qk2 - Kau Basalt, lava flow
- Qkld2 - Kau Basalt, littoral cone
- Qkc1 - Kau Basalt, cone
- Qkc1y - Kau Basalt, cone
- Qkc1o - Kau Basalt, cone
- Qk1 - Kau Basalt, lava flow
- Qk1y - Kau Basalt, lava flow
- Qk1o - Kau Basalt, lava flow
- Qkld1 - Kau Basalt, littoral cone
- Qkc - Kau Basalt, cone
- Qk - Kau Basalt, lava flow
- Qkh - Kahuku Basalt, lava flow
- Qn - Ninole Basalt, lava flow
- Qhc5 - Hualalai Volcanics, basalt, cone
- Qh5 - Hualalai Volcanics, basalt, lava flow
- Qh4 - Hualalai Volcanics, basalt, lava flow
- Qho4 - Hualalai Volcanics, basalt, cone
- Qha4 - Hualalai Volcanics, basalt, tephra deposit
- Qhc3 - Hualalai Volcanics, basalt, cone
- Qh3 - Hualalai Volcanics, basalt, lava flow
- Qh2 - Hualalai Volcanics, basalt, lava flow
- Qhc2 - Hualalai Volcanics, basalt, cone
- Qhc1y - Hualalai Volcanics, basalt, cone
- Qh1y - Hualalai Volcanics, basalt, lava flow
- Qh1o - Hualalai Volcanics, basalt, lava flow
- Qhc1o - Hualalai Volcanics, basalt, cone
- Qhc - Hualalai Volcanics, basalt, cone
- Qh - Hualalai Volcanics, basalt, lava flow
- Qwc - Hualalai Volcanics, Waawaa Trachyte Member, cone
- Qw - Hualalai Volcanics, Waawaa Trachyte Member, lava flow
- Qlcy - Laupahoehoe Volcanics, younger volcanic rocks member, cone
- Qly - Laupahoehoe Volcanics, younger volcanic rocks member, lava flow
- Qlay - Laupahoehoe Volcanics, younger volcanic rocks member, tephra deposit
- Qlc - Laupahoehoe Volcanics, older volcanic rocks member, cone
- Ql - Laupahoehoe Volcanics, older volcanic rocks member, lava flow
- Qla - Laupahoehoe Volcanics, older volcanic rocks member, tephra deposit
- Qlbc - Laupahoehoe Volcanics, older volcanic rocks member, cone
- Qlb - Laupahoehoe Volcanics, older volcanic rocks member, lava flow
- Qlmt - Laupahoehoe Volcanics, Makanaka Glacial member, glacial deposit
- Qlmo - Laupahoehoe Volcanics, Makanaka Glacial member, glacial deposit
- Qhmc - Hamakua Volcanics, basalt, cone
- Qhm - Hamakua Volcanics, basalt, lava flow
- Qhmw - Hamakua Volcanics, Waihu Glacial member, glacial deposit
- Qhwc - Hawi Volcanics, scoria cone
- Qhwd - Hawi Volcanics, lava dome
- Qhw - Hawi Volcanics, lava flow
- Qhwa - Hawi Volcanics, tephra deposit
- Qhwbc - Hawi Volcanics, scoria cone
- Qhwbd - Hawi Volcanics, lava dome
- Qhwb - Hawi Volcanics, lava flow
- Qhwtd - Hawi Volcanics, lava dome
- Qhwt - Hawi Volcanics, lava flow
- Qplc - Pololu Volcanics, scoria cone
- Qpl - Pololu Volcanics, lava flow
- Qpld - Pololu Volcanics, lava dome
- Qplmc - Pololu Volcanics, scoria cone
- Qplm - Pololu Volcanics, lava flow

Map Unit Properties Table: Pu‘ukoholā Heiau National Historic Site

Colored rows indicate geologic units mapped within Pu‘ukoholā Heiau National Historic Site.

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. *Qf is mapped within Pu‘ukoholā Heiau National Historic Site.	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 kīpukas surrounded 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 pāhoehoe to blocky ‘a‘ā. 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 Keanakāko‘i 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 ‘a‘ā 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. ‘A‘ā 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	Ka‘ū 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 ‘a‘ā (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 Pu'ukoholā Heiau National Historic Site.

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.
QUATERNARY (Pleistocene and/or Holocene)	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 Pu'ukoholā Heiau National Historic Site.	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.
QUATERNARY (Pleistocene and/or Holocene)	Hual	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.
QUATERNARY (Pleistocene and/or Holocene)	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 Pu'ukoholā Heiau National Historic Site.

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*	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 ʻaʻā 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. *Qhm is mapped within Puʻukoholā Heiau National Historic Site.	Moderately low to moderate	Avoid weathered and/or unconsolidated units for heavy infrastructure. ʻAʻā 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.
		Hāmākua Volcanics Waihū Glacial Member *glacial deposits:* Qhmw									
	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. *Qhwb is mapped within Puʻukoholā Heiau National Historic Site.	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.
		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 ʻaʻā, but most surface expression has been muted by weathering and erosion. Most surfaces are mantled by eolian and younger tephra-fall deposits. *Qpl is mapped within Puʻukoholā Heiau National Historic Site.	Moderately low to moderate	Avoid areas especially rich in clay or weathered on slopes for major infrastructure. ʻAʻā 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 Hawaiʻi. 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: Puʻukoholā Heiau National Historic Site

Geologic units mapped within Puʻukoholā Heiau National Historic Site 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).

Age		Age Group*	Surficial Deposits					Regional Ash Deposits	Kīlauea Volcano				Mauna Loa Volcano				Hualālai Volcano			Mauna Kea Volcano				Kohala Volcano						
									Spatter or tuff cones	Lava Flows		Littoral Cones	Tephra Deposits	Spatter or scoria cones		Lava Flows		Littoral Cones	Tephra Deposits	Spatter or Scoria Cones	Lava Flows	Tephra Deposits	Scoria Cones	Lava Flows	Tephra Deposits	Glacial Deposits	Scoria Cones	Lava domes		Lava Flows		Tephra Deposits
Quaternary	Holocene	Historic 1750 or younger)	Qf						Qpc5	Qp5		Qpld5	Qpa5	Qkc5		Qk5		Qkld5		Qhc5	Qh5											
		200-400		Qls					Qpc4y	Qp4	Qp4y			Qkc4		Qk4		Qkld4		Qhc4	Qh4	Qha4										
		400-750							Qpc4o		Qp4o	Qpld4o	Qpa4o																			
		750-1,500			Qac				Qpc3	Qp3		Qpld3		Qkc3		Qk3		Qkld3	Qka3	Qhc3	Qh3											
		1,500-3,000							Qpc2	Qp2			Qpa2	Qkc2		Qk2		Qkld2		Qhc2	Qh2											
		3,000-5,000								Qp1y				Qkc1	Qkc1y	Qk1	Qk1y	Qkld1		Qhc1y	Qh1y											
		5,000-10,000								Qp1o					Qkc1o		Qk1o			Qhc1o	Qh1o		Qlcy		Qly		Qlay					
	Pleistocene	>10,000				Qe	Qsd	Qpha						Qkc		Qk				Qhc	Qh							Qla	Qlmt	Qlmo		
																							Qlc	Qlbc	Ql	Qlb						
										Qhi						Qkh																
																				Qwc	Qw		Qhmc		Qhm			Qhmw				
																Qn																
																												Qhwc	Qhwbc	Qhwd	Qhwbd	Qhwtd	Qhw	Qhwb	Qhwt	Qhwa
																												Qplc	Qplmc	Qpld			Qpl	Qplm		

* = 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 web sites 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

NPS 454/107502, April 2011

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