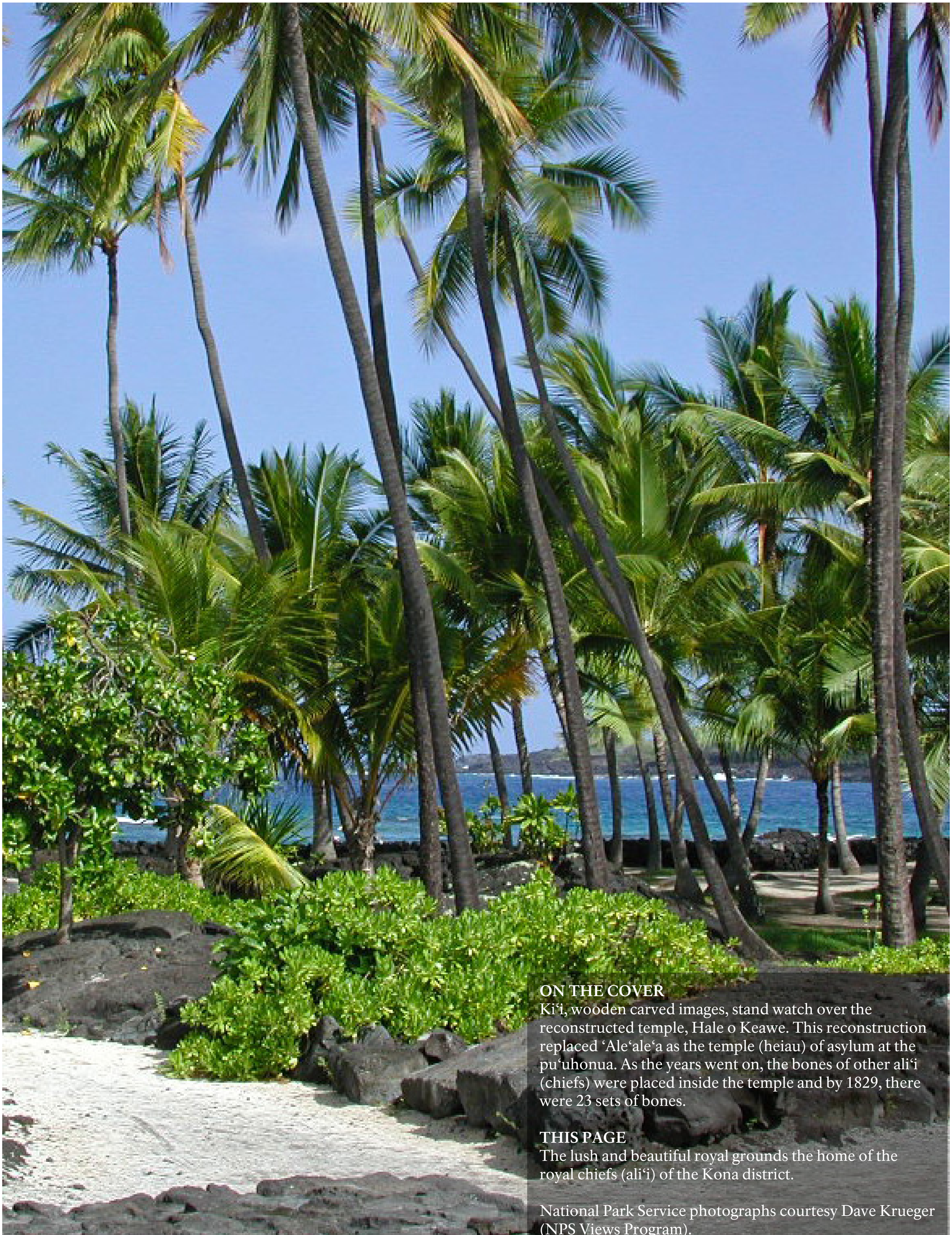
National Park Service
U.S. Department of the Interior

Natural Resource Program Center

Pu‘uhonua o Hōnaunau National Historical Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2011/385



ON THE COVER
Ki'i, wooden carved images, stand watch over the reconstructed temple, Hale o Keawe. This reconstruction replaced 'Ale'ale'a as the temple (heiau) of asylum at the pu'uhonua. As the years went on, the bones of other ali'i (chiefs) were placed inside the temple and by 1829, there were 23 sets of bones.

THIS PAGE
The lush and beautiful royal grounds the home of the royal chiefs (ali'i) of the Kona district.

National Park Service photographs courtesy Dave Krueger (NPS Views Program).

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

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

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Executive Summary

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

"Puʻuhonua" translates to place of refuge. Until 1819, Puʻuhonua o Hōnaunau was a place that violators of the ancient Hawaiian code of conduct, or "kapu," could use for refuge from a death sentence, by swimming to the Puʻuhonua across Kealakekua Bay. Puʻuhonua o Hōnaunau National Historical Park contains some of the few enduring religious relicts from old Hawaii, as well as Kiʻilae Village. These features are a testament to the daily life of ancient Hawaiians, as well as a reflection of the changes that occurred after the arrival of Europeans.

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

Geologic issues of particular significance for resource management at Puʻuhonua o Hōnaunau National Historical Park include:

- Groundwater recharge: freshwater on the relatively dry, leeward Kona coast is a valuable natural resource. In the Puʻuhonua o Hōnaunau National Historical Park area, aquifers are unconfined and range from thin, brackish water lenses to vertically-extensive freshwater bodies floating atop saline groundwater. Saltwater intrusion is a possibility near coastal areas and is among the factors limiting groundwater availability. Significant submarine groundwater discharge occurs all along the coast, through permeable lava flows from upslope recharge areas.
- Anchialine ponds: these ponds are among the most threatened ecosystems in Hawaii. The ponds are home to unusual plants and animals, and several exist at Puʻuhonua o Hōnaunau National Historical Park; they are relatively small, inland sources of brackish water influenced by tides and springs. Water levels, temperatures, and salinity vary in the ponds constantly, because the ponds are connected to the ocean via subterranean tunnels. It is unknown how sedimentation affects these anchialine ponds, or how exactly they can be restored from damage caused by invasive fish.
- Coral reef changes: the Kona coast of the Island of Hawaiʻi is relatively protected from high wave energy; coral reef development is relatively diverse, and it flourishes on mostly volcanic substrates. Heavy wave action, flooding, hurricanes, sea-level rise, climate change, or seismic events can disturb coral reef growth; the same is true of sedimentation and pollutants introduced by anthropogenic land clearing, agricultural development, dredging, overfishing, and heavy tourism. The U.S. Geological Survey produced a benthic habitat map for the park, a valuable resource.
- Geologic hazards: Puʻuhonua o Hōnaunau National Historical Park is underlain by relatively young volcanic flows from Mauna Loa, and volcanism remains a possibility in the area. Mass wasting from upslope areas may impact the park. Due to its coastal location, Puʻuhonua o Hōnaunau National Historical Park is susceptible to inundation during tsunamis. Tsunami modeling takes into account seismic events, bathymetry, storm issues, and wind and rain conditions. Coastal erosion and relative sea-level rise affect most of the shoreline at the park, causing beach loss, saltwater inundation, damage to shallow coral reefs, and potential loss of cultural resources. Seismicity is a concern throughout the Pacific basin. Earthquakes occur frequently on the Island of Hawaiʻi, as a result of (1) magma movement accompanying volcanism; (2) crustal stresses arising from areas of structural weakness; and (3) crustal loading by the volcanic mass. Seismicity has caused fatalities, ground rupture, localized uplift and subsidence, liquefaction, ground settlement, and extensive damage to roads, buildings and homes; it has also triggered tsunamis.

The scenic and natural resources of the park are closely linked to geologic features and processes. Active volcanism of Mauna Loa created lava flows that spread downslope to form landscape features of Puʻuhonua o Hōnaunau National Historical Park (geologic map units Qk1y, Qk2, and Qk3), including lava tubes, flows, tree molds, and benches. Erosion modifies the shorelines. Active volcanism at Kīlauea creates hazy "vog", comprised of acidic aerosols, unreacted sulfur gases, volcanic ash, and other fine particulate matter. The geology at Puʻuhonua o Hōnaunau National Historical Park is a fundamental component of an ecosystem that hosts several indigenous species.

Knowledge of the physical properties of the different geologic units mapped at Puʻuhonua o Hōnaunau National Historical Park contributes to understanding and managing the varying ecosystems and natural resources in the park. The Map Unit Properties Table includes, for each mapped geologic unit, characteristics such as erosion resistance, suitability for development, global significance, recreation potential, and associated cultural and mineral resources. In addition to their physical properties, the rock units at Puʻuhonua o Hōnaunau National Historical Park 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 provided as figs. 19 and 20.

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: Dave Krueger (NPS Views Program) for providing images taken by Erika Matteo and Deborah Luchsinger for NPS Views. David Sherrod (U.S. Geological Survey) provided review comments on the Hawaiʻi Volcanoes National Park GRI report. Those comments were also included in this report as appropriate.

Credits

Author

Trista Thornberry-Ehrlich (Colorado State University)

Review

Bruce Richmond (U.S. Geological Survey)
Susan Cochran (U.S. Geological Survey)
Ann Gibbs (U.S. Geological Survey)
Jason Kenworthy (NPS Geologic Resources Division)
Phil Reiker (NPS Geologic Resources Division)

Editing

Steven Hoffman (Write Science Right)

Digital Geologic Data Production

Greg Mack (NPS Pacific West Region)
Jim Chappell (Colorado State University)
Stephanie O'Meara (Colorado State University)

Digital Geologic Data Overview Layout Design

Phil Reiker (NPS Geologic Resources Division)
Benton Line (Colorado State University Intern)

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

Puʻuhonua o Hōnaunau National Historical Park covers 169.9 ha (419.8 ac) on the Island of Hawaiʻi, approximately 35 km (22 mi) south of Kailua-Kona (figs. 1- 2). Federal land is only 73.57 ha (181.80 ac) of this area. 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. 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.

Cultural History and Establishment of Puʻuhonua o Hōnaunau National Historical Park

"Puʻuhonua" means place of refuge. Until the death of King Kamehameha I in 1819, Puʻuhonua o Hōnaunau was a place where vanquished Hawaiian warriors and violators of the "kapu" (laws of conduct) could take refuge from a death sentence. In old Hawaii, kapu governed all aspects of society. Penalties were severe and quick. Puʻuhonua offered the only option for survival by swimming there across Kealakekua Bay. Puʻuhonua o Hōnaunau National Historical Park represents one of the few enduring religious sites from old Hawaii.

At Puʻuhonua o Hōnaunau National Historical Park, remnants of this sacred place include a great wall that marks the boundary between the royal grounds and the sanctuary. Kiʻi, or carved wooden images, surround the Hale o Keawe, which houses the bones of 23 Aliʻi (chiefs) that infuse the area with their "mana" (power) (figs. 3-5). Kiʻilae Village contains abandoned heiau (temples), agricultural features, holua slides (royalty would ride wooden "sleds" down the slides), animal pens, church foundations, and salt vats. These features reveal the daily life of ancient Hawaiians, as well as the changes that occurred after the arrival of Europeans.

Puʻuhonua o Hōnaunau National Historical Park and Keoneʻele Cove provide protected habitats for green turtles, the endangered ʻOpeʻapeʻa (Hawaiian hoary bat), the endangered ʻIlio holo i ka (Hawaiian monk seal), and 30 species of manu (Hawaiian birds, six of which are native). Among the 134 known vascular plant species in the park are 23 native Hawaiian plants, such as pohuehue (beach morning glory), hala trees, and naupaka (a shrub), within a diverse landscape.

An act of Congress established Puʻuhonua o Hōnaunau National Historical Park on July 26, 1955, for "the benefit and inspiration of the people." Although the park was set aside largely to preserve cultural and historical resources, there are also notable natural resources that are priorities for resource managers at the park. Preserving a precontact (i.e., prior to indigenous Hawaiians' contact with Europeans) historical context complements natural resource management goals and helps to maintain a relatively pristine ecosystem.

Additional information may be found at http://www.nps.gov/puho, the Puʻuhonua o Hōnaunau National Historical Park web site. The NPS Views program created a multimedia program highlighting the park and its natural resources. The program is accessible online at http://www.nature.nps.gov/views/layouts/Main.html#/PUHO/.

Geologic Setting

The Island of Hawaiʻi is one of the volcanic masses that make up the Hawaiian-Emperor volcanic chain. This volcanic chain includes many subaerial islands and submarine seamounts, stretching 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 land mass of the Island of Hawaiʻi contains 5 large volcanic centers: Kohala, Mauna Kea, Hualālai, Mauna Loa, and Kīlauea (fig. 1). The latter two are among the most active volcanoes in the world (see Hawaiʻi Volcanoes National Park; Thornberry-Ehrlich 2009). Puʻuhonua o Hōnaunau National Historical Park is on the western slope of Mauna Loa.

The seaward-sloping landscape within Puʻuhonua o Hōnaunau National Historical Park consists of relatively low-relief basalt flows (geologic map units Qk1y, Qk2, and Qk3, see Overview of Geologic Data section), that form broad benches along the shore, and that are mantled by pockets of sandy beaches and rocky areas covered with basalt boulders (Richmond et al. 2008). The park coastline is approximately 1.6 km (1 mi) long, and predominantly rocky, with an artificially nourished beach at Keoneʻele Bay on the northern edge (Richmond et al. 2008). Elevations generally range from sea level to about 30 m (100 ft) at the eastern park boundary. The exception to this is the Keanaeʻe Pali (cliffs), which rise dramatically to about 37 m (120 ft) in elevation near the coast. The volcanic flows of the Hōnaunau area are younger than much of the Island of Hawaiʻi. Prehistoric lava flows, erupted from the flanks and the summit of Mauna Loa, dominate the geology of the park. The largest and most recent of these is the 750-1500 year-old flow that extends from the north to the Keanaeʻe Pali (Qk3). A 3,000-5,000 year-old flow stretches from the Keanaeʻe Pali to the southwestern edge of the park (Qk1y), and a 1,500-3,000 year-old flow covers the southeasternmost tip of the park (Qk2). Some of these flows formed lava tube caves within the park.

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 Kea and Kohala are mapped within Puʻukoholā Heiau National Historic Site (Thornberry-Ehrlich 2011b).

The park contains only pockets of soil in a thin veneer, and no perennial streams. It is part of the Kiʻilae watershed, which begins at the crest of Mauna Loa. Kiʻilae Stream is an intermittent stream that crosses the park along its southern edge, and runs past Kiʻilae village toward the ocean at Kiʻilae Bay. The stream only flows after heavy upland rainfall events.

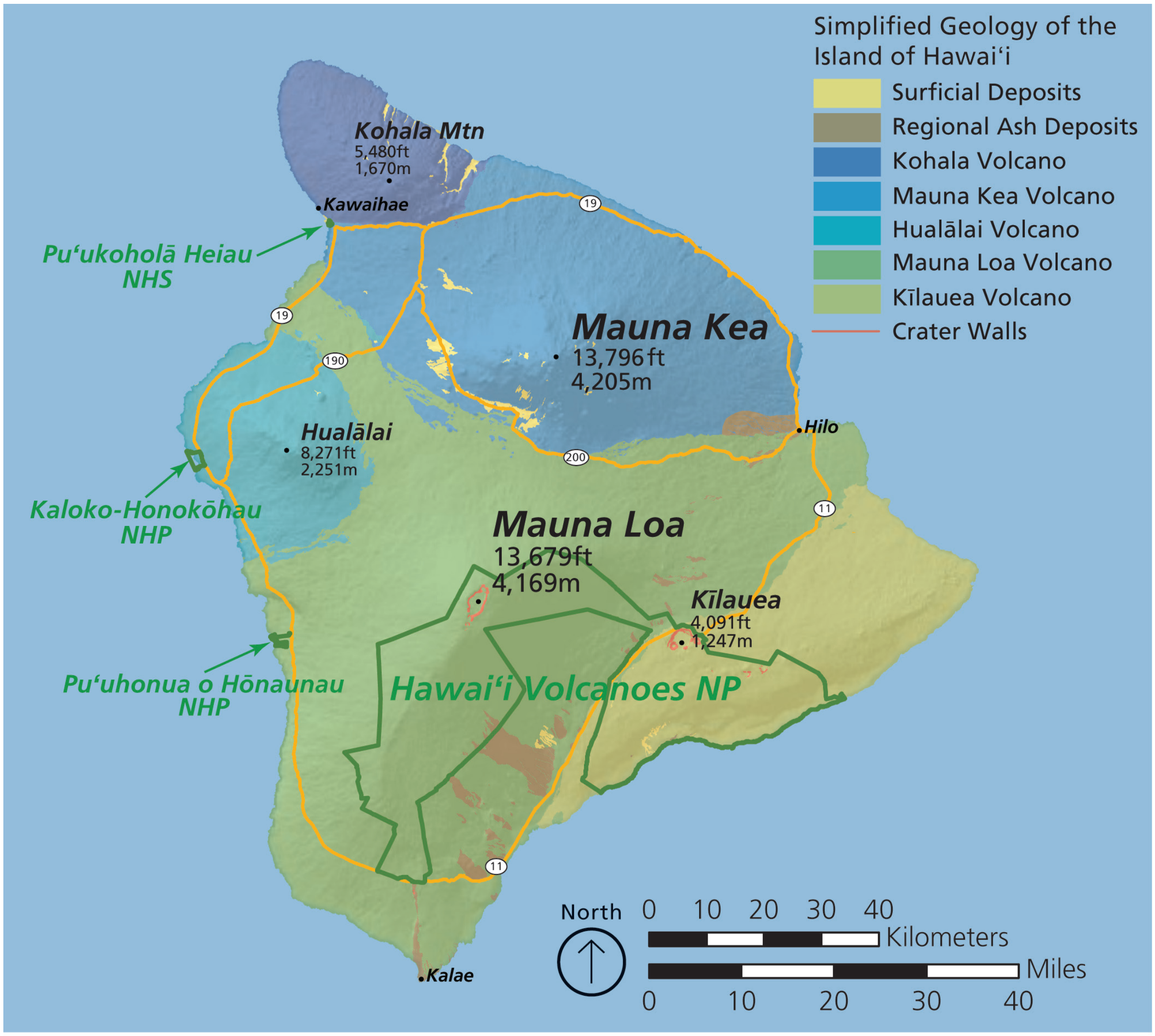

Figure 1. Shaded relief map of the Island of Hawai‘i. Peaks of the island's five volcanoes are indicated. Different colors show the extent of volcanic deposits from the five volcanic centers. National Park Service areas are outlined in green. The Kona coast stretches from Kawaihae to Kalae on the west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

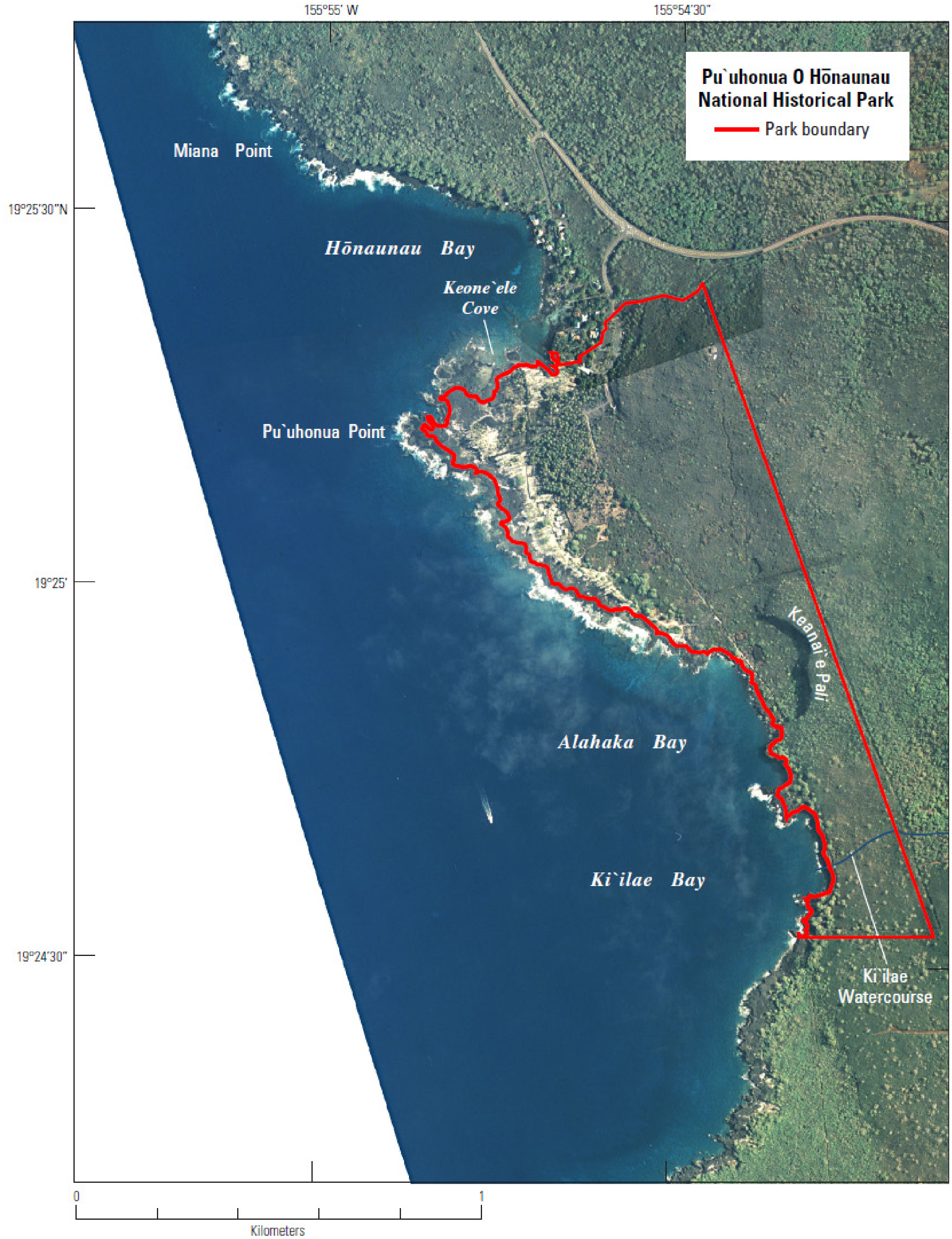

Figure 2. Aerial photomosaic of the location of Pu'uhonua o Hōnaunau National Historical Park. Note the visible basalt shelf at the north end of the park (Pu'uhonua Point) and the steep lava cliffs (Keanai'e Pali) in the center of the image. U.S. Geological Survey graphic from Richmond et al. (2008).

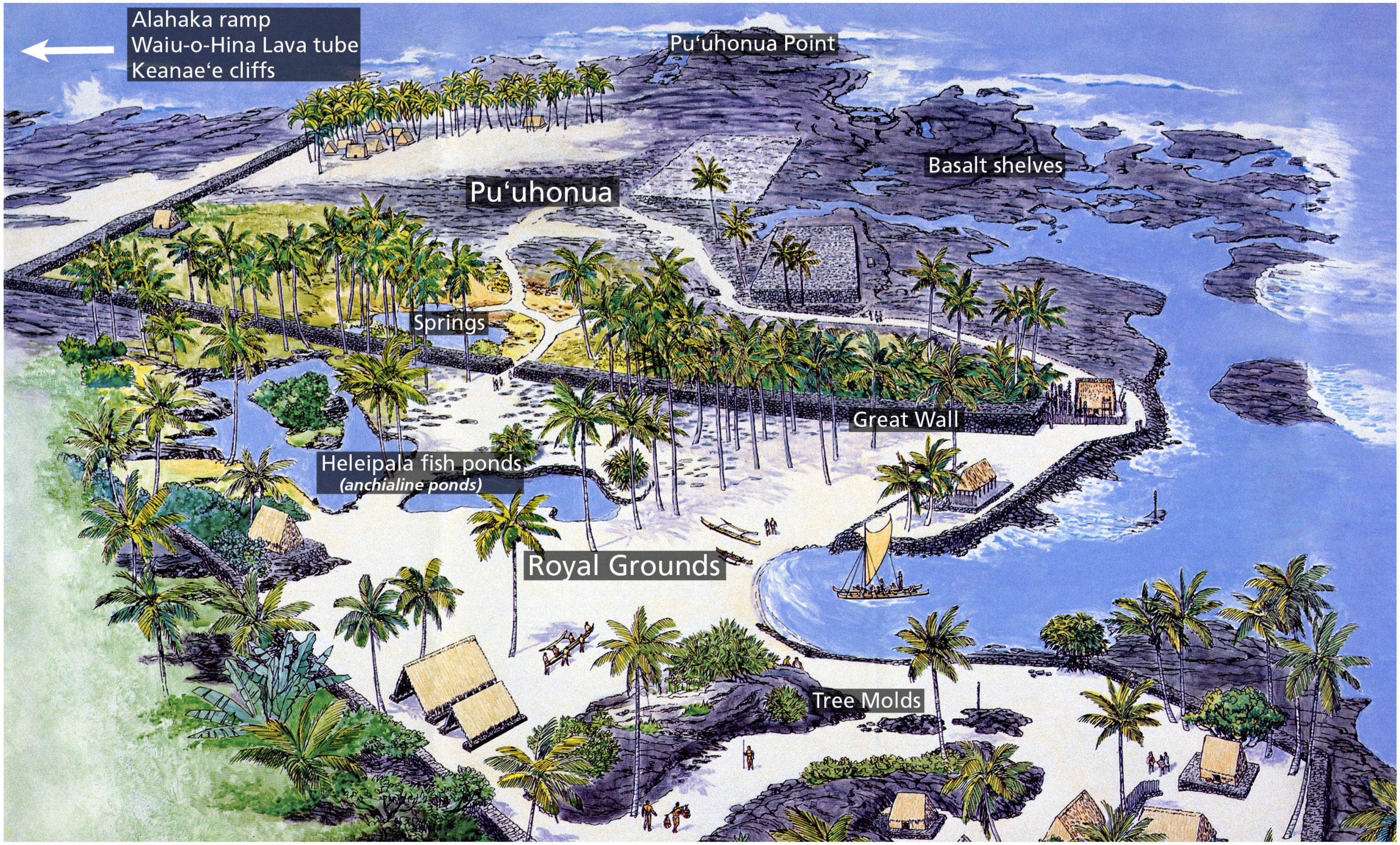

Figure 3. Oblique view of the Royal Grounds and the Pu‘uhonua in Pu‘uhonua o Hōnaunau National Historical Park. Several features in the park are directly related to geologic Processes, such as tree molds, lava tubes, pali (basalt cliffs), basalt shelves at the shoreline, and anchialine ponds. Hawaiians also used the geologic features to their advantage, building walls and ramps out of basalt blocks, as well as using the springs to hold fish. National Park Service image by Herb Kawainui Kane, courtesy Dave Krueger (NPS Views Program)

Figure 4. Two carved wooden images, called Ki‘i , overlooking Keone‘ele Cove in Pu‘uhonua o Hōnaunau National Historical Park. The Ki‘i are near the Hale o Keawe temple, a sacred place where the bones of 23 Hawaiian chiefs (Ali‘i) were once interred. National Park Service photograph courtesy Dave Krueger (NPS Views Program).

Figure 5. Hale o Keawe temple at Pu‘uhonua o Hōnaunau National Historical Park. Note constructed basalt walls and natural basalt shelf. National Park Service photograph courtesy Dave Krueger (NPS Views Program).

Geologic Issues

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

Introduction

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

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

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

Richmond, B. M., S. A. Cochran, and A. E. Gibbs. 2008. Geologic Resource Evaluation of Puʻuhonua O Hōnaunau National Historical Park, Hawaiʻi; Part I, Geology and Coastal Landforms. Open-File Report 2008-1192. U.S. Geological Survey, Reston, Virginia, USA. (http://pubs.usgs.gov/of/2008/1192/).

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

Cochran, S. A., A. E. Gibbs, and J. D. Logan. 2007. Geologic resource evaluation of Puʻuhonua O Hōnaunau National Historical Park, Hawaiʻi; Part II, Benthic habitat mapping. Scientific Investigations Report SIR 2006-5258. U.S. Geological Survey, Reston, Virginia, USA. (http://pubs.usgs.gov/sir/2006/5258/).

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

Groundwater Recharge

The availability of important, fresh groundwater resources on the Island of Hawaiʻi depends on the age and geologic structure of a given area. Most of the island's aquifers are unconfined, and range from thin, brackish water lenses to vertically-extensive freshwater bodies floating atop saline groundwater (Takasaki 1978; Rutherford and Kaye 2006). Some groundwater systems are impounded by linear volcanic dikes (locally, dikes occur deep within the rift zones of Mauna Loa). Saltwater intrusion is a possibility near coastal areas, and is among the factors limiting freshwater groundwater availability at Puʻuhonua o Hōnaunau National Historical Park. Seawater is the biggest local pollutant of fresh groundwater, and may further exacerbate the problem of increased groundwater demands placed by encroaching development (Takasaki 1978). The current status of park waters with respect to nutrient contamination is unknown. Agricultural activity, upslope residences, maintenance activities, and a small boat landing in Hōnaunau Bay, discharge pollutants into the park's watershed(Hoover and Gold 2006).

Another factor limiting freshwater supply at the park is its location on the leeward side of the island, where it is blocked from trade winds by Mauna Kea and Mauna Loa. Thus, the amount of precipitation at the park is 38 to 100 cm/year (15-40 in/year) (Davis and Yamanaga 1968). However, higher elevations can receive a mean annual rainfall of 102 cm (40 in) (Peterson et al. 2007). This precipitation can recharge aquifers downslope, but aquifer retention values may be low, given the high permeability of the lava flows. Recent data also indicate that groundwater flow in the park has decreased significantly over the last 20-30 years, presumably due to upslope groundwater withdrawals (Hoover and Gold 2006).

Most watersheds on the Island of Hawaiʻi are typically small, with steep slopes and little to no channel storage (Richmond et al. 2001). Because of these limitations, many streams, such as those in Puʻuhonua o Hōnaunau

National Historical Park, are ephemeral, only flowing after seasonal precipitation events—with water levels rising quickly during storms, and high runoff rates (little groundwater recharge). This in turn causes damaging coastal flooding, as well as transport and discharge of upland sediments into coastal areas (Rutherford and Kaye 2006). Flash flooding of low-lying areas and rapid discharge of sediment, though not common along the dry Kona coast (Richmond et al. 2008), could dramatically change the park landscape. Flash floods could alter Ki'ilae Stream (normally a dry channel) within Pu'uhonua o Hōnaunau National Historical Park (Richmond et al. 2008).

Aquifer characteristics vary, based on geologic features and structures (especially rock permeability), as well as recharge rates. Nearly all of the aquifers on the Island of Hawai'i are within volcanic rock. The permeability of volcanic rock is highly variable, and can change within small areas, depending on the mode of emplacement, degree of weathering, and overall rock thickness (Rutherford and Kaye 2006). Lava flows and scattered soils in the park are very porous and infiltration levels are high, resulting in a lack of surface water features and saturation near sea level (Davis and Yamanaga 1968; National Park Service 2005). The best-developed Hawaiian aquifers are in volcanic rocks that formed during the main, shield-building stage of volcano growth (see "Geologic History") (Richmond et al. 2008).

Groundwater recharge events are best observed at sea level from water discharge through lava tubes along the Kona coast (Davis and Yamanaga 1968). Submarine groundwater discharge (SGD) includes any and all outward movement of water from the aquifer to the overlying water column. Quantitative aerial thermal imaging and natural radon-salinity tracer tests reveal plumes of relatively cold SGD from distinct point sources along the leeward Kona coast (Peterson et al. 2007). SGD can be enhanced by high precipitation rates, high relief, and high permeability—all of which are common along the Kona coast (fig. 6) (Peterson et al. 2007). These factors make the area around Pu'uhonua o Hōnaunau National Historical Park an ideal study area for developing SGD assessment tools.

Understanding the hydrogeologic system is vital to managing water resources effectively. 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. 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.

The U. S. Geological Survey estimates groundwater recharge, and has worked to develop groundwater flow models, (1) To quantify the hydrologic effects of groundwater withdrawal for human use; and (2) To address long-term effects from such withdrawals on the Kona area of the Island of Hawai'i. Geophysical techniques for groundwater research at the park could include thermal infrared scanning (to locate fresh water outflows), low-level aeromagnetic surveys (to locate geologic barriers to flow), and DC resistivity measurements (to locate geoelectric anomalies associated with concentrations of fresh water) (Huber and Adams 1970). Audiomagnetotelluric (AMT) methodology, used in conjunction with other geophysical methods such as aerial infrared scanning and low-level aeromagnetic surveys, can be used to estimate the depth of the seawater interface with fresh water, or analyze underground structures that may control the movement of groundwater (Adams et al. 1971; Lepley and Adams 1971). In 1971, a 50-km (30-mi) stretch of the Kona Coast north of the park was measured using the AMT method (Lepley and Adams 1971) The study revealed features in the substrate, such as horizontal isotropy, vertical dike swarms, freshwater aquifers atop saline water, and other geologic structures (Lepley and Adams 1971). Similar work could aid the production of groundwater models for the park area.

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 Pu'uhonua o Hōnaunau National Historical Park for 1984, 1980, and 1999 (Rutherford and Kaye 2006). These data are available from the USGS office in Honolulu (http://hi.water.usgs.gov/).

Anchialine Ponds

Anchialine ponds are among the most threatened ecosystems in Hawaii (Tetra Tech 2004). These pools are relatively small, inland sources of brackish water influenced by tides and springs. Water levels and salinity in the ponds vary constantly, as they are connected to the ocean via subterranean tunnels (National Park Service 2005; Malama Kai Foundation 2008). 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).

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. Because relatively little information on erosion or sediment transport is available for Hawaiian watersheds, it is unknown how sedimentation affects these anchialine ponds (Rutherford and Kaye 2006). There are several anchialine pools at the park, but the number and locations of the pools are not well characterized, and no quantitative water quality data exists for them (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. At Pu'uhonua o Hōnaunau National Historical Park, park staff are in the process of removing invasive fish species. Since these ponds are partially underground, it is virtually impossible to manually remove all the invasive fish species (Malama Kai Foundation 2008). At least one pool at the park is impacted by a stockpile of plant waste, and other pools may be impacted by sedimentation from road and trail fill material (Hoover and Gold 2006).

At Pu'uhonua o Hōnaunau National Historical Park, in addition to the natural anchialine ponds, there are artificial fishponds, including a royal fishpond complex (Heleipala) (figs. 3, 8); this complex is surrounded by walls constructed to take advantage of variations in natural surface elevation. These anthropogenic features occupy a similar environment to the anchialine ponds, and have associated, small (≈2,500 m^2 [27,000 ft^2]) wetland areas (Richmond et al. 2008). Some preliminary water quality data suggest significant uptake of nutrients from groundwater inputs in the Royal Fishpond (Hoover and Gold 2006).

Coral Reef Changes

The boundary of Pu'uhonua o Hōnaunau National Historical Park extends to the mean high tide line, and does not officially include the marine environment; however, changes to this environment as a result of any development in the park area are of interest to park resource managers (Cochran et al. 2007). Fletcher et al. (2008) offers a comprehensive look at the geology of Hawaiian reefs. A brief description is presented here; however, the reader is encouraged to consult the following website for more information: (http://www.soest.hawaii.edu/coasts/publications/nbGeologyofHawaiiReefs.pdf).

Coral reefs are host to a high level of marine biodiversity. Coral reef ecosystems are also geologically productive, building islands such as atolls. The erosion of coral reefs by wave action can also create sand deposits and beaches. Typical reef growth within the coastal areas of the Hawaiian Islands consists of a thin, 1 to 2 m (3 to 6 ft) veneer of coral-algal growth (Grigg 1998). Substrate beneath reefs is either volcanic rock platforms or antecedent Pleistocene-age limestone (Grigg 1998; Richmond et al. 2001). However, at Pu'uhonua o Hōnaunau National Historical Park, there are no Pleistocene reef substrates; island subsidence has caused older reefs to be located in much deeper water (fig. 7) (Bruce Richmond, geologist, U.S. Geological Survey, written communication, November 2010). Although substrates may be similar throughout the Island of Hawai'i, different morphologies and coral cover make each offshore environment unique (Gibbs et al. 2004).

Compared with other regions of the island, rich coral reef communities exist off the Kona coast. This coral richness can likely be attributed to the sheltered environment provided by the island in which corals can thrive (Dollar 1975). This 115-km (70-mi) long coast stretches from Kawaihae, south to Kalae (South Point), and is mostly protected from tradewind-generated wave energy. The island of Maui also serves to protect this stretch of shoreline from waves arriving from the northwest. However, the Kona coast is not immune to high wave energy, as seasonal storms, tsunami, and south (generated by winter storms in the southern Pacific Ocean, active from April to October) and west swells do occasionally create high wave energy conditions (Dollar 1975; Gibbs et al. 2006; Ann Gibbs, geologist, U.S. Geological Survey, written communication, November 2010). Some of the highest coral cover rates observed in the Hawaiian Islands are found in the Pu'uhonua o Hōnaunau National Historical Park area (Gibbs et al. 2004).

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

1. The nearshore zone extends out to 36 m (118 ft), with as much as 8 m (26 ft) of depth. This zone is dominated by *Pocillopora meandrina* coral, growing on an irregular bottom cover of basalt boulders.
2. The second zone extends another 35 m (115 ft), out to depths of 6-14 m (20-46 ft). *Porites lobata* coral dominate the coral species of this zone, growing on gently-sloping basalt and limestone substrates.

3. The third zone extends to 14-30 m (46-98 ft) depth (an additional 18-37 m (59-121 ft) downslope), and contains predominantly *Porites compressa* coral.
4. The last zone extends out to 50 m (164 ft) depth, with abundant coral rubble and fine sand substrates. Coral succession in this zone is limited by illumination levels and influxes of sand and rubble.

Hawaiian corals tend to grow on fringing reefs with no separating moat or lagoon. The reefs formed on lava benches, carved during oceanic sea-level lowstands. These benches are further modified by subsidence, lava intrusion, and slumping. Coral reef zonation is affected by light gradients, as well as depth, temperature (25-29°C is ideal), water turbulence, sedimentation rates, and biological factors such as opportunism and competition (Dollar 1975).

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

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

NOAA has established a standard for characterization of coral-reef environments that describes benthic habitats on the basis of sea floor geomorphology, geographic zonation, and biological cover (fig. 9). The U.S. Geological Survey created benthic habitat maps using NOAA standards and classification schemes at a finer scale (Cochran et al. 2007). Data included in this process included aerial photography, SHOALS LiDAR bathymetry, underwater video, still photography, field checks and surveys, and GIS technology. Overall results of this mapping reveal that reef zonation off Pu‘uhonua o Hōnaunau National Historical Park is relatively simple, with a sloping volcanic shelf platform beginning at the shoreline, and descending to a sand-covered bottom toward deeper oceanic levels. A reef crest and spur-and-groove structures are not present (Cochran et al. 2007). This mapping will be useful as an inventory of baseline conditions, for any future monitoring projects off the coast of Pu‘uhonua o Hōnaunau National Historical Park. It will help to understand responses of the coral reef communities to changes in the marine environment: relative sea-level rise, contamination, changing oceanic conditions (e.g., temperatures, wave energy and direction, changes in groundwater discharge and chemistry, etc.), and increased sediment and nutrient input from local development (Ann Gibbs, geologist, U.S. Geological Survey, written communication, November 2010).

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

Geologic Hazards

Many natural phenomena pose threats to coastal and near-coastal areas of the Hawaiian Islands. Among these hazards are volcanism, mass wasting, coastal erosion, tsunami inundation, sea-level rise, and seismic activity (Richmond et al. 2008). Local slope and geologic setting must be taken into account, to accurately determine hazard potential for a specific area such as Pu‘uhonua o Hōnaunau National Historical Park (fig. 10) (Richmond et al. 2001; Fletcher et al. 2002). According to Richmond et al. (2008), the overall hazard assessment for the park is relatively high. Important tools in hazard assessment include records of past events, magnitude, and frequency of occurrence, determined from historic records, combined with accurate inventorying and regular monitoring of current conditions.

Volcanism

Kīlauea and Mauna Loa are two of the most active volcanoes in the world. Mauna Loa last erupted in 1984. Kīlauea, which started erupting in 1983, has added an additional 2.3 sq km (0.9 sq mi or 570 acres) 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 travel 50 km (30 mi) or more from the source vent. In 1950, flows from Mauna Loa reached the coast about 7 km (4 mi) south of the park (Wolfe and Morris, 1996a), a distance of about 35 km (22 mi). While lava generally flows slowly enough to allow people and animals to escape, anything in the path of a flow, such as rainforests or historical sites and communities, can be damaged or destroyed by burial, crushing, or fire ignition (Rutherford and Kaye 2006). Similar impacts result from 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). The entire park is mapped as Hazard Zone 2 for lava flows by Mullineaux et al. (1987). This zonation indicates that the area is adjacent to and downslope from active rift zones of Mauna Loa. Therefore it is subject to burial by lava flows of even small volume erupted from flanking rift zones. Over the past 200 years, lava flows have inundated about 20 percent of areas included in zone 2 (Mullineaux et al. 1987).

Samples taken for chemical analyses from the rift zones for Mauna Loa help improve models of how the volcano releases volatiles into the environment. Applicable to Pu'uhonua o Hōnaunau National Historical Park, the HVO performs periodic geodetic surveys (with GPS, electronic distance measurement [EDM], and dry tilt surveys) to precisely measure changes in ground deformation, as well as strain rates and velocities associated with potential volcanic activity; these are compared with previous measurements (Rutherford and Kaye 2006). Seismic refraction surveys can also yield valuable information leading to a fuller understanding of the volcanic and tectonic processes associated with the activity and growth of Hawaiian volcanoes (Zucca et al. 1982).

As lava flows and cools, inundation by lava and lava tube collapse are potential hazards. Tubes can collapse, posing a threat to visitor safety and park infrastructure. Caves may also contain valuable artifacts and cultural resources that could be targets for protection. Lava tubes are hollow, cave-like spaces sometimes filled by subsequent flows. The HVO library and the Hawaii Speleological Survey have recorded more than 250 large lava tubes in the state of Hawaii (Rutherford and Kaye 2006). In Pu'uhonua o Hōnaunau National Historical Park, there are no monitoring programs for old lava tubes.

Another potential issue associated with active volcanism in the vicinity of Pu'uhonua o Hōnaunau National Historical Park is airborne volcanic emissions. According to the U.S. Geological Survey HVO, the volcano emits hundreds of tons of toxic sulfur dioxide gas (SO_2) each day, making it among the largest stationary sources of SO_2 in the United States. Sulfur dioxide, combined with acid aerosols, and oxidized volcanic particulates 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. Depending on wind conditions, vog can be present at Pu'uhonua o Hōnaunau National Historical Park. The Kona coast of the Island of Hawai'i is somewhat buffered from the prevailing tradewinds by Mauna Loa, Mauna Kea, and Hualālai mountains. The coast is reliant on diurnal sea and air circulation, that drives winds downslope and offshore during the night, and upslope during the day. At times, this circulation is not enough to clear the air of vog that is trapped in the leeward Kona area of the south end of the island (National Park Service 2005). During particularly active eruptive periods, vog can cover the entire southern half of the island. 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.

Mass Wasting

Mass wasting involves the erosion of the landscape by either chemical or mechanical means. Landslides, rockfall, and slumps are three examples of mass wasting events. Throughout the Island of Hawai'i, anthropogenic changes, including the introduction of non-indigenous (exotic) species, urban development, and the placement of coastal structures can disturb the natural system and can increase erosion by disturbing the ground cover (Rutherford and Kaye 2006). Water flow in streams can scour stream valleys and transport sediment toward the coast. When water diversion systems and other anthropogenic structures interfere with stream flow, this can result in changes to turbidity, deposition cycles, and reduced productivity of the riparian and aquatic (both freshwater and marine) environments (Richmond et al. 2008). Relatively little information on erosion and sediment transport is available for the landscape in Pu'uhonua o Hōnaunau National Historical Park. Similarly, no modeling of areas at high risk for erosion and mass wasting is known for the park area. Pu'uhonua o Hōnaunau National Historical Park has isolated stretches of pali (or low cliffs) along isolated stretches of the shoreline. Though steep coastal cliffs pose a potential hazard to hikers (Richmond et al. 2008). In general, the modification of the landscape through erosion and weathering in the Island of Hawai'i varies dramatically because of variations in precipitation. Drier, leeward (western-facing) slopes along the Kona Coast do not have large canyons and surface gullying that are so prominent along the wetter, windward, eastern-facing slopes (Richmond et al. 2008).

Wieczorek and Snyder (2009) suggested five "vital signs" for monitoring slope movements: 1) types of landslides, 2) landslide triggers and causes, 3) geologic materials in landslides, 4) measurement of landslide movement, and 5) assessing landslide hazards and risks.

Tsunamis

Inundation and destruction by tsunamis is a threat along nearly all Pacific Ocean coastlines (fig. 10). Hawaii, situated in the middle of the Pacific Ocean, has been struck by more tsunamis than any other place on earth (Dudley and Lee 1998). Since recordkeeping began in 1837, at least 33 tsunamis of have struck Hawaii. At least four of these were locally generated, when earthquakes beneath the islands caused submarine landslides (Walker 1999; Richmond et al. 2001). These locally-generated tsunamis are especially dangerous, due to short warning time (Richmond et al. 2001). Earthquakes from around the Pacific Basin (e.g., Alaska, Japan, etc.) generated the other tsunamis that struck the Hawaiian Islands. The Hawaiian Islands experience a tsunami on average every two years, with significant damage occurring every five years on average (Dudley and Lee 1998). Other estimates put the recurrence interval for locally-generated destructive tsunamis at 20 years (Walker 1999). Following a magnitude 7.1 earthquake in the Aleutian trench (Alaska) on April 1, 1946, a tsunami traveled across the Pacific basin and struck the Hawaiian Islands, causing 159 fatalities (Pacific Disaster Center 2008). On May 23, 1960, a magnitude 8.3 earthquake in Chile triggered a 11 m (35 ft) tsunami that caused serious damage to Hilo, Hawai‘i and 61 deaths (Pacific Disaster Center 2008). A tsunami generated by a magnitude 9.0 earthquake off the coast of Japan struck Pu‘uhonua o Hōnaunau and Kaloko Honokōhau national historical parks on March 11, 2011. At Pu‘uhonua o Hōnaunau, repeated tsunami surges overtopped walls and travelled hundreds of feet inland. The surges scattered coastal vegetation and marine debris, necessitating the closure of much of the park. Several sites and features sustained damage, including collapsed, breached, and bulging walls, eroding cultural deposits, and washed out sections of trail. About 80% of the sand and fill material present in the Royal Grounds area of the park was either removed or displaced by the tsunami surges. (National Park Service 2011).

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

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

According to the 2007 Tsunami Warning Center operations manual (based on the operations manual by the PTWC), a local tsunami warning is issued for any earthquake in the State of Hawaii of moment magnitude (Mw) greater than 6.8. This is the most severe local bulletin, during which the Hawaii State Civil Defense will sound the tsunami sirens. Depending on the location of the quake, only select counties in the state may be placed in a warning. Initially, only the county in which the earthquake occurred and bordering counties are placed in a warning. For example if the earthquake occurred on Maui, then Moloka‘i, Maui and Hawai‘i counties would be placed in a warning. If the earthquake occurred on Hawai‘i Island, then only Hawai‘i 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 7.5 can 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 (PMEL) 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 Hawai‘i SOEST Institute of Geophysics also developed a model, which may be more applicable to tsunamis caused by local seismic events. The low-lying coastal area of Pu‘uhonua o Hōnaunau National Historical Park would certainly be at risk for serious damage should a tsunami strike the western side of the Island of Hawai‘i as illustrated by the damage from the March 11, 2011 teleseismic tsunami.

Coastal Erosion and Relative Sea-Level Rise

Puʻuhonua o Hōnaunau National Historical Park includes less than 10 km (6 mi) of coastline. 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).

Coastal geomorphology and geology, specifically the strength of the materials along the shore, influences the relative erodibility of a specific section of shoreline. The western coastline of the Island of Hawaiʻi varies from gently-sloping, sand-covered lava benches, to carbonate beaches, to low-lying rocky shorelines. Locally, coral reefs, embayments, anchialine ponds, intermittent streams, and anthropogenic developments (fish ponds) modify the Kona shoreline (Dollar 1975; Richmond et al. 2001). Erosion of the coast may cause beach loss, instability of lava benches, inundation, damage to shallow coral reefs, and increased sediment introduction to coastal waters.

Tidal range and wave height are linked to inundation hazards (Rutherford and Kaye 2006). A 1969 study by Rhodes and Raymond, details the currents, bathymetry, reefs, and beaches at the national historical park (Rutherford and Kaye 2006). This study could be used for comparison, with surveys of modern conditions, to determine relative change.

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

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

The relative sinking of the shore at Hōnaunau, measured at a rate of nearly 0.3 m/100 years (1 ft/100 years), could also threaten many park features. Bait cups, net-tanning tubs, and konami boards (a chess-like game surface hollowed out by ancient Hawaiians on the surface of pāhoehoe lava flows) once just above sea level at Hōnaunau are now submerged (Apple and Macdonald 1966). Hoover and Gold (2006) recognized the Royal Fishpond, park wetlands, and intertidal areas as at risk of degradation from rising seas. Active volcanism is adding significant mass to the southern end of the Island of Hawaiʻi, causing the underlying crust to bow downwards in response, and causing local rises in relative sea level. The island has subsided a total of nearly 1.2 km (0.75 mi), at a rate of about 2.6 mm/year (0.10 in/year) over the past 450,000 years (Zhong and Watts 2002; Richmond et al. 2008). The mass of Mauna Loa Volcano has depressed the base of the crust of about 9 km (6 mi) (Zucca et al. 1982).

Nearly one-quarter of the beaches in Hawaii have been significantly degraded over the last 50 years (Richmond et al. 2001). Erosion of the perched, carbonate-sand beach within the park necessitated artificial beach nourishment (Richmond et al. 2008 from oral communication by M. Laber, 2004). The beach at Keoneʻele Cove was also re-nourished with imported sand (Richmond et al. 2008). The causes of beach loss are generally not well understood or quantified. Possible causes include reduced sediment supply, major storms, anthropogenic shoreline armoring structures, and other development (Richmond et al. 2001; Rutherford and Kaye 2006). High quality still photography by Brian Powers (available at http://www.hawaiianimages.net/) may aid in determining current conditions (Bruce Richmond, geologist, U.S. Geological Survey, written communication, November 2010). Shoreline structures often exacerbate coastal erosion by changing a condition of shoreline erosion into one of beach loss (Richmond et al. 2001). Flooding of streams from intense rainfall events, are nearly annual events throughout Hawaii and cause beach loss or narrowing, (Richmond et al. 2001). Artificial beach nourishment may be preferable to hard-engineering solutions in areas with erosion problems. Carefully matching the native sediment type, size, and color is the most effective technique, and is more aesthetically pleasing to visitors (Richmond et al. 2008).

Following a site visit in January 2011, Williams (2011) provided short-term and long-term recommendations to the park regarding coastal erosion, cliff retreat, and flooding impacts, particularly in light of rising sea level associated with climate change. Alternatives discussed in Williams' trip report include: 1) a no-action alternative; 2)extension and reinforcement of the revetment and wall abutment of the Alahaka ramp; 3) utilizing wire mesh to stabilize the rock face along the Alahaka ramp; 4) beach nourishment; 5) planting of native trees and bushes for stabilization; and 6) construction of an offshore breakwater. Williams (2011) also discussed potential recommendations regarding climate change adaptation including the importance of planning for the coming changes, collecting LIDAR topography and bathymetry for the park and generating maps to depict areal effects of sea-level rise and storm surge flooding; generate risk and vulnerability maps based on the areal effects maps;

and establish a long term monitoring program to document changes as they occur.

Human activity, particularly the emission of greenhouse gases, very likely (more than 90% certain) contributes to global warming (IPCC 2007) and thus accelerating the rate of climate change and global sea-level rise. 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). Continued sea-level rise will eventually threaten many of the park's historical structures, parking facilities, fishponds, anchialine pools, 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.

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 the Island of Hawai'i. This study includes detailed recommendations for resource managers, including expertise, personnel, and equipment needed, approximate cost, and labor intensity.

Seismicity

The state of Hawaii is the most seismically active place in the U.S., with thousands of detectable tremors beneath the Island of Hawai'i each year. This frequency makes earthquake events a significant geologic hazard at Pu'uhonua o Hōnaunau National Historical Park (fig. 11) (Richmond et al. 2001). Hawaiian seismicity is closely linked with volcanism, as small earthquakes tend to accompany eruptions and subsurface magma movement within Kīlauea, Mauna Loa, Lō'ihi, and Hualālai volcanoes. Seismic refraction surveys can yield valuable insights into the locations and strengths of earthquakes occurring within active volcanoes, as well as the nature of the crust beneath volcanic masses (Zucca et al. 1982).

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

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).

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.

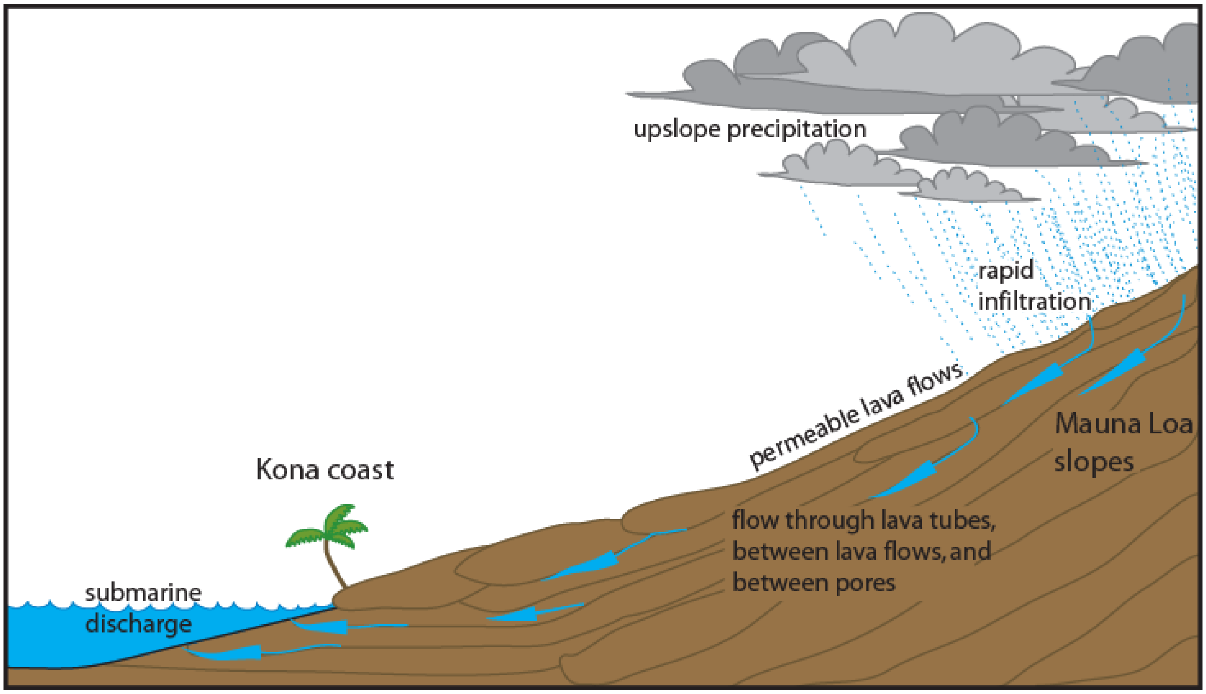

Figure 6. Diagrammatic model of precipitation-fueled submarine groundwater discharge along the Kona coast in Hawai'i. Not to scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), based on information from Oki et al. (1999).

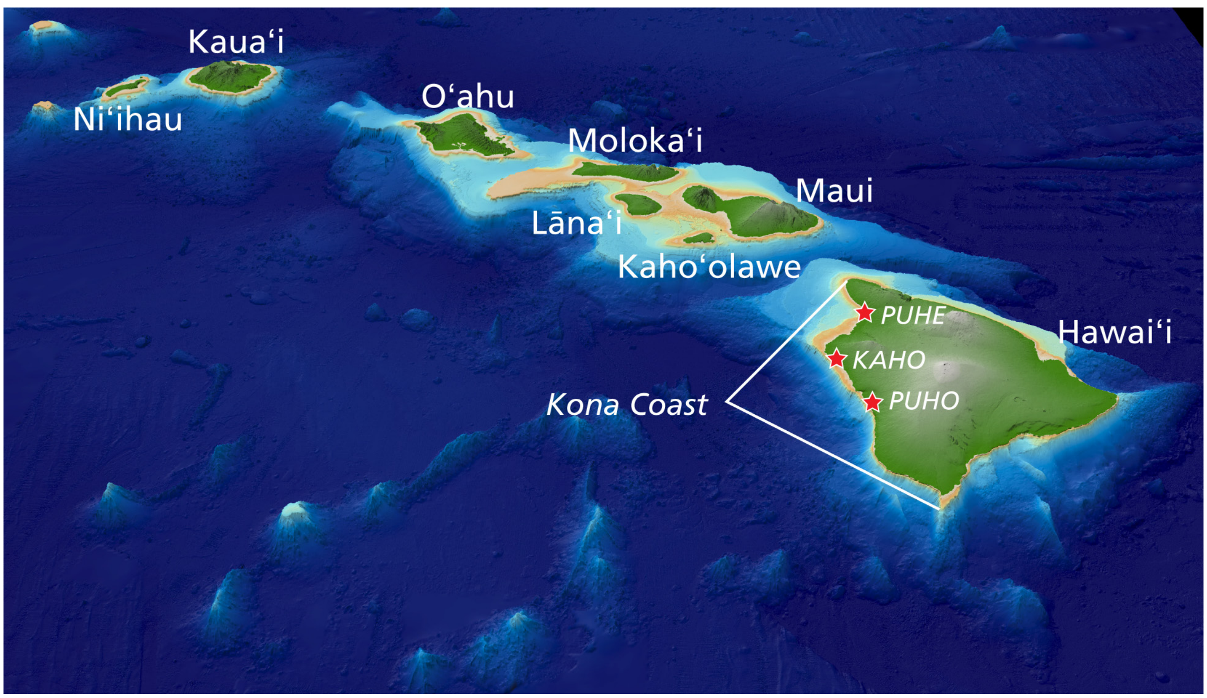

Figure 7. Bathymetry of the Hawaiian Islands. Note the relative lack of shallow, reef-sustaining substrate around the Island of Hawai'i compared to other islands such as O'ahu. Green areas are exposed land above sea level. Red stars are the location of the National Park Service areas along the Kona coast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

Figure 8. The historic and sacred fishing ponds at Pu'uhonua o Hōnaunau National Historical Park. National Park Service photograph courtesy Dave Krueger (NPS Views Program).

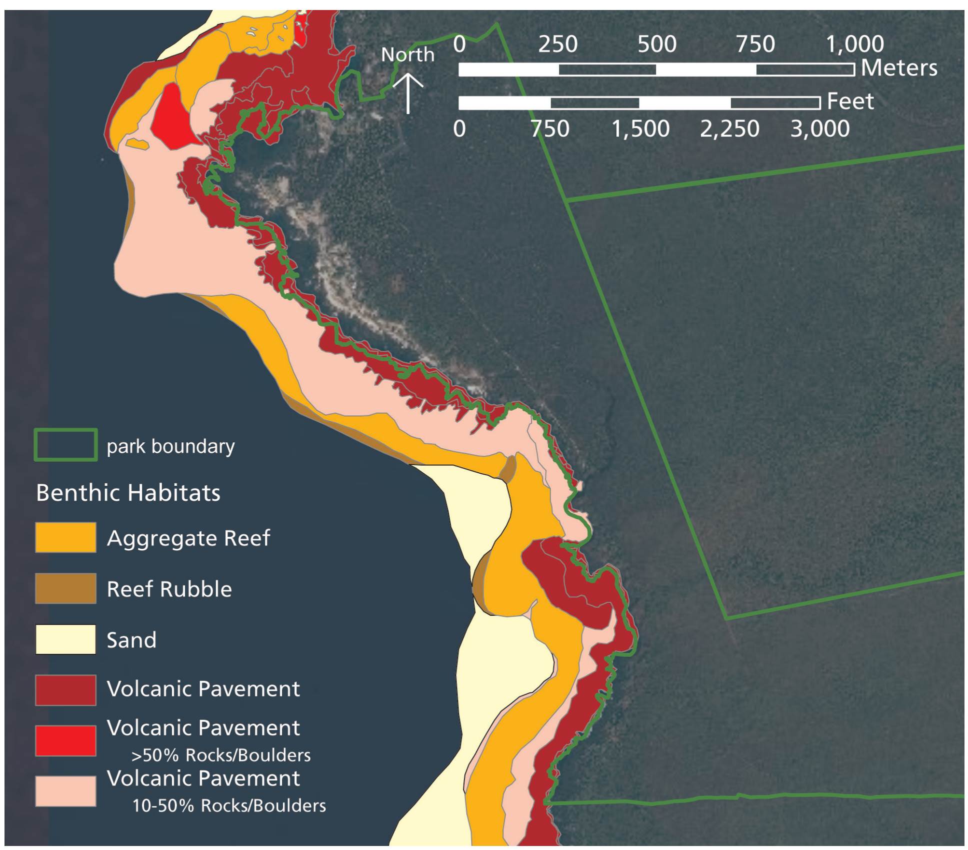

Figure 9. Benthic habitat map for Pu'uhonua o Hōnaunau National Historical Park showing the dominant structures. Graphic by Jason Kenworthy (NPS Geologic Resources Division) using benthic habitat data from Cochran et al. (2007) and ESRI ArcImage Service World Imagery (aerial image).

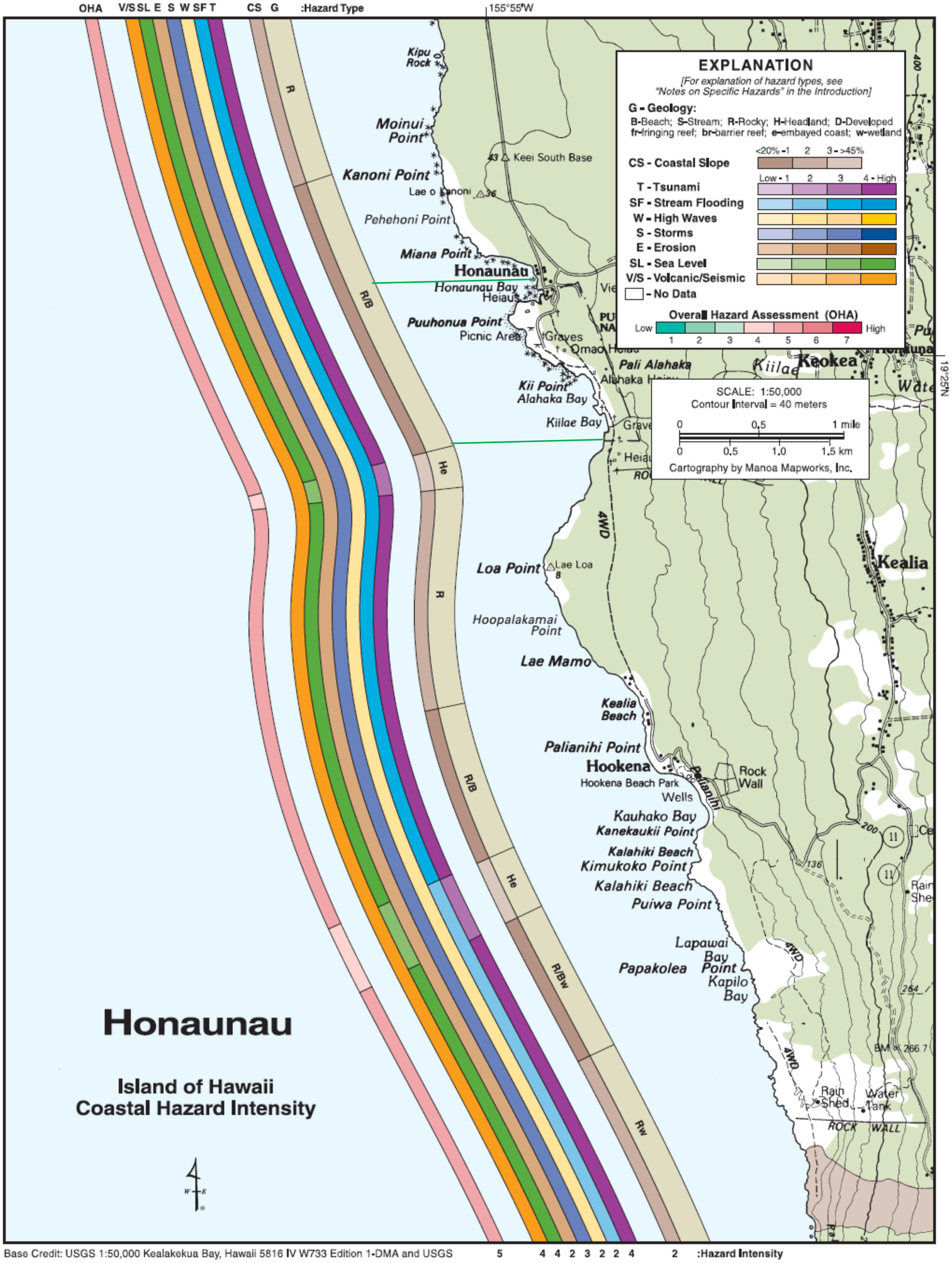

Figure 10. Coastal hazard intensity map for Pu'uhonua o Hōnaunau National Historical Park. Green lines bracket park's shoreline areas. U.S. Geological Survey graphic from Fletcher et al. (2002)

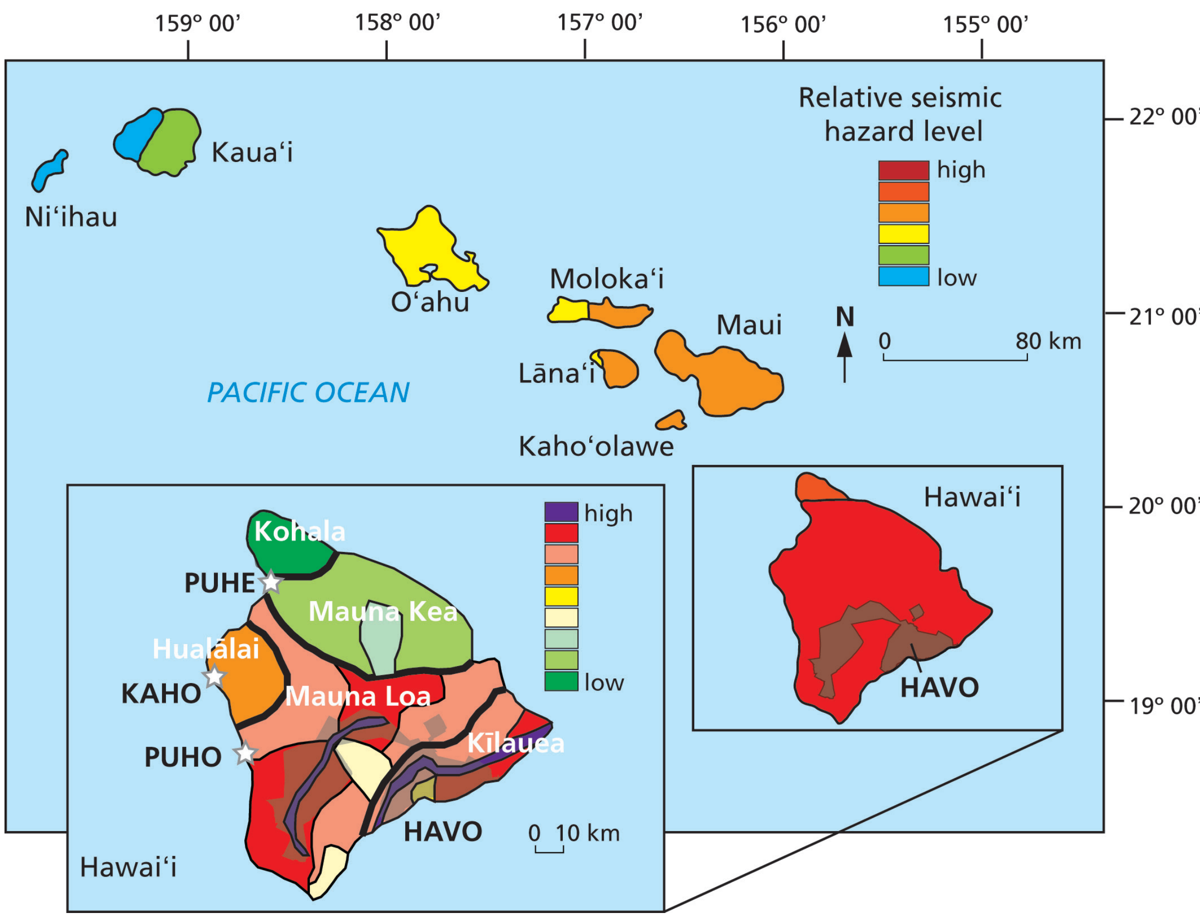

Figure 11. Earthquake hazard zones for the major Hawaiian Islands. White stars indicate park locations on the Island of Hawai‘i enlargement (PUHE: Pu‘ukoholā Heiau National Historic Site; KAHO: Kaloko-Honokōhau National Historical Park; PUHO: Pu‘uhonua o Hōnaunau National Historical Park; HAVO: Hawai‘i Volcanoes National Park). Volcanic centers on the Island of Hawai‘i are labeled in white and separated by thick black lines. Graphic is adapted from data provided by the U.S. Geological Survey (http://pubs.usgs.gov/imap/i-2724/**), Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) and Jason Kenworthy (NPS Geologic Resources Division).**

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Puʻuhonua o Hōnaunau National Historical Park.

Volcanic Features and Processes

The dominant geologic features at Puʻuhonua o Hōnaunau National Historical Park are the volcanic flows that descended along the gently-sloped western flank of Mauna Loa Volcano (geologic map units Qk1y, Qk2, and Qk3; see Overview of Geologic Data section). The youngest lava flows are virtually untouched by erosion, and maintain many original features of their emplacement (Davis and Yamanaga 1968).

Lava Tubes and Caves

When molten basaltic magma flows downhill, the upper surface cools faster than the underlying flow. This cooled upper surface often forms an insulating crust over the flowing lava. When the lava supply is extinguished, the flow leaves hollow spaces or tubes beneath the surface of the solidified lava flow. The HVO library (http://hvo.wr.usgs.gov/observatory/hvo_history_pubs.html) has more than 250 reports about lava tubes throughout the Hawaiian Islands, and the Hawaii Speleological Survey conducts explorations of larger tubes, including the famed Kaūmana lava tube near Hilo (Greeley 1974). At Puʻuhonua o Hōnaunau National Historical Park, networks of lava tube caves underlie many areas. Caves contain a number of unique geological formations, as well as cultural, paleontological, and biological resources. Of the 13 identified caves in the park, none has yet been inventoried (National Park Service 2005). One open lava tube ends at the face of a sea cliff, and is easily accessed by visitors (fig. 12) (National Park Service 2001). "Lavacicles" are an interesting cave formation unique to lava tubes (fig. 13). The Hawaiian Speleological Society has done some preliminary work in the area. A formal inventory would be helpful for resource management (Rutherford and Kaye 2006).

Tree Molds

Approximately 1,100 years ago, several lava flows descended from the flanks of Mauna Loa and inundated forests in the Puʻuhonua o Hōnaunau National Historical Park area (Woodcock and Kalodimos 2002). As lava flowed through the forests, molds of the larger trees were preserved in the basalt. Tree molds form when lava surrounds a tree and preserves its form upon cooling (fig. 14). Steam from moisture contained within the tree prevents it from burning—long enough to form a mold (Woodcock and Kalodimos 2005; Hunt et al. 2007). Many of the molds are from branched, woody dicots, but others are identifiable as the native loʻulu palm (*Pritchardia* sp.) These native plants were once prevalent throughout the lower elevations of the Island of Hawaiʻi, but declined after the arrival of ancient Polynesian peoples. The timing of the flows, in conjunction with the tree molds, suggests that the palms persisted in the Hōnaunau area even after the initial Polynesian era in southern Kona (Woodcock and Kalodimos 2002; Hunt et al. 2007).

Tree molds are valuable and fascinating resources, because the shape and orientation of a mold can help establish locations of individual volcanic vents that may be otherwise obscured and buried by later lava flows. Likewise, charred wood may be recoverable and provide information about flow temperature, vegetation present during the eruption period, and the age of the flow (if carbon dating is available). Tree molds at Puʻuhonua o Hōnaunau National Historical Park contain diagnostic features such as overall shape (including leaf bases and petioles) and surface features and patterns (bark and burn patterns) (Woodcock and Kalodimos 2005). The tree mold features occur in abundance near the coast at Alakaha Bay.

Coastal Landforms

As described by Richmond et al. (2008), coastal landforms that occur within the park include beaches, basalt-shore platforms, coastal cliffs (fig.15), and anchialine pools, wetlands, and fishponds. Three types of beaches occur within Puʻuhonua o Hōnaunau National Historical Park: perched, boulder, and intertidal. Perched beaches are wedge-shaped (maximum thickness is 1-2 m [3-6 ft]) deposits of primarily reef-derived carbonate sand, landward from the rocky shoreline, sitting atop gently sloping coastal terraces. Perched beach width ranges from 30 to 80 m (100 to 260 ft). This type of beach is usually active only during large wave events (Richmond et al. 2008).

The second type of beach occurring within the park is a natural beach composed of rounded, interlocking basalt boulders that form a wave-resistant structure. The boulders are naturally "quarried" from surrounding pali (low cliffs), possibly through a combination of mass movement and high wave energy events. Reef-derived carbonate sand and gravel is scattered among boulders ranging in size from 25 cm (10 in.) to more than 1 m (3 ft). The rounded boulders are probably only mobile during large storms (Richmond et al. 2008).

A small intertidal beach forms a barrier between the ocean and royal fishpond complex at Keoneʻele Cove. This area is sheltered from large waves by Puʻuhonua Point and its north-facing orientation towards Hōnaunau Bay. The beach has a gentle slope, and is less than 1 m (3 ft) in height. This beach contains both natural and artificially-nourished sand. The natural sand is moderately well-sorted, medium grained, and derived from adjacent reefs and basalt material, in contrast to the artificial, gray, angular beach-nourished sand (Richmond et al. 2008).

The majority of the shoreline at Puʻuhonua o Hōnaunau National Historical Park consists of a shore platform of pāhoehoe (ropy) basalt (fig. 16), that varies in width from 40 to 90 m (130 to 300 ft). This rocky, intertidal area is bare rock with tide pools and little sediment accumulation (fig 17), whereas the submerged portion of the platform is a substrate for corals (Richmond et al. 2008).

A narrow shore zone fronts basalt coastal cliffs in the southernmost portion of the park. In northern Alahaka Bay the shore platform narrows, increasing in elevation to the south, merging with the Keanaiʻe Pali. This forms nearly vertical cliffs, approximately 10 m (32 ft) high. The pali comprise the oldest lava flows within the park (Richmond et al. 2008).

Geology and Cultural Resources

Ancient Hawaiians revered the landscape; many of their traditions and cultural practices were directly related to geologic features and processes. Since 1966, Puʻuhonua o Hōnaunau National Historical Park has been listed on the National Register of Historic Places, with 321 sites listed within the park (National Park Service 2005). The National Park Service recognizes three designated cultural landscapes in the park. These are listed in the National Park Service Cultural Landscapes Inventory Database: 1) Puʻuhonua and Royal Grounds, 2) Kiʻilae Village, and 3) Keanaeʻe Cliffs. The National Park Service has not completed formal inventories of these three cultural features (National Park Service 2005). A 2006 survey indicated that nearly 1,500 archaeological sites and features exist within the park. Many of these have not been studied in detail (Tomonari-Tuggle and Tuggle 2006).

Traditional Hawaiian sites often used basalt boulders for construction, as well as features naturally occurring in the lava flows and shoreline areas (fig. 3). Examples include the Kings' Residence and Palace Grounds [Kauwalomalie] near Keoneʻele Cove, three holua (a sport using wooden sleds to descend a large slide, or holua), ceremonial sites and residences, and agricultural sites. The great wall that separates the palace area from the sanctuary is built with large blocks of basalt, some weighing up to five or six tons. This wall fits together without mortar, and demonstrates the remarkable engineering techniques of the early Hawaiians (Romey 1983). Other culturally significant sites in the park include two large temples (Alahaka Heiau and Omaʻo Heiau), and at least eight fishing shrines. Other archaeological sites include the remains of commoner settlements (preserved as surface structures or platforms), and cave shelters. Basalt shore platforms contain springs, net-tanning tubs, and bait cups (Richmond et al. 2008). Agricultural sites include the remains of animal pens and plant cultivation areas. Fishponds, refuge caves, ahupuaʻa boundary markers, ancient petroglyphs, old trails, and canoe landings are also listed sites (National Park Service 2005; Tomonari-Tuggle and Tuggle 2006). The Alakaha Ramp, along the 1871 Trail, is also constructed of basalt blocks (fig. 18). It was constructed so that horses could negotiate the steep basalt cliffs.

These numerous sites and resources are evidence of the sacred nature of the Puʻuhonua o Hōnaunau landscape to native Hawaiians, both past and modern. The refuge itself is located on a lava flow terrace that forms a point jutting into the Pacific (Romey 1983). Olivine nodules in lava, from the 1801 flow on the Kona Coast, may have attracted human interest (Pemberton 1964). The calm waters of Hōnaunau provided easy access to Kona's rich fishing grounds, numerous freshwater springs provided potable local water, and brackish pools made suitable holding pens for fish (Greene 1993; Hoover and Gold 2006). The Heleipala fishponds (fig. 8) are filled naturally by a mixture of seawater and fresh spring water welling up from below the sand. They also contain a valuable paleoenvironmental record in sediment cores containing pollen up to approximately 900 years old and changes in pollen assemblages approximately 500 years ago. This change reflects a change from native vegetation to coconut following increased settlement (Athens et al. 2006; Hunt et al. 2007).

Cultural resources are threatened by geologic processes, such as inundation by relative sea-level rise, storms, and tsunamis. Some features are already submerged, the shoreline is encroaching landward, and coastal processes will erode features such as petroglyphs and platforms along the coast (Apple and Macdonald 1966).

Figure 12. Molten lava once flowed through the Waiu-o-Hina lava tube from Mauna Loa to the sea. When the eruption stopped, all of the lava drained from the tube—some into the ocean—leaving a hollow tube. National Park Service photograph courtesy Dave Krueger (NPS Views Program).

Figure 13. These drips on the ceiling of the lava tube were created by the interactions of hardened lava and sea water. The surface of each drip is smooth, and the points are rounded from water action. National Park Service photograph courtesy Dave Krueger (NPS Views Program).

Figure 14. Tree molds in Pu'uhonua o Hōnaunau National Historical Park formed when lava surrounded a tree and preserved its form upon cooling. National Park Service photographs courtesy Dave Krueger (NPS Views Program).

Figure 15 The cliffs at the head of Ki‘ilae Bay were formed when a shelf of solid lava broke free from the rest of the land and slipped into the ocean. National Park Service photograph courtesy Dave Krueger (NPS Views Program).

Figure 16. Pāhoehoe lava is common in Pu‘uhonua o Hōnaunau National Historical Park. Pāhoehoe is a Hawaiian term describing lava with a smooth or ropy (as above) texture. National Park Service photograph courtesy Dave Krueger (NPS Views Program).

Figure 17. The majority of the shoreline at Pu‘uhonua o Hōnaunau National Historical Park consists of a shore platform of pāhoehoe. This rocky, intertidal area is bare rock with tide pools and little sediment accumulation Notice tree mold at lower right hand side (arrow). National Park Service photograph courtesy Dave Krueger (NPS Views Program).

Figure 18. The Alahaka Ramp, built after horses were introduced into Hawaii. People could climb up and down steep cliffs, but horses could not. Near the base of Alahaka ramp is the entrance to the Waiu-o-Hina lava tube. National Park Service photograph courtesy Dave Krueger (NPS Views Program).

Geologic History

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

In geologic terms, the rock units in Pu'uhonua o Hōnaunau National Historical Park (geologic map units Qk1y, Qk2, and Qk3) are young—dating back 5,000 years. Volcanism created the oldest 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. 19 and 20) (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. 21) (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. 22-23).

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. 23).

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. 24). Other such hotspots across the Pacific basin are the Caroline, Marquesas, Society, Pitcairn, Austral, and Easter hotspots (fig. 23) (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. 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 (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. 25) (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. 26) (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).

Relatively young volcanic deposits (Kaʻū Basalt) from the flanks and summit of Mauna Loa Volcano dominate the geologic units mapped for Puʻuhonua o Hōnaunau National Historical Park. Types of deposits include spatter or scoria cones and lava flows (geologic map units Qk1y, Qk2, and Qk3). The largest and most recent of these is the 750-1500 year-old flow that extends from the north to the Keanaeʻe Pali (geologic map unit Qk3). A 3,000-5,000 year-old flow stretches from the Keanaeʻe Pali to the southwestern edge of the park (geologic map unit Qk1y), and a 1,500-3,000 year-old flow covers the southeasternmost tip of the park (geologic map unit Qk2).

The pyroclastic vent deposits, consisting of spatter and some scoria, are mapped where they form prominent cones. These types of deposits result from lava fountains along concentrated southwest rift zones of Mauna Loa. Lava flows contain both pāhoehoe and ʻaʻā types, but predominantly the former, issued from elongated fissures on the volcano flank (Wolfe and Morris 1996a). Most of these flows formed during relatively brief (1-3 weeks) eruptions, with high rates of lava extrusion. These conditions favor development of extending, narrow, open lava channels flanked by levees, that efficiently supply lava to the broader toe of slowly advancing ʻaʻā (Wolfe and Morris 1996a).

Three periods of lava eruption are represented in the Kaʻū Basalt flows within the park: 5,000-3,000, 3,000-1,500, and 1,500-750 years before present. The Kaʻū Basalt overlies the Pāhala Ash (Qpha) and Kahuku Basalt (Qkh) on the gently-sloping lower flanks of Mauna Loa (Wolfe and Morris 1996a).

Recent flows from vents along the flanks of Mauna Loa are notoriously long, stretching from far southeast near 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). Volcanic activity is still a possibility at Puʻuhonua o Hōnaunau National Historical Park.

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) (such as the Keanea'e Pali at Puʻuhonua o Hōnaunau National Historical Park). 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 Hawaiʻi collect Holocene-age alluvium, colluvium, eolian deposits, and slope deposits.

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

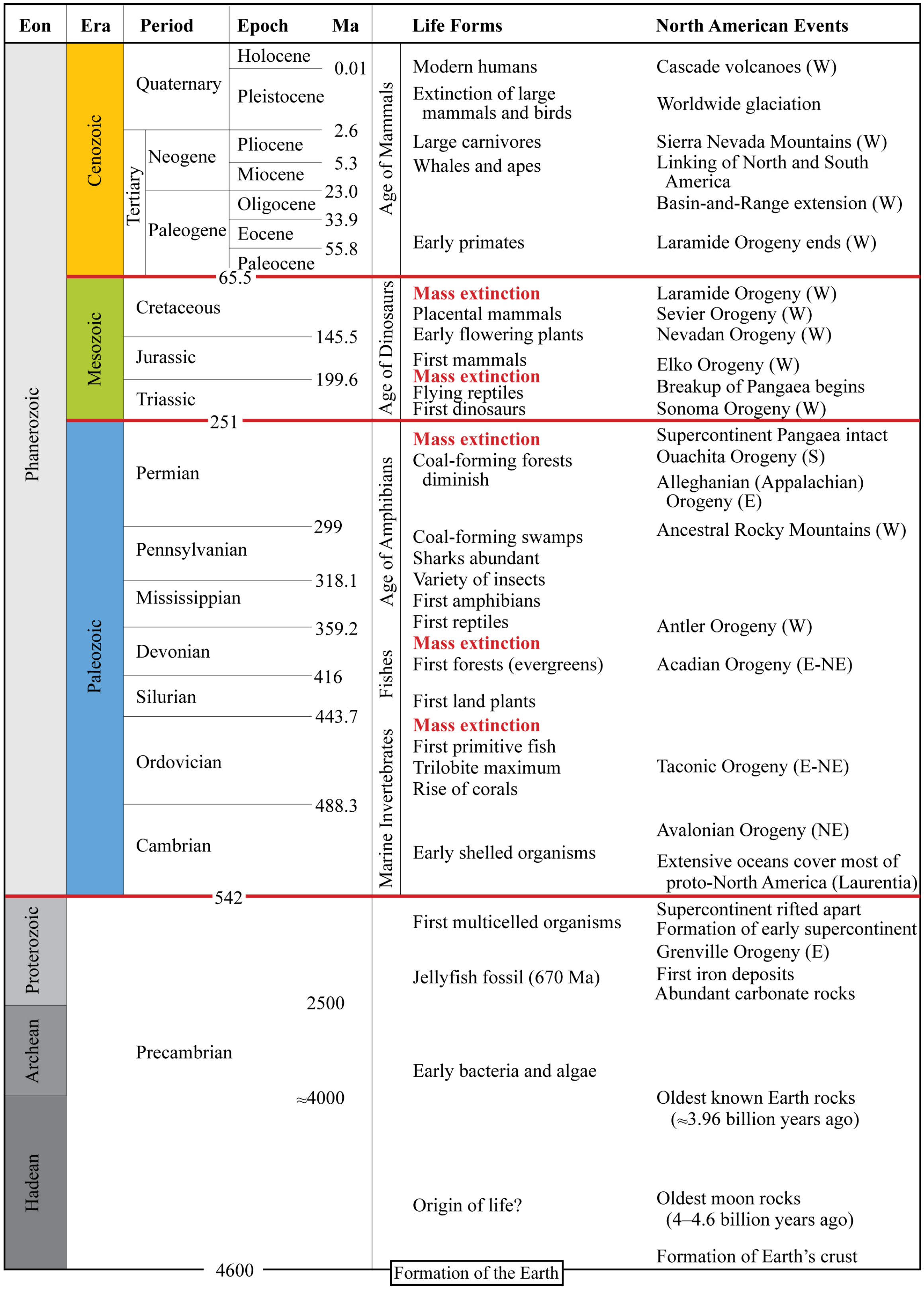

Figure 19. Geologic timescale. Included are major life history and tectonic events occurring in the Pacific region. Red lines indicate major unconformities between eras. Isotopic ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Adapted from the U.S. Geological Survey (http://pubs.usgs.gov/fs/2007/3015/) with additional information from the International Commission on Stratigraphy (http://www.stratigraphy.org/view.php?id=25), and Condie and Sloan (1998).

Era	Period	Epoch	Ma	Hawaiian Events	Volcanic Deposition
Cenozoic	Quaternary	Holocene	0.01	Active volcanism of Kīlauea and Mauna Loa	Puna Basalt, and Kaʻū Basalt deposition ongoing Laupāhoehoe Volcanics, and Hualālai Volcanics (Basalt Member) deposited
		Pleistocene		Shield stage volcanism on Mauna Kea Shield stage volcanism on Kohala	Pāhala Ash deposited Hilina Basalt, and Kahuku Basalt deposited Hualālai Volcanics (Waʻawaʻa Trachyte Member) deposited Hāwī Volcanics, Hāmākua Volcanics, and Nīnole Basalt deposited
			2.6	Shield stage volcanism on Haleakalā Shield stage volcanism on Kahoʻolawe Shield stage volcanism on West Maui Shield stage volcanism on Lānaʻi Shield stage volcanism on East Molokaʻi Shield stage volcanism on West Molokaʻi	Pololū Volcanics deposited
	Tertiary – Neogene	Pliocene	5.3	Shield stage volcanism on Niʻihau Shield stage volcanism on Kauaʻi	
		Miocene	23.0	Gardner Pinnacles volcanism	
	Tertiary – Paleogene	Oligocene	33.9	Midway Island volcanism	
		Eocene	55.8	Pacific plate changes motion, causing bend in seamount chain	
		Paleocene	65.5	Hotspot volcanism along Hawaiian-Emperor seamount chain ongoing throughout the Cenozoic	

Figure 20. Geologic time scale of events affecting the Hawaiian Islands throughout the Cenozoic Era; adapted from U.S. Geological Survey (http://pubs.usgs.gov/fs/2007/3015/) using information from Clague and Dalrymple (1987), written communication from D. Sherrod (2009), and the GRI digital geologic map for Hawaiʻi Volcanoes National Park. Ages of volcanic flows are generally relative and overlap considerably. Absolute ages in millions of years (Ma, or mega-annum).

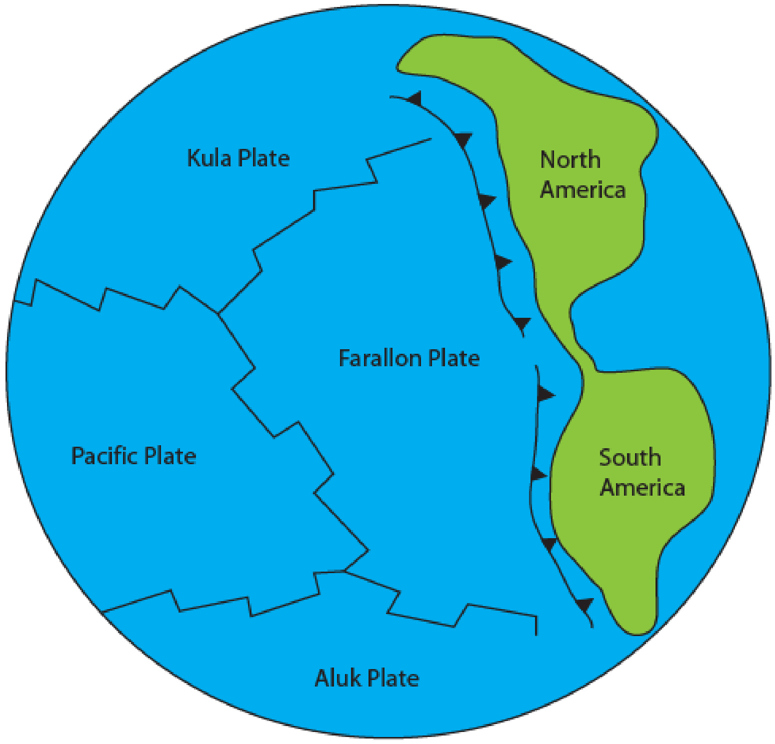

Figure 21. Generalized arrangement of plates in the Pacific Ocean basin during the middle Cretaceous. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

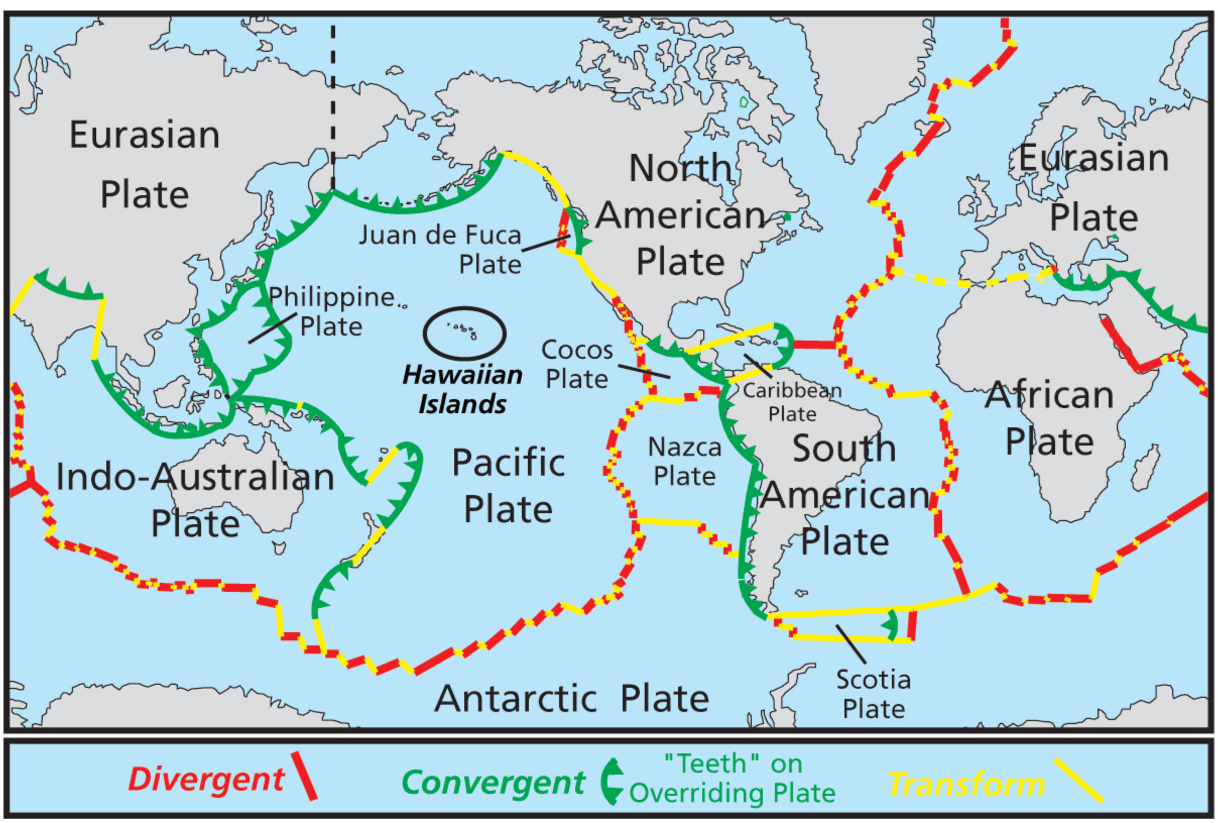

Figure 22. Map of the current tectonic plates. The Hawaiian Islands are circled. Divergent boundaries are where plates are pulling apart. Plates come together at convergent boundaries and slide past one another at transform boundaries. Graphic courtesy Robert J. Lillie (Oregon State University), modified from Lillie (2005).

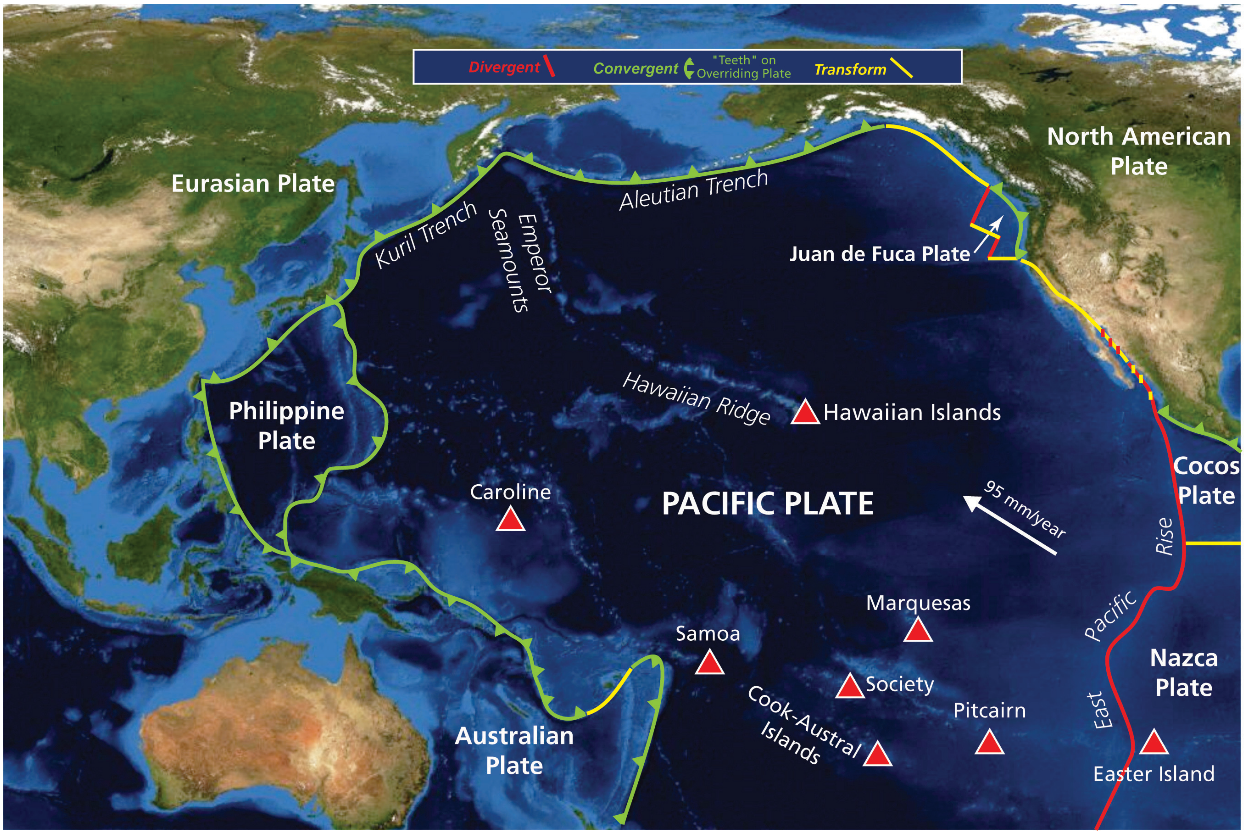

Figure 23. Tectonic setting of the Pacific Plate. This figure illustrates many of the features described in the Geologic History section. Note the extent of the Emperor Seamounts and Hawaiian Islands. Currently the Pacific Plate is moving to the northwest at about 95 mm (3.7 in.) per year. The "kink" between the Emperor Seamounts and Hawaiian Islands chain shows how the direction of motion changed while the Hawaiian hotspot remained stationary (see figs. 24 and 26). 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).

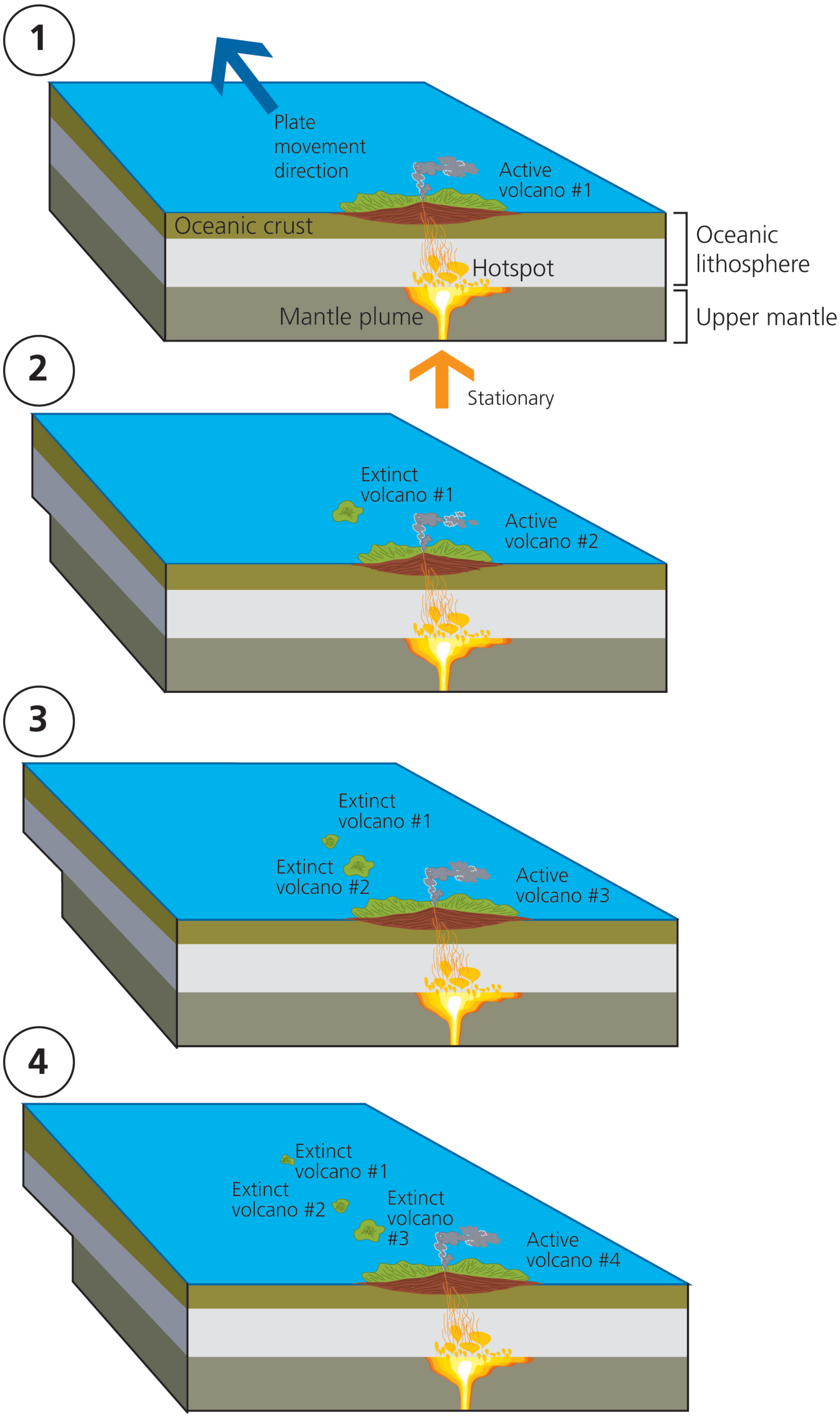

Figure 24. Evolution of a chain of islands over a stationary hotspot in Earth's crust. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

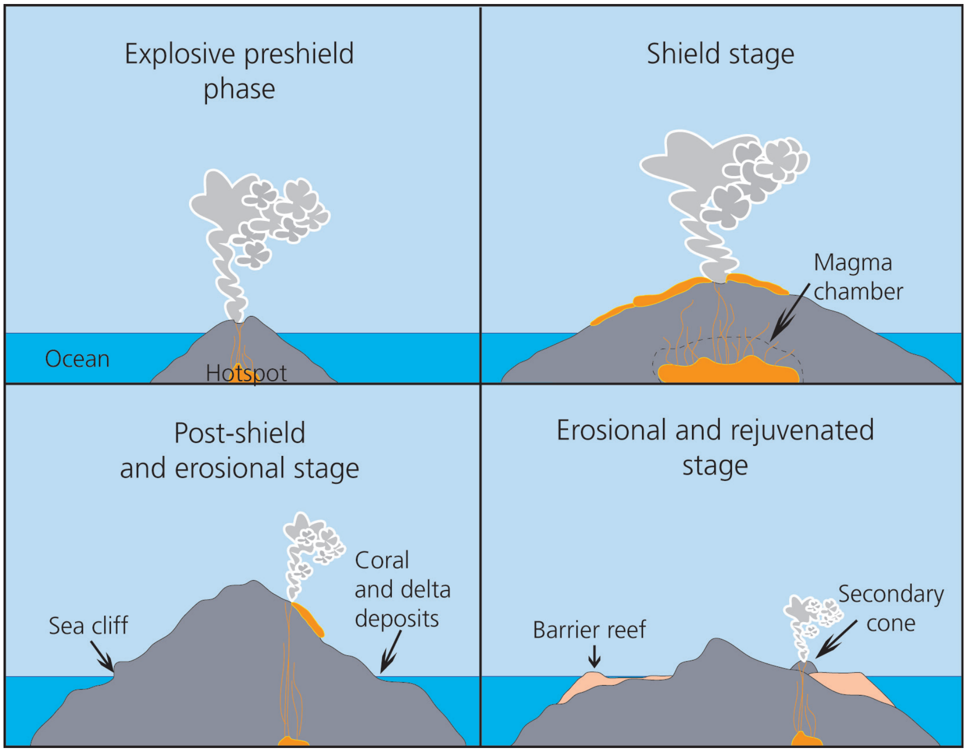

Figure 25. Simplified stages of Hawaiian hotspot island volcanism. After volcanism ceases, erosion and subsidence slowly reduce the island to a smaller subaerial remnant. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), after Keating (1992, fig. 29).

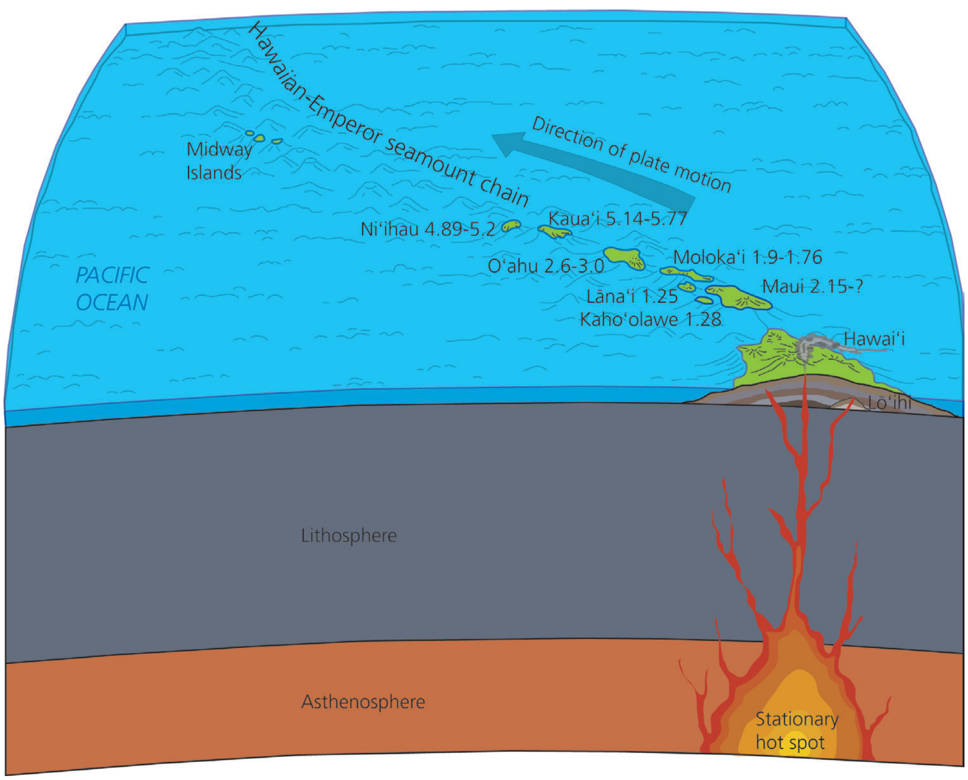

Figure 26. Evolution of the Hawaiian-Emperor seamount chain showing ages of shield-stage volcanism for the major Hawaiian Islands (ages are in millions of years). The specific type of age, error, and source are detailed in the text. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), 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 Puʻuhonua o Hōnaunau National Historical Park. It includes an overview graphic of the GIS data and a summary table that lists each map unit displayed on the digital geologic map for the park. Complete GIS data are included on the accompanying CD and are also available at the Geologic Resources Inventory (GRI) publications website: (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Geologic Maps

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

Source Maps

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

Trusdell, F. A., E. W. Wolfe, and J. Morris. 2006. Digital database of the geologic map of the Island of Hawaiʻi (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 Puʻu ʻŌʻō–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 Puʻuhonua o Hōnaunau National Historical Park using data model version 1.4.

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

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

Geology data layers in the Pu‘uhonua o Hōnaunau National Historical Park GIS data

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

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

Overview Graphic of Digital Geologic Data

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

Map Unit Properties Table and Correlation Table

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

Use Constraints

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

Please contact GRI with any questions.

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).

‘a‘ā. 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

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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National Park Service
U.S. Department of the Interior

Natural Resource Program Center
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov