National Park Service
U.S. Department of the Interior

Natural Resource Program Center

Hawai‘i Volcanoes National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/163

THIS PAGE:
Geologists have long been monitoring the volcanoes of Hawai‘i Volcanoes National Park. Here lava cascades during the 1969-1971 Mauna Ulu eruption of Kīlauea Volcano. Note the Mauna Ulu fountain in the background.

U.S. Geological Survey Photo by J. B. Judd (12/30/1969).

ON THE COVER:
Continuously erupting since 1983, Kīlauea Volcano continues to shape Hawai‘i Volcanoes National Park.

Photo courtesy Lisa Venture/University of Cincinnati.

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Geologic Resources Division
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P.O. Box 25287
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Natural Resource Program Center
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The Natural Resource Report Series is used to disseminate high-priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability.

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

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Executive Summary

This report accompanies the digital geologic map for Hawai‘i Volcanoes National Park in Hawai‘i, which the Geologic Resources Division produced 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.

Hawai‘i Volcanoes National Park is truly a place to experience geology first hand. Dynamic geologic processes of volcanism, mass wasting, and seismicity are changing the landscape on a dramatically short time scale. Native Hawaiians' oral traditions demonstrate a reverence for, and understanding of, the natural world. The geology on display at the park forms the foundation for myriad ecosystems and provides invaluable research opportunities in scientific fields such as volcanology, seismology, and speleology. The park strives to protect and preserve its unique environment while educating and providing safe access to more than a million visitors each year.

Geology is fundamental to the management of the scenic, natural, and cultural resources of the park. Geology contributes to climate, natural hazards, hydrology, and topography. Geology also strongly influenced the Native Hawaiian and early establishment history at the park. Geologic issues of particular significance for resource management at Hawai‘i Volcanoes National Park include:

- Volcanism.
  Kīlauea and Mauna Loa volcanoes crown Hawai‘i Volcanoes National Park. These volcanoes are among the most active in the world. Volcanic hazards include lava-flow inundation, forest fires, pyroclastic ejection, noxious gases, and lava-tube collapse. Scientists in cooperative networks are working to understand and predict volcanic activity to best protect park resources and human safety. The process of active volcanism at Kīlauea Volcano creates hazy "vog" that comprises acidic aerosols, unreacted sulfur gases, and volcanic ash and other fine particulate matter. This vog periodically obscures the vistas at the park.
- Mass wasting.
  Steep slopes, ground water and surface water flow, and frequent seismic activity create a setting prone to mass wasting. Mass wasting threatens visitor safety and buries local habitat, increases erosion, and disrupts the hydrologic system. There is a continuum between two main types of slope failures at the park: large, slow-moving slumps, and narrow, fast-moving debris avalanches. The Hilina slump covers most of the southern flank of Kīlauea Volcano. The largest slides, which extend offshore, could cause local tsunamis.
- Coastal erosion.
  Coastal erosion affects the shoreline at the park, causing potential loss of natural and cultural resources. Coastal erosion is a function of numerous factors. Relative sea level rise is locally high because of crustal loading from the active volcanic masses and relatively little removal of material by erosional processes.
- Seismicity and tsunamis.
  Seismicity is a concern throughout the Pacific Ocean basin. Earthquakes occur frequently on Hawai‘i as a result of magma movement accompanying volcanism, as well as crustal stresses arising from areas of structural weakness and crustal loading by the volcanic mass. Seismic activity has caused fatalities, ground rupture, localized uplift or subsidence, liquefaction, ground settling, and extensive damage to roads, buildings and homes, and it has triggered tsunamis. The coastal areas of Hawai‘i are susceptible to inundation during tsunamis. Interagency cooperators work to predict and warn populated areas of potential tsunami threats. Tsunami modeling considers all seismic events, bathymetry, storms, wind, and rain.

The scenic and cultural resources of the park are closely linked to its geologic features and processes. This theme is a potential interpretive topic. Kīlauea and Mauna Loa, with their volcanically active summits and rift zones, are the primary geologic features of the park. The ongoing eruption of Kīlauea is providing invaluable insights into lava-flow mechanics, hazard-zone assessment, and volcanic evolution of a Hawaiian island. Eruptions pumping lava downslope in lava tubes are adding new land to the island at rates of 4–70 ha/year (hectares) (10–170 acres). The vast network of lava tubes on the flanks of Mauna Loa and Kīlauea are a treasure for speleologists. Many new and transient lava tubes and other flow features are type localities at the park. Other features and processes of interest at Hawai‘i Volcanoes National Park include connections with biology and Hawaiian culture.

Knowing the physical properties of the different geologic units mapped at Hawai‘i Volcanoes National Park is important to managing the natural and cultural resources throughout the park. The table of map unit properties includes characteristics such as erosion resistance, suitability for infrastructure development, geologic significance, recreation potential, and associated cultural and mineral resources for each mapped geologic unit. In addition to their physical properties, the rock units and active geologic processes at Hawai‘i Volcanoes National Park provide information related to the evolution of volcanic islands and the geologic history of the Hawaiian-Emperor volcanic island and seamount chain in the Pacific Ocean basin.

Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Hawai‘i Volcanoes National Park.

Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded under the National Park Service (NPS) Natural Resource Challenge designed to enhance baseline information available to park managers. The program carries out the geologic component of the inventory effort. The Geologic Resources Division of the Natural Resource Program Center administers this program. The GRI team relies heavily on partnerships with the U.S. Geological Survey, Colorado State University, state geologic surveys, and others in developing GRI products.

The goal of the GRI is to increase understanding of the geologic processes at work in parks and provide sound geologic information for use in park decision making. Sound park stewardship relies on understanding natural resources and their role in the ecosystem. Geology is the foundation of park ecosystems. 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 this goal, the GRI team is systematically conducting a scoping meeting for each of the identified 270 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 by providing geologic data for use in a park GIS and facilitating the incorporation of geologic considerations into a wide range of resource management applications. The newest maps come complete with interactive help files. This geologic report aids in the use of the map and provides park managers with 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/).

Regional Information

Located on the southern end of the Island of Hawai‘i, the Hawai‘i Volcanoes National Park covers 1,348 km^2 (520 mi^2), an expanse that includes the 2003 acquisition of Kahuku Ranch (469 km^2, 115,788 acres) (figs. 1 and 2) (National Park Service 2009). Of the total area, 530 km^2 (205 mi^2) is in wilderness status (National Park Service 2009). The Island of Hawai‘i covers an area of about 10,432 km^2 (4,028 mi^2) and is the largest and youngest of the seven main Hawaiian Islands (fig. 3). The Hawaiian archipelago contains 18 islands, reefs, shoals, atolls, and pinnacles, the smallest of which, Gardner Pinnacle, is only about 1 ha (hectare) (2.5 acres). Hawai‘i lies southeast of the neighboring Island of Maui, separated by the 48-km- (30-mi-) wide ‘Alenuihāhā Channel, and is the southeasternmost landmass of the Hawaiian island chain. Hawai‘i is more than 3,500 km (2,200 mi) from the nearest continent, North America.

The Island of Hawai‘i is split geographically and ecologically into many areas and contains three volcanoes that have erupted in the past 200 years: Kīlauea, Mauna Loa, and Hualālai. The highest point on the island is the summit of Mauna Kea volcano, 4,205 m (13,797 ft) in elevation.

Cultural History and Establishment of Hawai‘i Volcanoes National Park

The climate at Hawai‘i Volcanoes is diverse, from the dry, high-elevation crater summit areas to the temperate western slopes and to the wet, tropical eastern slopes. The earliest human inhabitants took advantage of this varied environment, and evidence of their presence dots the landscape at Hawai‘i Volcanoes National Park. Lava-tube caves served as habitation sites, shelters in times of war, storage places for food, and work areas. Ritual sites were an integral part of a highly advanced religious society. Facets of this religion were defined in the kapu (laws of conduct). In old Hawai‘i, kapu governed all aspects of society. Penalties were severe and quick. After 1819, Hawaiians discontinued the kapu system and old religions. Hawai‘i Volcanoes National Park strives to demonstrate the intimate balance and spiritual connections between the early Hawaiians and their surrounding natural environment.

Hawai‘i Volcanoes National Park protects a variety of ecosystems, including tropical rainforest on the windward northern and eastern slopes, protected niches within old craters, arid desert on the leeward southern and western slopes, and subalpine to alpine environments at higher altitudes. Each ecosystem hosts flora and fauna uniquely suited to that area, and ancient Hawaiians found ways to use every environment.

Hawaiʻi Volcanoes National Park, when first established on August 1, 1916, was part of Hawaiʻi National Park. The establishment of the park followed years of pioneering, road building, exploring by early settlers and visitors to the area beginning in the mid-1800s and the evolution of Volcano House Hotel. In 1903, one of these visitors, William R. Castle, noted that the U.S. Government should reserve the region from Mauna Loa to Puna. The original Hawaiʻi National Park was divided and renamed on September 22, 1961, with its parts becoming Hawaiʻi Volcanoes and Haleakalā national parks. The wilderness within Hawaiʻi Volcanoes National Park was designated on November 10, 1978, and the park was recognized as a Biosphere Reserve in 1980. Hawaiʻi Volcanoes National Park preserves a variety of landforms, from erupting volcanic vents to seashores to the volcanic summit, fragile native Hawaiian ecosystems, and prehistoric cultural sites.

Additional park information may be found at http://www.nps.gov/havo, the Hawaiʻi Volcanoes National Park Web site.

Geologic Setting

Hawaiʻi is just one volcanic island among the many subaerial islands and submarine seamounts of the Hawaiian-Emperor volcanic chain (fig. 4). The chain stretches over 5,800 km (3,600 mi) from the Aleutian trench in the northwest Pacific Ocean basin to Lōʻihi seamount, which is approximately 35 km (22 mi) off the southeast coast of the Island of Hawaiʻi (fig. 3). The chain formed due to the movement of the Pacific tectonic plate over an essentially stationary hotspot of volcanic activity. From east to west, the Hawaiian Islands increase in age, degree of erosion, and subsidence into the sea.

Several of the islands are built by more than one volcano.The Island of Hawaiʻi encompasses five major shield volcanoes: Kohala, Mauna Kea, Hualālai, Mauna Loa, and Kīlauea (fig. 3). The latter two are among the most active volcanoes in the world. Hawaiʻi Volcanoes National Park includes the summits of Mauna Loa and Kīlauea, the active eruption area (Puʻu ʻŌʻō vent), stark volcanic flow fields, and numerous small craters. The majority of lava flows and vent deposits in the park are younger than 750 years, and volcanic rocks dominate the geology of the park. Kīlauea has been erupting almost nonstop since January 3, 1983.

The landscape within Hawaiʻi Volcanoes National Park consists of the relatively stark, rugged fresh lava flow areas, Kīlauea Crater, Mauna Loa's gentle slopes, and coastal areas where basalt flows form broad, sloping benches or terraces separating sheltered coves along the shore several meters below. Sparse beach areas include intertidal to supratidal accumulations of black sand, olivine green sand, and some coralline sediment from storms and marine highstands throughout the Holocene, as well as eolian deposits of fine sand. Natural features include barren, lava-inundated landscapes, ephemeral streams cutting narrow gorges, fresh volcanic deposits, cinder cones and craters, broad vegetated slopes, and a variety of unique and native Hawaiian ecosystems. Soil development is stunted at the higher elevations or where there have been recent eruptions.

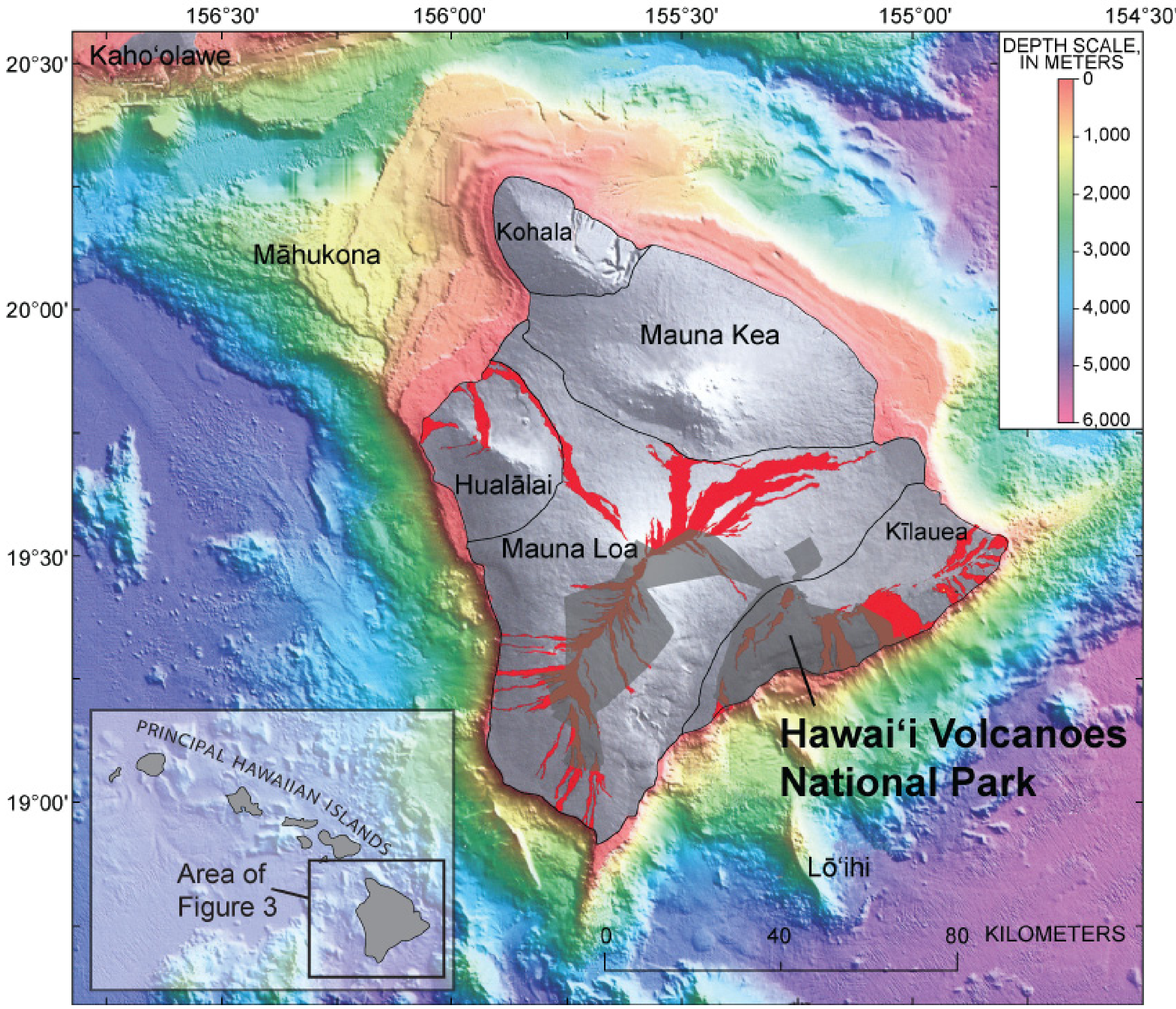

Figure 3. Map of the Island of Hawai'i and surrounding ocean floor. Note locations of the five volcanic centers on the island as well as benthic (sea floor) morphology. Gray areas are exposed land; red areas are historical lava flows. USGS graphic excerpted from map by Eakins and others (2003).

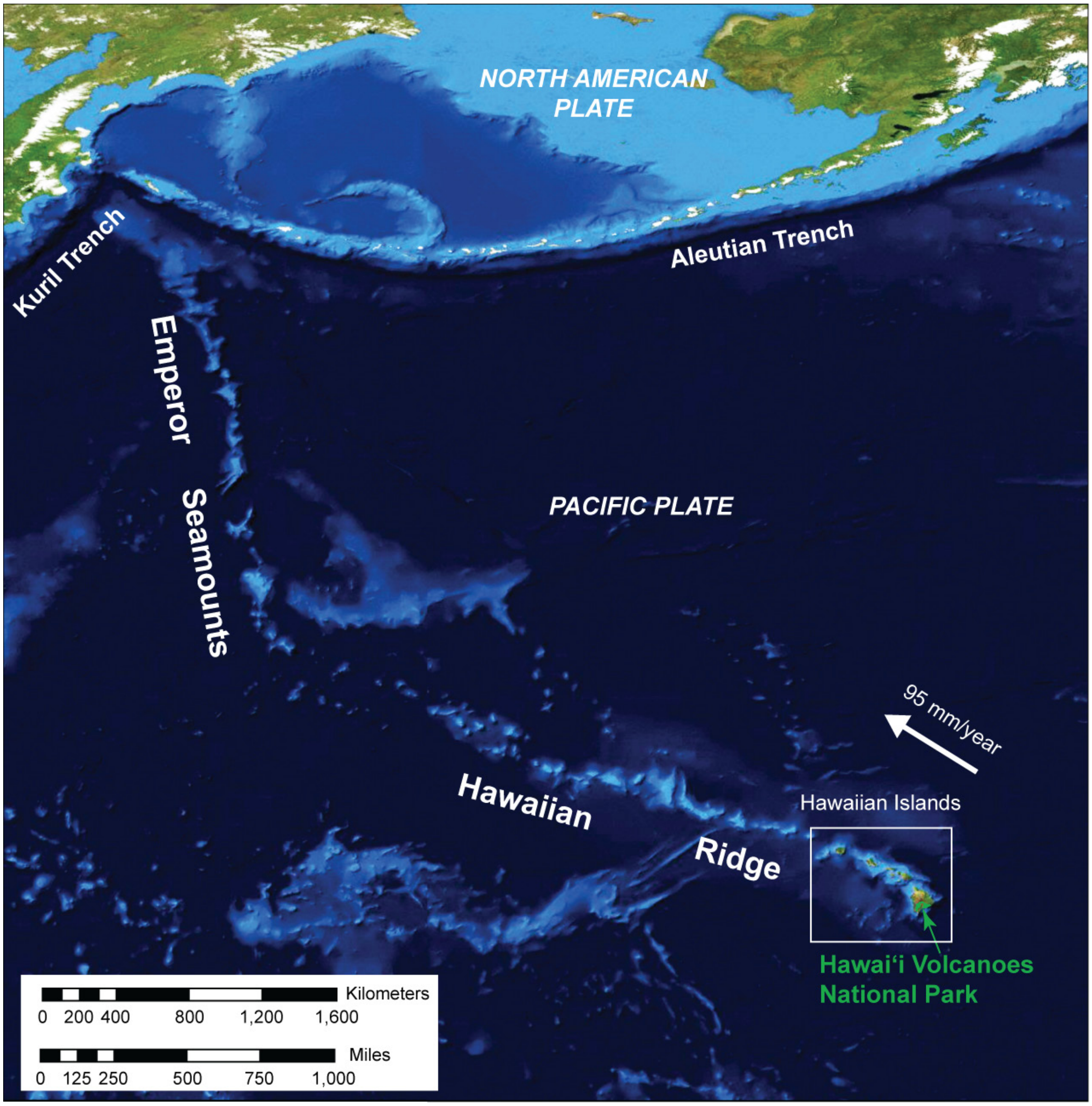

Figure 4. Aerial imagery of the northern Pacific Ocean basin, with deeper areas appearing dark blue to black and the Hawaiian-Emperor volcanic chain (and other relatively shallow areas) visible as lighter blue areas. The white box encloses the Hawaiian Islands. The white arrow indicates present motion of the Pacific plate at 95 mm/year (3.74 inches/year). Compiled by Jason Kenworthy (NPS Geologic Resources Division) from ESRI Arc Image Service, USA Prime Imagery with information from Eakins and others (2003).

Geologic Issues

The National Park Service held a Geologic Resources Inventory scoping session for Hawai'i Volcanoes National 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.

The primary resource management emphasis at Hawai'i Volcanoes National Park is preserving and protecting a variety of ecosystems and unique volcanic features on Mauna Loa and Kīlauea, as well as protecting and ensuring access for visitors. Natural resource management goals at Hawai'i Volcanoes National Park include better understanding of volcanic processes and reducing the impact of park activities on the environment while providing educational access for visitors and complementing the preservation of cultural landscape.

Hawai'i is the only state in the United States that is subject to earthquakes, volcanism, tsunamis, and hurricanes. The dynamic nature of the geomorphic processes at work on the Hawaiian landscape, including coastal erosion, rise in sea level, seasonal high waves, and stream erosion (Richmond et al. 2001), increases the importance of sound knowledge of the physical world underlying the tropical ecosystem. This section discusses the management of natural resources, focusing on the most important geologic issues at the park.

Many natural phenomena pose threats to populated areas of the Hawaiian Islands. Among these hazards are volcanism, mass wasting, coastal erosion, seismic activity, and tsunami inundation. Local slopes and geologic settings must be taken into account to accurately determine potential hazards for a specific area, such as Hawai'i Volcanoes National Park (Richmond et al. 2001). Important tools in hazard assessment include records of past events and their magnitude, in addition to accurate inventorying and regular monitoring of current conditions. Detailed geologic mapping provides an additional tool, linking underlying geology to specific hazards.

Volcanism

Hawai'i Volcanoes National Park contains two of the most active volcanoes on Earth: Kīlauea (erupting since January 3, 1983) and Mauna Loa (last erupted March 1984, with a recurrence interval of approximately 5 years since 1843) (Lockwood and Lipman 1987; U.S. Geological Survey 2006, 2009a). During the past 25 years, volcanism at Kīlauea has been an almost-daily occurrence in the park, pumping lava downslope in lava tubes and adding new land to the island at rates of 4–70 ha/year (10–170 acres/year) (Heliker and Mattox 2003). Associated with active volcanism are several areas of concern: lava eruption and destruction associated with flows, ejection of pyroclastic material, collapse of lava tubes, corrosive volcanic gases, and subsurface thermal heating. Heliker (1990) presents a thorough overview of hazards associated with volcanism and seismicity, including abundant photographs, in detail that is beyond the scope of this report. Additionally, Hon and others (2008) prepared a field interpretation of active volcanoes intended as a handbook for viewing lava that could provide a useful reference for resource managers at Hawai'i Volcanoes National Park.

Due to the dynamic nature of the landscape on active volcanoes, conditions or events are unpredictable and can change on a daily basis (Hon et al. 2008). In general, Hawaiian lava flows are considered among the most approachable in the world; however, molten lava is extremely dangerous material—hot and moving (Hon et al. 2008). Flows from Mauna Loa have reached distances of 50 km (30 mi) or more. While lava generally flows slowly enough to allow people and animals to escape, anything remaining in the path of a flow (such as rare rainforest, historical sites, or communities) will be damaged or destroyed by burial, crushing, or ignition (Rutherford and Kaye 2006). The ejection of pyroclastic materials (cinder or spatter cones) has a similar impact, but the spatial extent of the effect is limited to near the vent.

Eruptions are usually preceded and accompanied by seismic and volcanic unrest, as well as by the appearance of cracks in the ground (Crandell 1983). This unrest is expressed by earthquakes and by variations in the geophysical and gas-geochemical state of the volcanic system. Analysis of 52 historic eruptions supports an intriguing idea that stresses caused by fortnightly earth tides play a significant role in triggering volcanic activity at Kīlauea Volcano. Since 1832, nearly twice as many eruptions have occurred near the tidal maximum than near the minimum. Stresses induced by fortnightly earth tides acting in concert with volcanic and tectonic stresses along preexisting zones of weakness could trigger these. The same correlation was not found as definitively for Mauna Loa volcano, possibly due to differences in structure and internal plumbing (Dzurisin 1980).

When Kīlauea Volcano began erupting in 1983, the activity soon settled at a single vent to form the Pu'u 'Ō'ō cone (fig. 5). Flows from this vent inundated the Royal Gardens subdivision, destroying 16 residences. The eruptive center then shifted downrift, and a tube system developed, transporting lava to the sea. By the end of 1990, the Kalapana community was completely overrun and more than 100 residences were destroyed (Heliker and Wright 1992). The park's Wahaula Visitor Center was overrun and destroyed in 1989. Lava continues to claim abandoned homes in Royal Gardens, including one in July 2009 (Honolulu Star-Bulletin 2009).

The U.S. Geological Survey's Hawaiian Volcano Observatory (HVO) has, for the islands of Hawaiʻi and Maui, an extensive monitoring system for surface and subsurface deformation, seismicity, and volcanic emissions. Since its inception, HVO has been instrumental in short-term forecasting of eruptive activity at Kīlauea, and its role in park management is vital (Gebhart 1983). The HVO is part of a cooperative effort with the Center for the Study of Active Volcanoes (CSAV) and with institutions such as the University of Hawaiʻi and Stanford University to understand volcanic processes and attempt to lessen their potential threats to society (Rutherford and Kaye 2006). The HVO works carefully with the Hawaiʻi County Civil Defense Agency and Hawaiʻi Volcanoes National Park to provide timely information on location and movement of lava flows to guide decisions regarding road closures, evacuations, safe tourist viewing, and mitigation attempts (Heliker et al. 1986; Heliker and Wright 1992). Given the nearly continuous nature of lava eruption at Kīlauea, site-specific studies of lava-flow dynamics, thermal lava-flux monitoring, and lava-flow and lava-tube mapping are improving lava-flow hazard assessments and mitigation tools (Kauahikaua et al. 2003).

Though no two eruptions begin in exactly the same way, the most reliable precursors to eruptions in Hawaiʻi have been seismic activity and ground deformation as magma enters the summit reservoir and is discharged at the summit or along one of the rift zones. Seismic swarms often migrate ahead of the intruding magma (Heliker 1988). The observatory has real-time GPS receivers throughout the park, and HVO staff periodically conducts leveling, electronic distance measurement, and dry tilt surveys (Rutherford and Kaye 2006). These measurements, as well as infrared imagery from the geosynchronous-orbiting environmental satellite (GOES), Landsat imagery, and telemetered video, are useful to determine lava-flow spread (Kauahikaua et al. 2003).

The frequent monitoring of the long-lived eruptive activity provides basis for comparison with previous conditions and an invaluable record of ground deformation patterns associated with active volcanism. Further techniques are being discussed and developed to monitor the lava output from Puʻu ʻŌʻō. These techniques and data sets include (1) topographic (elevation) data over the entire flow field, (2) passive seismic listening or active ultrasound probing, (3) combining short-range remote sensing (hand-held multispectral imagers or interferometric radar) with ground-based observations, (4) real-time telemetered information from tube-flux monitors, microphones, and stationary video monitors with infrared sensors, and (5) time-lapse videography from oblique angles (Kauahikaua et al. 2003).

Understanding eruptive mechanics helps mitigate future volcanic hazards by supporting more precise estimates of both risk and hazard. This has applications for land-use planning because more accurate predictions of direction and advance rate of lava flows are made possible in the form of maps of lava sheds and preferred-gravitational-flow paths (Kauahikaua et al. 2003).

Lava-flow hazard zones, mapped on the basis of location of eruptive vents, past lava coverage, and topography, indicate that most of Hawaiʻi Volcanoes National Park lies within a very hazardous area (Wright et al. 1992). Areas most likely to be inundated by lava include those near active rift zones, downslope areas within the lava sheds (analogous to watersheds) of rift zones, and areas where lava is channeled by topographic features (fig. 6). Topographic obstructions also define areas at low risk of being inundated by lava flows, and large-scale mapping is necessary to delineate these sheltered areas. On Kīlauea Volcano, population density has increased in the lower east rift zone. Should vent activity shift farther down the rift, future eruptions could pose hazards for these populations. Since 1960, the population in high hazard zones on Kīlauea's flanks has more than quadrupled (Heliker and Wright 1992).

As volcanic activity evolves and shifts on the flanks of Kīlauea and Mauna Loa, park resource managers must be prepared to address potential hazards within the park and perhaps participate in cooperative efforts to assess hazards from lava flowing into surrounding areas. Since volcanic activity began in 1983, eruption sites have shifted along the east rift zone (Heliker et al. 2003). Sporadically, eruptions from the Puʻu ʻŌʻō–Kupaianaha vents have flowed north of the east rift zone, most recently in 2007 (fig. 7). Changes in eruptive behavior could cause future flows to advance downrift and impact communities in the Puna district that have thus far been unaffected by lava flows of the Puʻu ʻŌʻō–Kupaianaha eruption. However, several of these communities were impacted by previous eruptions in the 1960s (D. Sherrod, U.S. Geological Survey, written communication 2009). As of 2007, lava flows posed no immediate threats to any communities (Kauahikaua 2007). Potential lava-flow paths are estimated by calculating the path of steepest descent from a digital elevation model for the area in question (fig. 7). Since lava flows change local topography, the paths of steepest descent are always changing over the course of an eruption. The potential for inundation by a lava flow warrants increased public awareness and enhanced monitoring (Kauahikaua 2007). Wright and others (1992) assessed long-term lava-flow hazards for the Puna district, and their work is still considered a useful tool in predicting the locations at risk of inundation during lava eruptions.

Open Cracks and Fragile Ground

Ground movement frequently accompanies volcanism due to shallow underground movement of magma. This movement may result in large cracks across roads, trails, and other park infrastructure, and can compromise building foundations and road subgrades (fig. 8; Heliker 1990; D. Sherrod, U.S. Geological Survey, written communication 2009). Cracks and settling tend to occur in close proximity to active or recently active volcanic vents, and cracking may be due to seismic activity or may precede an eruption at a new site as magma is forcefully injected into the subsurface (Heliker 1990; Hon et al. 2008). Prior to eruptions in the Kapoho area on Kīlauea's lower east rift zone in 1924, 1955, and 1960, ground cracks as much as 2 m (7 ft) wide and more than 1.6 km (2 mi) long rapidly formed (Heliker 1990). Because of their rapid and unpredictable formation, and the fact that they can be obscured by heavy vegetation, ground cracks pose a significant threat to visitor safety at Hawai'i Volcanoes National Park (Heliker 1990; Hon et al. 2008; D. Sherrod, U.S. Geological Survey, written communication 2009).

Fragile ground associated with the existence of shallow lava tubes and shelly pāhoehoe (characterized by fragile gas cavities, small tubes, and buckled fragments of surface crust [Swanson 1973]) poses threats to the integrity and safety of roads and trails (D. Sherrod, U.S. Geological Survey, written communication 2009). Shallow tubes can collapse, and cavities with thin upper crusts or shells can break, creating sharp edges and fall hazards for visitors. Kīlauea is underlain mostly by hummocky, tube-fed pāhoehoe. Surface crusts can be less than 5 cm (2 in.) thick and cannot support much weight, so they are treacherous underfoot (Swanson 1973). Studied during the Mauna Ulu eruptions of the 1970s, shelly pāhoehoe occurs where gas-charged (or inflated) lava wells out of the source fissure with little or no accompanying fountaining (Swanson 1973). The pressure of expanding gas within the flow lobes during cooling is sufficient to expand the plastic crust upward like a balloon (Swanson 1973). Knowing under what conditions this type of flow develops can help prevent accidents for park visitors.

Airborne Hazards and Steam

Although lava flows are the most common hazards directly associated with volcanic activity and pose the greatest threat to property, another issue associated with active volcanism in the vicinity of Hawai'i Volcanoes National Park is airborne volcanic emissions of ash, gases, and steam (condensed water vapor) (Heliker 1990). Ejection of airborne "tephra" (particles of ash), cinder, and fragile strands of volcanic glass (called "Pele's hair") accompanies most Hawaiian eruptions and can cause irritation for people with respiratory problems and clog rainwater catchment systems (Heliker 1990). Tephra is usually a hazard only in the immediate vicinity of an erupting vent, but high lava fountains combined with strong prevailing winds have carried tephra great distances. Kona winds (high winds associated with rain and storms, blowing the opposite direction of the trade winds) during fountaining episodes at the Pu'u 'Ō'ō vent from 1984 to 1986 deposited tephra on the town of Hilo some 35 km (22 mi) away (Heliker 1990). Rarer explosive eruptions have the potential to produce pyroclastic surges, which are highly destructive, turbulent gas clouds that flow rapidly along the ground and contain mixtures of hot ash and rock fragments (Heliker 1990). An explosive eruption in 1790 caused 80 fatalities from a pyroclastic surge, and thick ash deposits exposed throughout the island attest to even larger explosive eruptions in prehistoric times (Heliker 1990)

Nearly ubiquitous with active volcanism is the emission of volcanic gases and steam. A gas plume rising from an active vent on Kīlauea consists of approximately 80% water vapor; lesser amounts of sulfur dioxide, carbon dioxide, and hydrogen; and minute amounts (less than 1% by volume) of carbon monoxide, hydrogen sulfide, and hydrogen fluoride (Heliker 1990). Part of Kīlauea Crater was closed briefly in the early to middle 2000s because of concern about toxic accumulations of carbon dioxide (CO_2) (D. Sherrod, U.S. Geological Survey, written communication 2009). In many areas accessible along the Crater Rim Drive of Kīlauea Volcano, steam vents pose a burn hazard for visitors (D. Sherrod, U.S. Geological Survey, written communication 2009).

Emitting roughly 1,500 tons of toxic sulfur dioxide gas (SO_2) each day (Elias and Sutton 2002), Kīlauea Volcano is the largest stationary source of SO_2 in the United States (fig. 9). The Environmental Protection Agency's guideline for industrial pollution is 0.25 tons of SO_2 emitted per day (Gibson 2001). Taken weekly with a correlation spectrometer, SO_2 emission rate measurements at Hawai'i Volcanoes National Park date back to 1979—an unusually complete data set. Carbon/sulfur ratios are also monitored on a weekly basis at the park (Rutherford and Kaye 2006). Air quality is continuously monitored, with information accessible on a National Park Service Air Resources Division Web site: http://www.nature.nps.gov/air/webcams/parks/havoso2alert/havoalert.cfm (accessed December, 2009).

Sulfur dioxide may combine with acid aerosols and fine particulates that form when volcanic and trace species react and become oxidized in the air. The result is a hazy atmosphere known as "vog" (Elias and Sutton 2002). Vog ("volcanic smog") can affect spatial and temporal trends in precipitation and surface temperatures (Gibson 2001). Sulfate aerosols have a surficial cooling effect locally due to the scattering of incoming radiation, and vog acts as nuclei for condensation in the formation of clouds. The presence of heavy vog correlates locally with reduced rainfall (Gibson 2001). Rainfall in turn has the potential to reduce sulfur species in the air, for example reducing SO_2 30%–80% (Michaud et al. 2007).

Depending on wind conditions, vog from Kīlauea can be problematic all across southern Hawai'i. During particularly active eruptive periods and in the absence of prevailing winds, vog can stretch as far as O'ahu, some 350 km (220 mi) northwest of Kīlauea. Elevated SO_2 levels at Hawai'i Volcanoes National Park tend to occur during the daytime between November and March (Michaud et al. 2007), when prevailing northeasterly trade winds subside and southerly winds periodically blow the fume inland (D. Sherrod, U.S. Geological Survey, written communication 2009). Volcanic emissions can destroy surrounding vegetation through large amounts of emitted carbon dioxide, sulfur dioxide, and hydrochloric and hydrofluoric acids (Rutherford and Kaye 2006; Michaud et al. 2007). These emissions acidify soils, lower rainfall pH (forming acid rain), and increase the proportion of heavy metals in soils and surface water (Heliker 1990; Gibson 2001). Acid rain in turn can leach lead from roof flashings, nails, and solder connections, and pose additional hazards for contamination of drinking water and soils (Heliker 1990).

During particularly fume-rich periods, closures of certain facilities of Hawai'i Volcanoes National Park are necessary to protect visitors from noxious gases. The major components of vog can have adverse effects on human respiratory and pulmonary function. The Island of Hawai'i leads the state in asthma death rate, one of the highest asthma death rates in the United States. The U.S. Geological Survey and the National Park Service cooperate in monitoring the volcanic emissions and air quality to inform park managers through a color-coded advisory system of appropriate times to limit access or to close facilities completely (Elias and Sutton 2002). Refer to the Air Resources Division Web site for near real-time air quality data (http://www.nature.nps.gov/air/webcams/parks/havoso2alert/havoalert.cfm, accessed December 2009).

Mass Wasting

Mass wasting is a significant resource management issue at Hawai'i Volcanoes National Park due to the dynamic environment there. Relatively little information on erosion and mass wasting exists for Hawai'i. Locally steep slopes, combined with flow of ground and surface water and frequent seismic episodes, create a setting prone to mass wasting by processes such as landsliding, mud flows, or slope creep (Rutherford and Kaye 2006). Affected areas include edges of volcanic craters and pits, some of which are near visitor facilities (fig. 8). Talus cones (fig. 9) and slope collapses occur in pit craters and caldera walls (D. Sherrod, U.S. Geological Survey, written communication 2009).

The nearly constant threat of seismic activity only increases the likelihood of rockfall and other mass wasting. During a 1983 earthquake, segments of park roads were lost into Kīlauea Iki. However, some mass-wasting processes are more continuous in nature. The Chain of Craters road was relocated in the late 1990s because the walls of an adjacent pit crater were slowly expanding outward by piecemeal collapse and encroaching on the roadway (D. Sherrod, U.S. Geological Survey, written communication 2009). Mass wasting buries local habitat, increases erosion, disrupts the hydrologic system, and, if the event is large enough, can cause tsunamis.

In Hawai'i, there is a continuum between two main types of slope failures: slumps and debris avalanches. Slumps (also called "slides") can be very large in area (as much as 40 km, or 25 mi, wide and 10 km, or 6 mi, deep) and have internal transverse ridges and steep toes. Slumps can occur abruptly or over a long time span (D. Sherrod, U.S. Geological Survey, written communication 2009). Some of these slides are marked by headwall cliffs (pali), such as the Hilina Pali at Hawai'i Volcanoes National Park. As described under "Seismicity and Tsunamis," the active Hilina slump covers most of the southern flank of Kīlauea Volcano, and the Punalu'u slump stretches over a broad area of Mauna Loa's southern flank (Clague and Denlinger 1993; Lipman et al. 2000). These slides extend offshore to great depths and could fail to such an extent as to cause local tsunamis (fig. 10).

Another type of mass wasting found at Hawai'i Volcanoes National Park is debris avalanche (also called "volcanic landslides"). Debris avalanches are gravity-driven, fast-moving mixtures of soil and bedrock that originate when slumps accelerate downslope, disaggregate, and transform to chaotic mixtures (Wright and Pierson 1992; D. Sherrod, U.S. Geological Survey, written communication 2009). They can occur in association with eruptions, heavy rainfall, or a large earthquake (Wright and Pierson 1992). The resulting deposits, which extend downslope from well-defined amphitheaters at their headwalls, typically are long, narrow (0.5–2.0 km, or 0.3–1.24 mi), and hummocky (lumpy) in the lower lobe. Famous Hawaiian examples of debris avalanches occur on the Island of Moloka'i.

Mass wasting can occur as topples in coastal areas where the cliffs literally tip over (D. Sherrod, U.S. Geological Survey, written communication 2009). In coastal areas where the growing edge of a lava bench covers a pile of fragmented lava to form a type of delta, an illusion of stability is created. This situation is exacerbated by violent and dangerous steam-driven explosions where molten lava interacts with cold sea water. Also, bubble bursts can occur inland of the leading edge of the new land if the delta subsides and allows sea water to infiltrate the lava-tube system (Hon et al. 2008). When wave action erodes the fragmented material beneath the new land, the pile becomes over-steepened and can collapse catastrophically (Hon et al. 2008). If the event is large enough, it can become a submarine landslide (Hon et al. 2008).

Coastal Erosion

According to the 2004 mapped boundary, Hawai'i Volcanoes National Park protects some 52 km (32 mi) of coastal environment on the southern side of the Island of Hawai'i (D. Sherrod, U.S. Geological Survey, written communication 2009). The coastline at the park is almost entirely a low cliff carved into lava flows, with shifting narrow sand or boulder beaches at the cliff foot.

Erosion of the coast may lead to loss of cultural resources and instability of lava benches, inundation, damage to benthic habitats (such as shallow coral reefs), and increased sediment load. Average erosion rates in the Hawaiian Islands are approximately 15-30 cm/year (0.5-1 ft/year) (Richmond et al. 2001). Many factors are involved in coastal evolution and vulnerability to erosion, including tidal range, wave height, coastal slope, historic rates of shoreline change, geomorphic features, and relative change in sea level. Tidal range and wave height are linked to inundation hazards. Tsunamis, a significant hazard in the Hawaiian Islands, can—in one disastrous event—erode the coastline, damage reefs, and inundate nearshore habitats with salt water.

When deep-water ocean swells encounter a shallow area, such as an island margin or seamount, they rise to great heights because friction along the shallower seafloor causes their crests to pile upon their more slowly moving bottoms. In the Hawaiian Islands, this effect is exacerbated by the steepness of the gradient between deep water and the shallow margins. Surface waves can grow abruptly and substantially over a short distance (City and County of Honolulu 2003). The swell effects vary seasonally. Sudden high waves and seasonal swells are among the most consistent and predictable coastal hazards in Hawai'i (Richmond et al. 2001).

The slope along the coastline directly determines the amount of land exposed to erosion processes (Richmond et al. 2001), which is linked to inundation and to the rates of shoreline advance or retreat. Geomorphology influences the relative erodability of a specific section of shoreline. Relative change in sea level corresponds to global (eustatic) fluctuations in sea level and local vertical land motion (uplift or subsidence). Volcanic loading in Hawai'i depresses the lithosphere and causes a relative rise in sea level. Each island has a localized rate of relative rise in sea level due to its isostatic response (Rutherford and Kaye 2006). The crustal structure beneath Mauna Loa Volcano has a maximum vertical deflection (depression) of the base of the crust of about 9 km (6 mi) (Zucca et al. 1982). On average, the rate of relative rise in sea level is 3.9 mm/year (1.5 in./decade) for the Island of Hawai'i, and the loading effect lessens with distance northwest from there (Richmond et al. 2001).

Human activity, particularly through the emission of greenhouse gases, is accelerating the rate of climate change and global rise in sea level. Predictions are variable, but many forecasts indicate that carbon dioxide in the atmosphere will double by 2050, and sea level will rise 50 cm (20 in.) by 2100, with a range of uncertainty of 20–86 cm (8–34 in.) (Warrick et al. 1996; Richmond et al. 2001; Rutherford and Kaye 2006). Increased variability in climate will, in turn, increase the frequency and intensity of storms. For low-lying coastal areas in Hawai'i Volcanoes National Park, a rise in sea level will cause increased encroachment by salt water, coastal erosion, and inundation (Rutherford and Kaye 2006).

Nearly one-quarter of the beaches throughout Hawai'i have been significantly eroded over the last 50 years (Richmond et al. 2001). The causes of this erosion are generally not well understood or quantified, but may include reduced sediment supply, major storms, and manmade shoreline-armoring structures and other development (Richmond et al. 2001; Rutherford and Kaye 2006). Shoreline structures often exacerbate coastal erosion (Richmond et al. 2001). Flooding of coastal streams from intense rainfall, causing beach loss or narrowing, are nearly annual events throughout Hawai'i (Richmond et al. 2001). A complete set of aerial videography of the Hawaiian coastal/beach zone, collected from an altitude of 90–150 m (300–500 ft) (Richmond et al. 2001), would be useful to inventory current conditions.

Seismicity and Tsunamis

The Island of Hawai'i is the most seismically active place in the United States, with thousands of detectable tremors beneath Hawai'i each year. This frequency makes earthquakes a significant geologic hazard at Hawai'i Volcanoes National Park (fig. 11) (Richmond et al. 2001). Earthquakes tend to cluster at different depths as a function of the triggering forces responsible. Hawaiian seismicity is closely linked with volcanism and dike intrusions because small earthquakes and micro-earthquake swarms tend to accompany eruptions and subsurface magma movement within the currently active volcanoes at depths shallower than 5 km (3 mi) (Klein and Koyanagi 1989; Okubo et al. 1996). Earthquakes having hypocenters between 5 and 13 km (3 and 8 mi) deep typically occur adjacent to rift zones and other localized fault zones, such as the Ka'ōiki fault system between Kīlauea and Mauna Loa, in response to lateral stresses generated by rift zone expansion (Klein and Koyanagi 1989).

Though less frequently, earthquakes also result from plate tectonic processes, such as stresses imposed by the location of the great volcanic mass of Hawai'i atop the mantle or melting and depletion of the asthenosphere below the island. This seismic activity occurs chiefly in areas of structural weakness, commonly deep within Earth's crust along faults, vertical magma conduits, and the Hawaiian hotspot (Klein and Koyanagi 1989). Suspected faults surround the Island of Hawai'i (Richmond et al. 2001). Seismic refraction surveys can yield valuable data as to the hypocenters and focal mechanisms of earthquakes occurring within the active volcanoes and aid understanding of the nature of the crust beneath and surrounding the volcanic masses (Zucca et al. 1982).

Large earthquakes have occurred locally (magnitude 7.9 in 1868, 6.9 in 1951, 7.2 in 1975, and 6.9 in 2006) (Clague and Denlinger 1993; Walker 1999; Lipman et al. 2000). Over the past 150 years, some of the larger Hawaiian earthquakes (magnitudes from 6 to 8) were tectonic in nature and caused loss of life and extensive damage to buildings, roads, and homes (Rutherford and Kaye 2006). On November 16, 1983, a magnitude-6.6 earthquake occurred in the Ka'ōiki fault system. Numerous aftershocks followed the initial earthquake. Earthquakes along the Ka'ōiki system demonstrate how tectonic processes are coupled with volcanic processes, in this case a series of magmatic dike intrusions (Okubo and Nakata 2003). On October 15, 2006, a magnitude-6.7 earthquake shook the Island of Hawaii, damaging more than 1,100 structures, initiating landslides, and causing a 10 cm (4 in.) tsunami as measured at Kawaihae Harbor on the northwestern coast of the Island of Hawai'i (U.S. Geological Survey 2009b). The earthquake occurred 15 km (9 mi) north-northwest of Kailua Kona and moderate to strong shaking was felt along the southeast coast of the island (U.S. Geological Survey 2009b).

Large earthquakes have triggered several enormous landslides on the Island of Hawai'i, including the Hilina, and possibly the Punalu'u, slumps in 1868 (Clague and

Denlinger 1993; Lipman et al. 2000). The Wai‘ohinu fault zone that bounds the Punalu‘u slump from Mauna Loa moved laterally 2–3 m (6–9 ft) during the 1868 earthquake (Lipman 1980; Lipman et al. 2000), and a locally generated tsunami swept the coast from Kalapana to South Point (F. Trusdell, written communication 2009). A magnitude 7.2 earthquake in 1975 was accompanied by meter-scale displacement along the Hilina fault system and large tsunamis (Lipman et al. 1985).

These slumps may encompass entire volcanic flanks, stretching far out to sea (Clague and Denlinger 1993; Lipman et al. 2000). The Hilina fault system bounds a submarine region of scarps and benches and extends 50 km (31 mi) south of the shoreline of Kīlauea to depths of 5,000 m (16,400 ft) (Lipman et al. 2000). The Hilina slump encompasses the entire south flank of Kīlauea, whereas the Punalu‘u slump stretches from the southwest rift zone of Mauna Loa on the upslope side, the western edge of the Ka‘ōiki fault zone on the northeast side, and along a fault zone extending to the southeast from the bend in the southwest rift on the southwest side (fig. 10). This slide extends offshore, south of the active Lō‘ihi seamount (Clague and Denlinger 1993). Should an earthquake produce active landsliding that extends seaward, the displacement of ocean water could cause local tsunamis.

At Hawai‘i Volcanoes National Park, the additional effects of earthquakes, such as ground rupture, uplift, disruption of ground-water flow, disruption of surface drainage patterns, shifting of roadways, subsidence, mudflows, liquefaction, and landslides could negatively impact the facilities and cultural resources at the park.

Seismograph networks in the state of Hawai‘i are operated by the U.S. Geological Survey (through its Hawaiian Volcanic Observatory and the National Strong Motion Program) and the Pacific Tsunami Warning Center (PTWC), a part of the National Oceanic and Atmospheric Administration (NOAA). Data are generally shared between entities. Seismic monitoring at HVO began in 1912. The HVO has a vast network monitoring program for ground deformation and seismicity on Mauna Loa and Kīlauea, having recently expanded to more than 60 stations on the Island of Hawai‘i. Data are continuously telemetered in real time to the HVO (Heliker et al. 1986) with near real time earthquake maps viewable on their Web site (http://tux.wr.usgs.gov/). In 1993, the HVO's global positioning system (GPS) network on Mauna Loa was expanded, to allow greater resolution of ground motions than was previously possible (U.S. Geological Survey 2009a). GPS receivers and dilatometers determine the long- and short-term time scale, respectively, of changes in inflation rate. Synthetic aperture radar (SAR) interferometry can provide extremely detailed resolution of the strain field on Mauna Loa and Kīlauea (Miklius and Owen 1996). Knowledge of small-scale inflation and deflation of the ground surface provides invaluable information about potential imminent eruptive and seismic activity. In addition to these resources, the most complete collection of data for location and magnitude of historical earthquake epicenters for Hawai‘i is available from the U.S. Geological Survey's National Earthquake Information Center (NEIC; http://earthquake.usgs.gov/regional/neic/).

Regardless of their origin, earthquakes are of particular importance because of their role as tsunami triggers. A tsunami is a series of large waves created when a body of water is rapidly displaced by some disturbance, such as earthquakes, volcanic eruptions, or submarine landslides. The hazard of inundation and destruction by tsunami from both local and regional (i.e., teleseismic from Alaska) sources is present throughout the Pacific basin. This is especially problematic because predicting whether a particular earthquake has generated a tsunami is difficult (D. Sherrod, U.S. Geological Survey, written communication 2009). Tsunamis have struck Hawai‘i more frequently than any other place on Earth (Dudley and Lee 1998) owing to its position in the center of an ocean basin surrounded by seismically active regions. Since record keeping began in 1837, 33 tsunamis have struck Hawai‘i with varying degrees of severity. At least four were locally generated from crustal shifts beneath the islands during massive submarine landslides (Walker 1999; Richmond et al. 2001). These locally generated tsunamis are especially dangerous due to the limited warning time (Richmond et al. 2001).

The Hawaiian Islands are struck by a tsunami, large or small, every 2 years; substantial damage occurs every 5 years on average (Dudley and Lee 1998). The recurrence interval for locally generated destructive tsunamis is 20 years (Walker 1999). Following a magnitude-7.1 earthquake in the Aleutian trench (Alaska) on April 1, 1946, a tsunami traversed 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 caused an 11-m (36-ft) tsunami that seriously damaged Hilo, Hawai‘i, and killed 61 people (Pacific Disaster Center 2008).

In addition to loss of life and threats to manmade structures, tsunamis can cause increased erosion along the coastline, destroy shoreline cultural resources, damage coral reefs, and inundate near-shore habitats and aquifers with salt water (Rutherford and Kaye 2006). Since the 1960s, widespread development along the Hawaiian shoreline has largely ignored the potential danger of inundation by tsunami (Richmond et al. 2001).

According to Walker (1999), an acceptable warning system requires not just seismic detectors but also wave recorders, modeling studies of wave heights or runups at various locations, new tsunami detectors, and automated warnings for highly localized tsunamis. The Pacific Tsunami Warning Center in Ewa Beach, Hawai‘i, provides warnings to most Pacific basin countries. As part of an operational objective, the international cooperative Tsunami Warning System (TWS) continuously monitors the seismic activity and ocean surface level within the Pacific basin to determine whether a tsunami was generated by earthquakes and to minimize risk to the population of the Pacific by providing warnings and information.

According to operating procedures (Tsunami Warning Centre 2007), a local tsunami warning is issued for any earthquake "in the State of Hawai'i for $M_w > 6.8$." Earthquakes of this magnitude initiate the most severe local bulletin. Hawai'i State Civil Defense will sound the tsunami sirens. Depending on the location of the quake, only some counties in the state may be placed in warning status; initially, only the county in which the earthquake occurred and its bordering counties are so placed. For example, if the earthquake occurred on Maui, then Honolulu, Maui, and Hawai'i counties are placed in warning status. If the earthquake occurred on Hawai'i Island, then Hawai'i and Maui counties are placed in warning status. For earthquakes of $M_w > 7.5$, the entire state is placed in warning status (Tsunami Warning Centre 2007).

Seismic activity and ocean surface levels of the Pacific Ocean basin are constantly monitored (Rutherford and Kaye 2006). This monitoring, in addition to recent modeling by NOAA of tsunami hazards and inundation zones by using seismic events, bathymetry, storm, wind, and rain conditions, is aimed at increasing accuracy and precision of tsunami prediction.

Figure 5. The Pu'u 'Ō'ō cone formed shortly after Kīlauea Volcano began erupting in 1983. This photograph was taken on January 31, 1984. USGS photograph by J.D. Griggs.

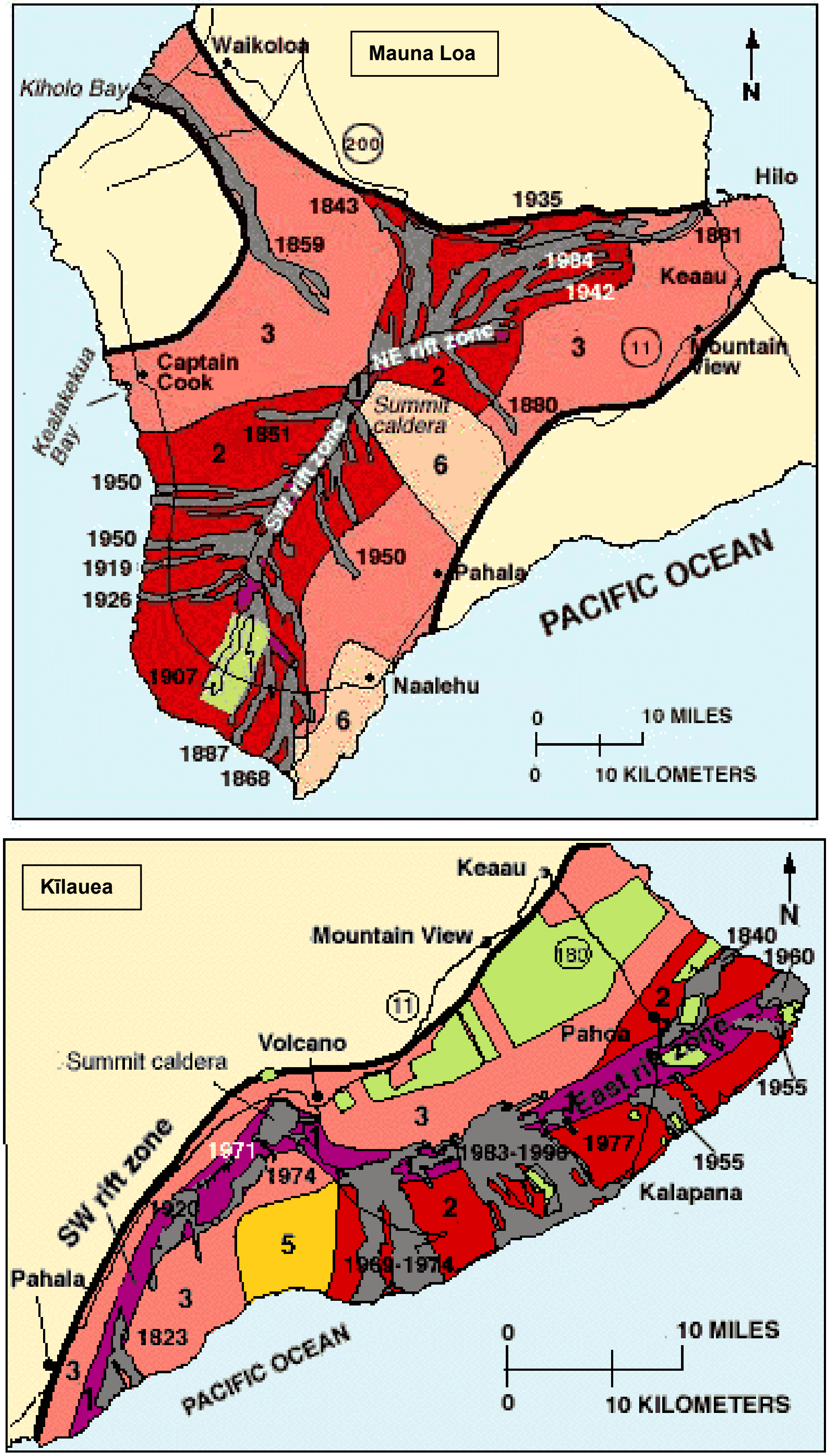

Figure 6. Maps showing volcanic-hazard zones for Mauna Loa (top) and Kīlauea (bottom). The island is divided into zones 1–9 (defined in Heliker, 1990) according to the likelihood of being inundated by lava flows; higher numbers indicate less likelihood of inundation. Major housing subdivisions shown in green. USGS graphics extracted from Heliker (1990).

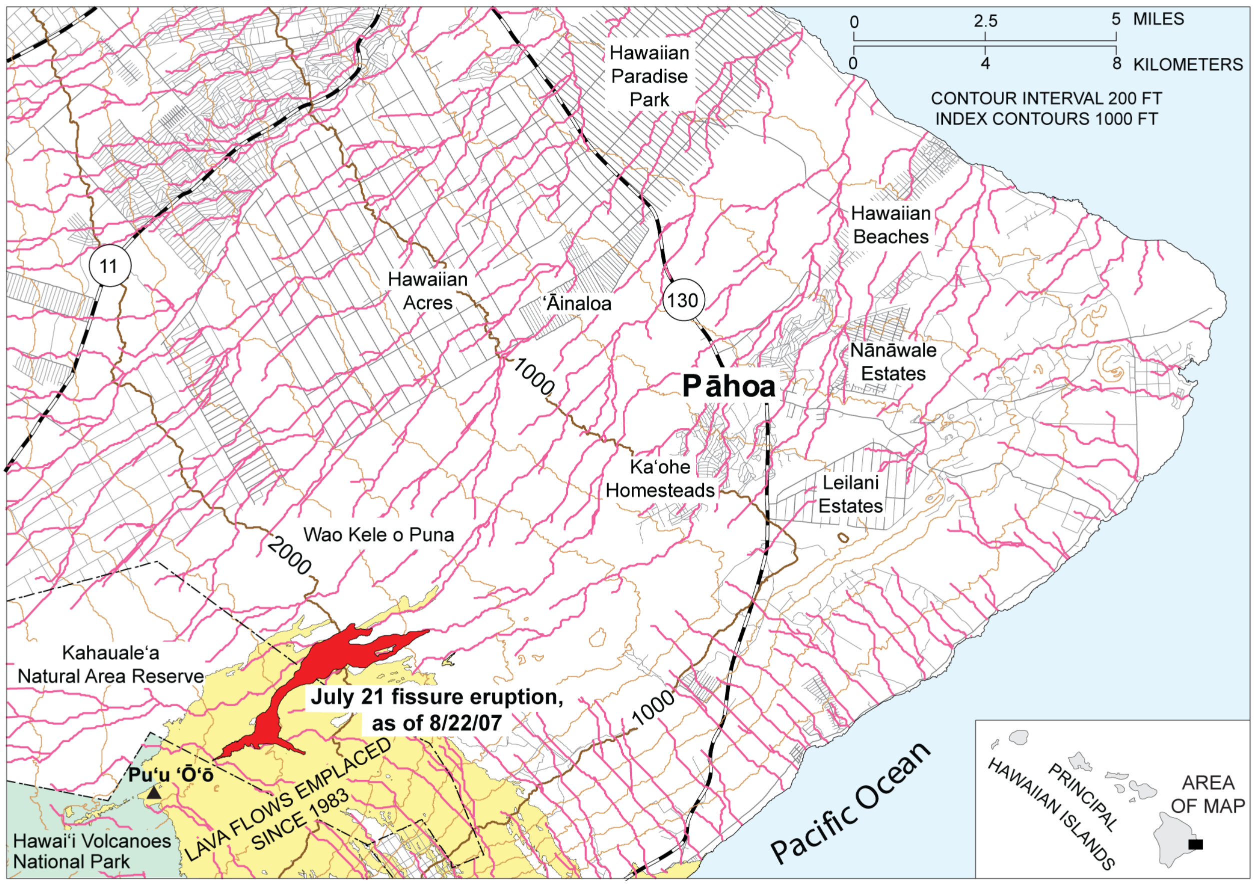

Figure 7. Map showing part of the Puna District near the Puʻu Ōʻō vent. Red area shows lava flows emplaced July–August 2007. Pink lines show modeled paths of steepest descent down topographic gulleys and valleys. Yellow area shows lava flows from Puʻu ʻŌʻō between 1983 and 2007. USGS graphic extracted from Kauahikaua (2007, fig. 1).

Figure 8. View southwest toward ground fissures that emit steam along a visitor trail near Steaming Bluff, in Hawai'i Volcanoes National Park. Kīlauea caldera's rim lies 160 m (525 ft) to the south, and surface cracking is an ongoing geologic process. Photograph is by Trista L. Thornberry-Ehrlich (Colorado State University), February 2007.

Figure 9. View west toward talus cones that mantle the crater wall of Halema‘uma‘u, at Kīlauea Volcano. Note yellow sulfur staining (arrow) on slope deposits from fumes that are constantly emitted from the volcano. Photograph is by Trista L. Thornberry-Ehrlich (Colorado State University), February 2007.

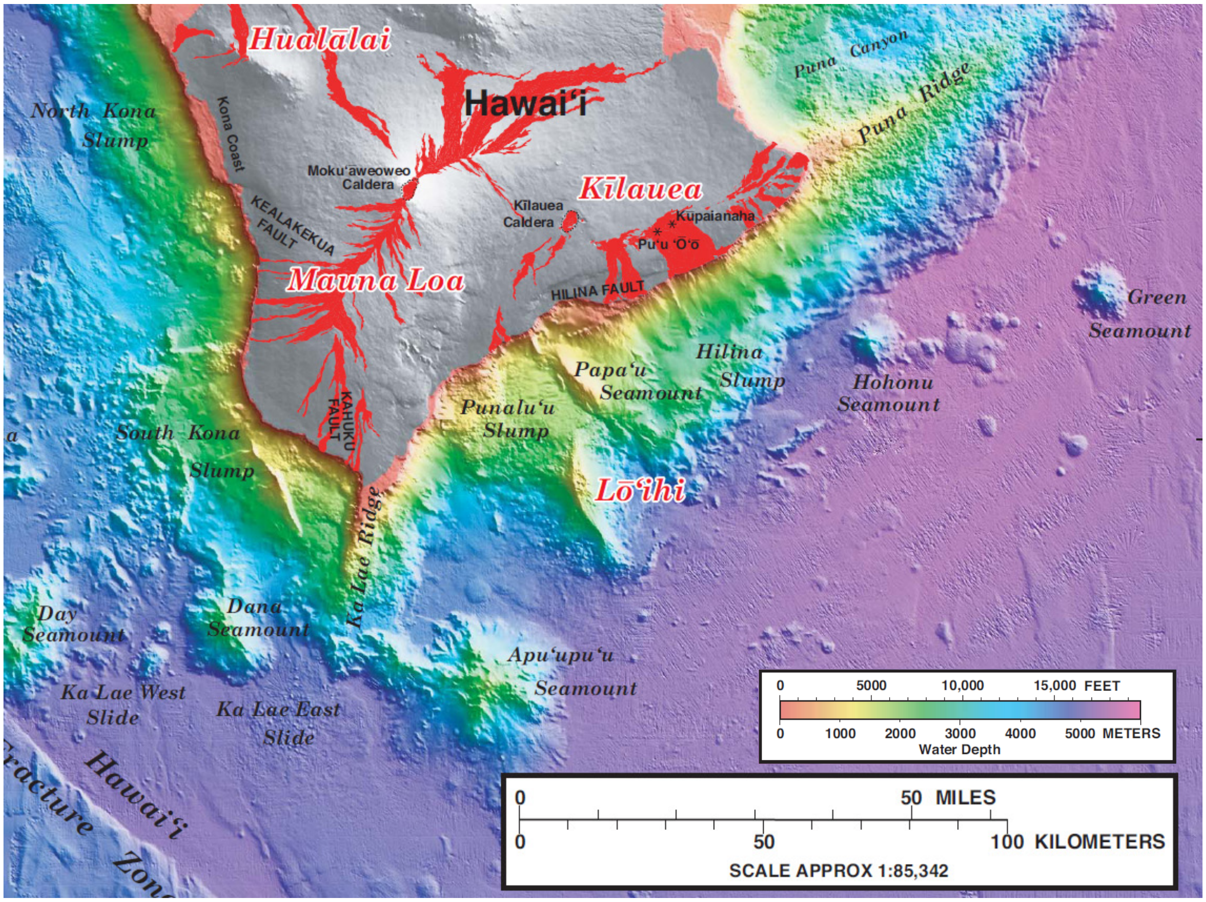

Figure 10. Bathymetric map of the south coast of Hawai'i showing the locations of the Hilina and Punalu'u slumps. USGS graphic excerpted from Eakins and others (2003).

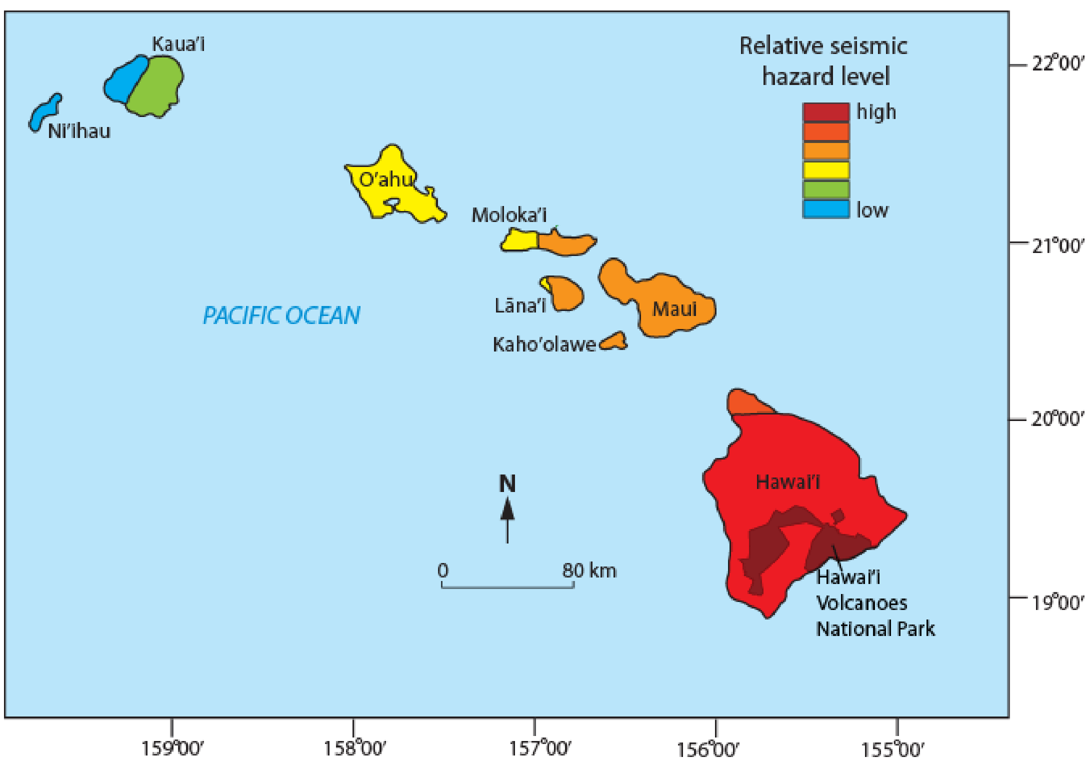

Figure 11. Map showing earthquake-hazard zones for the major Hawaiian Islands. Hawai'i Volcanoes National Park is within the area of greatest seismic hazard. Graphic was modified from Klein and others (2000) data by Rutherford and Kaye (2006) and redrafted by Trista L. Thornberry-Ehrlich (Colorado State University).

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Hawai‘i Volcanoes National Park.

Mauna Loa and Kīlauea Volcanoes

Mauna Loa and Kīlauea are among the most active volcanoes in the world and provide direct evidence for the movement of tectonic plates (Qi 1991). Mauna Loa rises to a height of 4,170 m (13,680 ft) above sea level and more than 17,070 m (56,000 ft) above its base, which depresses the surrounding ocean floor (Holland 2004; Hon et al. 2008). It is the most massive mountain in the world (fig. 12)! Mauna Loa abuts neighboring volcanoes Mauna Kea and Hualālai on its north and northwest flanks, respectively (figs. 1 and 3). On its southeastern slope is the smaller and younger Kīlauea shield volcano (figs. 1, 2, and 3; Macdonald 1943). Mauna Loa and Kīlauea are located in the midst of curved crustal fractures, observable as a series of normal faults (Geze 1963). The Ka‘ōiki normal fault system lies between the two volcanic summits (Okubo and Nakata 2003).

Three rift zones that appear as ridges transect the broad, gently sloping shield of Mauna Loa. These ridges intersect at the summit in the caldera of Moku‘āweoweo. The rift zones extend southwestward toward the southern tip of the island, northeastward toward Hilo, and northwestward toward Hualālai volcano. The rift zones are the sites of innumerable eruptions (averaging once every 3.6 years throughout recorded history) that built the volcano. On the surface, cinder cones, spatter cones, pit craters, and open fissures mark the rift zones (Macdonald 1943).

In 1975, Mauna Loa erupted at its summit. A summit-flank eruption followed for 3 weeks in 1984, threatening the city of Hilo. Geodetic measurements made since 1984 suggest the volcano is again inflating with molten magma; however, shallow and intermediate seismicity rates beneath the volcano remain relatively low during the late 1980s (Tokuuke et al. 1990) increasing slightly during the late 1990s and early 2000s (U.S. Geological Survey 2009a). Swarms of very deep earthquakes, never recorded before, occurred in late 2004 with seismicity returning to background levels since 2005 (U.S. Geological Survey 2009a).

Kīlauea is the most active volcano in the world, erupting from a rift-zone vent almost continuously since 1983—the longest lived eruption at Kīlauea in more than 500 years (Heliker et al. 2003). Halema‘uma‘u is the craterlike depression atop Kīlauea. Two rift zones diverge from the volcano's summit. One descends the east flank of the volcano (east rift zone) and the other trends southwest (southwest rift zone). Gravity and magnetic data reveal the presence of an elongate, dense, weakly magnetic core beneath the summit and rift zones of Kīlauea at widths of 20 km (12 mi) and 8 km (5 mi) respectively. The top of this core is approximately 3 km (2 mi) below the summit, and the bottom extends to the mantle (Kauahikaua et al. 1996, 2000).

Most of Kīlauea's recent eruptive activity has been in the Pu‘u ‘Ō‘ō–Kupaianaha area, where a large basaltic cone formed. Lava from the eruption has spread across five broad areas: (1) the vent at Pu‘u ‘Ō‘ō, (2) the upper flow field between the vent and the top of the Pūlama pali (steep slope or cliff), (3) the face and base of the pali, (4) the coastal plain below the pali, and (5) the coast, including the offshore submarine slope. Differing lava flow types and modes of emplacement characterize and separate these areas. Lava tubes transport lava from the source vents through the upper flow field during periods of steady effusion. On the face of the pali, active pāhoehoe lava frequently changes to ‘a‘ā (rough or blocky lava) as its flow velocity increases. The coastal plain has a prevalence of lava-flow inflation structures (formed by the process of continual growth of upper and lower crust surrounding a continuously replenished molten interior). Lava flows along the shoreline have many features resulting from interaction with water. These features include lava deltas, pillow lavas, lava tongues, collapsing lava deltas, and lava benches. This dynamic setting is also host to explosive events, including tephra jets, lithic blasts, bubble bursts, and littoral lava fountains (Kauahikaua et al. 2003). Since 1983, Kīlauea's eruptions have added more than 210 hm^2 (520 acres) to the southern coast of Hawai‘i (figs. 13 and 14) (Heliker and Mattox 2003).

Eruptions

At Kīlauea, magma generated by hotspot processes is stored in a chamber 1–4 km (0.6–2.5 mi) beneath the volcano's summit and travels some 20 km (12 mi) through a shallow dike system along the east rift zone to the active Pu‘u ‘Ō‘ō vent, where it reaches the surface (Barker et al. 2003). Eruptions can occur as simple flows or lava fountains reaching heights in excess of 150 m (500 ft) (Macdonald 1943). Lava fountains eject fragments of lava into the air, where they are quickly quenched and solidify, forming lapilli, blocks, and bombs. Some of these ejecta are brightly colored and shiny on the surface (fig. 15). Numerous ash deposits on Kīlauea and Mauna Loa attest to periodic explosive eruptions in Hawai‘i. Within the flows of the Puna Basalt and Hilina Basalt on Kīlauea are numerous ash layers. The two basalt groups are separated by a widespread ash layer—the Pāhala Ash—erupted from a larger caldera on Kīlauea than is present today (Clague et al. 1995).

Compared to the explosive eruptions of stratovolcanoes (e.g., Mt. St. Helens, Mt. Fuji, and Mt. Pinatubo), those of Hawaiian volcanoes are generally not considered violent. Frequently, relatively thin basaltic lava issues from fissures near the summit caldera or along rift zones. However, under certain conditions explosive, phreatic eruptions can occur at Kīlauea and Mauna Loa. In 1924, the lava lake at Halemaʻumaʻu drained, causing a rapid transfer of a large volume of magma from the reservoir beneath the summit to the east rift zone. This in turn lowered the magma column and reduced hydrostatic pressure beneath the lava lake, allowing a rapid influx of ground water into areas previously occupied by molten magma. The interaction of the ground water with the very hot surrounding rocks produced a steam explosion, a phreatic eruption (Dvorak 1992). As regional deposits of fallout and base-surge deposits suggest, these steam explosions are much more powerful and destructive than lava fountaining (Dvorak 1992; Wolfe and Morris 1996a).

A large crater along Kīlauea's east rift zone caps the Puʻu ʻŌʻō vent. A molten lava pond frequently occupies this crater (fig. 16). This lava pond's activity includes slow filling and rapid backdraining. Filling is usually passive, whereas ground deformation and heightened seismic tremors accompany backdraining. Filling is caused by vesiculation within the magma column beneath the vent, which causes the magma to expand. Backdraining is initiated by an abrupt release of gas as bubbles coalesce and then hollow out the core of the magma conduit. The process begins anew when infiltrating magma repressurizes the system (Barker et al. 2003).

The continuously evolving conduit system within the Puʻu ʻŌʻō vent and how it connects to the source dike and lava-tube system is still poorly understood. New monitoring techniques are constantly being developed to monitor the lava output from Puʻu ʻŌʻō and thus understand lava emplacement processes (Kauahikaua et al. 2003). GPS measurements, electronic borehole tiltmeters, and leveling surveys suggest the presence of two distinct summit magma reservoirs, a vent at Puʻu ʻŌʻō and a >5-m-wide (16-ft-wide) conduit connecting that vent to the shallower of the two summit reservoirs (Halemaʻumaʻu magma reservoir) at Kīlauea Volcano (Cervelli and Miklius 2003). Geochemical and geophysical data indicate that three magma sources have contributed to the eruption at Puʻu ʻŌʻō–Kupaianaha: (1) magma from a large, uniform magma reservoir in the mantle, (2) magma from a shallow summit reservoir that predates the 1983 eruptive onset, and (3) fractionated magma from a shallow pre-1983 rift-zone reservoir (Thornber 2003). Mixing of these three types through the past several decades of continuous eruptions has yielded unique geochemical signatures that may prove useful in understanding the shallow conduit and magma feeder system below the vent.

Pāhoehoe and ʻaʻā Lavas

Basaltic lava, being of low viscosity, tends to flow downslope in lava rivers, broad flows, and lava tubes. Kīpukas are sometimes left as wooded oases in the midst of broad lava sheets (Holland 2004). Lava from the 1942 eruption at Mauna Loa was timed flowing downslope at nearly 32 km/hr (20 mi/hr) (Macdonald 1943). Lava can spread laterally at slower speeds. Though many morphologic subtypes exist, basaltic lava at Hawaiʻi generally appears in two different forms: pāhoehoe and ʻaʻā (figs. 17 and 18). They are the same chemically; however, the surficial expression of these two types is very different. Pāhoehoe has a smooth, ropy appearance, whereas ʻaʻā has a sharp, blocky surface. Morphologic subtypes of pāhoehoe include entrail, shelly, shark-skin, filamented, corded, festooned, elephant-hide, slabby, P-type, dense-glass or blue-glassy, and shiny, silvery pāhoehoe. P-type pāhoehoe is currently attracting study at the Puʻu ʻŌʻō vent eruption. This type includes dense-glass and blue-glassy pāhoehoe. The resulting lava contains pipe visicles and a gun-metal-blue glassy rind as thick as 1 cm (0.4 in.). The surface of P-type pāhoehoe has a shark-skin texture resulting from olivine phenocrysts that were draped by highly fluid lava during emplacement (Kauahikaua et al. 2003).

Throughout more than two decades of continuous eruptions at the Puʻu ʻŌʻō vent, pāhoehoe flows have been more common (Kauahikaua et al. 2003). The surface expression depends largely on the rate of cooling and the rate of strain or deformation. For a typical Hawaiian basalt flow, pāhoehoe flows tend to evolve into ʻaʻā flows with distance from the source vent (Hon et al. 2003). This change, the pāhoehoe-ʻaʻā transition, may occur where the lava changes from a well-mixed fluid to a thermally stratified fluid with cooler edges and surface and a hotter flowing core (Hon et al. 2003). Surface cooling rates depend on wind speed and lava porosity, and core temperatures decrease at rates an order of magnitude higher within surface flows than within lava flowing inside lava tubes (Keszthelyi 1996). The pāhoehoe-ʻaʻā transition is also a function of the degree of crystallization of the lava; abundant tiny crystals increase the yield strength of the material (Hon et al. 2003). Although uncommon, the still-molten core of an ʻaʻā can discharge as pāhoehoe lava. Channelized ʻaʻā flows can evolve by roofing over to form lava tubes covered by pāhoehoe-type lava flows (Kauahikaua et al. 2003).

Pāhoehoe lobes can flow great distances, though each flow may be only a few tens of centimeters thick. This is due in part to the low viscosity of basaltic magma but also to lava-flow inflation. Inflation occurs when continued injection of lava into the molten core of a flow raises the upper, cooled and solidified surface. The process of inflation generates myriad distinguishing surface features, including sheet flow, lava-rise plateaus, and lava-rise ridges. Sheet flow results from an entire flow being evenly inflated, producing broad, flat surfaces. Less complete inflation produces lava-rise plateaus, and lava-rise ridges form elongate tumuli by compression and buckling of crust in the most localized manner. Lava-rise pits form in sheet flows where small areas are not inflated. The degree and homogeneity of inflation depends on the continuity of melt below the solidified crust (Keszthelyi et al. 1996).

Lava-Tube Caves

The upper and lower surfaces of a lava flow cool faster than the flow's interior. These cooled surfaces form insulating crusts surrounding the internally flowing lava.

If flow persists as inward cooling proceeds, then the molten lava becomes restricted to a lava conduit, or lava tube, within the lava flow. A lava tube is an extremely efficient system for transporting lava with minimal cooling. Temperature drops of 15°C over 15 km (9 mi) distance—about 1°C/ km—were reported for Kīlauean eruptions between 1969 and 1974 and 0.6°C/km for the Puʻu ʻŌʻō-Kupaianaha lava tubes between 1986 and 1990 (Moore et al. 1973; Swanson 1973; Swanson et al. 1979; Wood 1980; Helz et al. 2003; Hon et al. 2008); similar rates characterize the ongoing Puʻu ʻŌʻō eruption (Kauahikaua et al. 2003). Lava streams flowing within a tube are erosive; they can cut down through the base of the tube as much as 10 cm/day (4 in./day) for periods of several months (Kauahikaua et al. 2003). When the lava supply is extinguished, the tube drains, leaving hollow spaces beneath the surface of the solidified lava flow.

At Hawaiʻi Volcanoes National Park, networks of lava-tube caves underlie many areas. Indeed, as of 2004 some 1,000 cave entrances and nearly 320 km (200 mi) of cave passages were surveyed by the Hawaiʻi Speleological Society. The Hawaiʻi Speleological Survey explores larger tubes, including the famed Kaūmana lava tube near Hilo and the lengthy Kazumura Cave at Volcano (Greeley 1971). Other named caves in the park area include Keana Momoku Ahi–Calabash system, Ice Cave, Skylight Cave, Thurston's Tube, Mauna Iki tube, Kazumura Cave, and ʻĀinahou Ranch Cave. The latter contains outstanding petroglyphs, ancient stone structures, a human skeleton, and charcoal. Kazumura Cave is more than 11 km (7 mi) long, among the longest known lava tubes in the world (Wood 1980).

The volcanoes of Mauna Loa and Kīlauea hold potential for discovery of enormous, long lava-tube caves given the close proximity to active vents, the sheer volume of lava erupted, and the fresh, unforested pāhoehoe surface flows. Aerial photographs suggest that as many as 82% of the surface flows on Mauna Loa and Kīlauea are either tube-fed or channel-fed (Wood 1980). A 1979 expedition mapped 24 km (15 mi) of cave passages. These caves contain many unique features, including speleothems, lava stalagmites and stalactites, and ancient Hawaiian burial chambers, artifacts, and petroglyphs (Wood 1980). Nearly every large cave older than 200 years in Hawaiʻi Volcanoes National Park contains archeologically important cultural resources (Camara 1998). In 1997, geologists mapped and inventoried a 3-year-old lava tube, the Highcastle Lava Tube. Young lava tubes may not contain cultural resources but are invaluable in the research of transient features found only in recently formed tubes (Camara et al. 1998).

A summary of all mapped caves within Hawaiʻi Volcanoes National Park is beyond the scope of this report; however, a few notable examples are included here. Keana Oa Waa Cave is of exceptional geological importance. It is an example of a rare borehole lava tube arising in a pit crater. This cave is spacious, having areas 5–7 m (16–23 ft) high, and contains pendants, complex pāhoehoe flow patterns, glaze and dripstone, paleontological remains, secondary minerals, frozen lavafalls, and many more geological features. This cave is a geological reserve candidate (Halliday and Fulks 1997a). Red Slope Cave in Kīlauea Crater is one of the most intriguing and challenging caves in Hawaiʻi Volcanoes National Park. The cave is at least 557 m (1,828 ft) long, but ceiling heights are rarely more than 1.5 m (5 ft). This cave contains complex patterns, secondary mineralization, hackly ceilings, a lava column, dripstone, lava mounds and tongues, and squeezeups (Halliday and Fulks 1997b)

When Mauna Ulu originated in 1971, its eruptions allowed geologists to view the formation of a shield volcano and the role lava tubes play in efficiently conveying lava great distances from the source vent. The formations within these tubes—lavacicles, driblet spires, and secondary mineral deposits (fig. 19)—are testament to the processes of lava tube formation and evolution throughout eruptive activity. The lava speleothems in Hawaiʻi's lava tubes are vulnerable to accidental breakage and vandalism (Howarth and Stone 1993).

Hawaiʻi caves host more than 50 species of cave-adapted flora and fauna, a fact made more interesting by the isolation of the islands in the middle of the Pacific Ocean. For example, Thurston Lava Tube (fig. 20), the most visited lava-tube cave in the world, is host to a stable aerophilous flora of 49 taxa in its wet wall, hanging garden habitat (Rushforth et al. 1984; Halliday 1998b). Caves also host fossil remains, some of which are crucial to understanding the evolution of Hawaiʻi's birds (Howarth and Stone 1993). Notably abundant in some caves are the remains of now-extinct flightless birds, which may have entered or fallen into the cave and then been trapped (D. Sherrod, U.S. Geological Survey, written communication 2009).

Kīlauea caldera is the type locality for a lava rise (a special type of large lava tumulus found on basaltic flow fields) and many other lava-cave features and morphologic subtypes of lava flows. The lava rise features form from injection of very fluid lava beneath a still hot, deformable plastic crust. Many of these features partially collapse, or deflate, after their margins have solidified, forming a central depression surrounded by a ridge as much as several meters high. In the field, these lava rises resemble a hollow donut. These remain an important research topic in lava tumuli origins (Halliday 1998a). The "Pit-Crater District" is considered a type locality for volcanic steep-sided depressions where pits open directly downward from the surface with no ring of ejecta or overflow (Halliday 1998b). Other interesting lava features, such as hornitos, rootless shields, and shatter rings, form over active lava tubes at Hawaiʻi Volcanoes National Park (Kauahikaua et al 2003).

Once lava-tube caves form, they are subject to many processes of weathering and secondary mineralization. In Kīlauea caldera, a single flow from 1919 (the "Postal Rift") contains about 200 caves, including lava-tube, hollow-tumulus, flow-lobe, and lava-rise caves, some of which are intermittently hyperthermal (too hot for safe entry) with steam and fume emissions (Halliday 2004; Halliday 2007). These hot, saturated gases and vapors deposit secondary minerals along cracks and other locations, such as ceilings, walls, floors, and lava drip formations. Minerals include sulfates, chlorides, and elemental sulfur in crystals, soda straws, fist-sized clumps, and crusts (Camara 2000; Halliday 2004). The Laeʻapuki cave, which formed in 1996–97, showed transitory white depositional stalactites as much as 0.3 m (1 ft) long when visited 2.5 years later (Bunnell 2000). Secondary minerals include ilmenite, magnetite, plagioclase, copper-titanium oxide, iron-titanium oxide, and calcium sulfates (Camara 2000).

Volcanic-cave studies require an interface between volcanology and speleology, and there is specific terminology associated with lava-tube and flow features that gives rise to much confusion. Efforts to clarify and properly define terms such as "pit crater," "lava tube," "jameo," and "vertical volcanic conduits" are ongoing (Halliday 1998b), and the numerous volcanogenic features preserved and actively forming at Hawaiʻi Volcanoes National Park provide a unique opportunity to refine many of these terms.

Given the significant cultural, archeological, biological, paleontological, geological, recreational, and aesthetic value of the vast number of Hawaiian caves, preservation of these speleological features from threat of overuse is vital for the resource management team at Hawaiʻi Volcanoes National Park. In recent years, in part due to increased interest in caves and publications locating known entrances (the HVO library at http://hvo.wr.usgs.gov/observatory/hvo_history_pubs.html, accessed December 2009, has more than 250 reports about lava tubes throughout the Hawaiian Islands), degradation of Hawaiʻi's cave resources has escalated (Howarth and Stone 1993). With participation of spelunkers, Hawaiʻi Volcanoes National Park developed a management plan to protect and expose lava caves for recreational use (Taylor 1991).

Geology and Hawaiian Culture

As described above under "Lava-Tube Caves," the basalt flows on the flanks of Mauna Loa and Kīlauea volcanoes were used by ancient Hawaiians. These early people were profoundly aware of their natural environment, incorporating geologic processes into their deities and religious rituals. Old Hawaiian stories describe actual events, natural processes, and geologic hazards and serve to increase the historical and scientific understanding of the evolution of the volcano. Stories of the Hawaiian goddess of volcanoes, Pele-honua-mea, describe the noises produced during an eruption, lava movements, and textures of the cooled lava rocks (Reveira and Kauahikaua 2002). According to legend, Pele first settled on the island of Kauaʻi and moved progressively through the chain of islands, settling permanently in Halemaʻumaʻu, the caldera of Kīlauea Volcano (Castro 1953). A keen understanding of geologic processes was necessary to realize the age progression of the islands and in daily life to determine when it was safe to cross volcanic hazard zones (Reveira and Kauahikaua 2002). Footprints preserved in Keanakākoʻi Ash of the Kaʻū Desert area document human travel during a period of explosive, ash-rich eruptions between 1500 and 1790 C.E. (Common Era, or "A.D.") (Nakamura 2003). The so-called home of Pele is still hallowed ground to Hawaiians today (Castro 1953).

Geological and environmental factors were the most important influences on early farming and settlement practices on Hawaiʻi. Volcanic ash and weathered basaltic lava flows have produced fertile soil on Hawaiʻi (Gibson 2001). ʻAʻā flows have highly irregular surfaces that act as natural dust and tephra traps to form primitive unconsolidated soil substrate. Older lava flows are weathered and may have mantles of tephra (fine ash and coarser cinder) that can further support nutrient-rich, development of fine-grained soil, whereas younger flows usually lack the tephra and tend to support rocky, development of well-drained soil (Kirch et al. 2004). This distribution of substrate type was intimately connected with settlement patterns throughout ancient Hawaiʻi and even today distinguishes productive agricultural land from land better suited for other purposes.

The shield volcanoes of Mauna Loa and Kīlauea create local climate zones. Typically, below the inversion layer (approximately 2,000 m, or 6,560 ft, in elevation) precipitation increases and evapotranspiration decreases with increasing elevation on the leeward side of the volcano (Kirch et al. 2004). Air above and within the inversion layer (a layer characterized by a deviation from the normal change of temperature with increase in elevation) provides a source of positive heat advection that increases potential evaporation at higher elevations (Nullet and Giambelluca 1990; Giambelluca and Nullet 1992). Retention of soil moisture is a function of substrate permeability and porosity. Typically, lava-flow substrates are excellent conductors of water, and retention values tend to be low. Finer grained substrates, such as primitive soils, would have retained precipitation better than the rockier areas (Kirch et al. 2004). Ancient Hawaiians took advantage of these niche areas on the slopes of Mauna Loa and Kīlauea.

Geology and Biology Connections

Hawaiʻi hosts great biodiversity, with more than 150 kinds of natural communities identified, and is a valuable natural laboratory for ecosystem studies (Moffat et al. 1994; Miller et al. 2001). Within the national park boundary, seven ecological life zones (seacoast, lowland, mid-elevation woodland, rain forest, upland forest and woodland, sub-alpine, and alpine/aeolian) form contiguous habitat from sea to volcanic summit. This diversity and biogeographical distribution is a function of the variety and history of landforms and climate on the islands (Price and Elliott-Fisk 2004). As reflected in the pollen and spore record on Hawaiʻi, climate has changed from relatively dry and cool at around 28,000 years before present (ybp) to warmer and wetter than present after 16,000 ybp until at least 7,000 ybp (Hotchkiss 1998). Today, northeast trade winds create a spatially variable pattern of precipitation, causing the eastern windward flank to receive upward of 9,800 mm (386 in.) of precipitation per year, whereas the western, leeward areas receive approximately 250 mm (10 in.). Upland

areas are arid due to isolation by the inversion layer from coastal moisture. The inversion layer suppresses upward flow, causing trade wind circulation to divide around the highest mountains of Hawai‘i (Pérez 2003).
Prior to human settlement, the isolation of the islands in the middle of the Pacific Ocean allowed them to become a living laboratory of evolution. An island’s earliest lifeforms were likely algae, lichens, and ferns (Radlauer 1979; Price and Elliott-Fisk 2004). From a limited number of colonists, unique birds and plants evolved over thousands of years, each perfectly suited to its environment and dependent on a fragile ecological balance to survive (Price and Elliott-Fisk 2004). The presence of introduced and alien species, such as mouflon goats and pigs, has devastated the ecological balance in many parts of Hawai‘i (Hess et al. 2006).

Geology, biology, and climate influence soil development on Hawaiian volcanic slopes. In tropical and volcanic soils, phosphorous availability to plants is strongly influenced by geochemical sorption, which binds phosphorous to soil minerals (Olander and Vitousek 2004). Iron oxides, abundant in basalt-derived soils, act as sorbents for nutrients, pollutants, and natural organic matter. Fluctuating reducing-oxidizing conditions (Fe oxidation state) prevail in different climates as a function of the amount of precipitation (Thompson et al. 2002). Thus, different climate areas correspond to different biological zones with geologically controlled soil substrates. Further study might reveal how nutrients such as phosphates, pollutants such as heavy metals, and natural organic matter are distributed with respect to substrate in Hawai‘i’s soils

Lava and ash occasionally preserve evidence of vegetation overrun or buried during volcanic eruptions. Tree molds in lava, like those preserved near Kīlauea, are one example. Organic material, including a well-preserved fern leaf discovered by HVO founder Thomas Jaggar, was preserved in an ash layer dating to the late 1600s or early 1700s (Hunt et al. 2007).

Figure 12. Mauna Loa is the most massive mountain in the world. Its shield-like shape looms over the park’s landscape. This view is from the Ka‘ū Desert Trail. The summit of Muana Loa (4,170 m; 13,680 ft) is more than 3,200 m (10,600 ft) higher than the Ka‘ū Desert Trailhead. USGS photograph available at http://3dparks.wr.usgs.gov/havo/.

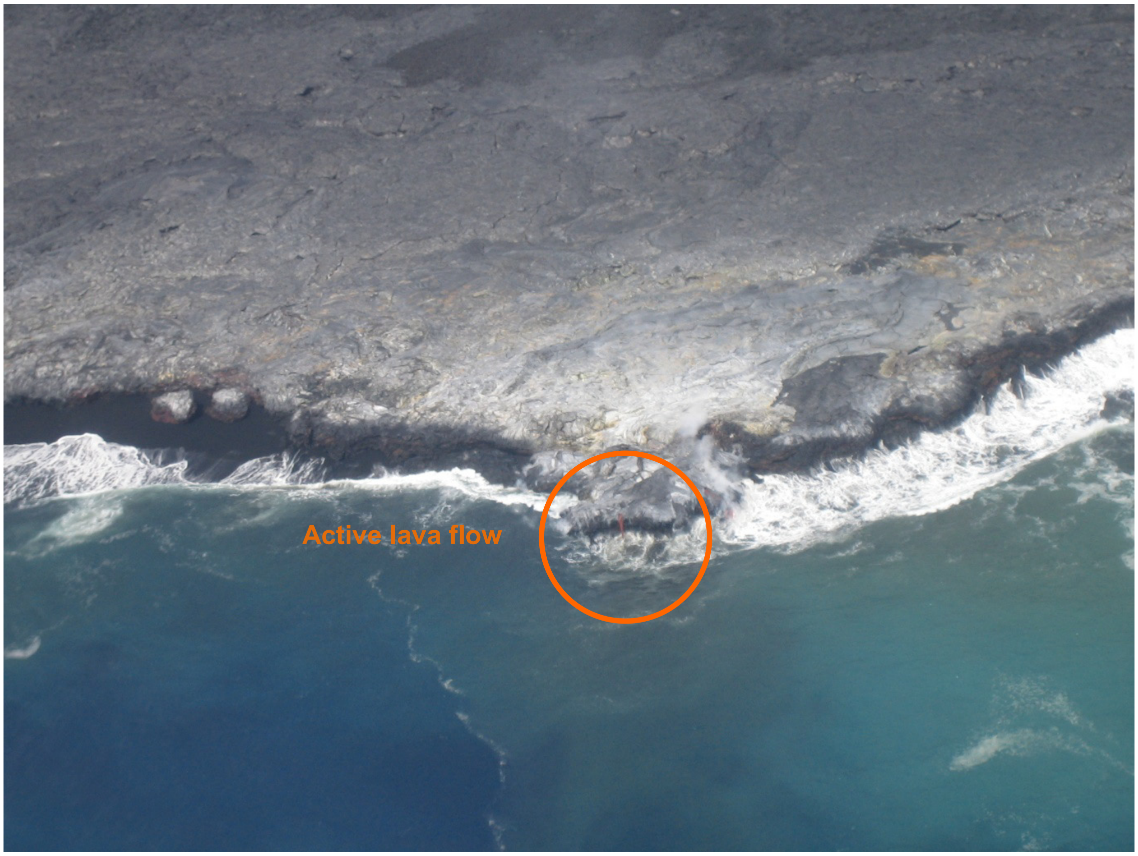

Figure 13. Aerial oblique view north toward newly created land at Hawai‘i Volcanoes National Park. Active lava discharge shown circled, behind which is wave-cut edge of recently active lava flows. Brownish to grayish green ocean coloration indicates sediment-laden seawater. Photograph is by Timothy Ehrlich (Old Dominion University), February 2007.

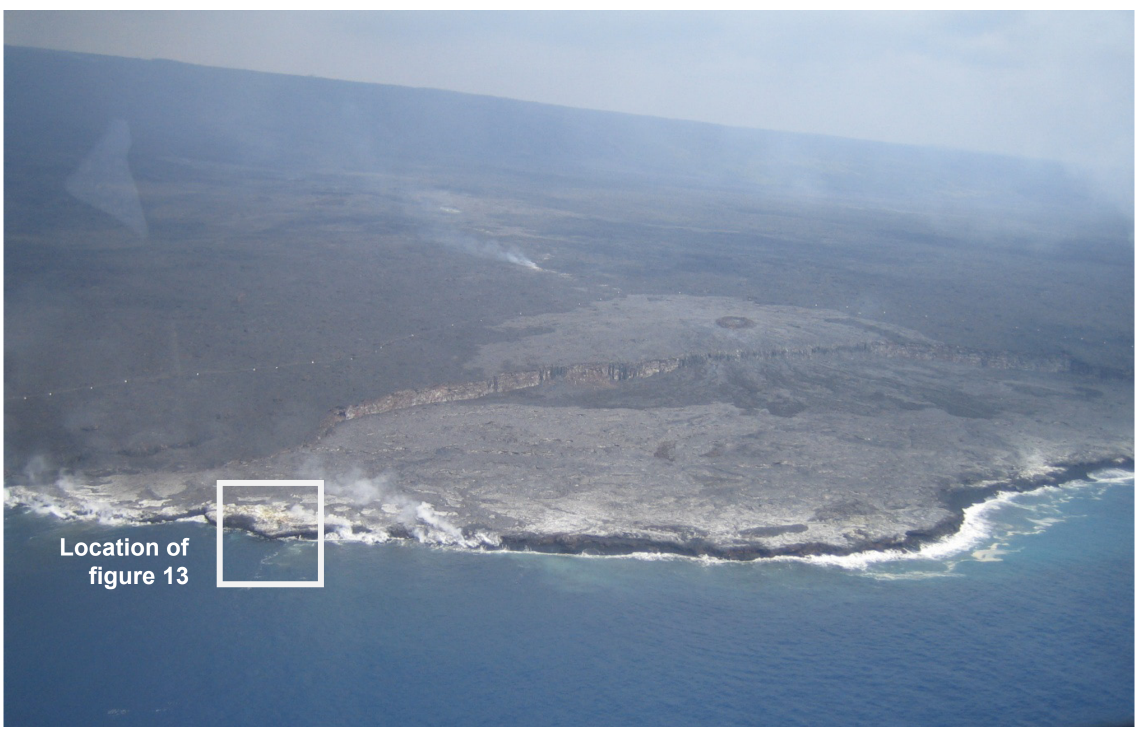

Figure 14. Aerial oblique view northeast toward new land of an active lava bench. The bench lies seaward of a former seacliff scarp along the southern coast of Hawai‘i. Photograph is by Timothy Ehrlich (Old Dominion University), February 2007.

Figure 15. Solidified lava spatter from fountaining in Hawaiʻi Volcanoes National Park. Vent is a part of Halemaʻumaʻu activity in 1974. Photograph is by Trista L. Thornberry-Ehrlich (Colorado State University), February 2007.

Figure 16. Molten lava lake within the Puʻu ʻŌʻō vent at Hawaiʻi Volcanoes National Park. Lava from the vent passes downslope through lava tubes to the Pacific Ocean. Photograph is by Timothy Ehrlich (Old Dominion University), February 2007.

Figure 17. Pāhoehoe lava flow that buried the Chain of Craters Road in 1972, Hawai‘i Volcanoes National Park. Photograph is by Trista L. Thornberry-Ehrlich (Colorado State University), February 2007.

Figure 18. Ropy-textured pāhoehoe and adjacent blocky-textured ‘a‘ā lava flows that buried the Chain of Craters Road in 1972, Hawai‘i Volcanoes National Park. Photograph is by Trista L. Thornberry-Ehrlich (Colorado State University), February 2007.

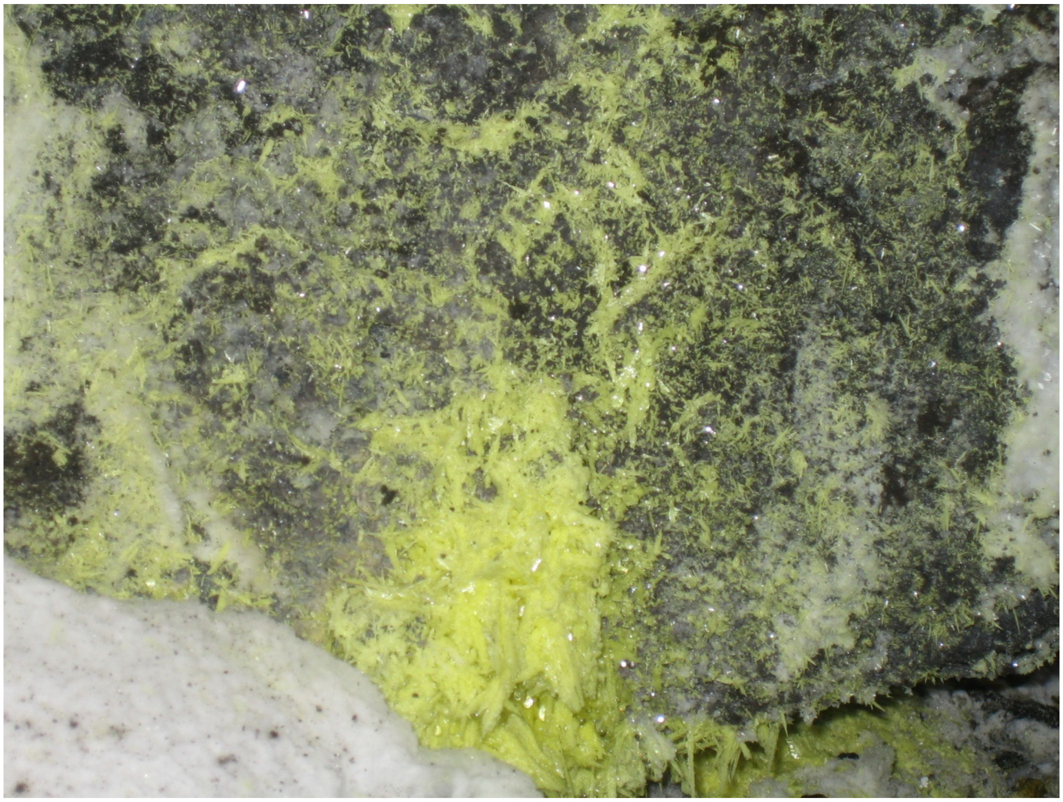

Figure 19. Secondary mineralization present as delicate sulfur crystals within a surficial cavity of a lava flow at Hawai'i Volcanoes National Park. Photograph is by Trista L. Thornberry-Ehrlich (Colorado State University), February 2007.

Figure 20. View out of the entrance to Thurston Lava Tube. USGS photograph available at http://3dparks.wr.usgs.gov/havo/.

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of Hawai'i Volcanoes National Park. The accompanying table is highly generalized and for background purposes only. Ground-disturbing activities should not be permitted or denied on the basis of information in this table.

Geologic maps facilitate an understanding of Earth, its processes, and the geologic history responsible for its formation. Hence, the geologic map for Hawai'i Volcanoes National Park informed the "Geologic History," "Geologic Features and Processes," and "Geologic Issues" of this report. Geologic maps are essentially two-dimensional representations of complex three-dimensional relationships. The various colors on geologic maps illustrate the distribution of rocks and unconsolidated deposits. Bold lines that cross and separate the color patterns mark structures such as faults and folds. Point symbols indicate features such as dipping strata, sample localities, mines, wells, and cave openings.

In serving the conservation and recreation needs of the nation, resource managers consider other resources—water, soils, vegetation, and cultural—in concert with geology. Incorporation of geologic data into a Geographic Information System (GIS) increases the usefulness of geologic maps by revealing the spatial relationships to other natural resources and anthropogenic features. Geologic maps are indicators of water resources because they show which rock units are potential aquifers and are useful for finding seeps and springs. Geologic maps do not show soil types and are not soil maps, but they do show parent material, a key factor in soil formation. Furthermore, resource managers have used geologic maps to make connections between geology and biology; for instance, geologic maps have served as tools for locating sensitive, threatened, and endangered plant species, which may prefer a particular rock unit.

Although geologic maps do not show where earthquakes will occur, the presence of a fault indicates past movement and possible future seismic activity. Geologic maps do not show where the next landslide, rockfall, or volcanic eruption will occur, but mapped deposits show areas that have been susceptible to such geologic hazards. Geologic maps do not show archaeological or cultural resources, but past peoples may have inhabited or been influenced by various geomorphic features that are shown on geologic maps. For example, alluvial terraces may preserve artifacts, and formerly inhabited alcoves may occur at the contact between two rock units.

The geologic units listed in the following table correspond to the accompanying digital geologic data. Map units are listed in the table from youngest to oldest; please refer to the geologic time scales (figs. 21 and 22) for the age associated with each time period. This table highlights characteristics of map units, such as susceptibility to hazards; occurrence of fossils, cultural resources, mineral resources, and caves; and suitability as habitat or for recreational use.

The GRI digital geologic maps reproduce essential elements of the source maps, including the unit descriptions, legend, map notes and graphics, and report. The following references are source data for the GRI digital geologic map for Hawai'i Volcanoes National Park:

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

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. Reston, VA: U.S. Geological Survey.

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. Reston, VA: U.S. Geological Survey.

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

The GRI team implements a geology-GIS data model that standardizes map deliverables. This data model dictates GIS data structure, including data layer architecture, feature attribution, and data relationships within ESRI ArcGIS software, increasing the overall quality and utility of the data. GRI digital geologic map products include data in ESRI personal geodatabase and shapefile GIS formats, layer files with feature symbology, Federal Geographic Data Committee (FGDC)–compliant metadata, a Windows help file that contains all of the ancillary map information and graphics, and an ESRI ArcMap map document file that easily displays the map, and connects the help file directly to the map document.GRI digital geologic data are included on the attached CD and are available through the NPS Data Store (http://science.nature.nps.gov/nrdata/).

Hawai'i Volcanoes National Park Map Units

Lava flows from Mauna Loa and Kīlauea volcanoes, emplaced during the Pleistocene and Holocene epochs, dominate the surface and subsurface rocks in Hawai'i

Volcanoes National Park. Mauna Loa beds exposed in the park are chiefly the Ka‘ū Basalt, a formation consisting of spatter cones, lava flows, littoral cones, and tephra deposits. Compositionally, these rocks are typically tholeiitic with some rarer transitional basalt present locally (Wolfe and Morris 1996a).

Kīlauea Volcano, which is currently erupting at Hawai‘i Volcanoes National Park, contains exposures of several formations but mainly the Puna Basalt and the Hilina Basalt. The latter includes lava flows and interlayered ash deposits exposed in kīpukas on the volcano's south flank. The flows are both ‘a‘ā and pāhoehoe types. The Hilina Basalt underlies a widespread ash unit, the Pāhala Ash. The Pāhala Ash, locally as thick as 27 m (89 ft), has an age in the range of 39,000 to 23,000 years. Its origins are somewhat enigmatic but may include reworked tephra-fall deposits from Kīlauea, Mauna Loa, Mauna Kea, and Kohala volcanoes (Clague et al. 1995; Wolfe and Morris 1996a).

The younger Puna Basalt group includes lava flows, spatter or tuff cones, littoral cones, and tephra deposits erupted from Kīlauea Volcano. The lava flows are both ‘a‘ā and pāhoehoe, primarily tholeiitic basalt. Other basalt compositions, including transitional and alkalic basalt, are rare but present locally. The tephra deposits include lapilli, ash, and larger blocks and bombs, some of which were produced by steam-driven eruptions (Wolfe and Morris 1996a).

Other mapped units within Hawai‘i Volcanoes National Park include caldera wall rocks, and alluvium and colluvium. The unit consisting of caldera wall rocks marks the steep walls of the calderas atop Kīlauea and Mauna Loa, where several formations may be exposed but are too thin to show in plan view at common map scales. Alluvium and colluvium consist of sand and gravel derived from erosion of lava flows and ash beds. The amount of rounding of grains in these deposits depends upon the distance they have been transported by the intermittent streams on the volcanoes. At the foot of most steep slopes are deposits of colluvium, landslides, and talus. Local eolian deposits (ash-rich sand dunes) and black to coralline beach sands may be present locally (Wolfe and Morris 1996a).

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Hawai'i Volcanoes National 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 Hawai'i Volcanoes National Park are young. Volcanism created the oldest of the rocks on the Island of Hawai'i less than 1 million years ago—compared to more than 4 billion years of Earth's history (figs. 21 and 22) (Clague and Dalrymple 1987; Rubin 2005). At Hawai'i Volcanoes National Park, new rocks are forming. Even so, the geologic setting and evolution of the Pacific basin and the Hawaiian Islands are vast and relevant to understanding key events in Earth's history. Knowing how the islands formed is vital to understanding the current landscape and to predicting potential geologic events.

Pre-Quaternary History of the Pacific Basin

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, whereas Gondwana eventually separated into the continents of South America, Africa, Australia, and Antarctica (Condie and Sloan 1998). Continental rifting opened new oceans, such as the Atlantic Ocean basin between the Americas and 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 changing and splitting during this time.

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 (Condie and Sloan 1998). This event correlates with rising sea level, global climate change (warming), and several extinction events in the middle Cretaceous.

The present Pacific plate fills most of the North Pacific Ocean basin, but this was not always so. The Pacific plate, on which the Hawaiian-Emperor volcanic chain is located, 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.

The Pacific plate started as 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. 23) (Condie and Sloan 1998; University of California Santa Barbara 2006). Separated by mid-ocean ridges, the plates surrounding the Pacific plate began moving away from it. During the middle Tertiary, the surrounding plates were mostly assimilated into Earth's crust by subduction. Oceanic crust is denser than continental crust, so in a collision between the two, the oceanic crust tends to sink (subduct) beneath the continental crust. This subduction generates heat as the plate sinks into the upper mantle. The oceanic crust melts and rises to the surface, often forming a volcanic arc above the melting plate and in effect recycling the oceanic crust.

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 the Sevier-Laramide orogenic event and the eventual formation of the San Andreas fault 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 (Condie and Sloan 1998). During this time, the Pacific plate enlarged by seafloor spreading to nearly fill the north Pacific basin. It now is moving slowly northward and westward—away from the East Pacific Rise spreading center and towards the subduction zones bordering the Australian-Indian plate, the Philippine plate, the Eurasian plate and the Aleutian Islands of the North American plate (fig. 24) (University of California Santa Barbara 2006).

Evolution of the Hawaiian-Emperor Seamount Chain

The Pacific plate encompasses about 20% of the Earth's crust and is the largest tectonic plate on the planet today. Throughout the Pacific basin are linear chains of volcanic islands and seamounts (submerged volcanoes). Many of these chains progress in age from one end to the other (fig. 25). The linear trend of the Hawaiian-Emperor islands and seamounts records the movement of the Pacific plate over a stationary hotspot in the upper mantle. Other such hotspots across the basin are the Caroline, Marquesas, Society, Pitcairn, Austral, and Easter hotspots (fig. 26) (Condie and Sloan 1998).

Hotspots form in response to rising plumes of material 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) deep), the lower pressure causes the material to melt. If this molten material (magma) finds a way to the outer crust, it may erupt and produce a series of volcanoes that decrease in age toward the plume (hotspot) (Condie and Sloan 1998).

The Hawaiian Islands are part of a volcanic chain that is located along the crest of the Hawaiian-Emperor seamount chain overlying the Hawaiian hotspot. 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) in the far northwest Pacific, southward and eastward to Lōʻihi, the submarine volcano off the coast of the Island of Hawaiʻi (fig. 4). The seamount chain is divided into two sections, the younger Hawaiian Ridge (from the Hawaiian Islands northwest to Kure Atoll) and the older Emperor Seamounts. The seamount chain contains islands, seamounts, atolls, shallows, banks, and reefs along a line trending southeast to northwest across the northern Pacific. The two components are divided at a distinctive kink 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 that took place over a period of 8 million years, from 50 to 42 million years ago (Sharp and Clague 2006).

Each volcanic island evolved through four idealized eruptive stages: preshield, shield, postshield, and rejuvenated stages (fig. 27) (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, include cinder and spatter cones, and mixed lava flows over a localized area (Clague et al. 1982; Sherrod et al. 2007). On the basis of the rate of movement of the Pacific plate and the average spacing of volcanic centers, it may be 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).

The massive outpouring of lava and the building of a large shield volcano depresses the oceanic crust beneath it. Beneath 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. When combined with erosion, volcanic quiescence and subsidence cause the islands to shrink and eventually submerge below the ocean surface (Clauge and Dalrymple 1987; Rubin 2005).

Because the northernmost extinct volcanoes are descending into the Aleutian trench, it is difficult to ascertain when the Hawaiian hotspot activity began. For the major Hawaiian Islands, age increases with distance from the hotspot (currently beneath Hawaiʻi and Lōʻihi) (Cross 1904). The oldest major island, Niʻihau, is the farthest distance away from Kīlauea, having shield-stage lava ages of 5.2 and 4.89±0.11 million years (oldest known age of 6 million years with large analytical error) (G. B. Dalrymple unpublished data 1982; Clague and Dalrymple 1987; Clague 1996; D. Sherrod, U.S. Geological Survey, written communication 2009). Kauaʻi is slightly younger and closer to Kīlauea with radiometric potassium-argon (K-Ar) shield lava ages of 5.77±0.28 and 5.14±0.20 million years (McDougall 1979; D. Sherrod, U.S. Geological Survey, written communication 2009).

The end of shield-building volcanism on Oahu dates between 3.0 and 2.6 million years ago (Clauge and Dalrymple 1987; Clague 1996). West Molokaʻi volcano has a K-Ar age of 1.90±0.06 million years, whereas East Molokaʻi volcano has an age of 1.76±0.07 million years; however, these ages are uncertain due to laboratory difficulties (Naughton et al. 1980; Clague and Dalrymple 1987; D. Sherrod, U.S. Geological Survey, written communication 2009). The neighboring islands of Kahoʻolawe and Lānaʻi have K-Ar shield lava ages of 1.25±0.15 and 1.28±0.04 million years, respectively (Bonhommet et al. 1977; D. Sherrod, U.S. Geological Survey, written communication 2009). The West Maui volcano erupted before Haleakalā on the Island of Maui, having K-Ar ages of 2.15 million years for shield stage lava versus the oldest reported age of 1.12 million years for post-shield lava on Haleakalā (McDougall 1964; D. Sherrod, U.S. Geological Survey, written communication 2009).

Although some of the Hawaiian Islands were built by a single volcano, others are the composite of several. The Island of Hawaiʻi today comprises five volcanoes above sea level; a sixth, extinct volcano lies flooded north of Kailua, and to the south of the island newly sprouted Lōʻihi has grown to within 1 km (0.6 mi) of breaking the ocean surface (fig. 3). The time over which a volcano remains active is long (hundreds of thousands to 2 million years or more), and there is significant overlap in volcanic age between neighboring islands. Island boundaries have evolved over thousands of years as sea level fluctuates. Relative sea level fluctuated globally throughout the Pleistocene in response to global climate change. Locally, as volcanic masses grew and their mass depressed the underlying crust, relative sea level rose. At one time, the so-called Maui Nui complex (consisting of

Maui, Molokaʻi, Lānaʻi, and Kahoʻolawe Islands) was a single subaerial landmass comprising six major shield volcanoes (West Molokaʻi, East Molokaʻi, Lānaʻi, Kahoʻolawe, West Maui, and Haleakalā) (Stearns 1946, 1985; Price and Elliott-Fisk 2004).

Overlap in volcanic age between islands is evident today. Haleakalā volcano on Maui last erupted only about 500 years ago, even though it is at a distance from the currently active Kīlauea volcano on Hawaiʻi and about 200 km (124 mi) northwest of Lōʻihi (Sherrod and McGeehin 1999; Sherrod 2002; Rubin 2005). Three Hawaiian 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 and likely will become the next Hawaiian island (Garcia et al. 1998; Rubin 2005). Volcanoes considered dormant include Hualālai (last erupted in 1801), Haleakalā (erupted at Kalua o Lapa between AD 1485 and 1600; its frequently cited age of AD 1790 is too young), and Mauna Kea (last erupted about 4,000 years ago) (Porter et al. 1977; Rubin 2005; Sherrod 2002).

Volcanic activity is ongoing at Hawaiʻi Volcanoes National Park, forming new deposits of lava and tephra that bury older layers. Eruptions at Mauna Loa and Kīlauea have added hundreds of acres of land to the island and inundated rare forests and populated areas. Caldera and pit-crater formation, lava-tube formation and collapse, lava flows, and other eruptive processes continue to modify the landscape at the park. These active areas shift between and along the summit and rift zones of the volcanoes, accompanied by seismic unrest. As forested areas attest, once volcanism stops inundating an area, weathering and biological processes quickly take a foothold on the landscape.

Submarine mass wasting, landslides, and debris flows carry material from the shoreline down the slopes of the islands to spread onto the deep sea floor. This process often leaves steep lava benches, precipitous slopes, and cliffs along the shoreline. These mass movements have been an important ongoing influence on the development of the overall ocean island volcanic complex of all the Hawaiian Islands (Keating et al. 2000). Subaerial massive landslides also play an important role in shaping the Hawaiian Islands. In 1868, a series of large (>M7.0) earthquakes triggered widespread ground cracking. Landslides, constituting as much as the entire south flank of Kīlauea (Hilina landslide), moved seaward during these events. Other large-scale landslides on Hawaiʻi include the Punaluʻu and Kealakekua landslides. The Punaluʻu landslide stretches from the southwest rift zone of Mauna Loa on the upslope side, the western edge of the Kaʻōiki fault zone on the northeast side, and a fault zone extending to the southeast from the bend in the southwest rift on the southwest side. This slide continues offshore south of Lōʻihi seamount. The Kealakekua landslide on the west flank of Mauna Loa was active in 1951 and 1952, accompanying large earthquakes (Clague and Denlinger 1993).

As on other volcanic islands throughout the Pacific Ocean basin, during periods of volcanic quiescence the basalt, tuff, breccia, cinder cones, and ash deposits of Hawaiʻi are exposed to intense weathering and erosion in the tropical Hawaiian climate. Landforms produced may 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 1988). Ocean waves continuously attack the shoreline, carrying away sand and gravel eroded by an island's rivers. Coral reefs fringe certain areas of the islands and contribute carbonate sediment to an island's beaches and nearshore dune deposits (Sherrod et al. 2007).

Pyroclastic ejections of material and weathering of volcanic units and coral reefs by wind, water, and slope processes produced the bulk of the unconsolidated geologic units on Hawaiʻi. Modern low-lying areas throughout the park collect Holocene-age alluvium, windblown ash, colluvium, talus, eolian deposits, and slope deposits. Some of these deposits mantle the older volcanic geologic units at Hawaiʻi Volcanoes National Park (Wolfe and Morris 1996a).

Eon	Era	Period	Epoch	Ma		Life Forms	Global Tectonics
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01	Age of Mammals	Modern man	Habitation of Hawaii begins, volcanism continues
			Pleistocene	2.6		Extinction of large mammals and birds	Worldwide glaciation
		Tertiary: Neogene	Pliocene	5.3		Large carnivores	
			Miocene	23.0		Whales and apes	Linking of N. and S. America
		Tertiary: Paleogene	Oligocene	33.9			Pacific plate dominates as adjacent plates subduct
			Eocene	55.8		Early primates	Australia and Antarctica separate
			Paleocene	65.5			
	Mesozoic	Cretaceous		145.5	Age of Dinosaurs	Mass extinctions Placental mammals Early flowering plants	Pacific superplumes, Pacific Kula, Nazca, and Farallon Plates separated by mid-ocean ridges
		Jurassic		199.6		First mammals Flying reptiles	Anoxic seas Breakup of Pangaea begins
		Triassic		251		First dinosaurs	
	Paleozoic	Permian		299	Age of Amphibians	Mass extinctions Coal-forming forests diminish	Supercontinent Pangaea intact Panthallassic Ocean
		Pennsylvanian		318.1		Coal-forming swamps Sharks abundant Variety of insects	Pangaea begins to form
		Mississippian		359.2		First amphibians First reptiles	Glaciation Anoxic seas
		Devonian		416	Fishes	Mass extinctions First forests (evergreens)	Southern hemisphere continents centered on south pole
		Silurian		443.7		First land plants	
		Ordovician		488.3	Marine Invertebrates	Mass extinctions First primitive fish Trilobite maximum Rise of corals	Large suture forms in Australia (450 Ma)
		Cambrian		542		Early shelled organisms	Glaciation Breakup of Rodinia, opening of Iapetus and Rheic oceans
Proterozoic		Precambrian		2500		First multicelled organisms Jellyfish fossil (670 Ma)	Formation of early Rodinia supercontinent First iron deposits Abundant carbonate rocks
Archean				≈3600		Early bacteria & algae	Oldest known Earth rocks (≈3.93 billion years ago)
Hadean				4600		Origin of life? Formation of the Earth	Oldest moon rocks (4-4.6 billion years ago) Earth's crust being formed

Figure 21. Geologic time scale. Included are major life history and tectonic events occurring on the North American continent. 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.

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

Figure 22. Geologic time scale of events affecting the Hawaiian Islands throughout the Cenozoic Era; adapted from U.S. Geological Survey (http://www.usgs.gov) using information from Clague and Dalrymple (1987), written communication from D. Sherrod (2009), and the GRI digital geologic map for Hawai‘i Volcanoes National Park. Ages of volcanic flows are generally relative and overlap considerably. Absolute ages in millions of years (Ma, or mega-annum).

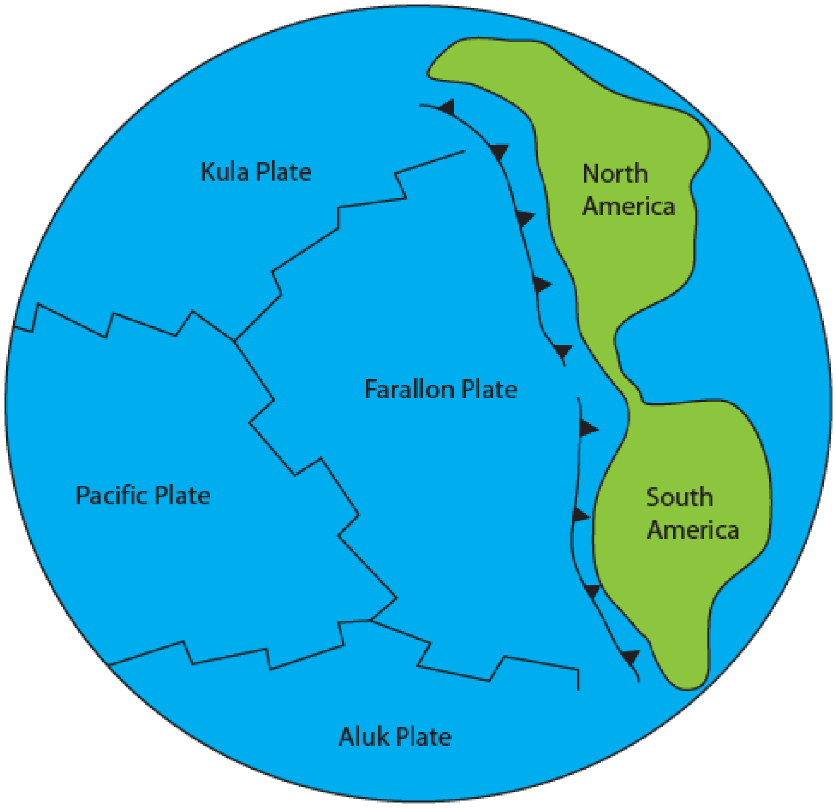

Figure 23. Generalized arrangement of plates in the Pacific Ocean basin during the middle Cretaceous. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

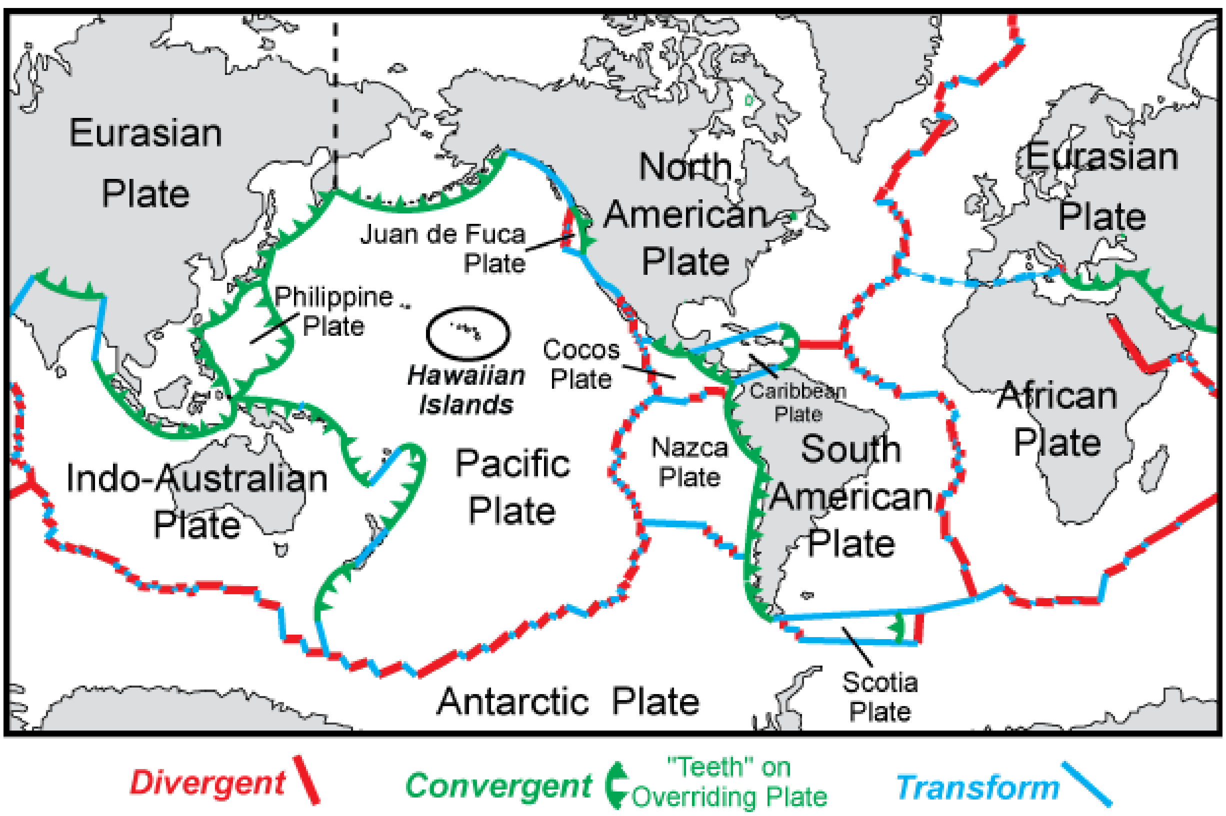

Figure 24. Map of the current tectonic plates. The Hawaiian Islands are circled. Divergent boundaries are where plates are pulling apart. Plates come together at convergent boundaries and slide past one another at transform boundaries. Graphic courtesy Robert J. Lillie (Oregon State University), modified from Lillie (2005).

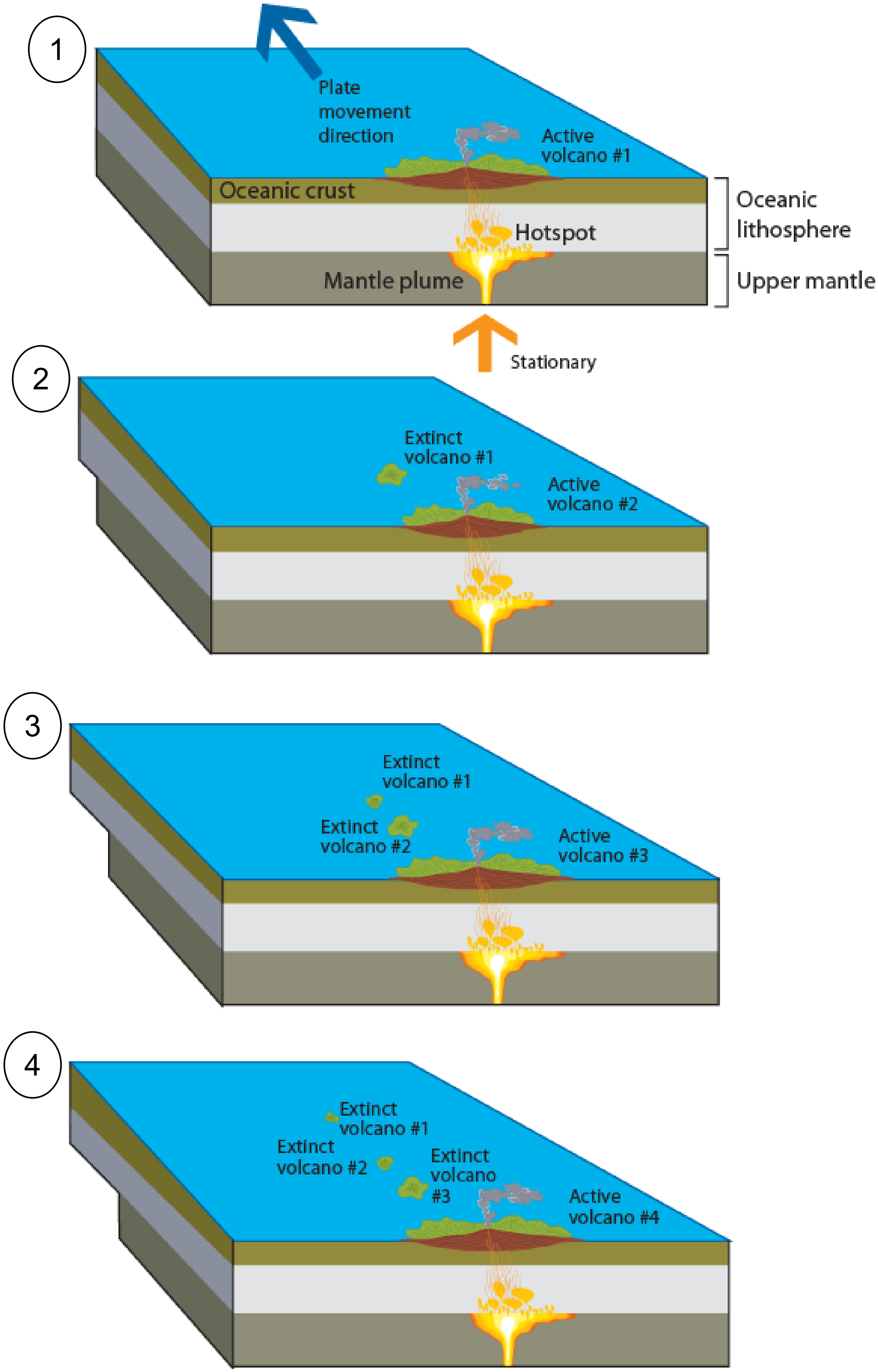

Figure 25. Evolution of a chain of islands over a stationary hotspot in Earth's crust. Graphic is by Trista L. Thornberry-Ehrlich (Colorado State University).

Figure 26. Location of hotspots across the South Pacific. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), adapted from figure 2 in Clouard and Bonneville (2001).

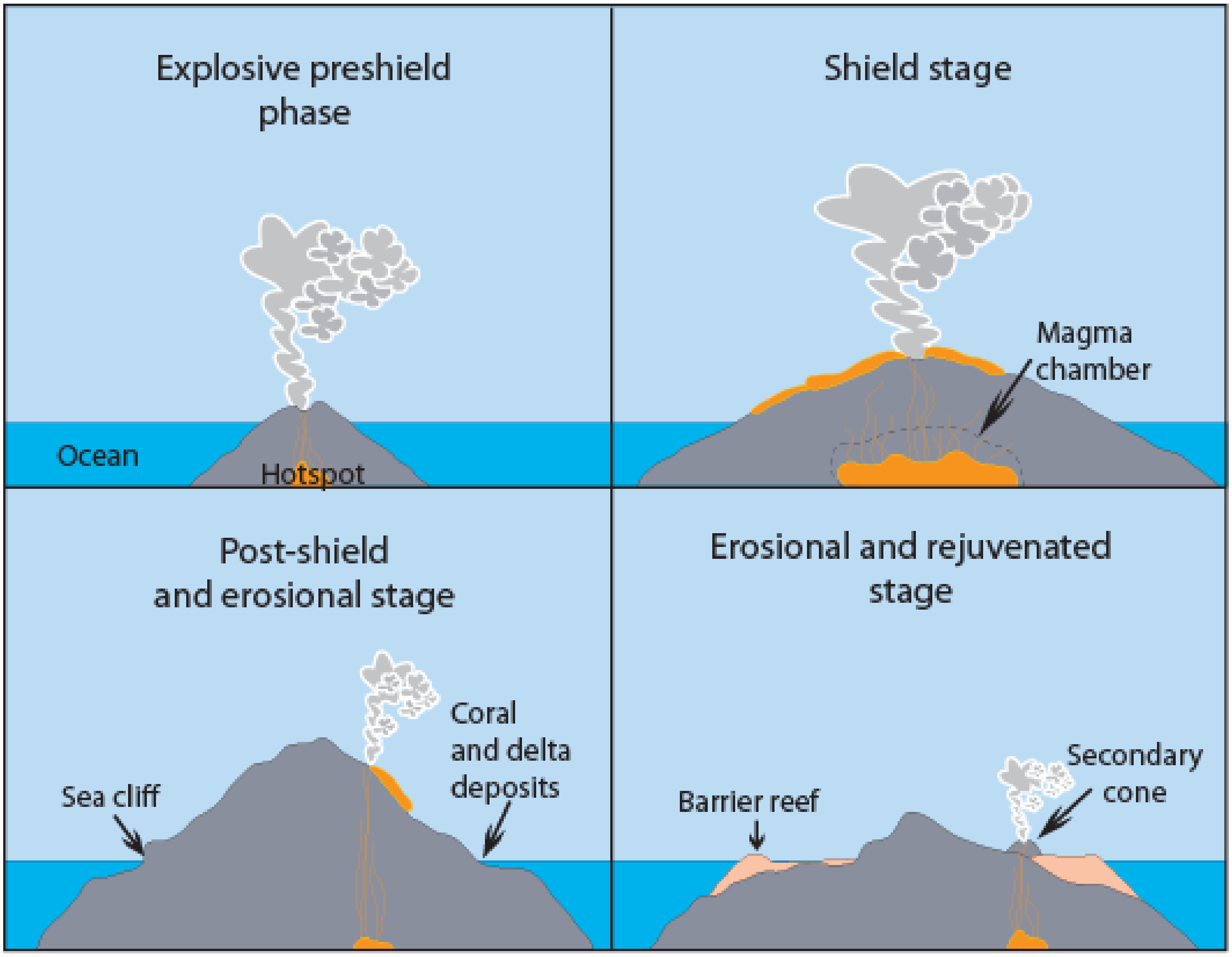

Figure 27. Simplified stages of Hawaiian hotspot island volcanism. After volcanism ceases, erosion and subsidence slowly reduce the island to a submarine stump. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), after Keating (1992, fig. 29).

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.

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

alluvium. Stream-deposited sediment.

aquifer. A rock or sedimentary unit that is sufficiently porous that it has a capacity 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 mafic igneous rock, commonly extrusive, composed chiefly of calcic plagioclase and clinopyroxene.

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

basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.

basinite. A very fine grained basalt.

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.

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 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.

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.

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

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 a vertically oriented plane.

crust. Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals (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.

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.

discordant. Having contacts that cut across or are set at an angle to the orientation of adjacent rocks.

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.

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

footwall. The mass of rock beneath a fault surface (also see "hanging wall").

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

glaze. A fired glassy surface on lava features.

hanging wall. The mass of rock above a fault surface (also see "footwall").

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.

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.

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 rocks—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 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.

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 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 due to 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 outmost shell of the Earth's structure, 50 to 100 km (31 to 62 miles) thick, that encompasses the crust and uppermost mantle.

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

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.

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

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. Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.

olivine. An olive-green orthorhombic 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.

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

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.

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.

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 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.

radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.

recharge. Infiltration processes that replenish ground water.

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).

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 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.

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.

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 with a shallowly 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.

tumulus. Dome or rise on the crust of a lava flow.

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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Appendix A: Geologic Map Graphic

The following page is a snapshot of the geologic map for Hawai'i Volcanoes National Park. For a poster-size PDF of this map or for digital geologic map data, please see the included CD or visit the Geologic Resources Inventory publications Web page (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Hawaiʻi Volcanoes National Park

Geologic Resources Inventory Report

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