National Park Service
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Natural Resource Program Center

Kalaupapa National Historical Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2010/243

THIS PAGE:
From 1866 until 1969, Hawaiian sufferers of Hansen's disease (leprosy) were forced to move to the isolated Kalaupapa Peninsula. This view is from the cemetery of St. Philomena church. The steep pali in the background furthered the isolation of the peninsula.

ON THE COVER:
The Kalaupapa Peninsula juts out from the base of the pali along the northern shore of Moloka'i. The pali are some of the tallest sea cliffs on Earth.

National Park Service photographs by T. Scott Williams (Kalaupapa National Historical Park).

Kalaupapa National Historical Park

Geologic Resources Inventory Report

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Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, Colorado 80225

September 2010

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

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Please cite this publication as:

Thornberry-Ehrlich, T. 2010. Kalaupapa National Historical Park: geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2010/243. National Park Service, Ft. Collins, Colorado.

NPS 491/105573, September 2010

Contents

List of Figures

Executive Summary

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

The Kalaupapa Peninsula juts off the northern shore of Moloka'i as a low-lying tongue of land at the base of some of the highest sea cliffs in the world. The site attracted early Hawaiians to settle there, and its isolation prompted the creation of the Moloka'i Island Hansen's disease (leprosy) settlement from 1886-1969. Through a cooperative effort with other agencies, Kalaupapa National Historical Park aims to provide for the preservation of the significant cultural, historic, educational, and scenic resources of the Kalaupapa Peninsula.

Geology is fundamental to the management of the scenic and natural resources of the park. Geology influences groundwater and surface water flow, and it contributes to climate, weather, hydrology, and topography, which in turn affect coral reefs and other submarine habitats. Geologic units and structures provide the framework for the craggy cliffs, eroded stream valleys, and low-lying coastal areas blanketed by lush vegetation. Geologic issues of particular significance for resource management at Kalaupapa National Historical Park include:

- Groundwater flow and streamflow. Freshwater on the island of Moloka'i is a valuable natural resource. At Kalaupapa National Historical Park, fresh water floats on salt water within the porous volcanic rock aquifer. Saltwater intrusion is a possibility near coastal areas and is among the factors limiting groundwater availability. Other limiting factors include anthropogenic reduction of stream discharge and lowering of aquifer water levels. Three large streams, Wai'ale'ia, Waihānau, and Waikolu, occupy valleys notched into the park's sea cliffs. Transbasin diversion within Waikolu Valley removes approximately 20% of the annual water yield from the watershed to supply freshwater to drier areas of south and west Moloka'i. Research needs exist to determine the effects this diversion is having on the hydrologic and biologic systems of the Waikolu Valley.
- Coral reef changes. The north shore of Moloka'i is subjected to high wave energy and coral reef development is limited to scattered coral colonies on basalt boulder habitat. Basalt and boulders are the dominant near-shore habitats. Reef communities are most extensive in a few sheltered areas around the peninsula and adjacent islets. Heavy wave action, flooding, hurricanes, sea level rise, climate change, and seismic events, in addition to anthropogenic land clearing, agricultural development, dredging, overfishing, and heavy tourism, disturb coral reef growth.
- Geologic hazards. Mass wasting formed precipitous sea cliffs at Kalauapapa and they are extremely prone to ongoing mass wasting events. This is due to several factors including steep slopes, erodable substrate, subsurface water movement, storm events, and frequent seismic activity. Due to its low-lying elevation, Kalaupapa is susceptible to inundation during tsunamis. Tsunami modeling factors in all seismic events, bathymetry, and storm conditions. Coastal erosion affects most of the shoreline at Kalaupapa causing beach loss, instability of sea cliffs, saltwater inundation, damage to shallow coral reefs, and increased sediment load. Seismicity is a concern throughout the Pacific basin. Earthquakes occur regularly on Moloka'i as a result of crustal stresses arising from areas of structural weakness beneath and near the island. Seismicity has caused fatalities, ground rupture, localized uplift or subsidence, liquefaction, ground settlement, extensive damage to roads, buildings and homes, and has triggered tsunamis.

The scenic and natural resources of the park are closely linked to its geologic features and processes. Ongoing mass wasting is responsible for the steep sea cliffs. Active slumps create new land along the coastline at the base of the cliffs. Volcanism created the Kalaupapa Peninsula and volcanic features such as Kauhākō Crater, lava tubes, and other cavernous features offer scientists intriguing terrestrial research analogs to lunar volcanic features and processes as well as hotspot development and history studies. The geology at Kalaupapa is a fundamental component to the ecosystem that hosts several endangered species.

Knowledge of the physical properties of the different geologic units mapped at Kalaupapa National Historical Park is vital to understanding and managing the varying ecosystems and natural resources throughout the park. The Map Unit Properties Table includes characteristics such as erosion resistance, suitability for infrastructure, geologic significance, recreation potential, and associated cultural and mineral resources for each mapped geologic unit. In addition to their physical properties, the rock units at Kalaupapa National Historical Park contain information related to volcanic island evolution and the geologic history of the Hawaiian-Emperor volcanic island and seamount chain. The glossary contains explanations of many technical terms used in this report and the Map Unit Properties Table.

Acknowledgements

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

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

Special thanks to: T. Scott Williams (Kalaupapa National Historical Park) for providing photographs of the park used throughout this report. Robert J. Lillie (Oregon State University) also provided graphics.

Credits

Author

Trista L. Thornberry-Ehrlich (Colorado State University)

Review

Curt Storlazzi (U.S. Geological Survey)
Jason Kenworthy (NPS Geologic Resources Division)

Editing

Jeffrey Matthews (Write Science Right)

Digital Geologic Data Production

Greg Mack (NPS Pacific West Region)
Ron Karpilo (Colorado State University)
Stephanie O'Meara (Colorado State University)

Digital Geologic Data Overview Layout Design

Phil Reiker (NPS Geologic Resources Division)

Introduction

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

Purpose of the Geologic Resources Inventory

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

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

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

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

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

Park Setting

Regional Information

Kalaupapa National Historical Park covers 4,362 hectares (10,779 acres) on the island of Molokaʻi. Of this area, Federal land is only 9.2 ha (22.88 ac) and park boundaries include approximately 809 ha (2,000 ac) of water area. The State of Hawaiʻi owns nearly all acreage within the park with some private ownership over approximately 28 ha (70 ac).

Along with the islands of Maui, Lānaʻi, and Kahoolawe, Molokaʻi is part of Maui County. Kalaupapa Peninsula is the exception, administered as Kalawao County. The island of Molokaʻi covers an area of about 673 sq km (260 sq mi) and is 78 km (48 mi) long and 16 km (10 mi) wide. It is the fifth largest of the seven main Hawaiian Islands. Molokaʻi lies east of Oʻahu, separated by the 40 km wide (25-mi) Kaiwi Channel. Molokaʻi is north of the island of Lānaʻi across the Kalohi Channel and is west of Maui separated by the Pailolo Channel.

Molokaʻi is geographically and ecologically split into two main areas. The lower western half is arid and lacking significant ground cover. This area is destructively overgrazed allowing invasion of non-native Kiawe trees. The higher plateau of the eastern half of the island contains lush rainforest receiving over 760 cm (300 in.) of precipitation each year. This area is host to an endemic flora and fauna that is extremely diverse.

The Kalaupapa Peninsula (also called the Makanalua Peninsula) appears tacked onto the northern shore of Molokaʻi as a low-lying tongue of land at the base of some of the highest sea cliffs in the world with a vertical drop of more than 610 m (2,000 ft). The highest cliffs on Molokaʻi stand 1,101 m (3,315 ft) above the Pacific Ocean. In 1972, the sea cliffs of the north shore of Molokaʻi were designated a national natural landmark because of their geological significance. The peninsula projects 4 km (2.4 mi) north of the cliffs and is 5 km (3 mi) wide at the base of the cliffs (fig. 1).

Cultural History and Establishment of Kalaupapa National Historical Park

Kalaupapa National Historical Park contains the location of the Molokaʻi Island Hansen's disease (leprosy) settlement set aside for isolation of leprosy patients from 1886-1969. It was the oldest site for sufferers of the disease in the United States enacted by an isolation law under King Kamehameha V. Among the more famous characters in the Kalaupapa story were Father Damien and Mother Marianne Cope. Today, approximately 30 former sufferers of leprosy continue to live in the colony that is now part of Kalaupapa National Historical Park. At its peak, nearly 1,200 men, women, and children were living there in exile.

This park also contains remnants of early Hawaiian settlements. Human occupation at Kalaupapa began as early as 1,000 years ago. The native population occupied much of what is now land contained within the park. The park is rich in archaeological resources in an excellent state of preservation. Remains include taro patch walls, stone terraces, heiau (Hawaiian temples), mollusk shells and debris, fortifications, small pavements, pens, a koa (fishing shrine), house sites, and a sacred lava tube cave. Much remains to be discovered, especially in the three large valleys within the park.

Kalaupapa National Historical Park provides habitats for rare and endangered species across a diverse landscape. Areas within the park have been divided into habitat zones including montane rainforest, lowland forest, lowland mesic forest, coastal shrubland, coastal dry mixed shrubland, coastal grassland, and sea cliffs. These distinctions are based on the vegetation patterns, which in turn reflect local differences in geological substrate, wind patterns, precipitation, and temperature.

Public Law 96-565 established Kalaupapa National Historical Park in 1980 "to provide for the preservation of the unique nationally and internationally significant cultural, historic, educational, and scenic resources of the Kalaupapa settlement on the island of Molokaʻi…" Administration of the park is a cooperative effort between the National Park Service, the State of Hawaiʻi, the Department of Health, the Department of Transportation, and the Department of Land and Natural Resources, the Roman Catholic Church in the State of Hawaiʻi, and the Hawaiʻi Conference Foundation. The latter two agencies own church buildings within the park. The National Park Service also leases more than 400 ha (1,000 ac) within the park held by the Department of Hawaiian Home Lands in trust for native Hawaiians.

Additional information may be found at http://www.nps.gov/kala, the Kalaupapa National Historical Park web site.

Geologic Setting

Molokaʻi is just one volcanic mass (composed of three volcanoes–East and West Molokaʻi, and Kauhākō Crater [Kalaupapa]) of many subaerial islands and submarine seamounts of the Hawaiian-Emperor volcanic chain. The chain stretches over 5,800 km (3,600 mi) from the Aleutian trench in the northwest Pacific basin to Lōʻihi seamount, which sits approximately 35 km (22 mi) off the coast of the Island of Hawaiʻi (fig. 2). The chain formed due to the movement of the Pacific tectonic plate over an essentially stationary mantle hotspot or plume. From southeast to northwest, the Hawaiian Islands increase in age, degree of erosion, and subsidence into the sea. A distinct bend in the chain where the Hawaiian Ridge (which includes the Hawaiian Islands at its southeast most extent) become the Emperor Seamounts represents an change in direction of plate motion millions of years ago.

Many islands are made of composites of more than one volcano. Two major, distinct volcanic masses comprise the island of Molokaʻi, referred to as East and West Molokaʻi. The Hoʻolehua Saddle bisects the island and is composed of eroded sediment of two large volcanic centers (fig. 3). It formed when lava flows from East Molokaʻi piled up against the flanks of West Molokaʻi and is mantled by easily eroded material as evidenced by deep gullies cutting through the landscape. East Molokaʻi has the highest peak on the island, Kamakou at 1,515 m (4,970 ft) in elevation. The East Molokaʻi volcano was once much larger. The northern half of the volcanic mass catastrophically collapsed along a 40 km (25 mi) long scarp, in effect halving the collapse caldera at its summit (fig. 4). This catastrophic event scattered debris northward across the Pacific Ocean bottom and generated a huge tsunami that inundated Molokaʻi and Lānaʻi 1.4 million years ago. This massive landslide created the famous cliffs (also called pali) of Molokaʻi. The southern flanks of the East Molokaʻi shield volcano slope gently to the sea floor. This style of catastrophic collapse along a zone of weakness is common to most, if not all of the Hawaiian Islands. The collapse occurs as each island moves off the hot spot. The crust cools and flexes downward, magmas that inflated the volcanic masses retreat. Heat flow is decreased resulting in significant accumulation of stress and generation of a pervasive weakness along a proto-rift system that is common to hotspot volcanic islands. The result is a catastrophic collapse, generation of significant cliffs and a general transformation of the islands from a round shape to a more rectilinear shape.

The landscape within Kalaupapa National Historical Park consists of the relatively flat peninsula with gently sloping flanks of the Kauhākō Crater, three steep-walled interior valleys, and the rim of the adjacent high cliffs. The 1,101-m (3,315-ft) steep cliffs or pali formed during the catastrophic landslide mentioned above and are some of the most dramatic geomorphic features of East Molokaʻi. The volcanic flows of the peninsula are younger than the rest of Molokaʻi having formed approximately 300,000 years ago. A small shield volcano, Puʻuʻuao, erupted during the late Pleistocene as a series of horizontal flows forming the Kalaupapa shield. The crater atop the younger volcano is approximately 0.5 km (0.3 mi) in diameter and reaches below sea level. It is filled with brackish water.

Over half of the park area is part of the older, East Molokaʻi volcanic mass. This part of the park contains the eroded Waiʻaleʻia, Waihānau, and Waikolu valleys that open into the north shore cliffs (fig. 4). Waikolu is the largest and easternmost valley within the park. It contains the park's only perennial stream. Transbasin diversion within this valley since 1961 has removed approximately 20% of the annual water yield from the watershed.

Figure 1. Photograph of the Kalaupapa Peninsula jutting off the north shore of Moloka'i at the base of the steep pali. Note the Kalaupapa settlement just left of center and the Kauhākō Crater to the right. The National Park Service photograph by T. Scott Williams (Kalaupapa National Historical Park).

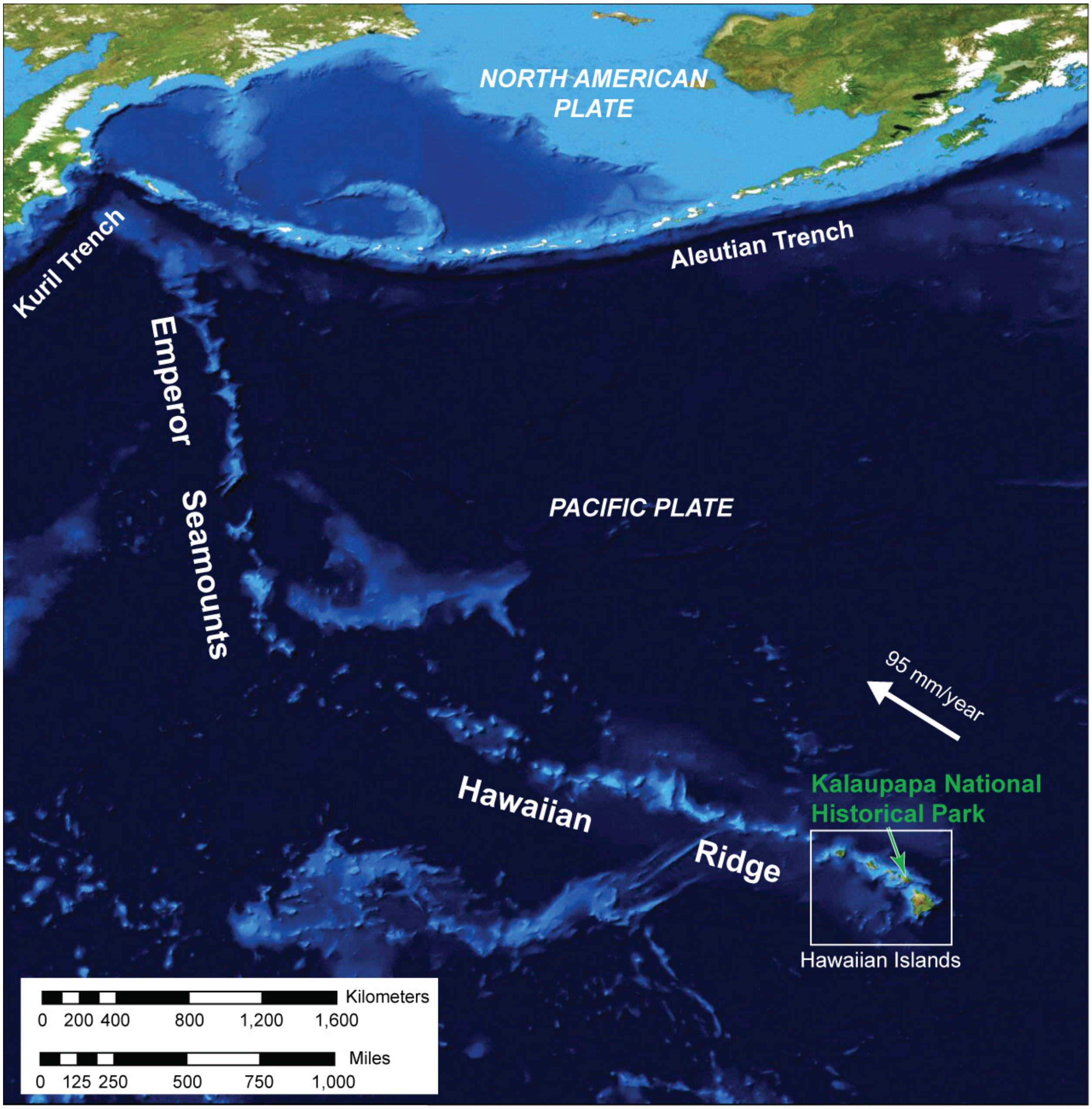


Figure 2. Bathymetric and aerial imagery of the northern Pacific Ocean basin, with deeper areas appearing dark blue to black and the Hawaiian-Emperor volcanic chain (and other relatively shallow areas) visible as lighter blue areas. The white box encloses the Hawaiian Islands. The white arrow indicates 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).

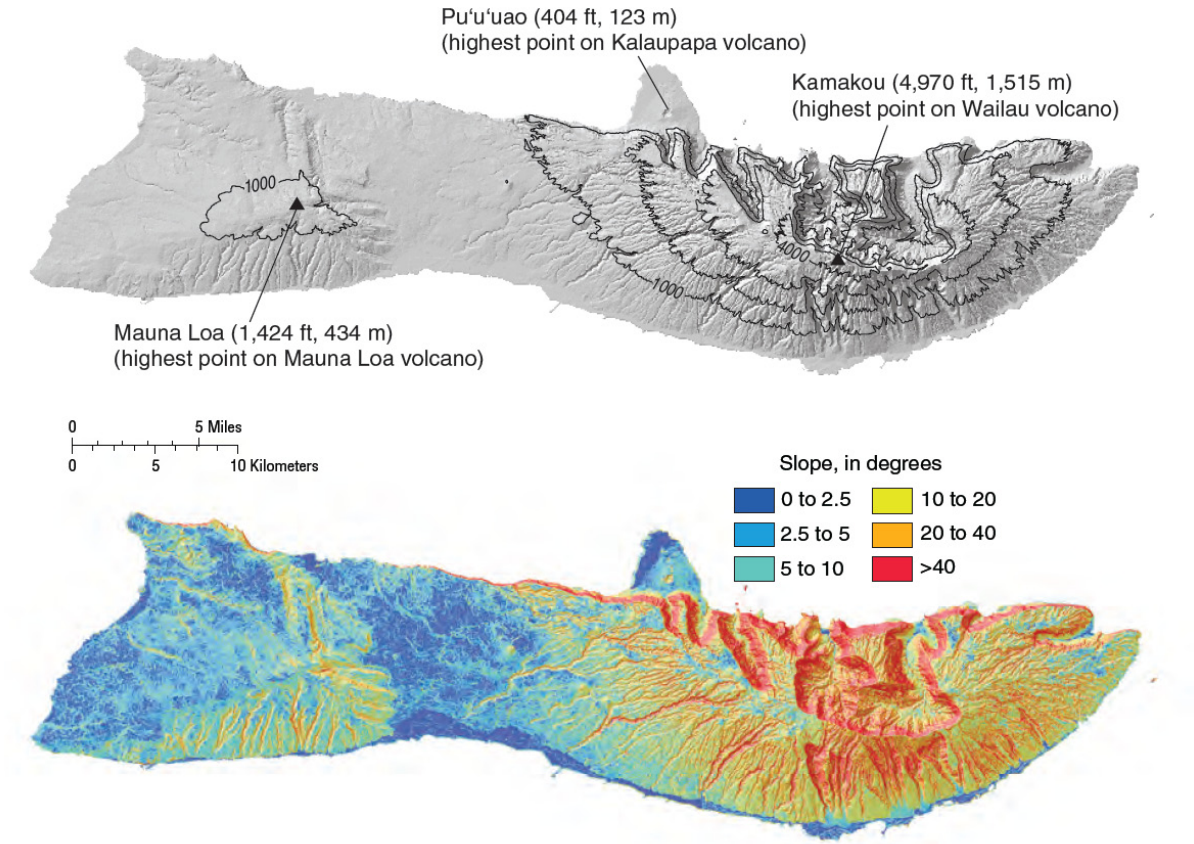


Figure 3. Maps showing the topography and steepness of slopes across the island of Moloka‘i. Note the presence of steep slopes and extreme topographic relief on the eastern half of the island. Kalaupapa is the tongue-shaped peninsula jutting off the north shore at the base of some of the highest sea cliffs in the world. The gently sloping Hoolehua saddle forms a transition between the East (Wailau) and West (Mauna Loa) Moloka‘i volcanoes. Graphic is figure 5 from Field et al. (2008).

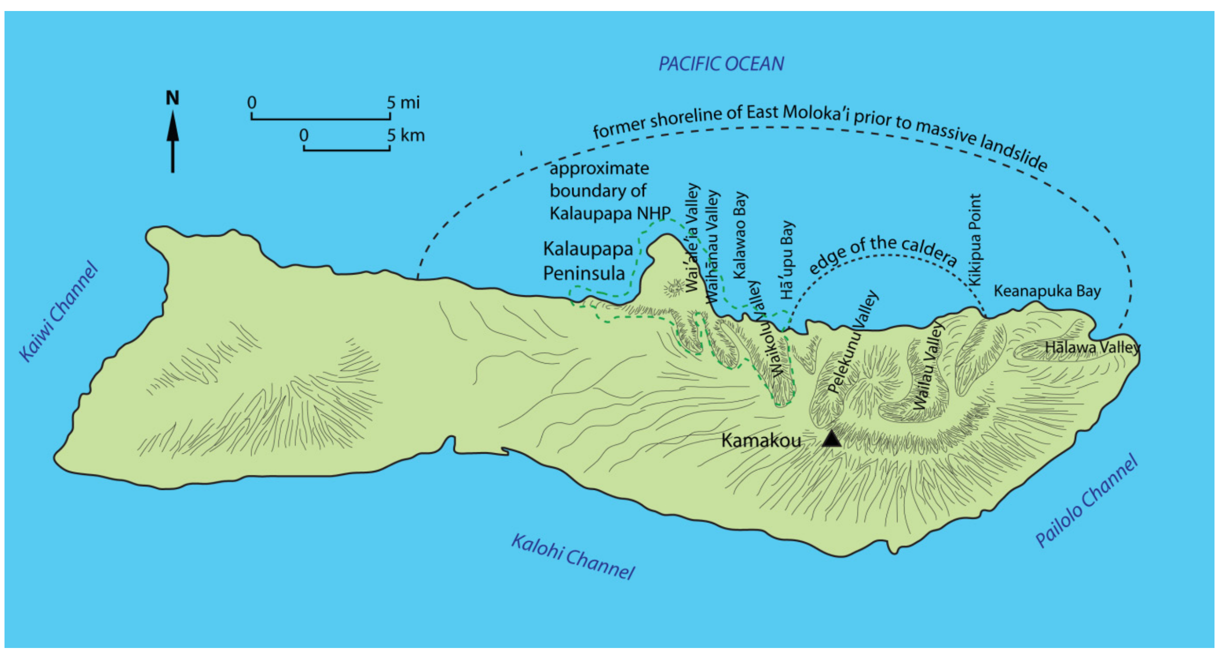


Figure 4. Physiographic map of Moloka‘i Island with features within and near Kalaupapa National Historical Park emphasized. Graphic is by Trista L. Thornberry-Ehrlich (Colorado State University) from information provided by figure 4 in National Park Service (2000).

Geologic Issues

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

The primary resource management emphasis at Kalaupapa National Historical Park is the preservation of the historic settlement structures. However, resource management objectives for the park also recognize the inherent natural resources. Natural resource management goals at Kalaupapa National Historical Park include conducting and encouraging research to (1) further define and gain insight into the park's native island ecosystem, (2) develop life history and ecologic understanding of plant and animal species facing extinction, and (3) develop management strategies for preserving endemic island ecosystems (National Park Service 2000). Hawai‘i is the only state in the U.S. 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, sea level rise, seasonal high waves, volcanic activity, and stream erosion (Richmond et al. 2001), combined with human impacts such as road and slope grading, stream diversion, infilling of rills, and development (Curt Storlazzi, geomorphologist, U.S. Geological Survey, written communication, March 2010), increases the importance of baseline information of the physical world underlying the tropical ecosystem. This section discusses the management of natural resources; focusing on the most prevalent geologic issues at the park.

Groundwater Flow

The availability of groundwater resources in a particular area of Moloka‘i depends on precipitation, age of the landscape, elevation, orographic effects, and geologic structure. Most of the island’s aquifers are unconfined and range from thin brackish water lenses to vertically extensive freshwater bodies (Rutherford and Kaye 2006). At Kalaupapa, fresh water floats on salt water within the porous volcanic rock mass (Kauahikaua 1983). Saltwater incursion is a possibility near coastal areas and is among the factors limiting groundwater availability at Kalaupapa National Historical Park. Other limiting factors include anthropogenic reduction of discharge to streams and lowering of aquifer or groundwater water levels (Rutherford and Kaye 2006).

Aquifer characteristics vary based on recharge rates and geologic features (especially rock porosity and permeability). Nearly all the aquifers on Moloka‘i are volcanic rock. The permeability of volcanic rock is highly variable and can change over small geographic areas depending on the mode of emplacement, degree of weathering, and overall thickness of the rock (Rutherford and Kaye 2006). At Kalaupapa, vertical electrical-resistivity soundings taken along the southern base of the peninsula indicate the estimated vertical thickness of fresh groundwater varies between 14 m and 95 m (46 to 312 ft) (Kauahikaua 1983). Kalaupapa is part of the wetter, Northeast Aquifer Sector and has a higher percentage of rainwater going to runoff and recharge rather than evaporation and transpiration such as in more arid areas (i.e. the West Aquifer Sector) (Field et al. 2008).

There are many demands made on the hydrologic system at Kalaupapa Park. Highly variable hydrologic processes can change over short intervals of space and time. The presence of a slightly less permeable vertical dike can impound freshwater, creating thicker aquifers locally (Kauahikaua 1983). Understanding the hydrogeologic system is vital to effectively manage water resources. Understanding groundwater flow is necessary to predict hydrologic response to inputs such as contaminants, as well as system response to diminished inflow. Failure to limit the amount of discharge loss may lead to loss of aquatic habitat, disruption of aquaculture practices, and saltwater incursion into fresh groundwater aquifers or lens-like zones (Rutherford and Kaye 2006).

The movement of contaminants in the aquifers can be modeled by monitoring the composition of inputs like precipitation and outputs like streamflow. Other sources of inputs include windblown materials, surface runoff, sewage, landfills, and fill dirt. Surface and groundwater flow is interconnected and contamination in one part of the system may be transferred to and detected in other parts of the hydrologic system. Streams (discussed in next subtopic) provide a measure of the chemical status of the watershed’s hydrologic system. Consistent measurement of these parameters is crucial to establish baseline values that can be used during monitoring efforts.

In addition to interpretive studies on the quantity, quality, and dynamics of groundwater, the U.S. Geological Survey (USGS) Water Resources Division, Hawai‘i District operates a network of monitoring stations that collect information on streamflow, suspended sediment, groundwater level, salinity, precipitation, and evapotranspiration (Rutherford and Kaye 2006). The main contact office is in Honolulu.

Streamflow

Groundwater and surface stream flow are interconnected at Kalaupapa National Historical Park. Most watersheds on Molokaʻi are typically small with steep slopes and little to no channel storage (Richmond et al. 2001). Because of these limitations, many streams are ephemeral, only flowing after precipitation events with water levels rising quickly during storms. This, in turn, causes damaging flooding in coastal areas as well as transport and discharge of upland sediment to coastal areas (Fletcher et al. 2002; Rutherford and Kaye 2006).

Kalaupapa's position on the windward, north facing coast of the island assures a relatively consistent supply of precipitation. Throughout Hawaiʻi, watersheds on the windward sides of islands tend to have perennial streams sustained by groundwater input, whereas the western sides are relatively arid (Fletcher et al. 2002; Rutherford and Kaye 2006). Flooding data are sparse for Molokaʻi, but low-lying coastal plains where streams empty to the sea are susceptible to damage from stream flooding, and there is significant runoff to the east of Pūwāhi (Fletcher et al. 2002). At Kalaupapa National Historical Park, three large streams occupy valleys notched into the sea cliffs: Waiʻaleʻia; Waihānau; and Waikolu streams. The easternmost Waikolu Stream is the largest valley and contains the park's only perennial stream. These deep valleys channelize floodwaters during high precipitation events (fig. 5) (Richmond et al. 2001).

Transbasin diversion within Waikolu Valley (since 1961) removes approximately 20% of the annual water yield from the watershed. Diverted water from Waikolu supplies freshwater to drier areas of Molokaʻi. Study needs exist for comparing the hydrologic and biologic attributes of the Waikolu watershed with the neighboring and, as yet, undiverted and pristine Pelekunu watershed. According to the Resource Management Plan for Kalaupapa National Historical Park, such a study could indicate the nature and extent of any adverse effects the diversions are having on riparian and aquatic habitats in Waikolu Valley (National Park Service 2000). Previous studies by the U.S. Geological Survey (USGS), Hawaiʻi's Department of Land and Natural Resources (DLNR), and others have included a basic inventory of the hydrology network for Molokaʻi (1970), as well as some groundwater (1983, 1991, 1992) and surface water studies (1985, 1986, 1990, 1995), and a park specific watershed study (1982, 1996) (Rutherford and Kaye 2006). Expansion of this research for incorporation into a park-wide monitoring plan would provide a useful resource management tool.

Kalaupapa National Historical Park is now part of the East Molokaʻi Watershed Partnership with the purpose of cooperatively managing natural ecosystems with a focus on preserving native ecosystems and on watershed conservation. The Watershed Partnership is composed of landowners, government agencies, and non-government organizations (Rutherford and Kaye 2006). The NPS Water Resources Division (Fort Collins, Colorado) is an additional source of technical assistance.

Coral Reef Changes

One of the largest coral reef complexes in Hawaiʻi stretches along the southern shore of Molokaʻi where the island provides a sheltered environment for the reef to thrive. The north shore is battered by large open-ocean swells and coral reef development is more limited (Storlazzi et al. 2002; Barnhardt et al. 2005). The predominant near-shore habitat at Kalaupapa is a reef community (Eichenlaub 2001). According to the park website, coral reef communities are extensive in a few sheltered areas around the peninsula and adjacent islets, but primarily consist of scattered coral colonies on basalt boulder habitat (National Park Service 2010). The website also maintains links to inventories of marine life for the park. Field et al. (2008) provides a comprehensive look at the processes and factors impacting Molokaʻi's coral reefs with special attention to anthropogenic influences. Land-derived silt, washed from neighboring slopes, threatens the health of the island's reef by blocking light and choking reef organisms (Field et al. 2008).

Coral reefs are host to amazing marine biodiversity. Coral reef ecosystems are also geologically productive, building islands such as atolls. The erosion of coral reefs by wave action can create sand deposits and beaches. As stated above, typical reef growth within the coastal areas of Hawaiian Islands consists of a thin, 1 to 2 m (3 to 6 ft) veneer of coral-algal growth. Reefs exist on either volcanic rock platforms or Pleistocene-age limestones (Richmond et al. 2001). Natural processes such as heavy wave action, flooding, hurricanes, sea level rise, sedimentation, climate change, and seismic events disturb coral reef growth (Richmond et al. 2001; Rutherford and Kaye 2006; Presto et al. 2006). Human practices of land clearing, agricultural development, dredging, overfishing, and tourism negatively impact reefs on Molokaʻi (Cochran et al. 2002). When natural reef-building processes are disturbed by human activities (such as increased sedimentation due to deforestation) or extreme natural conditions (e.g. high wave energy), erosion of the reef will dominate and the reef ecosystem will deteriorate (Fletcher et al. 2002; Rutherford and Kaye 2006; Storlazzi et al. 2005).

Kalaupapa National Historical Park identified research needs of 1) intertidal mapping (suggested contact at U.S. Geological Survey [Santa Cruz, California] is Michael Field), 2) side scan sonar tow-board surveys and collected imagery for a high-resolution habitat classification of coral reefs, and 3) bathymetric and benthic habitat mapping (see Cochran-Marquez 2005) (GRI scoping meeting notes 2003). Seismic-reflection profiling can yield a wealth of information about coral reef development and provides an alternative to coring which can be damaging to a reef, labor intensive, and spatially limited (Barnhardt et al. 2005). Offshore sediment traps could be used to evaluate the frequency, cause, and relative intensity of sediment mobility and re-suspension along fringing coral reefs and to identify contributions of clastic and carbonate sediments, and the impact storm-derived sediment may have on coral reef development (Bothner et al. 2006). Storlazzi et al. (2005)

presented a model to help understand the physical controls on reef morphology and coral species distribution for the fringing reef off southern Moloka‘i. Their model calculates wave-induced hydrodynamic forces on corals of a specific form and mechanical strength and predicts coral distribution patterns taking into account wave model output for different oceanographic conditions. These same types of models, quantifying the interplay between wave-induced forces and coral species distribution (Storlazzi et al. 2005), could be implemented for Kalaupapa National Historical Park coral reef habitats. They would be especially useful to predict the impact of severe but infrequent storms or to determine coral reef degradation caused by natural forces versus anthropogenic changes.

Geologic Hazards

Many natural phenomena pose threats to coastal and near-coastal areas of the Hawaiian Islands. Among these hazards are mass wasting, coastal erosion, storm-induced inundation, tsunami inundation, volcanic activity and seismic activity. Local slopes and geologic settings must be taken into account to accurately determine hazard potential for a specific area such as Kalaupapa National Historical Park (Richmond et al. 2001). Important tools in hazard assessment include past records of events, magnitudes, and occurrence from historic records in addition to accurate inventorying and regular monitoring of current conditions. Fletcher et al. (2002) produced a hazards map for the Kalaupapa Peninsula (fig. 7).

Mass Wasting

Erosional processes involve the denudation of the landscape by either chemical or mechanical means. Rock and unconsolidated regolith are worn away or removed by wind, water, animals including man. Throughout Hawai‘i, anthropogenic changes including non-indigenous species introduction (invasive plants and feral ungulates for example), urban development, and placement of coastal structures disturb the natural system. These structures can increase erosion locally by disturbing the groundcover (Fletcher et al. 2002). Because Kalaupapa National Historical Park sits on the windward side of Moloka‘i, water is the primary erosive agent (Rutherford and Kaye 2006). Water in streams scours stream valleys carrying sediment toward the coast. When water diversion systems and other human structures interfere, this can result in changes to turbidity, deposition cycles, and reduced productivity of the riparian and aquatic (both freshwater and marine) environment. Changes to the hydrologic system can also trigger mass wasting.

The precipitous sea cliffs (pali) along the southern edge of the Kalauapapa Peninsula are extremely prone to mass wasting events. This is due to several factors including the inherent nature of their formation (the Wailau slide ca. 1.5-1.4 million years ago), subsurface water movement, storm events, and frequent seismic activity (Rutherford and Kaye 2006). In May of 1999, a major landslide occurred just east of the Pelekunu Valley. This slide originated near the top of the 760-m (2,500-ft) high sea cliffs and contained enough rock and debris to reach the shoreline and create 2.4 ha (6 ac) of land (National Park Service 2000). Events of this nature and even smaller landslides and slumps can bury habitat, increase erosion rates locally, and disrupt the hydrologic system (Rutherford and Kaye 2006).

To date, relatively little information on erosion and sediment transport is available for the watersheds in Kalaupapa National Historical Park. Similarly, no modeling of areas at high risk for erosion and mass wasting is known for the park area. Such models would incorporate ground cover types (soil and regolith), vegetation, geologic units and properties (Appendix A), slope and aspect, and precipitation (especially rate) to predict areas prone to mass wasting. Wieczorek and Snyder (2009) have suggested methods to monitor slope movements and mass wasting.

Tsunamis

The threat of inundation and destruction by tsunamis arises from both local and distant sources (e.g. the Aleutian trench of Alaska and the South American subduction zone). This problem is systemic in the Pacific Basin. Hawai‘i, situated in the middle of the Pacific Ocean, has been struck by more tsunamis than any other place on earth (Dudley and Lee 1998). Since record keeping began in 1837, 33 tsunamis have struck Hawai‘i with varying degrees of severity. At least four of these were locally generated from seismicity beneath the islands. These locally generated tsunamis are especially dangerous due to the limited warning time available (Richmond et al. 2001). Following a magnitude-7.1 earthquake in the Aleutian trench (Alaska) on April 1, 1946, a tsunami traveled across the Pacific basin and struck the Hawaiian Islands causing 159 fatalities (Pacific Disaster Center 2008). On May 23, 1960, a magnitude 8.3 earthquake in Chile caused a 11 m (35 ft) tsunami that caused serious damage to Hilo, Hawai‘i, and 61 deaths (Pacific Disaster Center 2008).

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

According to the 2007 Tsunami Warning Center operations manual (after the operations manual by the PTWC), a local tsunami warning is issued for any earthquake in the State of Hawai‘i with moment magnitude (Mw) greater than 6.8. Hawai‘i State Civil Defense will sound the tsunami sirens. Initially only the county in which the earthquake occurred and bordering counties are placed in a warning. If an earthquake has a Mw > 7.5, the entire state is placed in a warning.

The National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory (PMEL) has created a tsunami hazard assessment model, which is being used to create and update identified inundation zones. Tsunami modeling must factor in seismic events, which can original locally or distant, in addition to bathymetry, storm, wind and rain conditions and especially coastal terrain (Rutherford and Kaye 2006). The University of Hawai‘i School of Earth Science and Technology, Institute of Geophysics also developed a model that may be more applicable to tsunamis caused by local seismic events (http://www.soest.hawaii.edu/).

A 1968 study of potential tsunami inundation zones identified areas across Moloka‘i susceptible to flooding. Since 1812, 8 tsunamis have had significant damaging effects on either Moloka‘i or Lāna‘i indicating a chance that another damaging tsunami is possible to probable in the relatively near future (Fletcher et al. 2002). The low-lying Kalaupapa Pensinula would certainly be at risk for serious damage should a tsunami strike the northern side of Moloka‘i and the impacts can vary greatly over short distances. During a tsunami in 1946 (triggered by seismicity in the Aleutian Islands), the run-up height on the west side of Kalaupapa Peninsula was recorded at 2 m (6 ft) whereas on the east side it was 16 m (54 ft) (Fletcher et al. 2002). In addition to loss of life and threats to infrastructure, tsunamis can cause increased erosion along the coastline, damage reefs and inundate near shore habitats with saltwater (Rutherford and Kaye 2006). Since the 1960s, widespread development along the Hawaiian shoreline ignores the potential danger of inundation by tsunami (Richmond et al. 2001).

Coastal Erosion

Kalaupapa National Historical Park includes 13-14 km (8-9 mi) of coastline. Coastal slope determines the amount of land exposed to erosion (Richmond et al. 2001). The coastline includes gently sloping sand covered lava benches, carbonate beaches, low-lying rocky shorelines, steep rocky cliffs of differing heights, and stream mouths (figs. 6–9) (Eichenlaub 2001). Locally, coral reefs, embayments, lagoons, coastal wetlands, streams, and various developments modify these shorelines (Richmond et al. 2001). Cliffs front the shoreline west of Pūwāhi. The shoreline to the east it is low and rocky. Between Kalaupapa and Ka Lae‘ā, a fringing reef buffers the rocky coast and between Kalaemau (Kae Lae Mau on older maps) and Kaupikiawa, the shore is rocky and windblown (Fletcher et al. 2002).

Erosion of the coast may cause beach loss, instability of sea cliffs, inundation, damage to shallow coral reefs, and increased suspended sediment load. Approximate average erosion rates in Hawai‘i are 15-30 cm/yr (0.5-1 ft/yr) (Richmond et al. 2001). Many factors are involved in coastal evolution and susceptibility to erosion including tidal range, wave height, coastal slope, historic rates of shoreline change, geomorphology, and relative sea level change. Tidal range and wave height are linked to inundation hazards. Northeast tradewind swell, North Pacific swell, Kona storm swell, and southern swell are sources of waves that influence the Moloka‘i coastline (Storlazzi et al. 2002; Storlazzi et al. 2005). Of these, the North Pacific swell, generated by strong winter storms, generates the highest wave heights between 3 and 8 m (9 and 25 ft) (Storlazzi et al. 2005). The north coast of Moloka‘i receives the full force of these waves, sheltering other areas of the island and provides a wave shadow for the northern coast of Lāna‘i and western coast of Maui (Storlazzi et al. 2002).

When deep-water ocean swells encounter a shallow area such as an island margin or seamount, they rise because their crests pile up resulting from wave base encountering the rising ocean bottom. In the Hawaiian Islands, this effect is exacerbated because the contact between deep water and the shallow margins is especially abrupt. Surface waves can grow very tall, rapidly and over a short distance (City and County of Honolulu 2003). The swell effects vary seasonally. North Pacific swell deliver the highest waves annually with moderate-to long-wave periods (10-18 seconds). The swells are due to the high intensity and relative proximity of sub-polar and mid-latitude storms in the north Pacific basin (City and County of Honolulu 2003). Sudden high waves and seasonal swells are among the most consistent and predictable coastal hazards in Hawai‘i (Richmond et al. 2001).

Among the other factors involved in coastal evolution and vulnerability to erosion is coastal slope 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 sea level changes correspond to global sea level fluctuations and local tectonic uplift and subsidence. The weight of material added through volcanic eruptions (volcanic loading) depresses the lithosphere causing relative sea level rise. This is accentuated by cooling of the volcanic pile, withdrawal and/or cooling and crystallization of hot and buoyant magma which together result in thermal subsidence (relative lowering of land). At Kalaupapa National Historical Park, a 1998 study concerning the impacts of sand mining on dunes in the park showed that each island has a localized rate of relative sea level rise due to its isostatic response (Rutherford and Kaye 2006). On average, the rate of relative sea level rise is 3.9 mm/yr (1.5 in/decade) for the Island of Hawai‘i and the loading effect lessens with distance from the active volcanism. For Moloka‘i, the relative rate of sea level rise is less than 0.97 mm/yr (0.9 in/decade) recorded for Maui (Richmond et al. 2001).

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

Nearly one-quarter of the beaches throughout Hawai'i have been significantly degraded over the last 50 years (Richmond et al. 2001). Beach loss has been identified on Moloka'i. The causes of beach loss are generally not well understood or quantified. Possible causes include reduced sediment supply, major storms, and anthropogenic effects from shoreline armoring structures and other development (Richmond et al. 2001; Rutherford and Kaye 2006). Shoreline structures often exacerbate coastal erosion by changing a condition of shoreline erosion into one of beach loss (Richmond et al. 2001). Coastal stream flooding from intense rainfall events, causing beach loss or narrowing, are nearly annual events throughout Hawai'i (Richmond et al. 2001).

Beach areas are limited on Moloka'i. Small perched carbonate beaches and narrow dunes exist on the west side of the peninsula between Kaleaupapa and Ka Laea and on the east side just south of Lae Hoolehua. White carbonate sands exist at Papaloa, Kahili, and Hoolehua. Black Sands Beach at Awahua has a large terrestrial component to the sand (Fletcher et al. 2002). Most Moloka'i beach sand contains mixtures of volcaniclasts and bioclastic carbonate grains derived from corals, mollusks, and other carbonate-producing organisms. Because typical reef growth within the coastal areas of the Hawaiian Islands consists of a thin, 1 to 2 m (3 to 6 ft) veneer of coral-algal growth, source material for beach sands is relatively limited (Richmond et al. 2001). Sediment collection along the southern Moloka'i coast demonstrated that sediment trapping increases over 1000 times (compared with non-storm periods) during storm periods with high rainfall, floods, and high waves (Bothner et al. 2006).

The USGS Coastal and Marine Geology Program (http://walrus.wr.usgs.gov/index.html) has collected data for Moloka'i including aerial photography, multibeam data (available online), dual frequency acoustic data and digital video transects of the island (such as Gibbs et al. 2005), as well as high resolution (4-6 m, 13-20 ft) Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) data (suggested contact at U.S. Geological Survey [Santa Cruz, California] is Michael Field) (GRI scoping meeting notes 2003). Much of this previous data collection is focused on the south side of Moloka'i. Additional work for the north shore would be most useful to resource management at Kalaupapa National Historical Park. Taken together these data represent a very powerful and precise baseline for documenting and quantifying additional change. A complete set of aerial videography of the Hawaiian coastal zone, collected from an elevation of 90-150 m (300-500 ft) (Richmond et al. 2001) would be useful to inventory current conditions. Bush and Young (2009) have suggested methodology for monitoring coastal features and processes.

Seismicity

Hawai'i is the most seismically active place in the U.S. making earthquake events a significant geologic hazard (fig. 10) (Richmond et al. 2001). While not as frequent as the seismic events related to active volcanism on other Hawaiian islands, earthquakes do occur on Moloka'i as a result of relative hotspot migration away from the island, thermal subsidence and crustal flexure (deformation). These earthquakes occur locally due to areas of structural weakness beneath the island. Throughout Hawai'i over the last 150 years, several strong earthquakes (magnitude 6 to 8) caused fatalities, extensive damage to roads, buildings and homes, and triggered tsunamis. Notable local areas of seismic activity occur between Moloka'i and Lāna'i, along a fracture zone near Moloka'i (the Moloka'i seismic zone or fracture zone), and off the north coast of Moloka'i (Fletcher et al. 2002; Rutherford and Kaye 2006). The Moloka'i seismic zone experienced a roughly magnitude 7 quake in 1871 near Lāna'i (Borg 2005).

Seismic shaking can cause ground rupture, localized uplift or subsidence, liquefaction, ground settlement, and disruption of groundwater flow and surface drainage patterns. Even moderate earthquakes can trigger landslides, rockfalls, mudflows, or other mass wasting in addition to damaging buildings.

The USGS Hawaiian Volcano Observatory (HVO), USGS National Strong-Motion Project, and the NOAA Pacific Tsunami Warning Center operate seismographic monitoring networks in the state of Hawai`i. Seismic monitoring at HVO began in 1912 and data from more than 60 remote stations are continuously monitored in real time by HVO. This system focuses primarily on the Island of Hawai'i. For other areas, the most comprehensive data collection on earthquake epicenter locations including attributes such as date, depth and magnitude is available from the USGS National Earthquake Information Center (http://earthquake.usgs.gov/). Braile (2009) also suggested methodology for seismic monitoring.

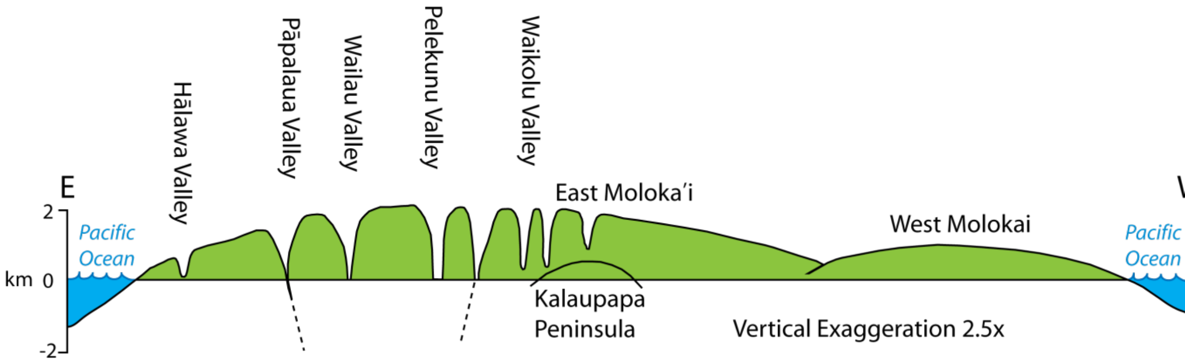


Figure 5. An east-west profile of the deeply notched valleys of the northern (windward) pali on Moloka'i in the vicinity of Kalaupapa National Historical Park. Graphic is by Trista L. Thornberry-Ehrlich (Colorado State University) adapted from figure 1 in Holcomb (1985).

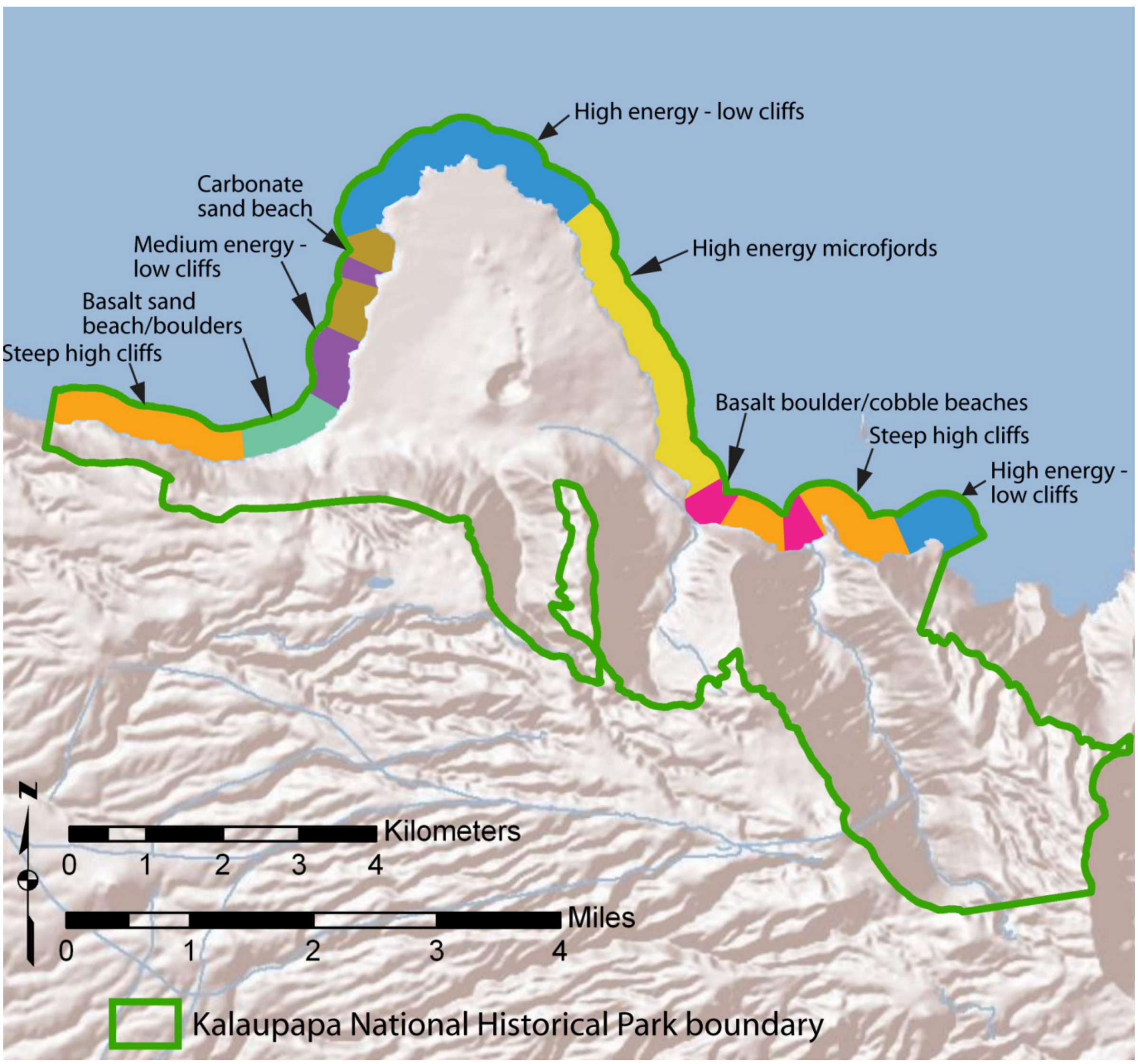
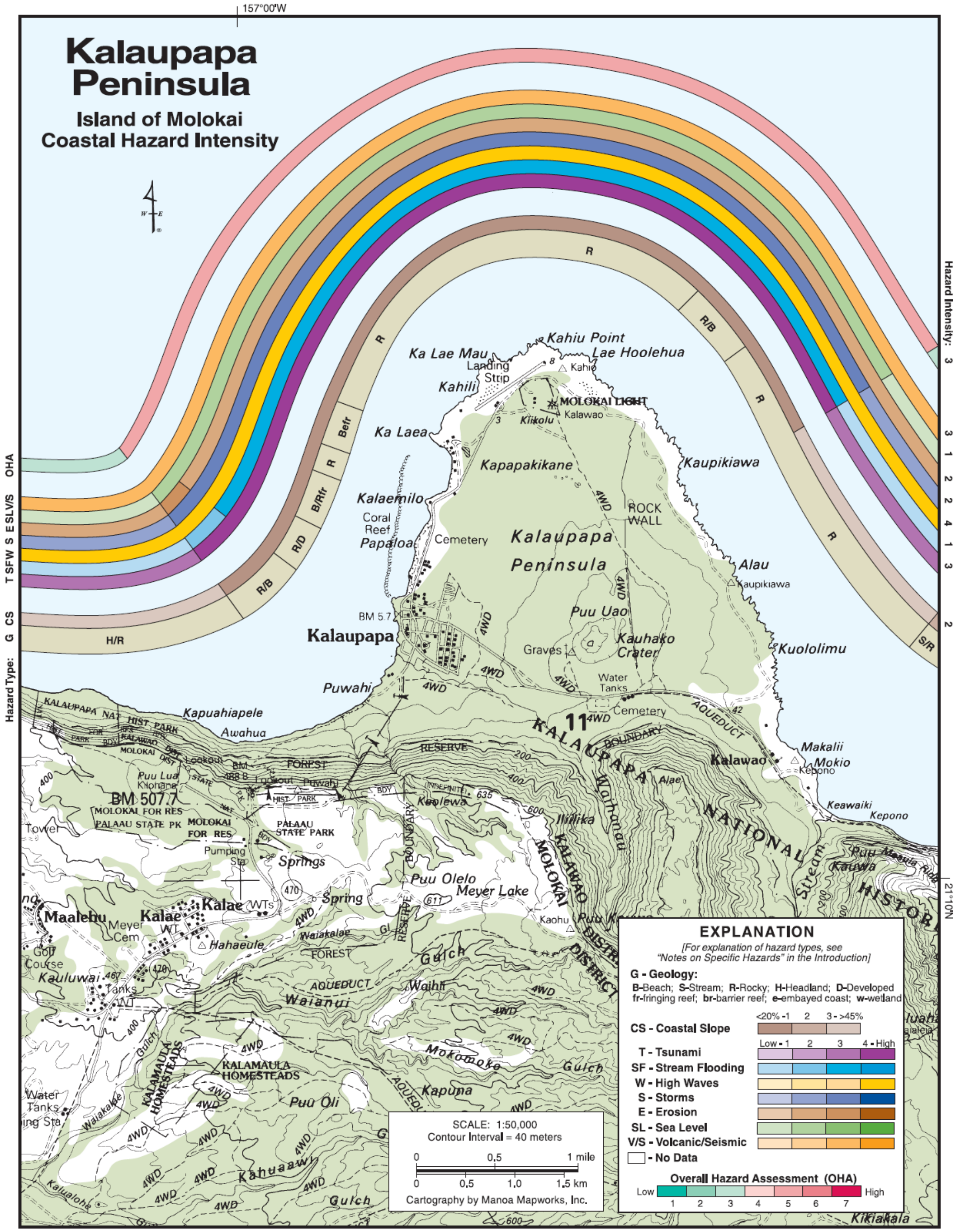


Figure 6. Map showing the shoreline geomorphology at Kalaupapa National Historical Park. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Eichenlaub (2001). Base shaded relief compiled from ESRI Arc Image Service.



Base Credit: USGS 1:50,000 Western Molokai, Hawaii 5520 II W733 Edition 1-DMA and USGS 1:50,000 Eastern Molokai, Hawaii 5620 III W733 Edition 1-DMA

Figure 7. Hazard intensity map for Kalaupapa Peninsula. Note the high hazard potential from tsunamis, sea level rise, high waves, stream flooding, storms, erosion, and seismicity. The overall hazard assessment is a 5 on a scale of 1 to 7. U.S. Geological Survey graphic from Fletcher et al. (2002).

Figure 8. Photograph of lava bedrock benches (the most common benthic substrate) at Kalaupapa National Historical Park. National Park Service photograph by T. Scott Williams (Kalaupapa National Historical Park).

Figure 9. Photograph of beach west of Kalaupapa. Sandy beaches are uncommon on the Kalaupapa peninsula. National Park Service photograph by T. Scott Williams (Kalaupapa National Historical Park).

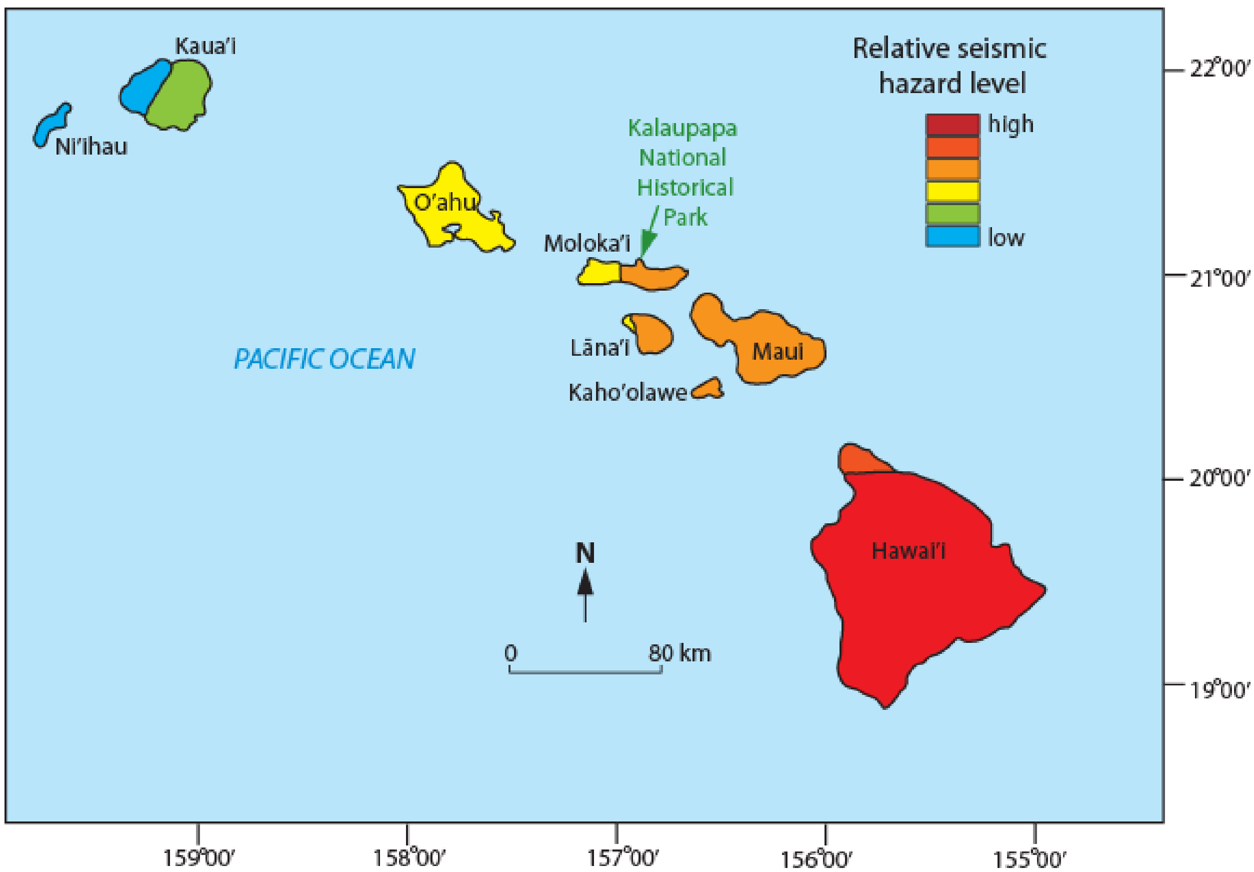


Figure 10. Map showing earthquake-hazard zones for the major Hawaiian Islands. Note the location of Kalaupapa National Historical Park. Graphic was modified from Klein et al. (2000) by Rutherford and Kaye (2006) and redrafted by Trista L. Thornberry-Ehrlich (Colorado State University).

Geologic Features and Processes

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

Ancient and Modern Landslides

When volcanic activity of the East Molokaʻi volcano ceased some 1.5 million years ago, the mass resembled typical Hawaiian shield volcanoes capped by a collapse caldera with gently sloping flanks descending to the shoreline. In cross section, these volcanoes look like the top half of an ellipse split along its major axis composed of numerous overlapping basalt flows (see layers in fig. 12) (Holcomb 1985). At this time, West and East Molokaʻi stood 1.6 and 3 km (1 and 1.9 mi) above sea level, respectively (Clague and Moore 2002). This normal shape was altered when the northern third of the volcanic mass collapsed catastrophically and slid into the sea some 1.4-1.5 million years ago (fig. 11). The remnants of this collapse include the steep sea cliffs (pali) that flank the northeast shoreline of Molokaʻi. The average slope for the highest portion of the pali is approximately 55 degrees (Clague and Moore 2002). In certain areas, these cliffs rise up to 910 m (3,000 ft) above the Pacific Ocean. They are among the tallest in the world (fig. 12).

The collapse of the northeast Molokaʻi Volcano is now referred to as the Wailau slide (Moore and Clague 2002). Approximately 2,500 cu. km (600 cu. mi) of island failed along a 40-km (25-mi) landslide. The momentum of the slide was such that it moved out underwater as far as 190 km(120 mi), the last 130 km (80 mi) of which was slightly uphill. The slide climbed some 275 m (900 ft) up from the Hawaiian Deep (the crustal depression caused by volcanic loading) (National Park Service 2000; Moore and Clague 2002). The effects of this sudden landslide were far-reaching. Displacement of so much volcanic mass into the ocean generated a 610-m (2,000-ft) tsunami that inundated Molokaʻi and Lānaʻi.

Earlier studies debated the landslide interpretation for the formation of Molokaʻi's pali. Alternate theories presented the idea that the cliffs were merely erosional features carved by the trade wind driven Pacific Ocean based on the presence of intrusions, breccias, and ponded lava flows near the present center of East Molokaʻi (Holcomb 1985). Recent studies by the U.S. Geological Survey confirmed the presence of a major submarine landslide off the north coast of Molokaʻi. Sidescreen-sonar system (Geological LOng-Range Inclined Asdic or GLORIA) surveys covered a 1,400-km (870-mi) long reach of the Hawaiian Ridge. Remarkably, the survey revealed mass movement deposits along roughly one-half of the flanks of the Hawaiian Ridge covering more than 98,000 sq. km (38,000 sq. mi) or more than five times the subaerial exposure of all the major islands (National Park Service 2000; Moore and Clague 2002). These surveys show these major landslide events are relatively common for the Hawaiian volcanic masses throughout geologic history. The average rate is one about every 350,000 years, but this can vary broadly (Moore and Clague 2002). Such massive slope failures could occur again. Active shield or postshield volcanism (including dikes intruding along rift zones) and high precipitation are two components thought to trigger giant Hawaiian landslides (Clague and Moore 2002). The shields deform in response to gravitational and magmatic stresses (Holcomb 1985). The Kalaupapa peninsula was built by a volcano younger than the shield volcano as detailed in the "Volcanic Features and Processes" section (fig. 13) (Moore and Clague 2002).

Modern slope failures in Hawaiʻi are natural geomorphological processes continually sculpturing the landscape. Slumps and debris avalanches are the most common forms of slope failure on the islands today. Slumps tend to be slow moving and larger, up to 40 km (25 mi) wide and more than 10 km (6 mi) thick. They tend to display transverse ridges and steep toes and move intermittently. In contrast to the slow slumps, debris avalanches quickly move downslope in single pulses. They are longer (more than 225 km, 140 mi) and thinner at 0.5 to 2 km (0.3-1.25 mi). The catastrophic Wailau slide is an extreme example of a debris avalanche. They typically have well-defined amphitheatre headlands and hummocky terrain in their lower reaches formed by smaller landslide blocks (Moore and Clague 2002). Understanding these older, weathered features lends understanding to features currently developing on the Island of Hawaiʻi such as the Hilina slump (mentioned in relation to Hawaiʻi Volcanoes National Park by Thornberry-Ehrlich [2009]).

The processes of cliff formation tend to be self-sustaining. That is, once a cliff forms, the steep slopes are inherently unstable and much more prone to failure than gentler grades. Adams et al. (2005) suggest that in addition to the wave-driven mechanical abrasion and plucking (or quarrying) of rocks exposed to direct wave action along the coast, ocean microseisms (ground motions generated by wave action in coastal regions) weaken the sea cliff bedrock by microcracking. The pali along Molokaʻi's north shore continue to form and change (fig. 12). The heavily altered rocks of the caldera complex that comprise the pali are relatively easily eroded and strong wave action is nearly continuous along the north coast of Molokaʻi (Beeson 1976; Storlazzi et al. 2002). In May 1999, just east of the Pelekunu Valley, a major landslide carried enough rock and debris from near the top of 760-m (2,500-ft) high cliffs to create about six acres of new land jutting out into the Pacific Ocean (Rutherford and Kaye 2006).

Volcanic Features and Processes

The island of Molokaʻi contains two large volcanic centers, East and West Molokaʻi, as well as a small post-erosional shield volcano, Puʻuʻuao (comprised of two source vents: Puʻuʻula and Kauhākō Crater) associated with the Kalaupapa peninsula (Coombs et al. 1990). East Molokaʻi Volcano ceased activity about 1.5 million years ago. The pali, resulting from the Wailau slide provide an excellent cross sectional view through the layers of basalt and ash that compose the East Molokaʻi volcanic complex; magnetic stratigraphy also reveals a halved caldera complex (Holcomb 1983). Approximately one million years later, the Puʻuʻuao volcano formed the Kalaupapa Peninsula at the base of the pali by a series of small-scale eruptions and basalt flows around 340,000-570,000 years ago (Clague et al. 1982). At least six different flow fields flank the sides of the volcano. There are at least four discrete vents along the axis of the peninsula (note depressions on Appendix A and fig. 6) (Halliday 2001). A funnel-like pit containing a lake and circum-crater terrace, Kauhākō Crater, cap the small volcanic shield (fig. 13) (Coombs et al. 1990; Moore et al. 1997). The crater is approximately 0.5 km (0.3 mi) in diameter with a rim elevation of 135 m (443 ft) above sea level (Halliday 2001). The crater reaches at least 200 m (660 ft) below sea level at its deepest point making it among the deepest lava pits in Hawaiʻi (Halliday 2001). It is filled with brackish water. The Puʻuʻula cone, 1.4 km (0.9 mi) southwest of the crater, contains late-stage ash deposits from explosive eruption events (Coombs et al. 1990; Clague and Moore 2002).

Along much of the coastal areas of the Kalaupapa Peninsula are 1 to 3 m (3 to 9 ft) thick lava flows. At the shoreline, the tops of flows appear as benches or pavement. When submerged, these flows create small-scale cliffs at the erosional end of a single flows. Slumping forms cliffs of multi-layer lava flows that may be exposed or submerged. Many of the benches are covered with large (1 to 8 m, 3 to 26 ft diameter) basalt boulders. These boulder bench areas create important marine habitat including niches for fish (Eichenlaub 2001).

Lava Tubes and Caves

When relatively liquid basaltic magma flows downhill, the upper surface tends to cool faster than the underlying flow. This cooled upper surface often forms an insulating crust over the flowing lava. When the lava supply is stopped, the flow sometimes leaves hollow spaces or tubes beneath the surface. The HVO library (http://hvo.wr.usgs.gov/observatory/hvo_history_pubs.html) has more than 250 reports of lava tubes throughout the Hawaiian Islands and the Hawaiʻi Speleological Survey conducts explorations of larger tubes. On Kalaupapa Peninsula, caves and cavernous features occur in several groupings: within Kauhākō Crater, along the eruptive alignment north of the crater, on the northeast flank of Puʻuʻuao in the Kaupikiawa Cave System, on the eastern flank of Puʻuʻuao in seaside littoral cliffs, and on the eastern side of the peninsula in the littoral cliffs (Halliday 2001).

Within Kauhākō Crater are several cavernous structures including a rockshelter (a deadend lava tube), and the complex cavernous structure known as Ka Lua o Kahoalii (Kalauokahoalii). This cave opens downward from the northeastern part of the crater terrace. From the surface, it looks like a 22 m (72 ft) wide, 10 m (33 ft) deep pit. The pit-like opening intersects a north-south trending lava tube at its base that measures 7 m (23 ft) wide and 5 m (16 ft) high. Several portions of this tube have collapsed. Bird bones and other animal remains are present in the tube (Halliday 2001).

From Kauhākō Crater, an open lava channel extends from the north side of the carter about 1 km (0.6 mi) down the flank and transforms into a lava tube that fed secondary volcanic activity that added an additional 1.3 km (0.8 mi) to the shoreline. A secondary smaller lava tube branches from the primary tube about 1 km (0.6 mi) north of the crater rim and trends north-northeast almost to the east shoreline of the peninsula. Eight collapse skylights and elongate tumuli are present in this tube (Clague and Moore 2002). Together these features and several other cavernous sites comprise the braided Kaupikiawa Cave System (Halliday 2001). Several of the caves host significant cultural resources. Of note is the NPS Burial Cave that contains human remains. Interring human remains in caves is not a traditional practice (Halliday 2001).

Other notable cave features of Kalaupapa Peninsula include Anakahalele ("cave", "lava tube"). This is among the most important caves known on this part of Molokaʻi. It was partially walled off by early Hawaiians and contains other cultural features (Halliday 2001). Other lesser known cavernous features include Lava Dome "kid", "New Crater", "Shelter Cave", Two Boulder Overhang, Noni Tree Cave, "Sleeping Cave", and "Frank Howarth's cave" (Halliday 2001).

There are numerous cave features of geological and cultural significance on Kalaupapa Peninsula. The Hawaiian Speleological Society has done some mapping in the area. A formal inventory would be helpful for resource management. At Kalaupapa National Historical As of the scoping meeting in 2003, a cave monitoring program had not been initiated for the park. Toomey (2009) has suggested vital signs for monitoring caves and associated landscapes.

Thermal Erosion

As mentioned in the previous section, a 50-100 m (165-330 ft) wide lava channel extends from Kauhākō Crater in the center of the Puʻuʻuao shield. Modeling suggests lava volumes of up to 0.2 cu. km (0.05 cu. mi) erupted at a rate of 260 cu. m/sec (340 cu. yd/sec) (Coombs et al. 1990). This and other Hawaiian channels have provided geologists with important analogs (albeit much smaller) to lunar sinuous rilles, or channels similar in appearance to river valleys possibly formed by thermal erosion. Hypothesis for lunar sinuous rille origins include: 1) thermal erosion by lava, 2) structural control of the lava flows, 3) formation as constructional features, 4) the result of drainage of a lava lake, or, 5) some combination of the above (Coombs and Hawke 1988). Thermal erosion refers to the process of downcutting by liquid lava.

Lunar sinuous rilles are among the most recognizable (from Earth) small volcanic lunar features. They are also obviously difficult to study in the field, which is why Hawaiian analogs are so valuable (Coombs and Hawke 1988; Volcano World 2008). They usually flow away from small pit structures. Because of the very dry nature of the lunar landscape, sinuous rilles probably mark lava channels or collapsed lava tubes some of which may have melted their way down into older rocks, much like erosion by rivers (Volcano World 2008). Like lunar rilles, morphologically, the Kalaupapa lava conduit has a deep head crater, sinuous channel, and gentle slope (Coombs et al. 1990).

Based on the postulated volumes and high velocities of lava flow through the Kauhākō Crater channel, flow was turbulent at times. Turbulent flow, in which heat is mixed throughout the flow, causes extreme heating at the base of the flow allowing, given a long enough flow duration, the flowing lava to melt and pluck away the underlying substrate (Coombs et al. 1990; Pinkerton and Norton 1990). Thermal erosion requires a high flow velocity to maximize the heat transfer to the contact with the underlying rocks. Vertical thermal erosion is always greatest nearest the source vent especially where the velocity increases due to steepening in slope (Coombs et al. 1990; Pinkerton and Norton 1990). Thermal erosion (vertical channel downcutting) at Kauhākō Crater occurred at a rate of ~10.5 μm/sec (0.0004 in./sec) to produce 5-10 m (16-33 ft) of incision (Coombs 1990; Coombs et al. 1990).

Vog

There is no active volcanism on Molokaʻi. However, Kīlauea on the Island of Hawaiʻi is very active and affects nearby islands. The volcanic activity emits roughly 1,500 tons of toxic sulfur dioxide gas (SO_2) each day. It is the largest stationary source of SO_2 in the United States. SO_2 is a major component of vog—a local term for volcanic haze or smog. Vog forms a visible haze comprised of acidic aerosols, unreacted sulfur gases, and volcanic ash and other fine particulate matter that forms as volcanic and trace species react and become oxidized in the atmosphere.

Whether or not Kīlauean vog affects Molokaʻi depends largely on wind conditions. Under the right conditions, the vog can reach the island of Oʻahu, some 350 km (217 mi) northwest of Kīlauea. At greater distances, the vog tends to thin out consisting of acidic or neutral aerosol (Rutherford and Kaye 2006). In cooperation with the U.S. Geological Survey, the National Park Service Air Resources Division maintains air quality monitors on Kīlauea. Real time data is available at: http://www.nature.nps.gov/air/webcams/parks/havoso2alert/havoalert.cfm.

Geological Influences on Biodiversity

The physical component of the ecosystem at Kalaupapa National Historical Park includes three basic parts: geology, hydrology, and meteorology. Monitoring these physical components provides important information on their influences on biodiversity and ecosystem health. Areas within the park of particular natural resource interest are designated Special Ecological Areas (SEAs). These include the State of Hawaii's Puʻualiʻi (Puu Alii) Natural Area Reserve, Waikolu Valley, and the pali. They are so designated because they possess the most intact, diverse, unique, and manageable sites.

At Kalaupapa National Historical Park, several geologic features directly correlate to biological systems present there. At Puʻualiʻi, one of the best Hawaiian examples of ʻohiʻa (*Metrosideros polymorpha*) rainforest is an essential habitat for rare and endangered native forest birds including the Molokaʻi thrush (*Myadestes lanaiensis rutha*). The Waikolu Valley, cutting back into the highly altered rocks of the pali, contains the park's sole perennial stream that is vital habitat for native diadromous fish and mollusks as well as native gobie fish including the ʻoʻopu alamoʻo (*Lentipes concolor*—a candidate for the endangered species list), ʻoʻopu nakea (*Awaous guamensis*) and ʻoʻopu nopili (*Sicyopterus stimpsoni*) (Beeson 1976; National Park Service 2000). Waikolu Stream also supports a large population of relatively uncommon hihiwai (*Neritina granosa*), a native stream snail. The valley, deeply eroded into the pali protects several species of federally endangered plants including Carter's panicgrass (*Pancium fauriei* var *carteri*), haha (*Cyanea procera*) and lava melicope (*Melicope reflexa*) (National Park Service 2000).

The precipitous pali separate the peninsula from the rest of Molokaʻi, essentially isolating portions of land. Their incredible steepness renders them inaccessible to invasive feral pigs (*Sus scrofa*) and axis deer (*Axis axis*). Because of their relative isolation and inaccessibility, these sheer faces are vital nesting habitat for native and endangered birds. Three endangered plant species grow on the cliffs: ʻawikiwiki (*Canavalia molokaiensis*), Kamalō Gulch schiedea (*Schiedea lydgatei*) and makou (*Peucedanum sandwicense*) (National Park Service 2000). These plants are the subject of study and monitoring.

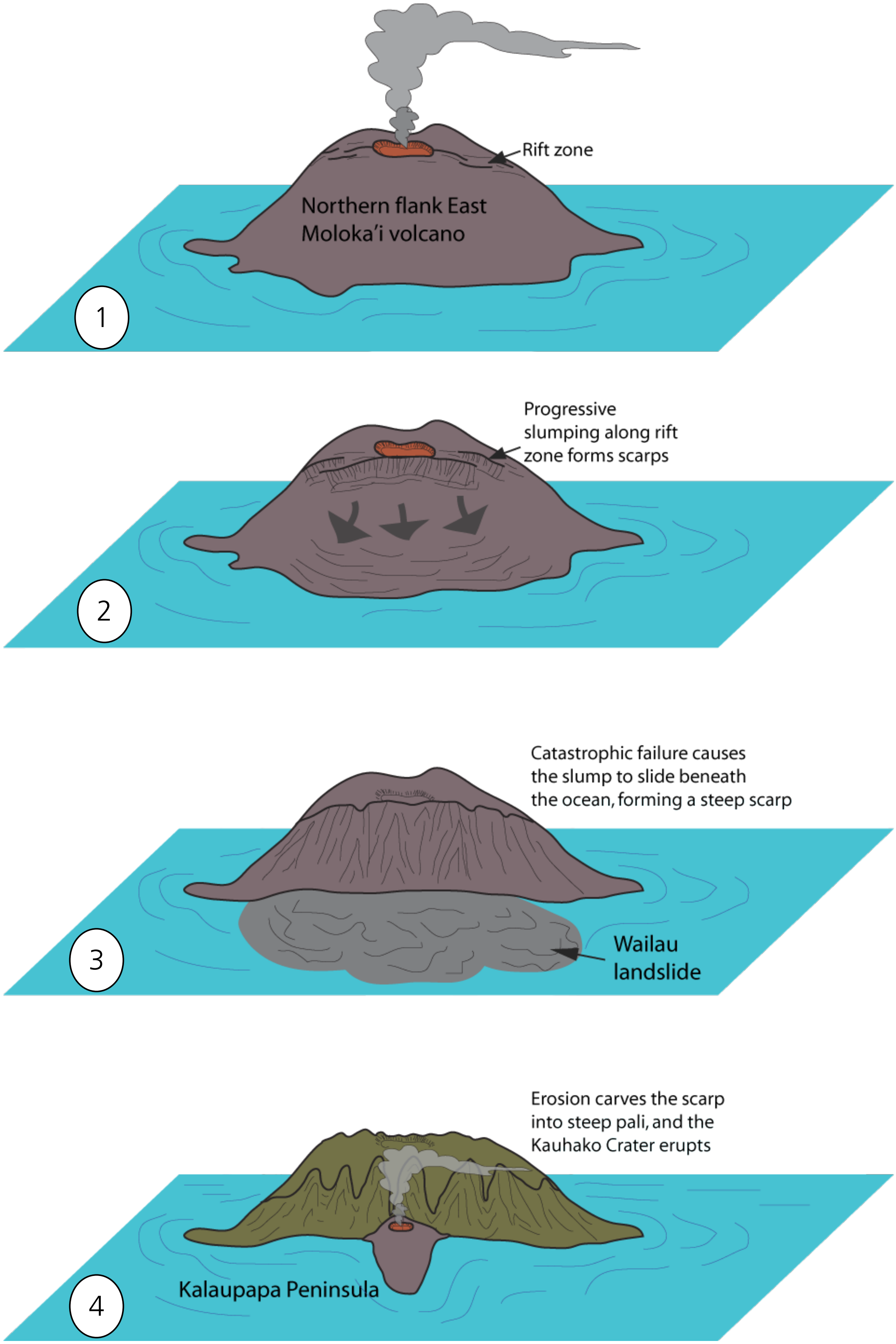


Figure 11. Schematic diagram of the evolution of the steep pali and Kalaupapa Peninsula on the north shore. Graphic is not to scale and by Trista L. Thornberry-Ehrlich after information from Cochran et al. (2002).

Figure 12. Photographs of the steep pali along the northern shore of Moloka'i. These are some of the highest sea cliffs on Earth. National Park Service photographs by T. Scott Williams (Kalaupapa National Historical Park).

Figure 13. Photograph of the Kauhākō Crater atop the Pu'u'uao shield in Kalaupapa National Historical Park. This volcanic center was last active approximately 340,000 years ago. National Park Service photograph by T. Scott Williams (Kalaupapa National Historical Park).

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of Kalaupapa National Historical 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 Kalaupapa National Historical Park provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report. Geologic maps are two-dimensional representations of complex three-dimensional relationships; their color coding illustrates the distribution of rocks and unconsolidated deposits. Bold lines that cross or 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.

Incorporation of geologic data into a Geographic Information System (GIS) increases the usefulness of geologic maps by revealing the spatial relationships among geologic features, 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 are not soil maps, and do not show soil types, 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. Similarly, map units show areas that have been susceptible to hazards such as landslides, rockfalls, and volcanic eruptions. Geologic maps do not show archaeological or cultural resources, but past peoples may have inhabited or been influenced by depicted geomorphic features. For example, alluvial terraces may have been preferred use areas 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 timescale (figs. 14 and 15) for the age associated with each time period. The table highlights characteristics of map units such as: susceptibility to erosion and hazards; the occurrence of paleontological resources (fossils), cultural resources, mineral resources, and caves or karst; and suitability as habitat or for recreational use. Some information on the table is conjectural and meant to serve as suggestions for further investigation.

The GRI digital geologic maps reproduce essential elements of the source maps including the unit descriptions, legend, map notes, graphics, and report. The following reference is the source for the GRI digital geologic data for Kalaupapa National Historical Park:

Sherrod, D. R., J. M. Sinton, S. E. Watkins, and K. M. Brunt. 2007. Geologic Map of the State of Hawai'i, Sheet 4. Island of Moloka'i (scale 1:100,000). Open-File Report 2007-1089. U.S. Geological Survey, Reston, Virginia, USA.

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, and increases the overall 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/). Data will be available on the Natural Resource Information Portal when the portal goes online. As of August 2010, access is limited to NPS computers at http://nrinfo/Home.mvc.

Geologic Units of Moloka'i

On the basis of age dating and stratigraphy, geologists divide the geologic units of the island of Moloka'i into two broad categories, the East Moloka'i Volcanics and the West Moloka'i Volcanics; the Kalaupapa volcanic center is much smaller than the two main volcanoes (Sherrod et al. 2007). These distinctions correspond to the evolution of the island's structure. The West Moloka'i volcanic suite contains alkalic basalt, tholeiite, and hawaiite flows with interlayered cinder and spatter cones, and coarser grained intrusive dikes (Sherrod et al. 2007).

The younger and larger East Moloka'i volcano covers two-thirds of the island. Flows from this volcano are well exposed on the pali within Kalaupapa National Historical Park. The map units associated with this volcano include pāhoehoe and ʻaʻā flows of olivine-rich basalt with localized cinder and spatter cones, intrusive plugs, and dike swarms (Sherrod et al. 2007). Beeson (1976) described this pile of volcanic deposits in detail. The lower flows are mostly transitional to tholeiitic grading upwards to more alkalic, hawaiite, and mugearite compositions towards the top (Clague and Beeson 1980). Relatively young deposits (Pleistocene age) of this group include pāhoehoe flows and ashy soil beds with some vent deposits and cinder cones (Sherrod et al. 2007).

The Kalaupapa Peninsula distinctively juts off the north shore of Molokaʻi. Younger volcanic rocks of the Kalaupapa volcanic suite comprise the more recent addition to the island. The rocks include pāhoehoe flows of tholeiitic to alkalic basalt and basinite with cinder cones and spatter near the Kauhākō Crater (Sherrod et al. 2007).

Another recent volcanic event formed the islands of Mokuhoʻoniki and Kanahā off the eastern end of Molokaʻi. These islands contain tuff deposits, spatter, ash, sparse lava flows, and several basaltic dikes (Walker 1990; Sherrod et al. 2007).

Flanking much of the islands shores and river valleys are unconsolidated surficial deposits. These reflect the continual processes of erosion and deposition all over the island. Oldest among these are poorly consolidated sands and gravels deposited as alluvial terraces, valley fill, and locally mantling ridges. Calcareous breccia and conglomerate contain marine-derived sedimentary deposits extending 2 km (0.7 mi) inland. The youngest deposits on Molokaʻi include beach deposits, alluvium, dune deposits of varying age, and lagoon deposits. Manmade fill of concrete and debris forms piers and breakwaters along the coastline (Sherrod et al. 2007).

Map Unit Properties Table: Kalaupapa National Historical Park

Colored rows indicate units mapped within Kalaupapa National Historical Park

Age	Unit Name (Symbol)	Features and Geologic Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Paleontological Resources	Cultural Resources	Karst	Mineral Occurrence	Habitat	Recreation	Geologic Significance
QUATERNARY (Holocene)	Fill (Qf) Beach deposits (Qbd) Younger dune deposits (Qdy) Lagoon deposits (Qlg)	***Qf*** consists of manmade fill of concrete and rock debris forming piers and breakwaters along the coastline. ***Qbd*** contains surf-reworked, cream-colored calcareous sand and gravel forming unconsolidated strand-line deposits parallel to the coastline. Unit includes local stream-derived volcanic detritus as black sand and minor sandstone fragments. ***Qdy*** includes unconsolidated coral sand forming eolian dunes and sheets up to 15 m (45 ft) thick. Unit typically occurs adjacent to ***Qbd***. ***Qlg*** contains poorly consolidated to unconsolidated mud, silt, and sand present as mudflats in back-beach areas and estuaries. Some marine marl or limey beds present locally.	Very low, except for ***Qf***	High porosity and permeability in addition to proximity to flowing water renders unit unsuitable for waste facilities; building projects on this unit should avoid areas with slopes present.	Heavy erosion, slumps, slides, and mass wasting possible. Shoreline areas are prograding west of Kaunakakai inundating mangrove swamps.	Finely broken coral, shells, and foraminifera	***Qlg*** contains reddish-brown mud as a result of erosion caused by overgrazing in the past 200 years	None	Sand, silt, gravel, black sand, marl	Nearshore, lagoon, estuarine, and mangrove swamp habitat.	Subaerial units are suitable for light recreation, ***Qlg*** should be avoided for any impactful recreation due to fragile nature of estuarine habitats.	***Qdy*** contains glassy and lithic sand reworked downwind from 200-500-year-old tephra deposits from the volcano's southwest rift zone.
QUATERNARY (Pleistocene–Holocene)	Alluvium (Qa) Older dune deposits (Qdo)	***Qa*** contains deposits of silt, sand, and gravel along valley bottoms and streams, locally grading upwards into unconsolidated talus and colluvium as well as ***QTao***. ***Qdo*** consists of lithified calcareous sand or eolianite in fields inland of the modern coastline. Degree of lithification increases with age and some caliche or red paleosol caps are present locally.	Very low to low for ***Qdo***	Building projects should avoid areas with slopes and close proximity to coastlines.	Erosion, blockfall, slumps, and slides are possible for units with slopes present.	***Qdo*** contains shells and bird bones.	Unit may contain early Hawaiian artifacts and relicts of the Kalaupapa settlement	Karst dissolution is possible for ***Qdo*** cemented by calcite	Sand, caliche, paleosol, and gravel	***Qa*** provides permeable substrate for valley floor vegetation	Unit is suitable for most recreation unless in flash flood prone narrow valleys	***Qdo*** contains remains with radiocarbon dates of 4,700 to 6,750 years before present
QUATERNARY (Pleistocene)	Calcareous breccia and conglomerate (Qcbc)	Unit contains poorly to moderately sorted marine-derived sedimentary deposits which extend 2 km (0.7 mi) inland at elevations as high as 72 m (216 ft). Fragments are encased in a sandy lime mud matrix and calcitic cement.	Low	The poorly lithified nature of this unit may render it unstable for heavy development.	If undercut, unit may pose rockfall hazard	Coralline algae, branching coral, shell fragments, gastropod shells, echinoid remains	Unit may contain early Hawaiian artifacts	Karst dissolution is possible for unit cemented by calcite	Sand, basaltic rock clasts, carbonate mud rip-up clasts	Unit provides perched ledges of porous substrate for vegetation	Avoid undercut areas due to risk of landslides	Unit records marine transgression event during the Pleistocene
QUATERNARY (Pleistocene)	Kalaupapa Volcanics (Qppl) Kalaupapa Volcanics; vent deposits (Qppv) Tuff of Mokuhoʻoniki cone (Qmv)	***Qppl*** contains porphyritic pāhoehoe lava flows ranging in composition from tholeiitic to alkalic basalt and basanite that comprises the broad Kalaupapa Peninsula of East Molokaʻi. ***Qppv*** consists of a cinder cone, low lava cone, and Kauhākō Crater on top. ***Qmv*** contains palagonitic basaltic ash, spatter, sparse lava flows, and a few dikes comprising the islands of Mokuhoʻoniki and Kanahā off the eastern end of Molokaʻi.	Moderate	Units are present at the base of a great windward cliff and should be avoided for development due to the threat of rockfall.	Units can weather to slippery clays, lava tube collapse is possible for flow units	Coralliferous limestone fragments entrained in bedded ash as blocks. Potential paleontological resources of animals that lived in or were transported into lava tubes and caves.	Unit may have contributed to the building of the Kalaupapa settlement and may have spiritual significance for early Hawaiians	None	Basalt, volcanic ash, olivine phenocrysts, coralliferous limestone fragments	Lava tubes may provide cave habitat	Avoid flow areas due to potential for collapse	***Qppl*** has radiometric (potassium-argon) age dates of 0.57 to 0.34 million years. ***Qmv*** is younger than 1.3 million years and contains rocks indicative of shallow eruptions.
QUATERNARY (Pleistocene)	East Molokaʻi Volcanics Upper member: lava flows (Qemul) vent deposits (Qemuv) domes (Qemud)	***Qemul*** contains ʻaʻā flows 6-30 m (18-90 ft) thick with rare pāhoehoe flows and ashy soil beds. Unit weathers to a medium to light gray. ***Qemuv*** consists of cinder and spatter layers that form bulky cones. ***Qemud*** contains lava extrusions covering and obscuring vent sites of ***Qemuv*** and flowing within craters of vent deposits.	Moderate	Rough textures and unconsolidated nature of some volcanic deposits make them unsuitable for extensive development.	Units are prone to washing downslope and can weather to slippery clays, lava tube collapse is possible for flow units	Potential paleontological resources of animals that lived in or were transported into lava tubes and caves.	Unit may have spiritual significance for early Hawaiians	None	Cinders, volcanic ash	Units weather to contribute to fertile, iron rich soils	ʻaʻā lavas form unstable, dangerous trailbase	In concert, units record the localized volcanic history of the East Molokaʻi area

Colored rows indicate geologic units mapped within Kalaupapa National Historical Park

Age	Unit Name (Symbol)	Features and Geologic Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Paleontological Resources	Cultural Resources	Karst	Mineral Occurrence	Habitat	Recreation	Geologic Significance
QUATERNARY (Pleistocene–Pliocene)	Older alluvium (QTao)	Unit consists of poorly consolidated to lithified sand and gravel. In places, texture is coarse enough to be considered conglomeratic with well rounded and moderately sorted clasts. Some colluvial lenses present locally. Unit is present as terraces, thick valley fill, and locally mantling ridges.	Low	Heterogeneous layering may result in structural weakness making units unsuitable for heavy development.	Rockfall hazard due to some ledge-forming layers exposed along slopes incised by modern drainages	Pleistocene and Pliocene fossil fragments are possible.	Unit may have provided tool material for early Hawaiians	None documented.	Sand, gravel, volcanic clasts	Units form terraced benches	Good for most uses unless incised and undercut by local streams.	Unit records early weathering and deposition patterns on Moloka‘i
QUATERNARY (Pleistocene–Pliocene)	East Moloka‘i Volcanics Lower member: lava flows (QTemll) vent deposits (QTemlv) caldera complex (QTemlcc) Intrusive rocks (QTemli)	***QTemll*** contains pāhoehoe and ‘a‘ā flows of aphyric to porphyritic olivine basalt. Unit weathers darker gray, distinguishable from the overlying ***Qemu***. ***QTemlv*** consists of cinder and localized spatter cones. ***QTemlcc*** contains thick lava flows with many intrusive plugs, talus, and fault breccia. Unit is permeated by dike swarms. Ponded areas are thickest and secondary mineralization is a field characteristic of the caldera complex. ***QTemli*** consists of steep, near-vertical dikes, stocks and plugs within ***QTemlcc***.	Moderately low	Heterogeneous layering of lava types may result in structural weakness making the terrane unsuitable for heavy development.	***QTemlc*** weathers to clay and may weaken stacks of lava flows rendering them susceptible to slides. Lava tubes may collapse.	Potential paleontological resources of animals that lived in or were transported into lava tubes and caves.	Filled amygdules may have provided trade and tool material for early Hawaiians	None	Olivine, augite phenocrysts, volcanic rocks, ash, vesicle linings and amygdules filled with calcite, quartz, chalcedony, smectite-group clay minerals	Lava tubes may provide cave habitat	‘a‘ā lavas form unstable, dangerous trailbase	Units record volcanic evolution of the eastern side of Moloka‘i
QUATERNARY (Pleistocene–Pliocene)	West Moloka‘i Volcanics: Wai‘ele and other late lava (QTwmw) Wai‘ele and other late lava; vent deposits (QTwmwv) lava flows (QTwml) vent deposits (QTwmv), Intrusive rocks (QTwmi)	***QTwmw*** is an informal unit underlain by red ashy soils from 0.2 to 1.2 m (0.6-3.6 ft) thick. Flows range in composition from alkalic basalt to hawaiite with some tholeittic layers at Ka‘eo. ***QTwmwv*** consists of cinder and spatter cones. ***QTwml*** lack the red ashy soil interbeds of ***QTwmw*** and contains pāhoehoe and ‘a‘ā flows with thin beds less than 0.6 m (1.5 ft) thick at several localities. ***QTwmv*** contains localized vent deposits of cinder and spatter cones. ***QTwmi*** contains coarser-grained intrusive dikes.	Moderate	Heterogeneous nature of units could pose stability issues on slopes, avoid flow areas that may contain lava tubes for wastewater treatment facility development.	Flows separated by ashy layers may be prone to rockfall and sliding on slopes	Potential paleontological resources of animals that lived in or were transported into lava tubes and caves.	Early Hawaiians quarried late lava flows of ***QTwmw*** lending the name Kalau ko‘i (the adze pit) to the features	None	Volcanic rocks, ash	Unit weathers to reddish, iron rich soils	‘a‘ā lavas form unstable, dangerous trailbase, avoid flow areas due to potential for collapse	***QTwmw*** ranges in age from 1.80 to 1.73 million years old and represent postshield-stage volcanism.

Geologic History

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

In geologic terms, the rock units in Kalaupapa National Historical Park are young. Volcanism created the oldest of Moloka'i's rocks approximately 2 million years ago—compared to more than 4.5 billion years of Earth's history (figs. 14 and 15) (Rubin 2005). 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. Knowledge of how the islands formed contributes to understanding the current landscape and to predicting potential future geologic events.

Pre-Quaternary History of the Pacific Basin

In the late Paleozoic Era, 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 Eon (about 570 million years ago), when it formed 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. Era The oceanic crust of the Panthallassic Ocean basin was also changing and splitting during this time.

At approximately 125 million years ago (Early to Middle Cretaceous), evidence suggests that a massive increase in volcanic activity in the western Pacific Ocean basin produced large volcanic plateaus above several large mantle plumes. This activity was concurrent with a rapid increase in rates of sea-floor spreading. Rates increased by 50%–100% and remained high until the Late Cretaceous (Condie and Sloan 1998). This event correlates with rising sea level, global climate change (warming), and several extinction events in the middle Cretaceous.

The modern 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 Period, 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. 16) (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 the 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 mountain-building event (responsible for uplift of the Rocky Mountains) 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. 17) (University of California Santa Barbara 2006).

Evolution of the Hawaiian-Emperor Seamount Chain

The Pacific plate covers 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. 18). 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 (fig. 2). Other such spots across the basin are the Caroline, Marquesas, Society, Pitcairn, Austral, and Easter hotspots (fig. 19) (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. The chain is divided into two sections, the younger Hawaiian Ridge (from the Hawaiian Islands northwest to Kure Atoll) and the older Emperor Seamounts. The 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)

Building Volcanoes

Each volcanic island evolved through four idealized eruptive stages: preshield, shield, postshield, and rejuvenated stages (fig. 20) (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 4.89±0.11 and 5.2 million years ago (oldest known age of 6 million years ago with large analytical error) (G. B. Dalrymple unpublished data 1982; Clague and Dalrymple 1987; Clague 1996; David Sherrod, geologist, U.S. Geological Survey, written communication, July 2009). Kauaʻi is slightly younger and closer to Kīlauea with shield lava ages of 5.14±0.20 and 5.77±0.28 million years ago as determined by isotopes of potassium and argon (K-Ar) (McDougall 1979; David Sherrod, geologist, U.S. Geological Survey, written communication, July 2009). The end of shield-building volcanism on Oʻahu dates between 2.6 and 3.0 million years ago (Clauge and Dalrymple 1987; Clague 1996). West Molokaʻi volcano has a K-Ar age of 1.90±0.06 million years ago, whereas East Molokaʻi volcano has an age of 1.76±0.07 million years ago; however, these ages are uncertain due to laboratory difficulties (Naughton et al. 1980; Clague and Dalrymple 1987; David Sherrod, geologist, U.S. Geological Survey, written communication, July 2009). The neighboring islands of Kahoʻolawe and Lānaʻi have K-Ar shield lava ages of 1.25±0.15 million years ago and 1.28±0.04 million years ago, respectively (Bonhommet et al. 1977; David Sherrod, geologist, U.S. Geological Survey, written communication, July 2009). The West Maui volcano erupted before Haleakalā on Maui, having K-Ar ages of 2.15 million years ago for shield stage lava versus the oldest reported age of 1.12 million years ago for post-shield lava on Haleakalā (McDougall 1964; David Sherrod, geologist, U.S. Geological Survey, written communication, July 2009).

Although some of the Hawaiian Islands were built by a single volcano, others are the composite of several. The time over which a volcano remains active is long (hundreds of thousands to 2 million yr or more), and there is significant overlap in volcanic age between neighboring islands. For instance, Haleakalā volcano on Maui last erupted only about 200 years ago even though its distance from the currently active Kīlauea volcano on Hawaiʻi is about 175 km (110 mi) (Rubin 2005). Three volcanoes are considered active: Kīlauea (erupting since 1983), Mauna Loa (last erupted in 1984), and Lōʻihi (erupted in 1996). The active submarine volcano, Lōʻihi, is building layers of basaltic lava and venting hydrothermal, mineral-laden water towards the ocean's surface and may in the future become the next Hawaiian island (Rubin 2005). Volcanoes considered dormant include Hualālai (last erupted in 1801), Haleakalā (last erupted in about 1790), and Mauna Kea (last erupted about 4,000 years ago) (Rubin 2005). Though extremely remote, volcanic activity is still a possibility at Kalaupapa National Historical Park. The Kalaupapa Peninsula formed only 340,000-570,000 years ago during a renewed volcanic phase.

Volcanoes of Moloka'i

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; Holcomb 1985; Price and Elliott-Fisk 2004).The oldest volcanic mound on Molokaʻi is the West Molokaʻi volcano. Once the primary volcanic building phase ended (1.90 million years ago), erosion has reduced it into a low-lying mass of rolling hills and gentle ridges whose highest point is only about 430 m (1,410 ft) above sea level (Rubin 2005; Sherrod et al. 2007). Most of the rocks now exposed are from the shield-stage volcanism. Some coarser grained dikes uphold northwest-striking ridges (Sherrod et al. 2007).

The younger East Molokaʻi volcano erupted from approximately 1.76 to less than 1.35 million years ago and now covers two-thirds of the island. It stemmed from an east-west oriented fissure zone. Several rift zones marked by linear volcanic dikes trend west-northwest, and east-northeast from the summit area (Appendix A). Once the magma chamber of this large volcano was relatively emptied, the volcano collapsed on itself forming a caldera complex as much as 11 km (7 mi) in diameter.

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 precipitous slopes and cliffs on island shorelines. These mass movements have been an especially important ongoing influence on the lowering of the landscape at Molokaʻi and the development of the overall ocean island volcanic complex of all the Hawaiian Islands (Keating et al. 2000). The Wailau slide removed nearly a third of the island of Molokaʻi as the northern flank of the East Molokaʻi volcano slumped and bulged and then catastrophically failed and slid into the Pacific Ocean more than 150 km (90 mi) offshore (Moore and Clague 2002; Field et al. 2008). Rifting and rift zone dikes (feeding fissure eruptive vents) on the East Molokaʻi volcano may have contributed to the triggering of the landslide failure (Moore and Clague 2002). Two dike swarms mark the locations of rift zones on the west edge of the slide, oriented west-northwest, and another swarm oriented east-northeast marks the east edge rift zone (Clague and Moore 2002).

After the major landslide on Molokaʻi, much younger volcanic activity resurged as the small shield vent of Kalaupapa (Puʻuʻuao) experienced a single, monogenetic lava eruption during the Pleistocene Epoch. Age dates of these lavas range from 0.34 to 0.57 million years ago (Clague et al. 1982; Sherrod et al. 2007). Other small-scale eruptive vents are located nearby on the sea cliffs, offshore as submarine cones, and on the Mokuhoʻniki and Kanaha islets. These two islets are composed of eroded tuff deposits totaling an area of 0.06 sq. km (0.02 sq. mi) (Walker 1990).

As on other volcanic islands throughout the Pacific Ocean basin, during periods of volcanic quiescence, the basalts, tuffs, breccias, cinder cones, and ash deposits are exposed to intense weathering and erosion in the tropical Hawaiian climate. Landforms produced may include amphitheatre valleys, 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 pound the shorelines, carrying away sands and gravels eroded by the islands' rivers. Coral reefs fringe certain areas of the islands and contribute carbonate sediments to the island's beaches and younger dune deposits (Sherrod et al. 2007). At 21,000 years before present, during the last major glacial advance of the Pleistocene, sea level was ~130 m (430 ft) lower than at present. This lowstand created carbonate platforms around many of the Hawaiian Islands that now form a carbonate substrate for modern coral reefs (Barnhardt et al. 2005). Significant reef development occurred around Molokaʻi beginning between 9,000 and 8,000 years ago as postglacial sea-level rise inundated the flanks of the islands. Coral reef vertical accretion and sea level stabilized about 5,000 to 3,000 years ago. The vertical development is now naturally limited by wave action (Field et al. 2008).

Weathering of volcanic units and coral reefs produced the bulk of the unconsolidated geologic units on Molokaʻi. Older alluvial units and dune deposits have been accumulating as terraces, fan deltas, coastal plain deposits, and alluvial valley fills since the Pliocene (Walker 1990; Sherrod et al. 2007). Other young sedimentary units include lagoon deposits present in mudflats, estuaries, and back-beach areas. These sediments collect as beach deposits and younger sand dunes wash from higher areas to the shore during seasonal runoff events (Sherrod et al. 2007). Modern drainages across Molokaʻi collect Holocene-age alluvium.

Human Impacts

Since the first settlers began farming on Molokaʻi, anthropogenic changes are impacting the geologic processes and features of the island. The earliest people to use the landscape cleared tracts of land and burned vegetation, causing accelerated erosion (Cochran et al. 2002). Hawaiians built fishponds, which drastically modified the coastline and altered sediment transport down-slope and along-shore (Cochran et al. 2002). Westerners introduced livestock to the islands during the late 1700s. Feral animals continue to thrive in less accessible areas of eastern Molokaʻi causing deforestation, and increased erosion of the upland soils (Cochran et al. 2002). Modern development activities such as grading, stream diversion, piers, wharfs, harbor breakwaters, and infilling rills is continuing to affect the geomorphology of Kalaupapa Peninsula exacerbating erosion, increasing sediment load, and disrupting sediment transport and deposition patterns (Cochran et al. 2002; Curt Storlazzi, geomorphologist, U.S. Geological Survey, written communication, March 2010). Shoreline structures tend to impede currents that would otherwise flush out the nearshore areas of suspended sediment (Cochran et al. 2002). The development of Kalaupapa is relatively light compared with other portions of the island due mostly to its isolated location and lack of easy access.

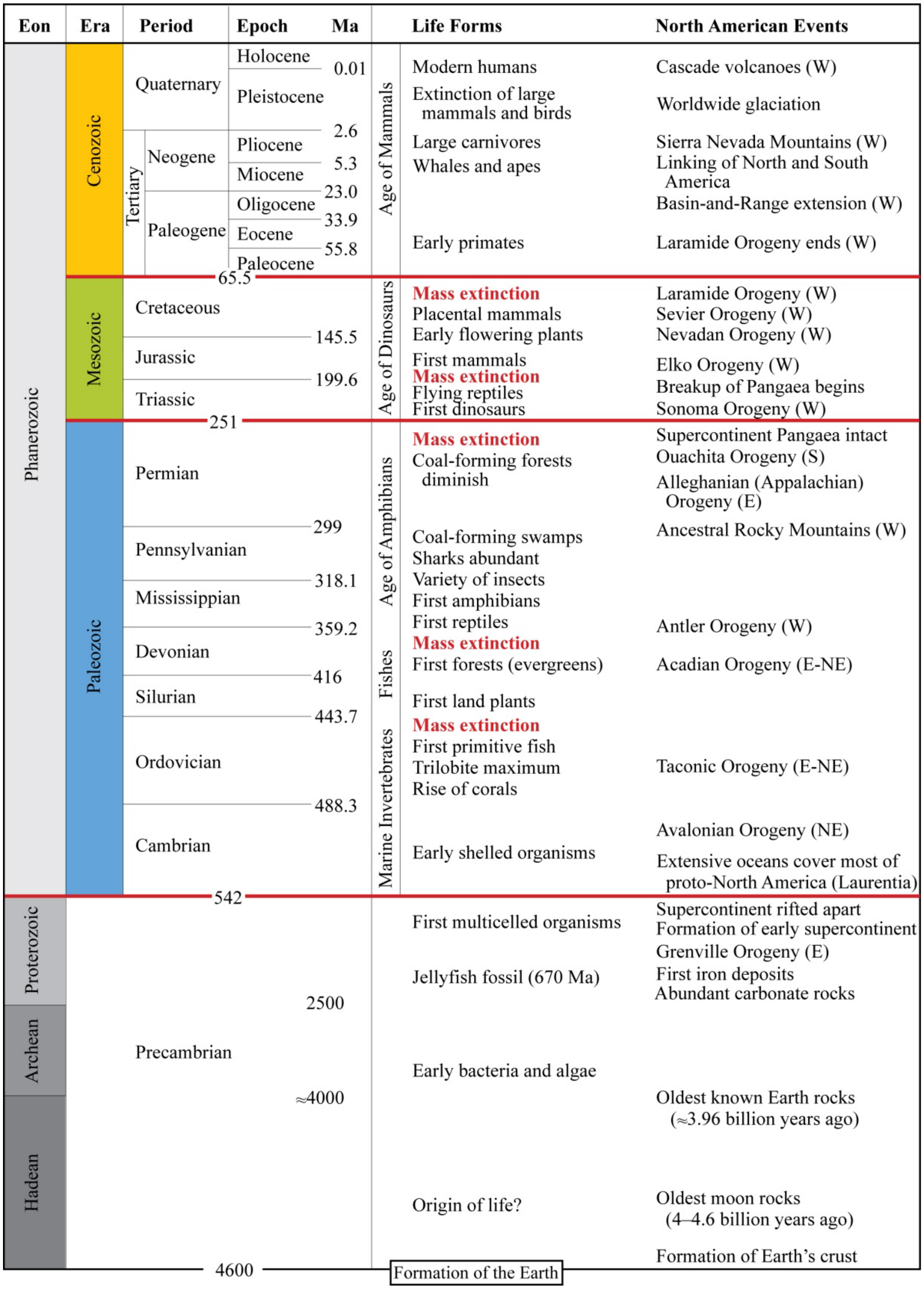


Figure 14. Geologic timescale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Isotopic ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual 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	0.01	Active volcanism of Kīlauea and Mauna Loa	Puna Basalt, and Ka'ū Basalt deposition ongoing Laupāhoehoe Volcanics, and Hualālai Volcanics (Basalt Member) deposited
Cenozoic		Quaternary	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
Cenozoic		Quaternary	Pleistocene	2.6	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
Cenozoic	Tertiary	Neogene	Pliocene	5.3	Shield stage volcanism on Ni'ihau Shield stage volcanism on Kaua'i	
Cenozoic	Tertiary	Neogene	Miocene	23.0	Gardner Pinnacles volcanism	
Cenozoic	Tertiary	Paleogene	Oligocene	33.9	Midway Island volcanism	
Cenozoic	Tertiary	Paleogene	Eocene	55.8	Pacific plate changes motion, causing bend in seamount chain	
Cenozoic	Tertiary	Paleogene	Paleocene	65.5	Hotspot volcanism along Hawaiian-Emperor seamount chain ongoing throughout the Cenozoic	

Figure 15. Geologic time scale of events affecting the Hawaiian Islands throughout the Cenozoic Era; adapted from U.S. Geological Survey 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).

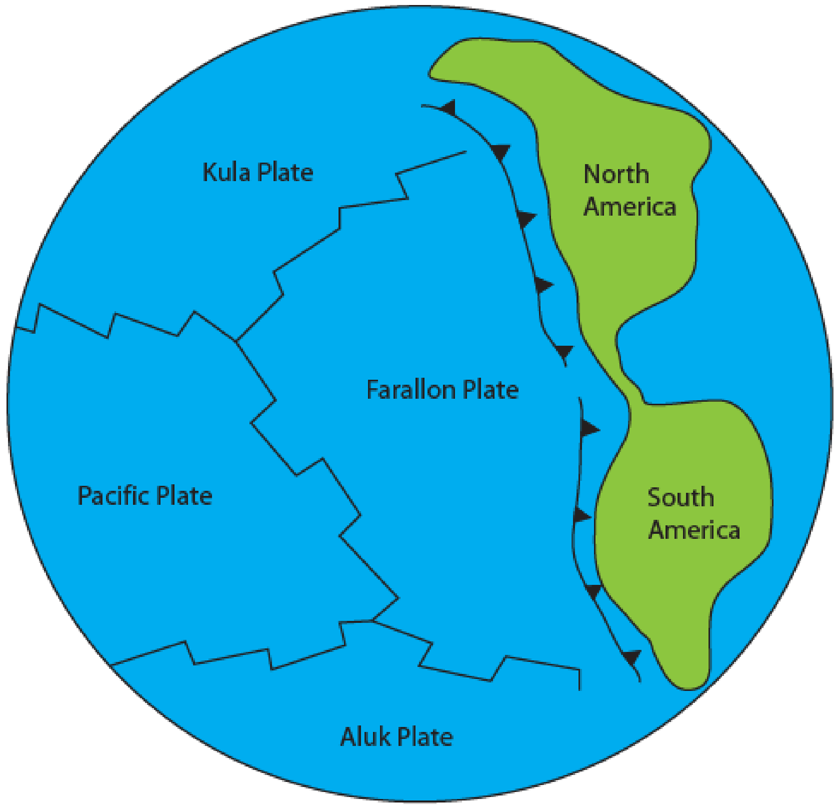


Figure 16. Generalized arrangement of plates in the Pacific Ocean basin during the middle Cretaceous. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

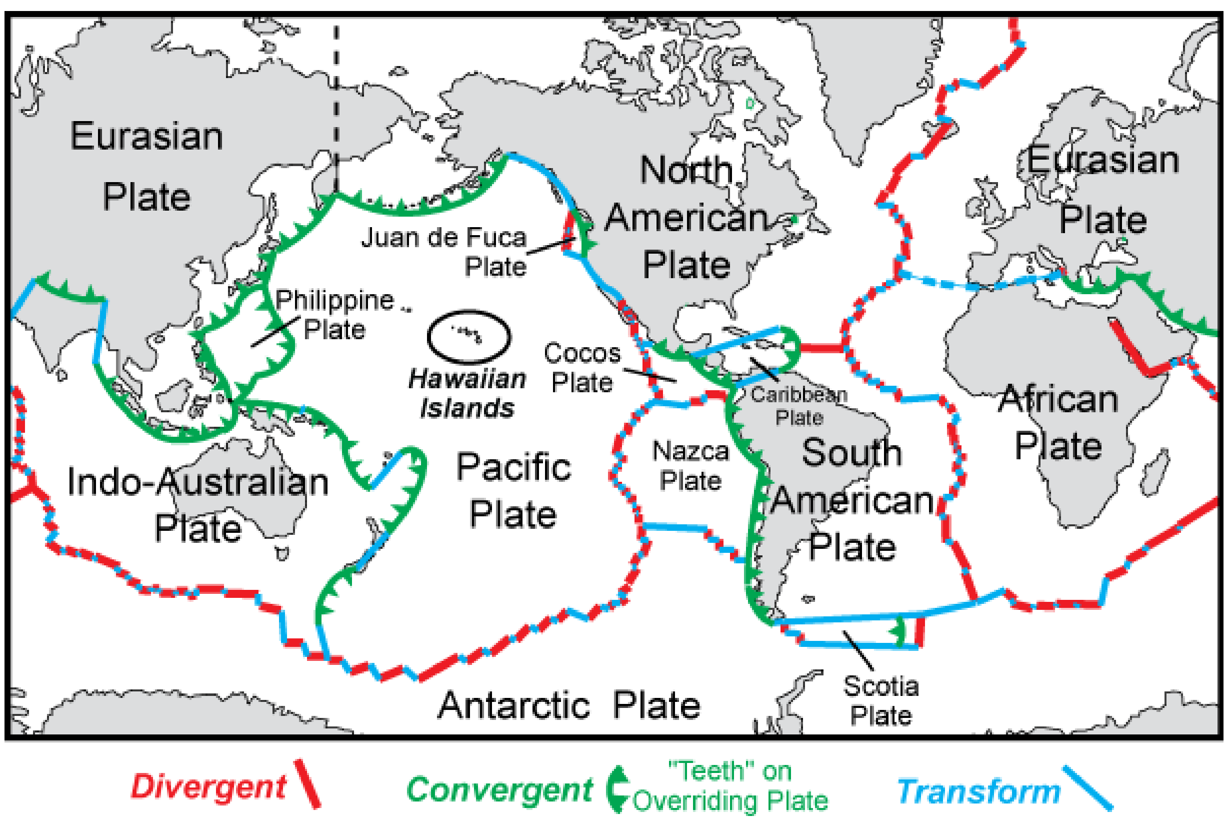


Figure 17. Map of the current tectonic plates. The Hawaiian Islands are circled. Divergent boundaries are where plates are pulling apart. Plates come together at convergent boundaries and slide past one another at transform boundaries. Graphic courtesy Robert J. Lillie (Oregon State University), modified from Lillie (2005).

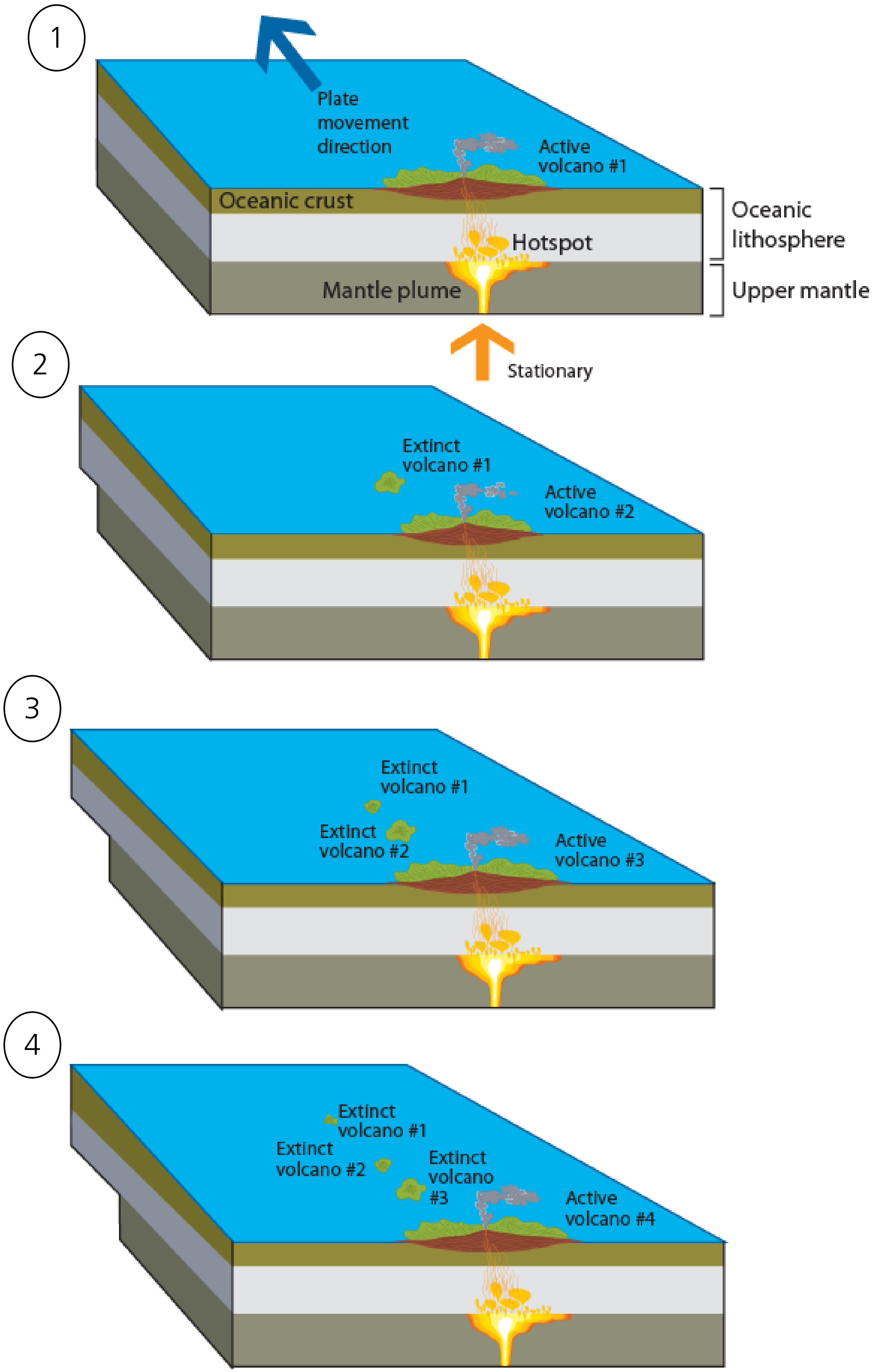


Figure 18. Evolution of a chain of islands over a stationary hotspot in Earth's crust. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

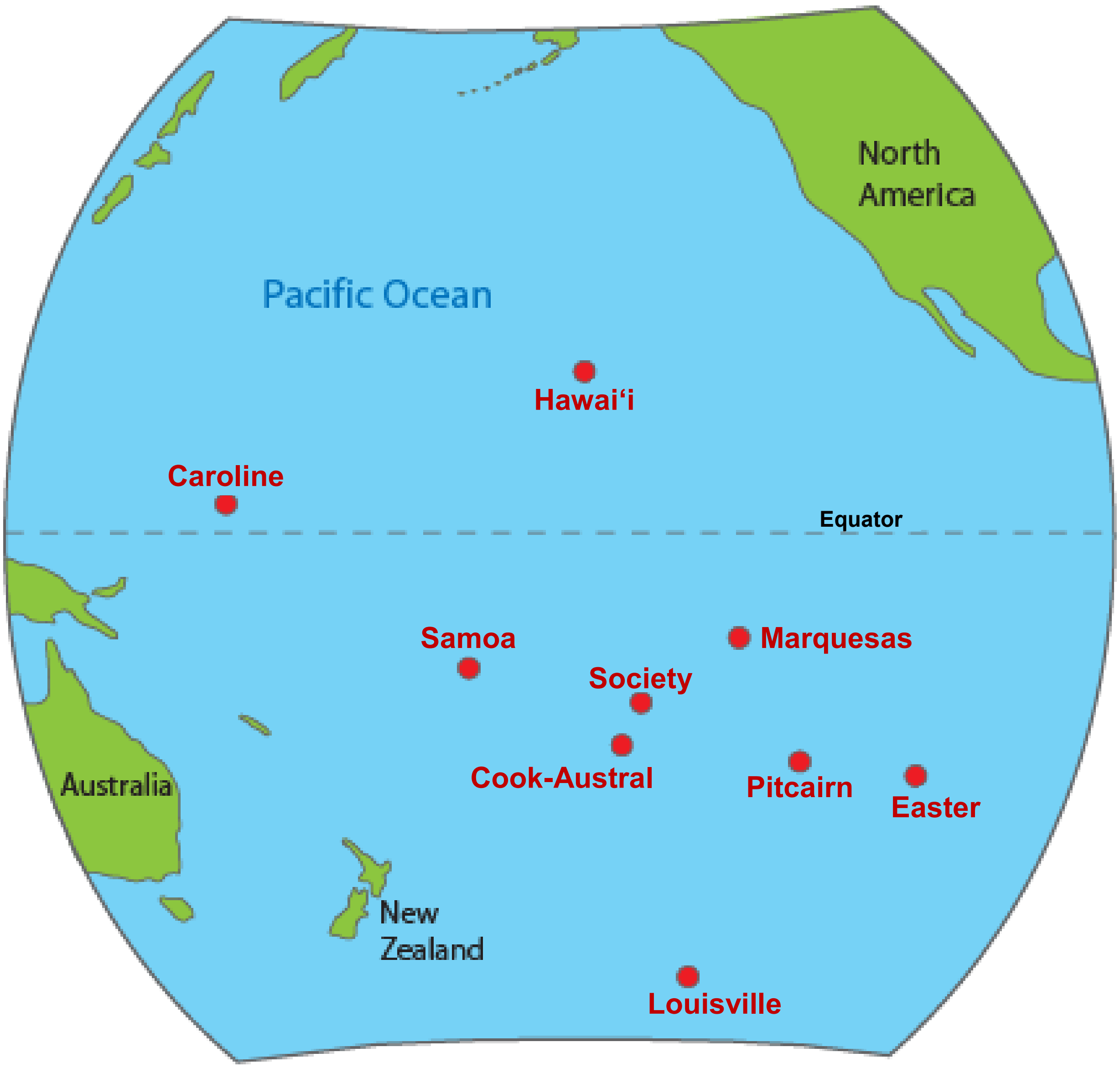


Figure 19. Location of hotspots across the South Pacific. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) adapted from figure 2 in Clouard and Bonneville (2001).

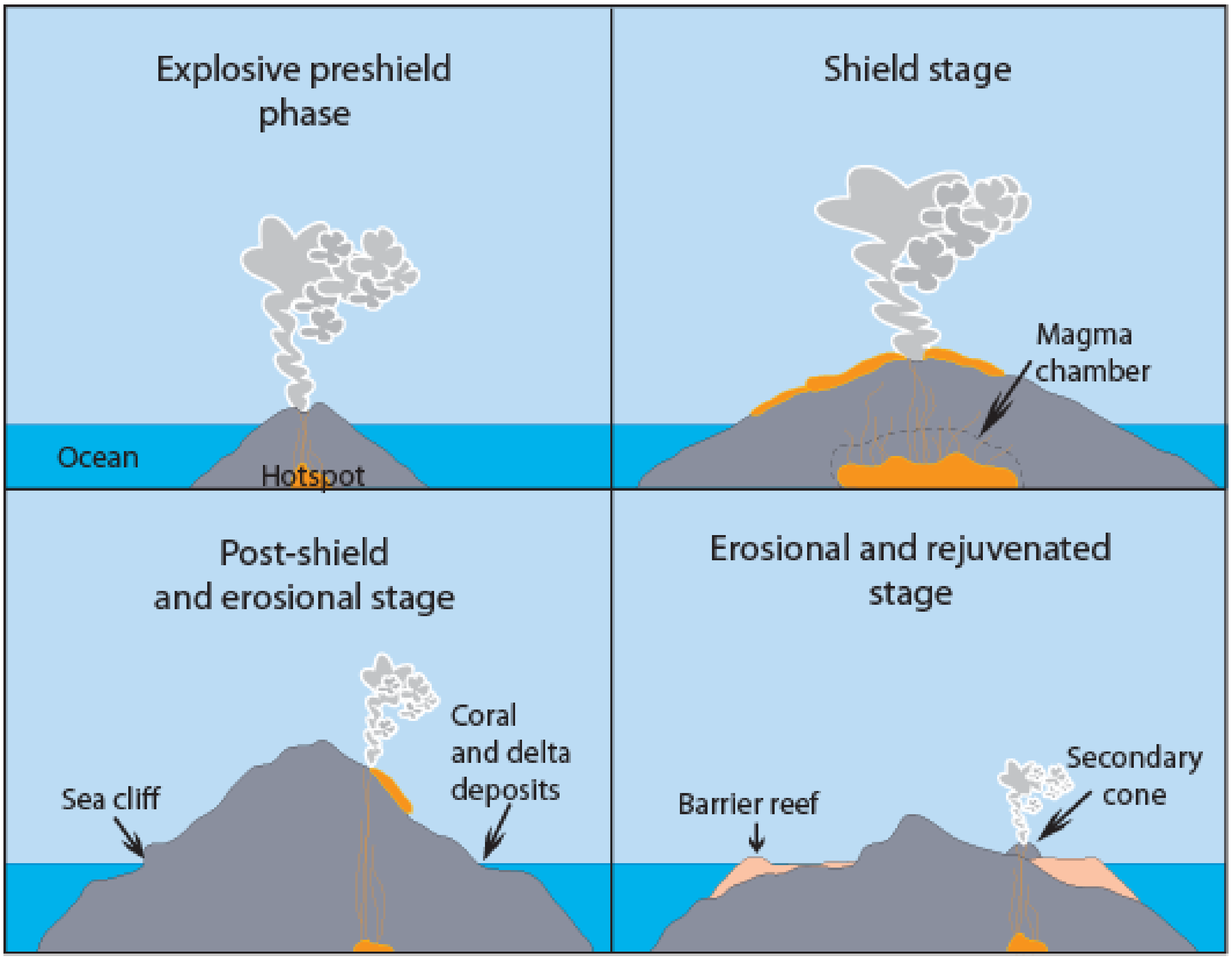


Figure 20. Simplified stages of Hawaiian hotspot island volcanism. After volcanism ceases, erosion and subsidence slowly lower the island into the sea. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 29 in Keating (1992).

Glossary

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

alkalic. Describes rocks that are enriched in sodium and potassium.

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 material ejected from a volcano (also see "tuff").

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

base flow. Stream flow supported by groundwater; flow not attributed to direct runoff from precipitation or snow melt.

base level. The lowest level to which a stream can erode its channel. The ultimate base level for the land surface is sea level, but temporary base levels may exist locally.

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

basinite. A very fine-grained basalt.

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

bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.

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

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

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

calcareous. Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).

caldera. A large bowl- or cone-shaped depression at the summit of a volcano. Formed by explosion or collapse.

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

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).

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

continental crust. 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 boundary. A plate 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, in which more than half the particles of which are larger than sand size.

deformation. A general term for the processes 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 narrow igneous intrusion that cuts across bedding planes or other geologic structures.

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

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

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

drainage basin. The total area from which a stream system receives or drains precipitation runoff.

driblet. Volcanic spatter.

drift. All rock material (clay, silt, sand, gravel, boulders) transported by a glacier and deposited directly by or from the ice, or by running water emanating from a glacier. Includes unstratified material (till) and stratified deposits (outwash plains and fluvial deposits).

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

fault. A break in rock along which relative movement has occurred between the two sides.

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

glaze. A fired glassy surface on lava features.

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

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 that is thought to be the surface expression of a rising plume of hot mantle material.

hydrogeologic. Refers to the geologic influences on groundwater and surface water composition, movement and distribution.

inflation. Process by which a local area of pahoehoe lava swells as a result of injection of lava beneath its surface 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.

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

jameo. A large collapse sink formed by collapse 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 to 64 mm (0.08 to 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 of lava and the more fluid lava below.

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

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

lithosphere. The relatively rigid outmost shell of 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.

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

magma. Molten rock beneath Earth's surface 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 Earth's interior between the crust and core.

mugearite. An extrusive volcanic 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 mineral rich in iron, magnesium, and manganese that is commonly found in low-silica (basaltic) igneous rocks.

outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

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.

perched aquifer. An aquifer containing unconfined groundwater separated from an underlying main body of groundwater by an unsaturated zone.

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

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

phreatic explosion. A volcanic eruption or explosion of steam, mud, or other material that is not hot enough to glow; it is caused by the heating and consequent expansion of groundwater due to an underlying igneous heat source.

picrite. Olivine-rich basalt.

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

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

pluton (plutonic). A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.

porphyry. An igneous rock consisting of abundant coarse crystals in a fine-grained matrix.

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

pumice. Solidified "frothy" lava. It is highly vesicular and has very low density.

pumiceous. Volcanic vesicular texture involving tiny gas holes such as in pumice. Finer than scoriaceous.

pyroclast. An individual particle ejected during a volcanic eruption.

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

recharge. Infiltration processes that replenish groundwater.

regolith. General term for the layer of rock debris, organic matter, and soil that commonly forms the land surface and overlies most bedrock.

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 many related normal faults, often associated with volcanic activity.

rift valley. A depression formed by grabens along the crest of an oceanic spreading ridge or in a continental rift zone.

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

riprap. A layer of large, durable, broken rock fragments irregularly thrown together in an attempt to prevent erosion by waves or currents and thereby preserve the shape of a surface, slope, or underlying structure.

rock. A solid, cohesive aggregate of one or more minerals.

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

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

shield volcano. A volcano in the shape of a flattened dome, broad and low, built by flows of very fluid basaltic lava. The Hawaiian Mauna Loa volcano is one example.

shoreface. The zone between the seaward limit of the shore and the more nearly horizontal surface of the offshore zone; typically extends seaward to storm wave depth or about 10 m (32 ft).

slope. The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."

slump. A generally large, coherent mass movement with 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 of 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.

stream. Any body of water moving under gravity flow in a clearly confined channel.

stream terrace. Step-like benches surrounding the present floodplain of a stream due to dissection of previous flood plain(s), stream bed(s), and/or valley floor(s).

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

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Said to be "sinistral" (left-lateral) if relative motion of the block opposite the observer appears to be to the left. "Dextral" (right-lateral) describes relative motion to the right.

structural geology. The branch of geology that deals with the description, representation, and analysis of structures, chiefly on a moderate to small scale. The subject is similar to tectonics, but the latter is generally used for the broader regional or historical phases.

structure. The attitude and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusions.

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 Earth's surface.

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

tectonic. Relating to large-scale movement and deformation of Earth's crust.

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 Earth's surface, including relief and locations of natural and anthropogenic features.

trace (fault). The exposed intersection of a fault with Earth's surface.

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 geologic feature.

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

ultramafic. Describes rock composed chiefly of mafic (dark-colored, iron and magnesium rich) minerals.

unconfined groundwater. Groundwater that has a water table; i.e., water not confined under pressure beneath a confining bed.

vent. An opening at Earth's surface where volcanic materials emerge.

vesicle. A void in an igneous rock formed by a gas bubble trapped when the lava solidified.

vesicular. Describes a volcanic rock with abundant holes that formed from the expansion of gases while the lava was still molten.

vitric. Describes pyroclastic material that is characteristically glassy.

volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).

volcanic arc. A commonly curved, linear, zone of volcanoes above a subduction zone.

volcaniclastic. Describes clastic volcanic materials formed by any process of fragmentation, dispersed by any kind of transporting agent, deposited in any environment.

volcanogenic. Describes material formed by volcanic processes.

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

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

Literature Cited

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Additional References

This section lists additional references, resources, and web sites that may be of use to resource managers. Web addresses are current as of May 2010

Geology of National Park Service Areas

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

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

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

Resource Management/Legislation Documents

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

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

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

Geologic Monitoring Manual
R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado.

[Website under development]. Contact the Geologic Resources Division to obtain a copy.

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

Geological Survey Websites

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

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

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

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

Other Geology/Resource Management Tools

Hawaiʻi Department of Land and Natural Resources (DLNR): http://hawaii.gov/dlnr

Bates, R. L. and J. A. Jackson, editors. American Geological Institute dictionary of geological terms (3rd Edition). Bantam Doubleday Dell Publishing Group, New York.

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

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

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

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

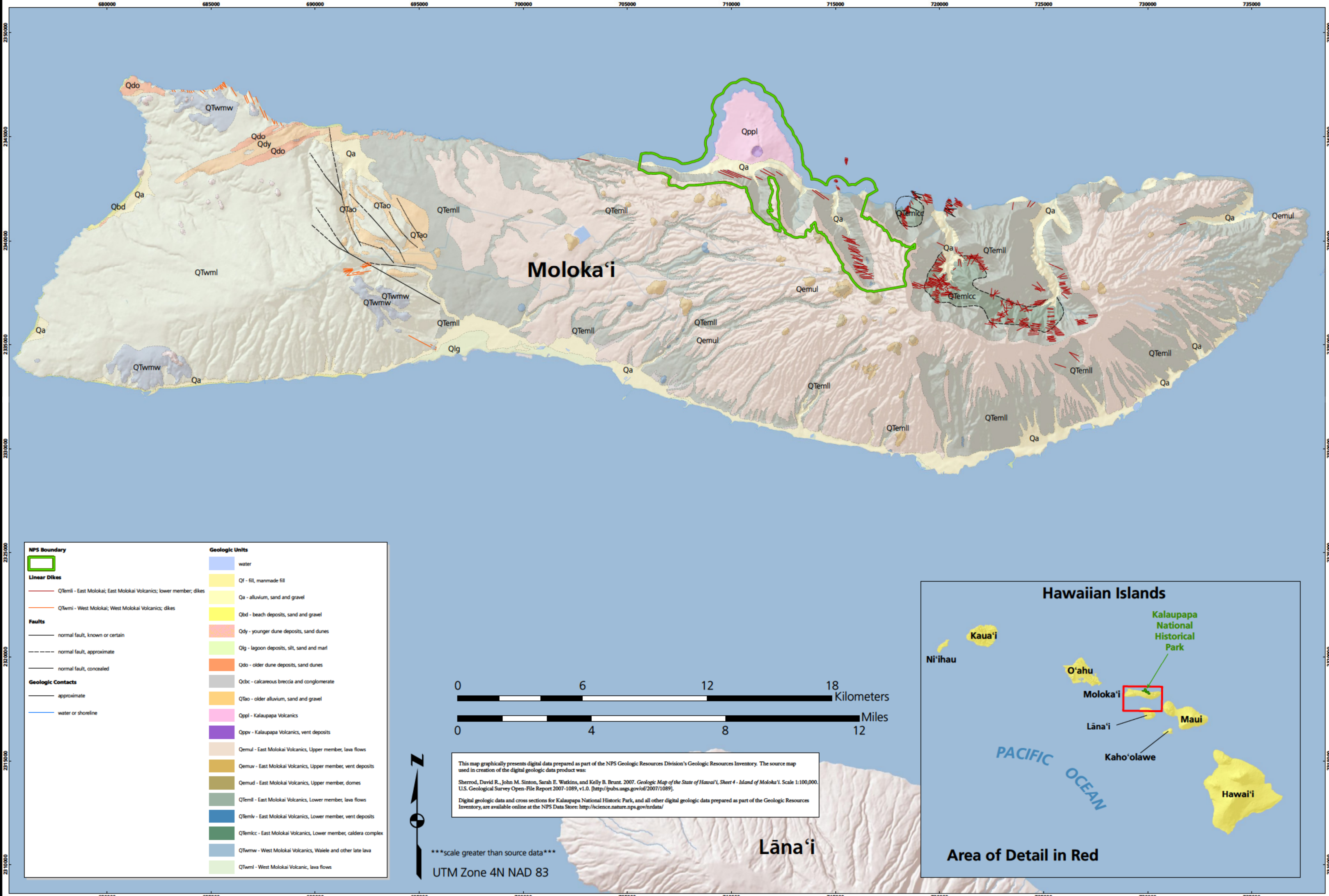
U.S. Geological Survey Publications Warehouse (many USGS publications are available online): http://pubs.usgs.gov

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

Appendix A: Overview of Digital Geologic Data

The following page is an overview of the digital geologic data for Kalaupapa National Historical Park. For a poster-size PDF of this overview and complete digital data, please see the included CD or visit the Geologic Resources Inventory publications web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Overview of Digital Geologic Data for Kalaupapa NHP



Appendix B: Scoping Session Participants

The following is a list of participants from the GRI scoping session for Kalaupapa National Historical Park held on March 20, 2003. The contact information and email addresses in this appendix may be outdated; please contact the Geologic Resources Division for current information.

Name	Affiliation	Position	Phone	E-mail
Momi Aiu	Science and Technology International	GIS specialist	808-540-4711	momi@sti-hawaii.com
Janet Babb	Hawaii Volcanoes National Park	Exhibit Specialist	808-985-6014	janet_babb@nps.gov
Larry Basch	NPS Pacific Island Coral Reef Program (University of Hawaii, Manoa)	Senior Scientist	808-956-8820	lbasch@hawaii.edu
Rebecca Beavers	NPS Geologic Resources Division	Geologist	303-987-6945	rebecca_beavers@nps.gov
Tim Connors	NPS Geologic Resources Division	Geologist	303-969-2093	tim_connors@nps.gov
Peter Craig	National Park of American Samoa	Biologist	684-633-7082	peter_craig@nps.gov
David Deardorff	NPS Pacific Islands Network	Network Coordinator	808-985-6180	david_deardorff@nps.gov
Eva DiDonato	National Park of American Samoa	Ecologist	684-633-7082	eva_didonato@nps.gov
Charlotte Forbes-Perry	Hawaii Volcanoes National Park	Workgroup Facilitator	808-985-6180	c_forbes_perry@ contractor.nps.gov
Joe Gregson	NPS Natural Resources Information Division	Physical Scientist	970-225-3559	joe_gregson@nps.gov
Bruce Heise	NPS Geologic Resources Division	Geologist	303-969-2017	bruce_heise@nps.gov
Darcy Hu	NPS Pacific Island Support Office	Ecologist	808-985-6092	darcy_hu@nps.gov
Andrea Kaawaloa	Hawaii Volcanoes National Park	Park Ranger	808-985-8013	andrea_kaawaloa@nps.gov
Darcee Killpack	NOAA Pacific Services Center	Spatial Technology Coordinator	808-532-3202	darcee.killpack@noaa.gov
Dwayne Minton	War in the Pacific National Historical Park	Ecologist	671-472-7240 x345	dwayne_minton@nps.gov
Bruce Richmond	USGS Coastal Mapping Group	Geologist	831-427-4731	brichmond@usgs.gov
John Rooney	University of Hawaii	Researcher	808-956-3605	jrooney@hawaii.edu
Eric Rutherford	NPS Pacific Islands Network/USGS	Research Facilitator	808-967-8034	erutherford@ hvomail.wr.usgs.gov
Chuck Sayon	American Memorial Park	Site Manager	670-234-7207	chuck_sayon@nps.gov
Dave Sherrod	USGS Hawaiian Volcano Observatory	Geologist	808-967-8034	dsherrod@usgs.gov
Gordon Tribble	U.S. Geological Survey	Hydrologist	808-587-2405	gtribble@usgs.gov
Frank Trusdell	USGS Hawaiian Volcano Observatory	Geologist	808-967-8812	trusdell@usgs.gov

NPS 491/105573, September 2010

National Park Service
U.S. Department of the Interior

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

www.nature.nps.gov