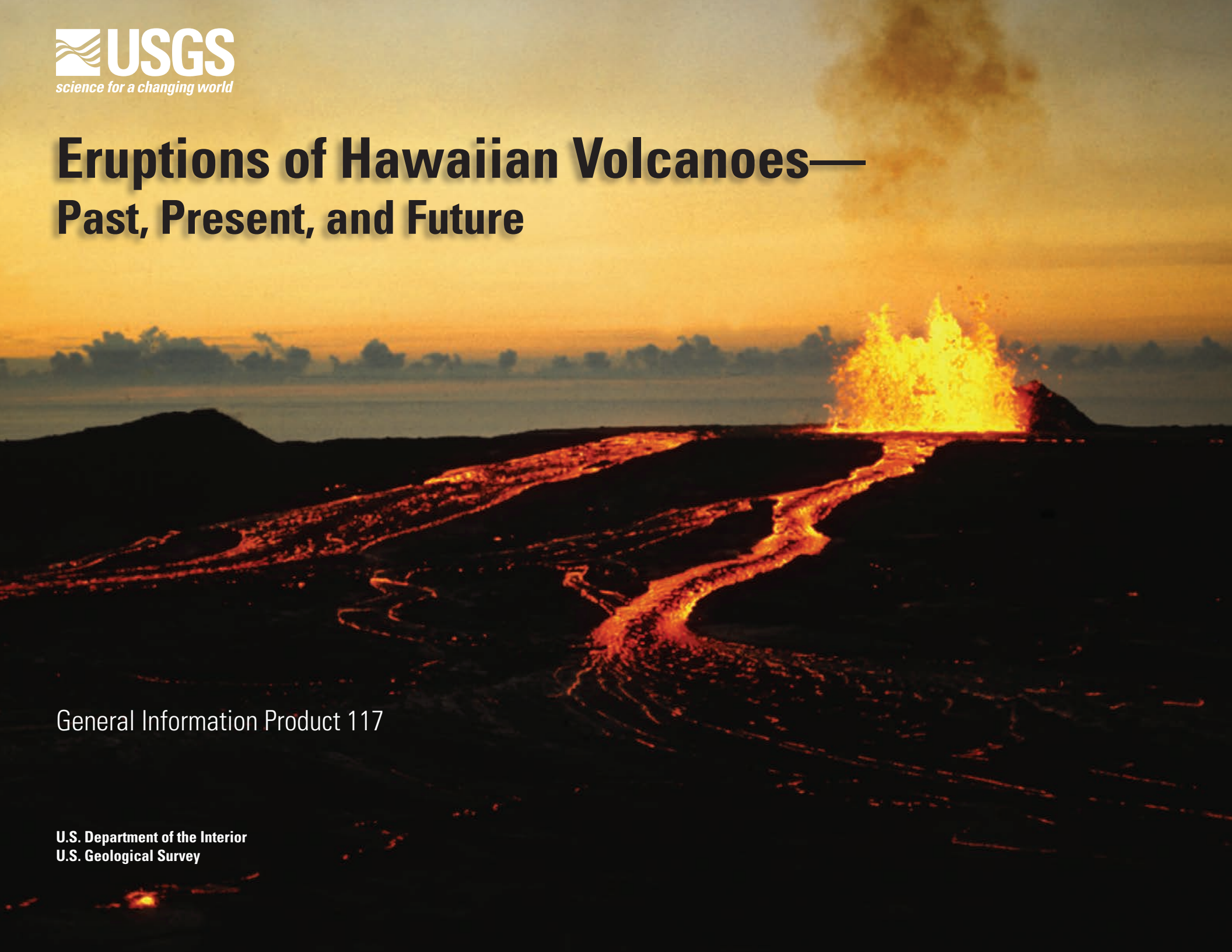

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Eruptions of Hawaiian Volcanoes—
Past, Present, and Future

General Information Product 117

U.S. Department of the Interior
U.S. Geological Survey

Cascades of lava fed by fountains at vent (seen spouting on the skyline) fall more than 75 feet to fill ʻĀloʻi Crater during the 1969–71 Mauna Ulu eruption of Kīlauea Volcano. (USGS photograph by Donald A. Swanson)*

*This publication uses English units of measurement. For readers who use metric units, a conversion table is given in the back of the booklet.

***Cover**—Eruption of Kīlauea Volcano, as viewed at dawn on January 30, 1974. Overflows from an active lava lake spill down the flank of the volcanic shield at Mauna Ulu, built by many such overflows since 1969. The height of this shield was nearly 400 feet when the Mauna Ulu eruptions ended in July 1974. (USGS photograph by Robert I. Tilling.)*

Eruptions of Hawaiian Volcanoes—
Past, Present, and Future

By Robert I. Tilling, Christina Heliker, and Donald A. Swanson

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Lava shoots 1,000 feet into the air in April 1983 during a high-fountaining episode of the Pu‘u ‘Ō‘ō-Kupaianaha eruption of Kīlauea Volcano. (USGS photograph by J.D. Griggs.)

Preface

Viewing an erupting volcano is a memorable experience, one that has inspired fear, superstition, worship, curiosity, and fascination since before the dawn of civilization. In modern times, volcanic phenomena have attracted intense scientific interest, because they provide the key to understanding processes that have created and shaped more than 80 percent of the Earth's surface. The active Hawaiian volcanoes have received special attention worldwide because of their frequent spectacular eruptions, which often can be viewed and studied with relative ease and safety.

In January 1987, the Hawaiian Volcano Observatory (HVO), located on the rim of Kīlauea Volcano, celebrated its 75th Anniversary. In honor of HVO's Diamond Jubilee, the U.S. Geological Survey (USGS) published Professional Paper 1350 (see list of Selected Readings, page 57), a comprehensive summary of the many studies on Hawaiian volcanism by USGS and other scientists through the mid-1980s. Drawing from the wealth of data contained in that volume, the USGS also published in 1987 the original edition of this general-interest booklet, focusing on selected aspects of the eruptive history, style, and products of two of Hawai‘i's active volcanoes, Kīlauea and Mauna Loa. This revised edition of the booklet—spurred by the approaching Centennial of HVO in January 2012—summarizes new information gained since the January 1983 onset of Kīlauea’s Pu‘u ‘Ō‘ō-Kupaianaha eruption, which has continued essentially nonstop through 2010 and shows no signs of letup. It also includes description of Kīlauea’s summit activity within Halema‘uma‘u Crater, which began in mid-March 2008 and continues as of this writing (late 2010).

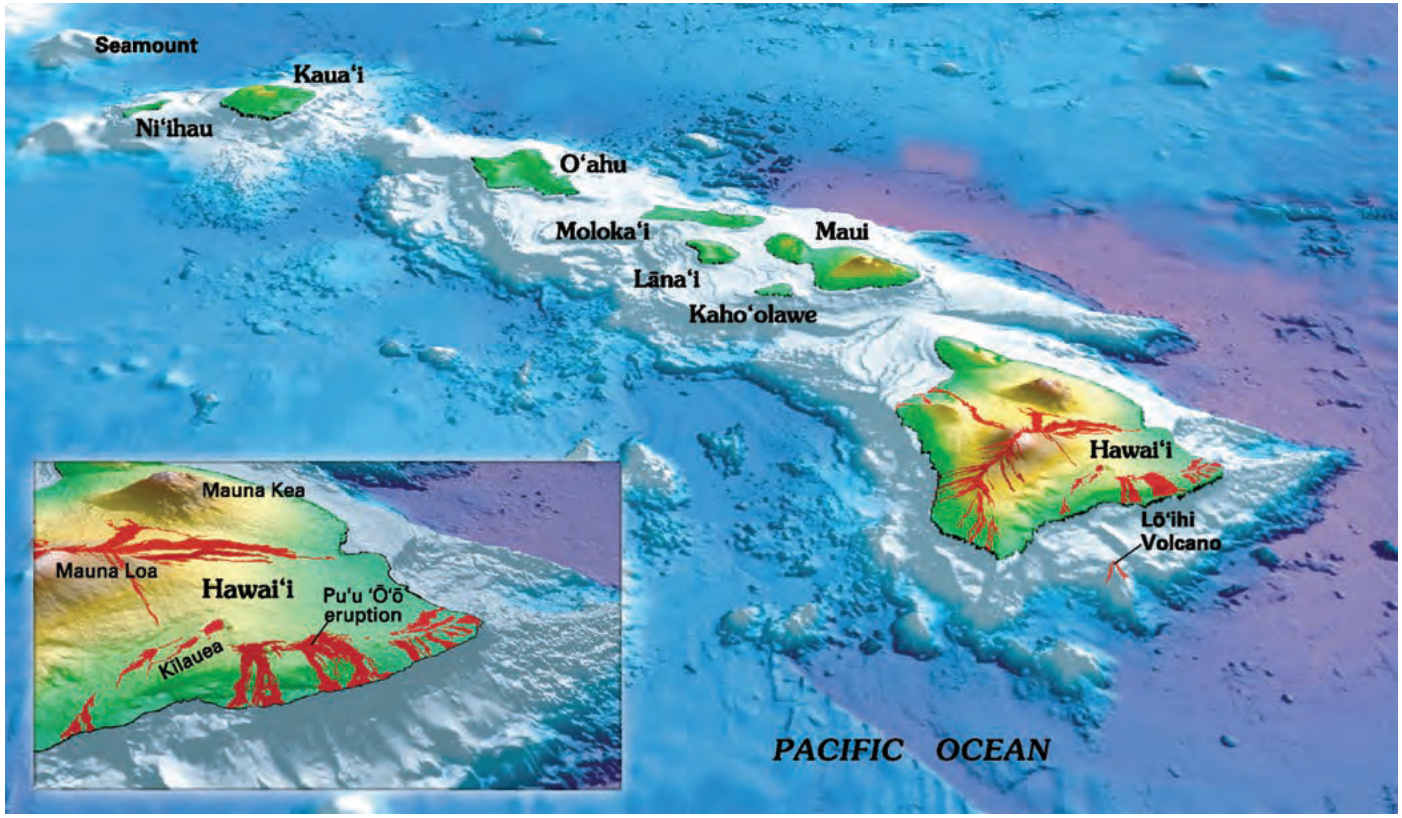
This general-interest booklet is a companion to the one on Mount St. Helens Volcano first published in 1984 and revised in 1990 (see Selected Readings). Together, these publications illustrate the contrast between the two main types of volcanoes: shield volcanoes, such as those in Hawai‘i, which generally are nonexplosive; and composite volcanoes, such as Mount St. Helens in the Cascade Range, which are renowned for their explosive eruptions.

Introduction

“The loveliest fleet of islands that lies anchored in any ocean.”—Mark Twain

Few would quarrel with Mark Twain's vivid description of Hawai‘i, written after his 4-month stay in 1866. Archeologists believe that the Hawaiian Islands were discovered and settled around the 9th century C.E. or earlier by Polynesians sailing from islands, probably the Marquesas, in the southern tropical Pacific. Subsequently, nearly a thousand years of cultural isolation passed before the first documented visit to Hawai‘i by non-Polynesians. On January 18, 1778, during his third major voyage in the Pacific, the famous British navigator and explorer, Captain James Cook, sighted the Polynesians' secluded home. Cook named his discovery the "Sandwich Islands," in honor of the Earl of Sandwich, then First Lord of the British Admiralty. Mark Twain's fleet of islands is larger than Rhode Island and Connecticut combined. The Island of Hawai‘i, commonly called the "Big Island," covers more than twice the total area of the other islands.

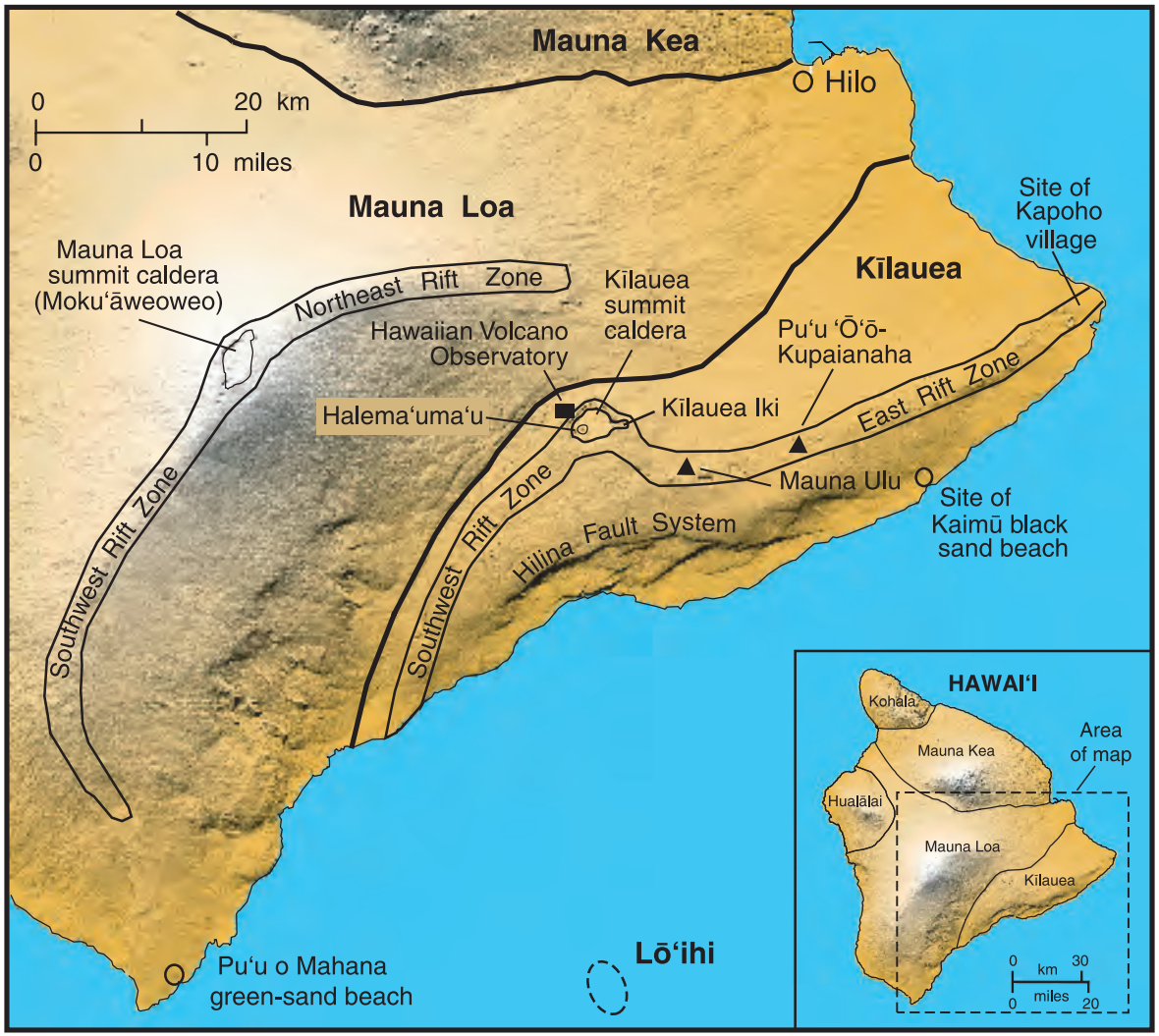
Hawai‘i, which became our 50th state in 1959, is now home for more than 1.2 million people and hosts many times that number of visitors each year. Hawai‘i's worldwide image as an idyllic tropical paradise is well deserved. What is less well known, however, is that the islands exist only because of nearly continuous volcanic activity. Most of the prominent features of the Hawaiian Islands, such as Diamond Head on O‘ahu, Haleakalā Crater on Maui, and the huge mountains of Mauna Loa and Mauna Kea on the Island of Hawai‘i, are volcanic.



The principal Hawaiian islands, stretching about 400 miles from Ni'ihau in the northwest to the Island of Hawai'i in the southeast, are the exposed tops of volcanoes that rise tens of thousands of feet above the ocean floor. Some islands are made up of two or more volcanoes. Areas in red on the Island of Hawai‘i indicate lava flows erupted during the past two centuries. Lō‘ihi Seamount, Hawai‘i's newest (and still submarine) volcano, lies about 3,100 feet beneath the sea. (Modified from image by Joel E. Robinson, USGS, in “This Dynamic Planet” map of Simkin and others, 1996.)

Since the early 19th century, frequent eruptions have been documented at Mauna Loa and Kīlauea; these two volcanoes on the Island of Hawai‘i are among the most active in the world. Nearby Lō‘ihi Seamount, off the island's south coast, is the newest Hawaiian volcano, actively growing on the seafloor deep beneath the ocean surface.

Most eruptions of Mauna Loa and Kīlauea are nonexplosive, and both volcanoes are readily accessible, such that scientists generally can study them at close range in relative safety. As a result, these are two of the most intensely observed and best understood volcanoes on our planet. Research on these active volcanoes provides a basis for understanding the life story of older, now inactive Hawaiian volcanoes and similar volcanoes worldwide. Because of their frequent activity and accessibility, Hawaiian volcanoes serve as a superb natural laboratory for scientists from around the world to study volcanic eruptions.



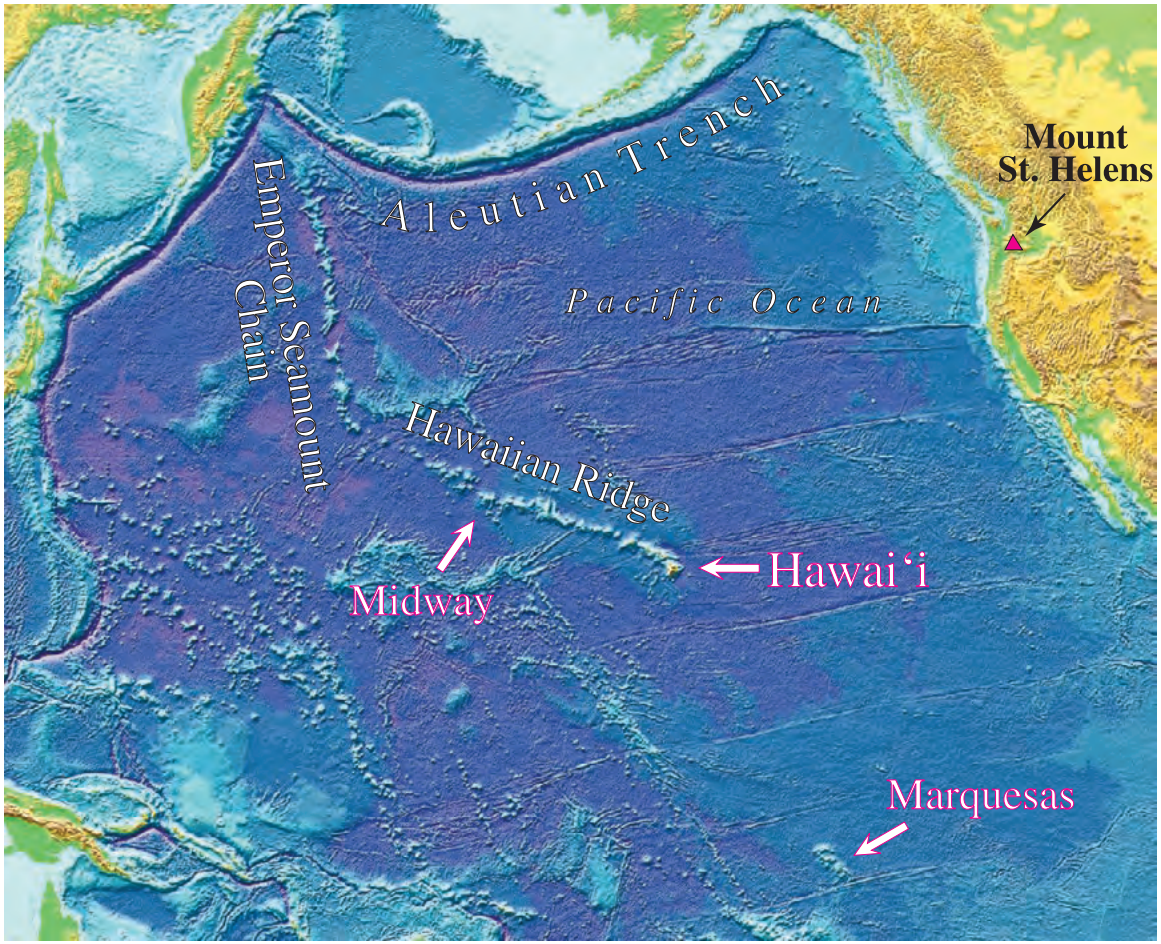
Shaded relief map of the southeastern part of the Island of Hawai‘i, showing the principal features and localities of Mauna Loa, Kīlauea, and Lō‘ihi Volcanoes discussed in the text.

Lili‘uokalani Park, in the city of Hilo on the Island of Hawai'i, typifies the tropical beauty and serenity of the Hawaiian Islands. (USGS photograph by Taeko Jane Takahashi.)

Origin of the Hawaiian Islands

The Hawaiian Islands are the tops of gigantic volcanic mountains formed by countless eruptions of fluid *lava** over several million years; some tower more than 30,000 feet above the seafloor. These volcanic peaks rising above the ocean surface represent only the tiny, visible part of an immense submarine ridge, the Hawaiian Ridge—Emperor Seamount Chain, composed of more than 80 large volcanoes. This range stretches across the Pacific Ocean floor from the Hawaiian Islands to the Aleutian Trench. The length of the Hawaiian Ridge segment alone, between the Island of Hawai‘i and Midway Island to the northwest, is about 1,600 miles, roughly the distance from Washington, D.C., to Denver, Colorado. The amount of lava erupted to form this huge ridge, about 186,000 cubic miles, is more than enough to cover the State of California with a layer 1 mile thick.

*Most of the italicized terms in the text are defined and explained as an integral part of the discussion. However, for those terms perhaps not fully explained, a Glossary at the back of this booklet (p. 62) provides supplementary information or broader context.



Map of the Pacific basin showing the location of the Hawaiian Ridge-Emperor Seamount Chain in relation to some other features and localities mentioned in the text. (Base map from the third edition of "This Dynamic Planet" map, 2006)

Hawaiian Legends and Early Scientific Work

The distinctive northwest-southeast alignment of the Hawaiian chain was known to early explorers of the Pacific Ocean, including the Polynesians who first settled the islands. The ancient Hawaiians were superb sailors, excellent navigators, and keen observers of nature, including volcanic eruptions and their effects. They noticed the varying extent of erosion from island to island, the amount of vegetation on the slopes of the various volcanoes, the freshness of lava flows, and other indicators of the relative ages of the islands. Some of the legends of the early Hawaiians suggest that they recognized that the islands become younger from the northwest to the southeast.

Hawaiian legends tell that eruptions were caused by Pele, the sometimes-tempestuous Goddess of Fire, during her frequent moments of anger. Pele was both revered and feared; her immense power and many adventures figured prominently in ancient Hawaiian songs and chants. She could cause earthquakes by stamping her feet and volcanic eruptions and fiery devastation by digging with the "pāoa," her magic stick. One oft-told legend describes the long and bitter quarrel between Pele and her older sister Namakaokahaʻi, the Goddess of the Sea, that drove Pele to migrate—from northwest to southeast along the island chain—to her present stopping place on the Island of Hawaiʻi.

Pele first used her pāoa on Kauaʻi, where she subsequently was attacked by Namakaokahaʻi and left for dead. Recovering, she fled to Oahʻu, where she dug a number of "fire pits"—including the crater we now call Diamond Head, the tourist's landmark of modern Honolulu. Pele then left her mark on the island of Molokaʻi before traveling farther southeast to Maui and creating Haleakalā Volcano, which forms the eastern half of that island. By then Namakaokahaʻi realized that Pele was still alive and went to Maui to do battle with her. After

Above: *Pele, the Goddess of Fire (or Volcanoes), as portrayed by artist D. Howard Hitchcock. (USGS photograph by J.D. Griggs, with permission of the Volcano House Hotel, owner of the original painting.)* ***Below:*** *Night view (time exposure) of Pele's home during the 1967–68 eruption within Halemaʻumaʻu Crater. (Photograph by Richard S. Fiske.) Similar views can be seen on a clear night during the current (2010) eruption at Halemaʻumaʻu.*

a terrific fight, Namakaokaha‘i again believed that she had killed her younger sister, only to discover later, however, that Pele was very much alive and busily working at Mauna Loa Volcano on the Island of Hawai‘i. Namakaokaha‘i then conceded that she could never permanently crush her sister's indomitable spirit and gave up the struggle. Pele dug her final and eternal fire pit, Halema‘uma‘u Crater, at the summit of Kīlauea Volcano, where her spirit is said to reside to this day.

Some interpretations directly link Pele’s epic migration to the actual successive creation of the islands. Other—and more accepted—interpretations assume that the islands were already in place and that Pele’s arrival at each caused new or rejuvenated volcanism. In any case, the various accounts of migration of volcanic activity from Kaua‘i to Hawai‘i in Hawaiian legends are in accord with modern scientific studies.

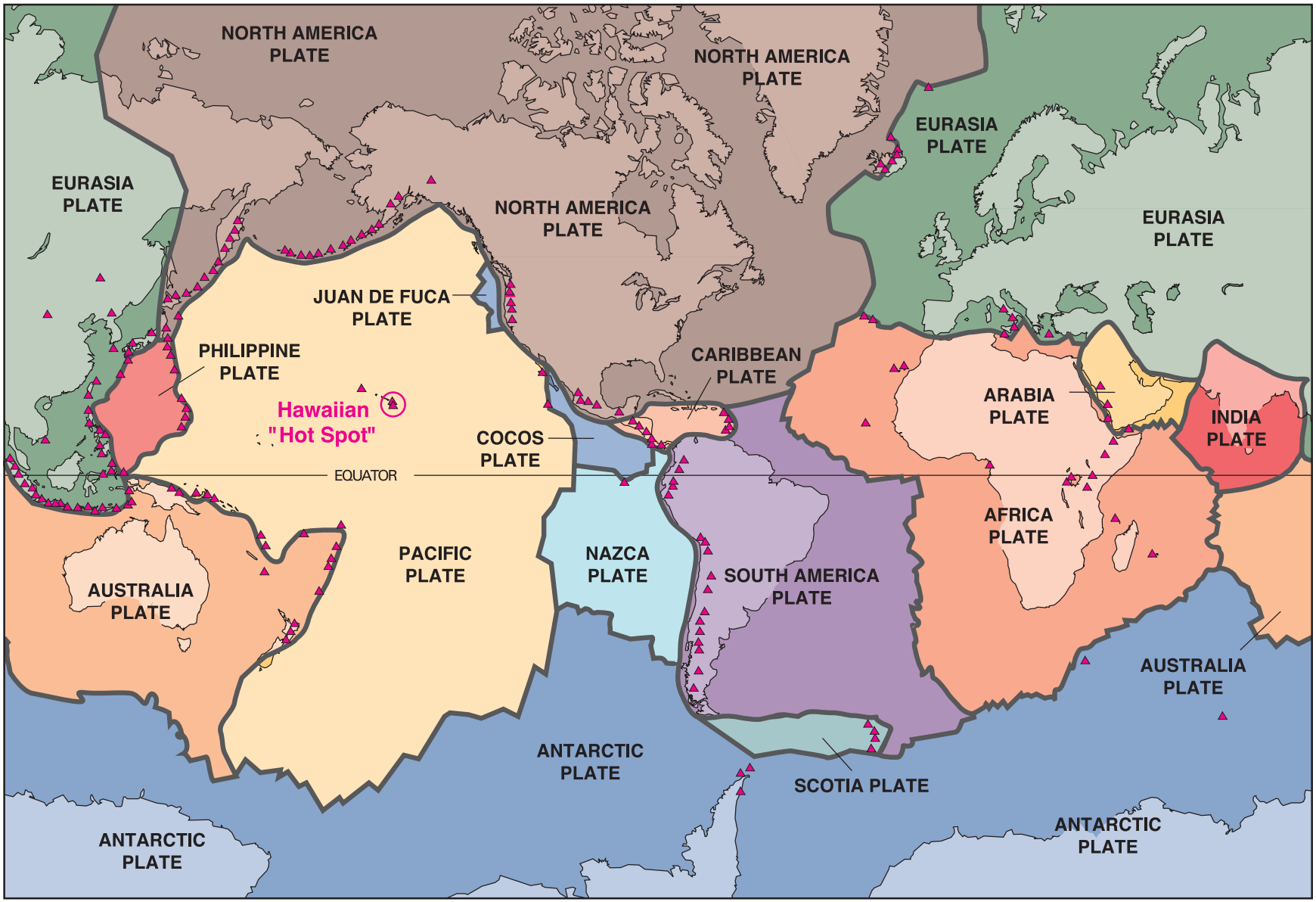
A painting by renowned Hawaiian artist Herb Kawainui Kane depicting Pele fighting with her older sister and nemesis Namakaokaha‘i (the Goddess of the Sea) during the fierce battles between these two deities in legends of Pele’s migration along the Hawaiian island chain (see text). (Image used with permission of the artist.)

The first geologic study of the Hawaiian Islands was conducted during six months in 1840–1841, as part of the U.S. Exploring Expedition of 1838–1842, commanded by Lieutenant Charles Wilkes of the U.S. Navy. The expedition's geological investigations were directed by James Dwight Dana. Though only 25 years old in 1838, Dana was no stranger to volcanoes. In 1834 he had studied Vesuvius, the active volcano near Naples, Italy.

Dana and his colleagues recognized that the islands become increasingly younger from northwest to southeast along the Hawaiian volcanic chain, largely because of differences in their degree of erosion. The greater the length of time since its last eruption, the greater the erosion of the volcano. He also suggested that some other island chains in the Pacific showed a similar general decrease in age from northwest to southeast.

The alignment of the Hawaiian Islands, Dana proposed, reflected localized volcanic activity along segments of a major fissure zone slashing across the ocean floor. Dana's "great fissure" origin for the islands served as a prominent working hypothesis for many subsequent studies until the mid-20th century. The monumental work of Dana—considered to be the first American volcanologist—resulted in greatly increased awareness of the Hawaiian volcanoes, which have continued to attract much scientific attention since.

Left: *The deeply eroded Koʻolau Volcano on the Island of Oʻahu is 2 to 3 million years older than Mauna Loa Volcano on Hawaiʻi (skyline, right photograph), whose profile is unscarred by erosion. (Photograph by Richard S. Fiske.)* ***Right:*** *The Hawaiian Volcano Observatory (circled) can be seen perched on Uwēkahuna Bluff, the highest point on Kīlauea's caldera rim. (USGS photograph by J.D. Griggs.)*



Tectonic Plates and Active Volcanoes of the World. *Most active volcanoes are located along or near the boundaries of Earth's shifting tectonic plates. Hawaiian volcanoes, however, occur in the middle of the Pacific Plate and are formed by volcanism over the Hawaiian "Hot Spot" (see text). Only some of the Earth's more than 500 active volcanoes are shown here (red triangles). (Sketch map from Kious and Tilling, 1996.)*

Plate Tectonics and the Hawaiian "Hot Spot"

In the early 1960s, the related concepts of "seafloor spreading" and "plate tectonics" emerged as powerful new hypotheses that geologists used to interpret the features and movements of the Earth's surface layer. According to the plate tectonic theory, the Earth's rigid outer layer, or "lithosphere," consists of about a dozen slabs or plates, each averaging 50 to 100 miles thick. These plates move relative to one another at average speeds of a few inches per year—about as fast as human fingernails grow. Scientists recognize three common types of boundaries between these moving plates (see diagrams at right):

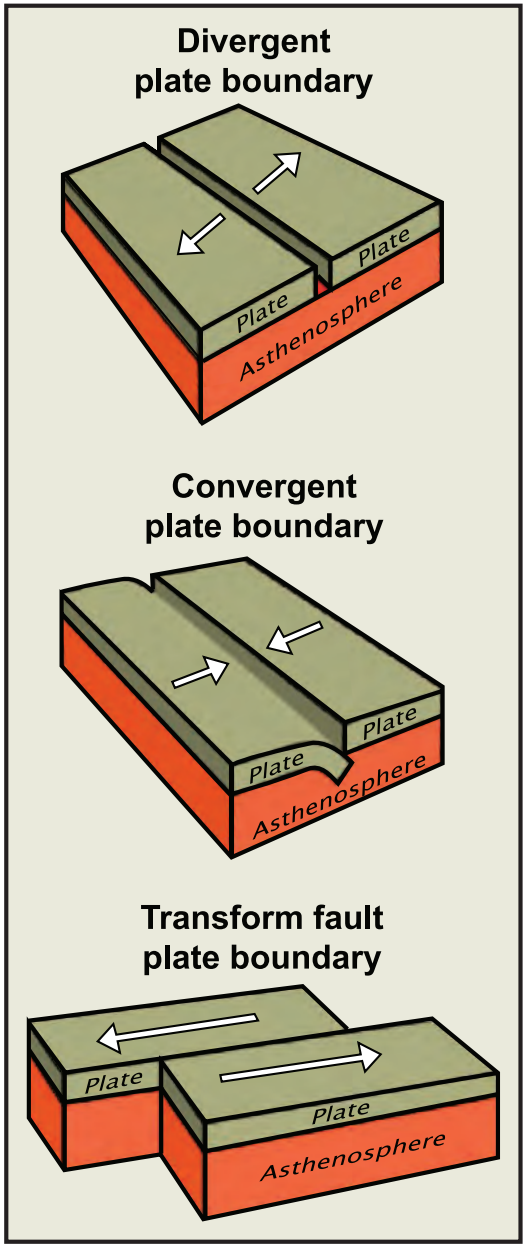
(1) *Divergent or spreading*—adjacent plates pull apart, such as at the Mid-Atlantic Ridge, which separates the North and South America Plates from the Eurasia and Africa Plates. This pulling apart causes "seafloor spreading" as new material from the underlying less rigid layer, or "asthenosphere," fills the cracks and adds to these oceanic plates.

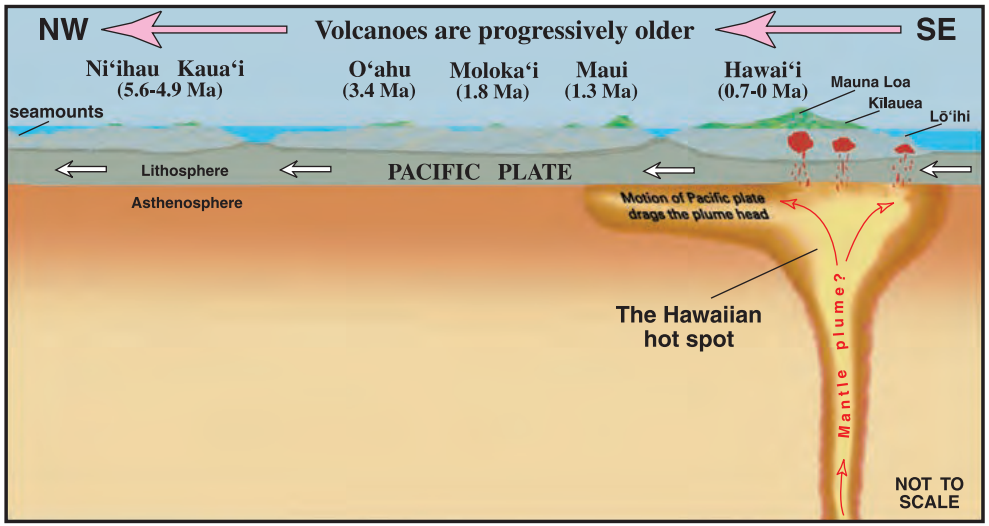
(2) *Convergent*—two plates move towards one another and one is dragged down (or "subducted") beneath the other. Convergent plate boundaries are also called "subduction zones" and are typified by the Aleutian Trench, where the Pacific Plate is being subducted under the North America Plate. Mount St. Helens (southwest Washington) and Mount Fuji (Japan) are excellent examples of subduction-zone volcanoes formed along convergent plate boundaries.

(3) *Transform fault*—one plate slides horizontally past another. The best-known example is the earthquake-prone San Andreas Fault Zone of California, which marks the boundary between the Pacific and North America Plates.

Nearly all of the world's earthquakes and active volcanoes occur along or near the boundaries of the Earth's shifting plates. Why then are the Hawaiian volcanoes located in the middle of the Pacific Plate, more than 2,000 miles from the nearest boundary with any other tectonic plate? The proponents of plate tectonics at first had no explanation for the occurrence of volcanoes within plate interiors ("intraplate" volcanism). Then in 1963, J. Tuzo Wilson, a Canadian geophysicist, provided an ingenious explanation within the framework of plate tectonics by proposing the "hot spot" hypothesis. Wilson's hypothesis has come to be accepted widely, because it agrees well with much of the scientific data on linear volcanic island chains in the Pacific Ocean in general—and the Hawaiian Islands in particular.

According to Wilson, the distinctive linear shape of the Hawaiian-Emperor Chain reflects the progressive movement of the Pacific Plate over a "deep" and "fixed" hot spot. In recent years, scientists have been debating about the actual depth(s) of the Hawaiian and other Earth hot spots. Do they extend only a few hundred miles beneath the lithosphere? Or do they extend down thousands of miles, perhaps to Earth's core-mantle boundary? Also, while scientists general agree that hot spots are fixed in position relative to the faster moving overriding plates, some recent studies have shown that hot spots can migrate slowly over geologic time. In any case, the Hawaiian hot spot partly melts the region just below the overriding Pacific Plate, producing small, isolated blobs of molten rock (*magma*). Less dense than the surrounding solid rock, the magma blobs come together and rise buoyantly through structurally weak zones and ultimately erupt as lava onto the ocean floor to build volcanoes.





A cutaway view along the Hawaiian island chain showing the inferred mantle plume that has fed the Hawaiian hot spot on the overriding Pacific Plate. The geologic ages of the oldest volcano on each island (Ma = millions of years ago) are progressively older to the northwest, consistent with the hot spot model for the origin of the Hawaiian Ridge-Emperor Seamount Chain. (Modified from image of Joel E. Robinson, USGS, in "This Dynamic Planet" map of Simkin and others, 2006.)

Over a span of about 70 million years, the combined processes of magma formation, eruption, and continuous movement of the Pacific Plate over the stationary hot spot have left the trail of volcanoes across the ocean floor that we now call the Hawaiian-Emperor Chain. A sharp bend in the chain about 2,200 miles northwest of the Island of Hawai‘i was previously interpreted as a major change in the direction of plate motion around 43–45 million years ago (Ma), as suggested by the ages of the volcanoes bracketing the bend. However, recent studies suggest that the northern segment (Emperor Chain) formed as the hot spot moved southward until about 45 Ma, when it became fixed. Thereafter, northwesterly plate movement prevailed, resulting in the formation of the Hawaiian Ridge "downstream" from the hotspot.

The Island of Hawai‘i is the southeasternmost and youngest island in the chain. The southeasternmost part of the Island of Hawai‘i presently overlies the hot spot and still taps the magma source to feed its active volcanoes. The active submarine volcano Lō‘ihi, off the Island of Hawai‘i's south coast, may mark the beginning of the zone of magma formation at the southeastern edge of the hot spot. With the possible exception of Maui, the other Hawaiian islands have moved northwestward beyond the hot spot—they were successively cut off from the sustaining magma source and are no longer volcanically active.

The progressive northwesterly drift of the islands from their point of origin over the hot spot is well shown by the ages of the principal lava flows on the various Hawaiian Islands from northwest (oldest) to southeast (youngest), given in millions of years: Ni‘ihau and Kaua‘i, 5.6 to 3.8; O‘ahu, 3.4 to 2.2; Moloka‘i, 1.8 to 1.3; Maui, 1.3 to 0.8; and Hawai‘i, less than 0.7 and still growing.

Even for the Island of Hawai‘i alone, the relative ages of its five volcanoes are compatible with the hot-spot theory (see map, page 3). Kohala, at the northwestern corner of the island, is the oldest, having ceased eruptive activity about 120,000 years ago. The second oldest is Mauna Kea, which last erupted about 4,000 years ago; next is Hualālai, which has had only one eruption (1800–1801) in written history. Lastly, both Mauna Loa and Kīlauea have been vigorously and repeatedly active in the past two centuries. Because it is growing on the southeastern flank of Mauna Loa, Kīlauea is believed to be younger than its huge neighbor.

The size of the Hawaiian hot spot is not well known, but it presumably is large enough to encompass and feed the currently active volcanoes of Mauna Loa, Kīlauea, Lō‘ihi and, possibly, also Hualālai and Haleakalā. Some scientists have estimated the Hawaiian hot spot to be about 200 miles across, with much narrower vertical passageways that feed magma to the individual volcanoes.

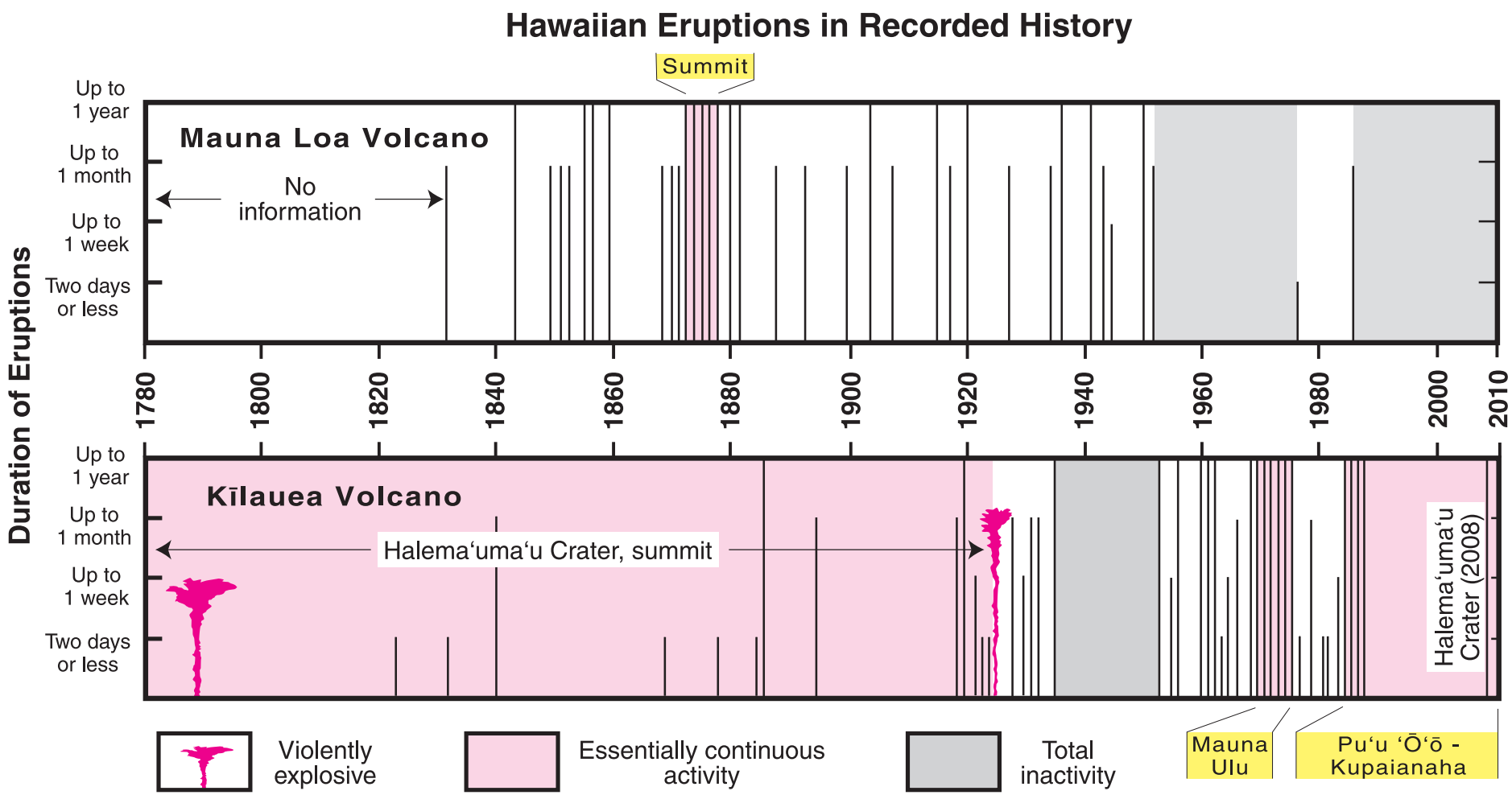
Hawaiian Eruptions in Recorded History

Hawai‘i has a brief written history, extending back only about 200 years, compared to such volcanic regions as Iceland, Indonesia, Italy, and Japan. Written accounts exist for most Hawaiian eruptions since 1823, when the first American missionaries visited the Island of Hawai‘i. Descriptions of earlier eruptions are sketchier, because they are based only on interpretations of ancient Hawaiian chants and stories told to the American missionaries by Hawaiian elders and early European residents.

All the known Hawaiian eruptions since 1778 have been at Mauna Loa and Kīlauea Volcanoes, except for the 1800–1801 eruption of Hualālai Volcano on the west coast of the Island of Hawai‘i. In an exception to the overall northwest-southeast shift of volcanic activity, a series of minor submarine eruptions probably occurred in 1955–56 between the islands of O‘ahu and Kaua‘i and near Necker Island, about 350 miles northwest of Kaua‘i.

For the past 200 years, Mauna Loa and Kīlauea have tended to erupt on average every two or three years, placing them among the most frequently active volcanoes of the world. At each volcano, some intervals of repose between eruptions at a given volcano have been much longer than its long-term average. The individual Kīlauea eruptions recorded since 1778 are in addition to the nearly continuous eruptive activity within or near Halema‘uma‘u Crater, extending throughout the 19th century and into the early 20th century.

On March 30, 1984, Kīlauea and Mauna Loa were in simultaneous eruption, the first time since 1924. ***Above:*** *Kīlauea's Pu‘u ‘Ō‘ō vent during its 17th high-fountaining episode.* ***Below:*** *Aerial view of a long lava flow during the Mauna Loa eruption, which began on March 25; this eruption fed a major lava flow that advanced toward the city of Hilo. (Upper photograph by Edward W. Wolfe, USGS; lower photograph by Scott Lopez, National Park Service.)*



Graph summarizing the eruptions of Mauna Loa and Kīlauea Volcanoes during the past 200 years. The Puʻu ʻŌʻō- Kupaianaha eruption has continued into the 21st century. Information is sketchy for eruptions before 1823, when the first missionaries arrived on the Island of Hawaiʻi. The total duration of eruptive activity in a given year, shown by the length of the vertical bar, may be for a single eruption or a combination of several separate eruptions.

The active lava lake within Halemaʻumaʻu Crater overflowing its levee, as painted by D. Howard Hitchcock in 1894. Snow-capped Mauna Loa forms the far horizon. (USGS photograph by J.D. Griggs, with permission of the Volcano House Hotel, owner of the original painting.)

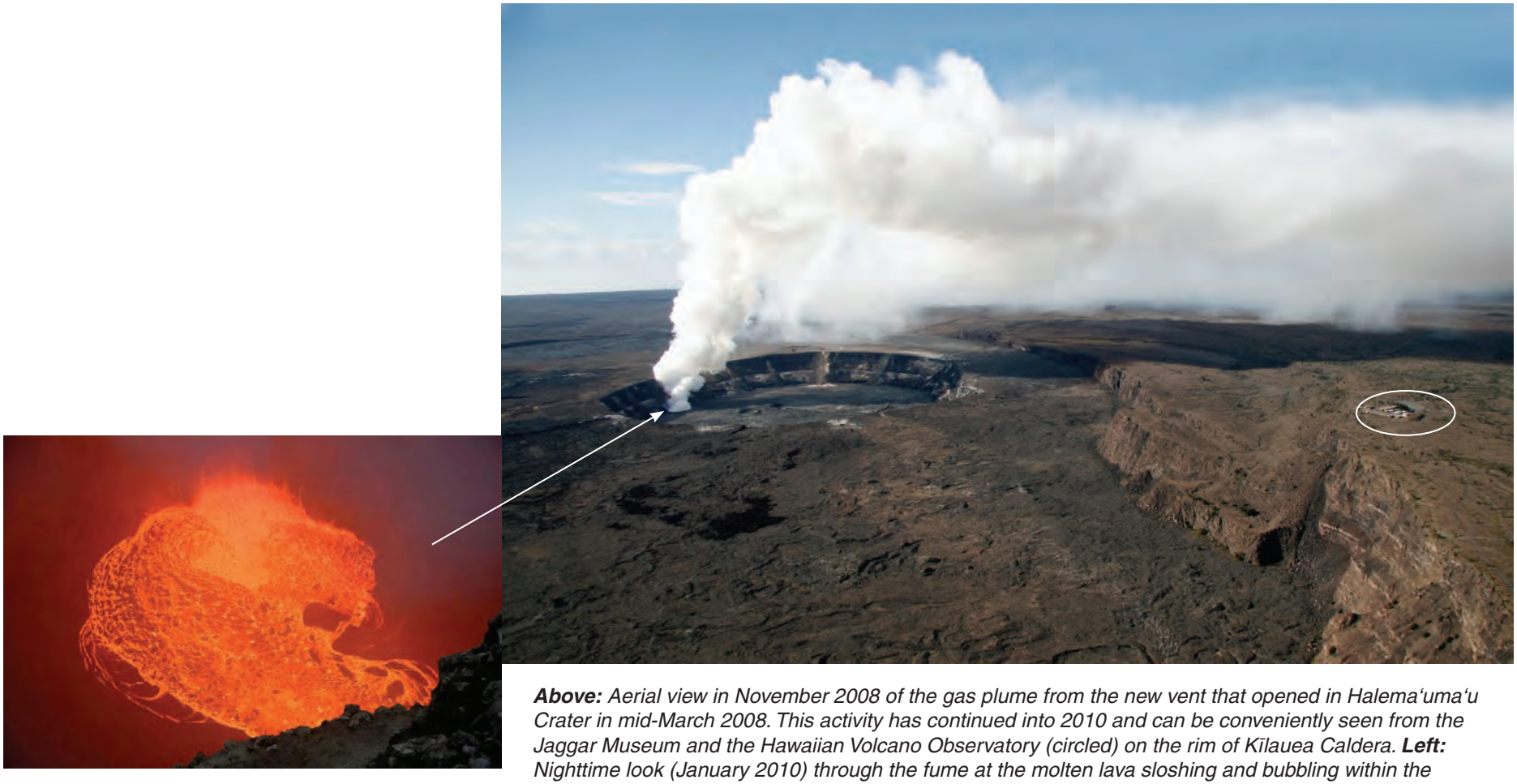
Simultaneous eruption of both volcanoes has been rare, except at times when Kīlauea was continuously active before 1924. The only post-1924 occurrence of simultaneous eruption was in March 1984, when activity at both volcanoes overlapped for one day. Long repose intervals for one volcano correlate approximately with increased activity at the other. This general relation is imperfect but holds well for post-1924 eruptive activity. Between 1934 and 1952, only Mauna Loa was active; between 1952 and 1974, only Kīlauea was.

Since July 1950, Hawaiian eruptive activity has been dominated by frequent and sometimes prolonged eruptions at Kīlauea, while only two short-lived eruptions have occurred at Mauna Loa (July 1975 and March–April 1984). As of 2010, Kīlauea's Puʻu ʻŌʻō-Kupaianaha eruption, which began in January 1983, showed no signs of decline. This eruption has been primarily fed by the Puʻu ʻŌʻō vent, except for two extended periods: (1) July 1986–February 1992 at the Kupaianaha vent; and (2) July 2007–present at vents about a half mile uprift from Kupaianaha.

Except for the nearly continuous eruptive activity at Halemaʻumaʻu for a century before 1924, the Puʻu ʻŌʻō-Kupaianaha eruption—still continuing through 2010—has now become the longest lasting Hawaiian eruption in recorded history.

In mid-March 2008, a new vent opened within Halemaʻumaʻu Crater, and a faint glow could be seen at night. Early on the morning of March 19, a small explosion occurred at this vent—the first explosive activity at Kīlauea's summit since 1924. Rock debris from the explosion—with a few blocks as large as a yard across—was strewn over about 75 acres, covered a stretch of Crater Rim Drive, and damaged the Halemaʻumaʻu visitor overlook. People in Pahala (~ 20 miles downwind) reported a light dusting of ash on their cars. In early September 2008, molten lava was observed bubbling and sloshing within the pit, and lava has been present intermittently into 2010. As the summit activity continued—characterized by heavy fuming with elevated sulfur dioxide emissions, nighttime glow, and occasional explosions—the vent was enlarged by repeated wall collapses, becoming about 450 feet in diameter and 650 feet deep by April 2010. The 2008–present Halemaʻumaʻu activity is the longest summit eruption at Kīlauea since 1924.

For the first year, the eruption at the new summit vent had no appreciable effect on the continuing eruption near Puʻu ʻŌʻō, marking the longest known occurrence of simultaneous summit and rift eruptions at Kīlauea. Past simultaneous activity, such as in 1971, was rare and of short duration, generally lasting only a few days at most. The ongoing concurrent summit-rift eruption, now approaching three years in duration, is unprecedented for Kīlauea in recorded history.



Above: *Aerial view in November 2008 of the gas plume from the new vent that opened in Halemaʻumaʻu Crater in mid-March 2008. This activity has continued into 2010 and can be conveniently seen from the Jaggar Museum and the Hawaiian Volcano Observatory (circled) on the rim of Kīlauea Caldera.* ***Left:*** *Nighttime look (January 2010) through the fume at the molten lava sloshing and bubbling within the Halemaʻumaʻu vent, about 400 feet in diameter. (USGS photographs by Tim Orr).*

A pattern of dominant activity alternating between Mauna Loa and Kīlauea could imply that both volcanoes may alternately tap the same deep magma source. Whether this is so is a topic of scientific debate and continuing research, because abundant physical evidence indicates that each volcano has its own shallow magma reservoir that operates independently of the other. Also, available data suggest that the lavas of the two volcanoes are chemically and isotopically distinct.

The average volume of lava erupted at Kīlauea Volcano since 1956 is between 110 and 130 million cubic yards per year. In contrast, the average rate of lava output along the entire Hawaiian-Emperor Chain during its 70-million-year life is only about 20 million cubic yards per year. For reasons not yet understood, the rate of eruptive activity associated with the Hawaiian hot spot for the past few centuries appears exceptionally high relative to its long-term average.

The first Hawaiian Volcano Observatory (HVO), located near the site of the present Volcano House Hotel, as it appeared around 1922. (Photographer unknown; courtesy of the Bishop Museum, Honolulu, Hawai‘i.)

Volcano Monitoring and Research

Before the 20th century, most scientific studies of volcanoes were conducted during short-lived expeditions, generally undertaken as a response to major eruptions. Thomas A. Jaggar, Jr., a geologist at the Massachusetts Institute of Technology (MIT), was not satisfied with that approach. He recognized that, to understand volcanoes fully, one must study them continuously before, during, and after eruptions. Jaggar's views were profoundly affected by a memorable visit in 1902 to the Island of Martinique (West Indies). He went as a member of the international scientific expedition sent to study that year's catastrophic eruption of Mont Pelée, which devastated the city of St. Pierre and killed about 30,000 people.

In 1911, spurred by a stimulating lecture delivered by Jaggar, a group of Hawaiian residents founded the Hawaiian Volcano Research Association (HVRA). The logo of the HVRA included the motto *Ne plus haustae aut obrutae urbes* (loosely translated as “Let no more cities be destroyed or buried”), reflecting Jaggar's memory of Mont Pelée's destructive force and his optimistic belief that better understanding of volcanoes could reduce the hazard to life and property from eruptions.

In 1912, with support from the HVRA and the Whitney Fund of MIT, Jaggar established the Hawaiian Volcano Observatory (HVO) to study the activity of Mauna Loa and Kīlauea on a permanent, scientific basis. "Volcanology" emerged as a modern science with the founding of HVO, which between 1912 and 1948 was managed by the HVRA, the U.S. Weather Bureau, the U.S. Geological Survey (USGS), and the National Park Service. Since 1948, it has been operated by the USGS.

During the past nearly 100 years of research, HVO scientists have developed and refined most of the surveillance techniques now commonly employed by volcano observatories worldwide.

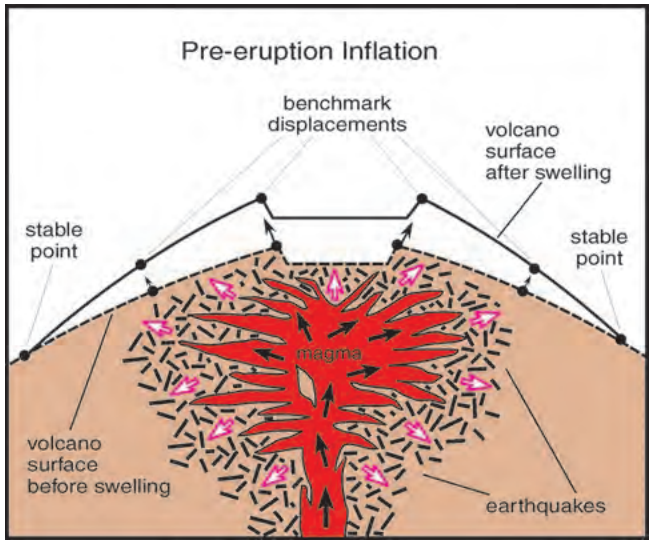
Helicopter view of HVO at its present site on the western edge of Kīlauea Caldera, after renovation and the addition of a new wing (with observation tower) in 1986. In the background, fume rises from the active vent within Halema‘uma‘u Crater on the caldera floor. (USGS photograph by Tim Orr, November 2010.)

Volcano Monitoring

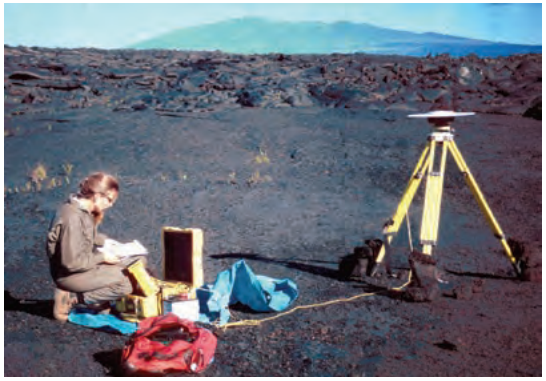
The term "volcano monitoring" refers to the observations and measurements—visual and instrumental—scientists make to document changes in the state a volcano during and between eruptions. Such changes are now well known for Kīlauea, and a pattern of similar changes is becoming apparent for the less studied Mauna Loa. As magma enters the shallow summit reservoir, the volcano undergoes swelling or inflation (a process similar to the stretching of a balloon being filled with air). This swelling in turn causes changes in the shape of the volcano's surface. During inflation, the slope or tilt of the volcano increases, and reference points (benchmarks) on the volcano are uplifted relative to a stable point and move farther apart from one another. For Hawaiian volcanoes, pre-eruption inflation is generally slow and gradual, lasting for weeks to years. However, once an eruption begins, the shrinking or deflation of the volcano typically occurs rapidly as pressure on the magma reservoir is suddenly relieved—a process not unlike deflating a balloon. During deflation, changes in tilt and in vertical and horizontal distances between benchmarks are opposite to those during inflation.

Changes in the shape of the volcano during inflation and deflation are determined by ground-deformation measurements. Tilt changes can be measured continuously and extremely precisely by use of instruments called tiltmeters, which can detect a change in angle of less than 1 microradian (about 0.00006 degree). A 1-microradian increase in tilt would be equivalent to steepening the slope of a board about 0.8 mile long by placing a coin under one end.

Tilt changes and associated relative vertical displacements can also be detected by periodic remeasurement of arrays of benchmarks by leveling, a high-precision field surveying method. Changes in horizontal distances between benchmarks can be monitored in the field by using portable electronic-distance-measurement (EDM) instruments that use laser or infrared beams. Collectively, these commonly used ground-deformation monitoring techniques have



Hypothetical slice through Kīlauea Volcano. Magma entering the shallow reservoir exerts pressure on the volcano, causing earthquakes and distorting its shape from the dashed-line profile to the solid-line profile. During inflation, reference points (benchmarks) on the volcano's surface are pushed upward and outward relative to points assumed to be stable. Changes in the volcano's shape and the occurrence of the earthquakes can be tracked precisely by volcano-monitoring techniques.

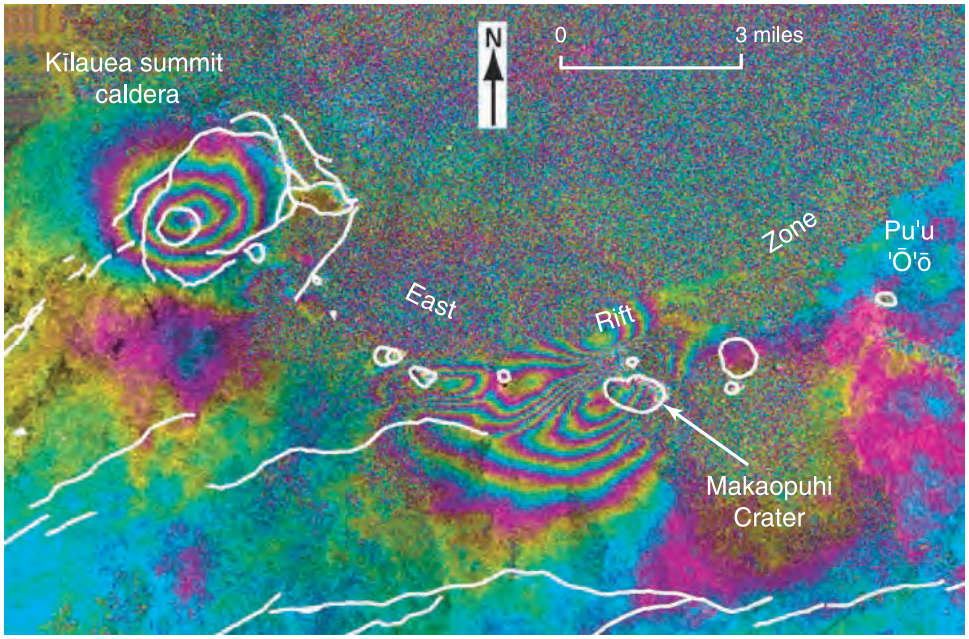


Above: *Hawaiian Volcano Observatory (HVO) scientists use a laser-ranging instrument in the mid-1980s to make an electronic distance measurement (EDM). Snow-capped summit of Mauna Loa can be seen in background. (USGS photograph by J.D. Griggs.)* ***Below:*** *An HVO scientist takes notes at a global positioning system (GPS) measurement site near the Pu‘u ‘Ō‘ō vent, while an antenna receiver (on tripod centered over a benchmark) acquires signals emitted from several GPS satellites. Mauna Kea Volcano is visible in background. Repeated measurements at the same benchmark will reveal horizontal and vertical motions of that point on the volcano. (USGS photograph by Christina Heliker.)*

a measurement precision of a few parts per million or less. For distances, the notion of one part per million (ppm) can be visualized as about 1 inch in 16 miles, or one car length in bumper-to-bumper traffic from Cleveland to San Francisco.

During the past 15 years, the global positioning system (GPS)—a satellite-based technology—has been increasingly used to monitor the ground movements at active volcanoes. Originally deployed for military purposes by the Department of Defense, the GPS involves an array of 24 satellites (orbiting about 12,000 miles above the Earth) that continuously send very accurate time signals, which can be picked up by GPS receivers on the ground. Using high-resolution GPS receivers (not the inexpensive devices used by hikers and drivers) and sophisticated computer processing of signals received from four or more satellites, scientists can determine both distance (longitude and latitude) and elevation changes at a given ground reference point ("benchmark") with parts-per-million precision. Repeated measurements of a GPS network of many benchmarks make it possible to monitor an entire volcano. In addition to monitoring inflation/deflation movements at the volcano summits, GPS measurements show that the south flank of Kīlauea and, at times, the southeast flank of Mauna Loa are moving seaward (to the southeast) at an average rate of a few inches per year. As the costs and computer-processing time of GPS measurements continue to decrease, they will likely replace all other types of ground-deformation measurements, especially since GPS measurements can be made around the clock regardless of the weather and do not require one benchmark to be seen from another.

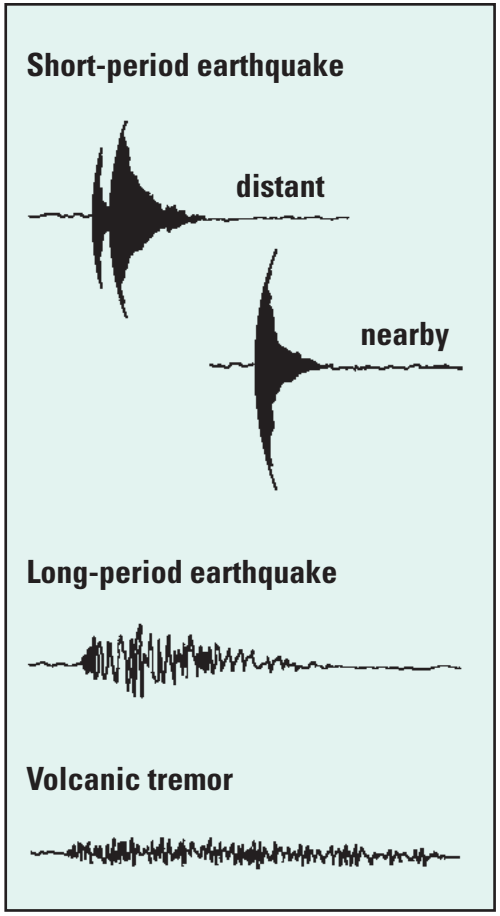
In recent years, there has been increasing use of another satellite-based tool to track ground deformation at Hawaiian and other volcanoes—**In**terferometric **S**ynthetic **A**perture **R**adar (**InSAR**). This technique involves processing radar signals sent by an orbiting satellite and bounced back from the ground surface. Changes in the position of the Earth's surface can be determined by analyzing a pair of radar images acquired at two different times. Like GPS measurements, InSAR monitoring can be done in all weather conditions and can map ground deformation over a wide area (typically 30 x 60 miles). InSAR data cover a large area but are obtained and processed periodically, whereas GPS measurements refer to specific points (benchmarks) but can be made frequently or even continuously. Taken together, data from these two techniques are complementary and give a better picture of the overall ground deformation than measurements obtained through either technique by itself.

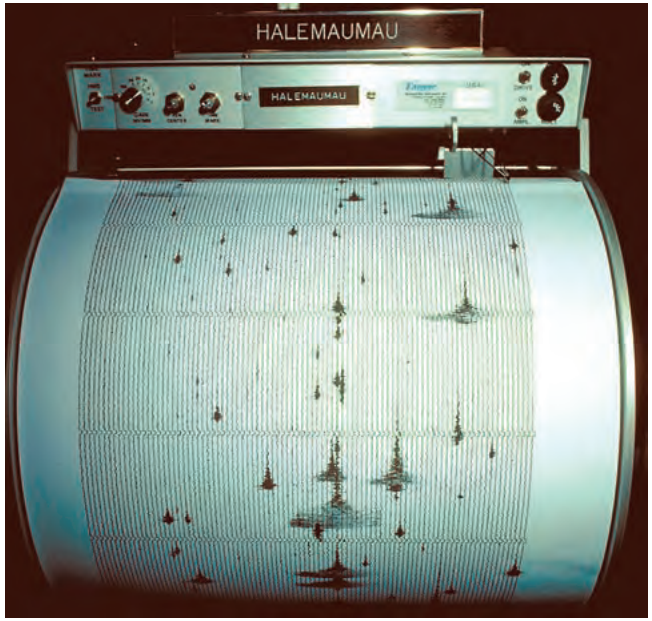


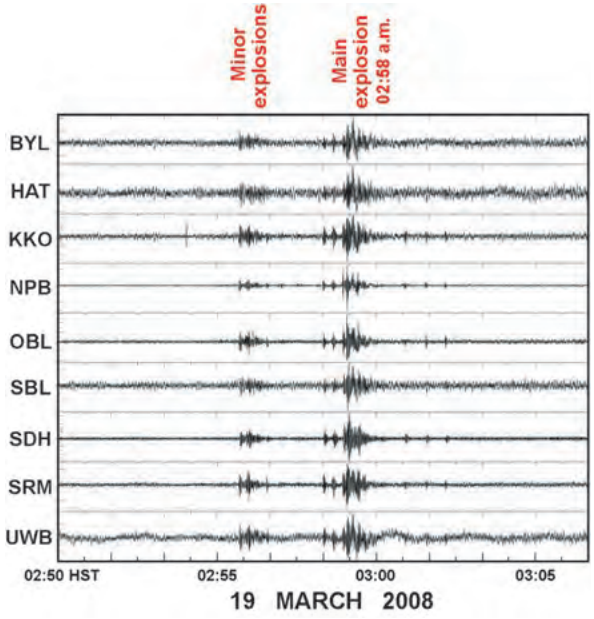
Areas of color bands, or "fringes," in this InSAR image—produced from a pair of satellite radar images acquired 35 days apart in 2007 by the European Space Agency's ENVISAT satellite—show subsidence at Kīlauea's summit caldera and a combination of uplift and subsidence centered near Makaopuhi Crater. This pattern of deformation reflects an intrusion of magma from the summit reservoir into the east rift zone. Each fringe of color bands (violet-blue-green-yellow-red) represents about 1.1 inch of deformation (up or down) of the ground surface. In this image, a progression of yellow-to-violet colors toward the center of a pattern demonstrates uplift, and the opposite color progression indicates subsidence. (Image courtesy of Michael Poland, USGS.)

The mainstay of volcano monitoring is the continuous recording of seismic activity. Virtually all Hawaiian eruptions are preceded and accompanied by an increase in the number of shallow earthquakes. As magma moves into the reservoir during inflation, it must make room for itself by rupturing or crowding aside the solidified lava that surrounds the reservoir. Such underground ruptures produce seismic waves that travel through the volcano and are recorded by a network of *seismometers* placed on the volcano's surface. Ground motions sensed by seismometer are converted into electronic signals, which are transmitted by radio and are recorded on *seismographs* located at the volcano observatory. Seismic data are analyzed to determine the time, location, depth, and magnitude of earthquakes. Mapping earthquake activity allows HVO scientists to track the subsurface movement of magma.

All Hawaiian eruptions are accompanied by *volcanic tremor*. Quite distinct from the discrete seismic shocks associated with rupture-caused earthquakes, volcanic tremor is a continuous vibration of the ground caused by movement of fluids (magma or gas). Volcanic tremor generally is detectable and recorded only by seismic instruments; however, if especially vigorous, tremor can be felt by people as far as 5 miles from an eruption site.

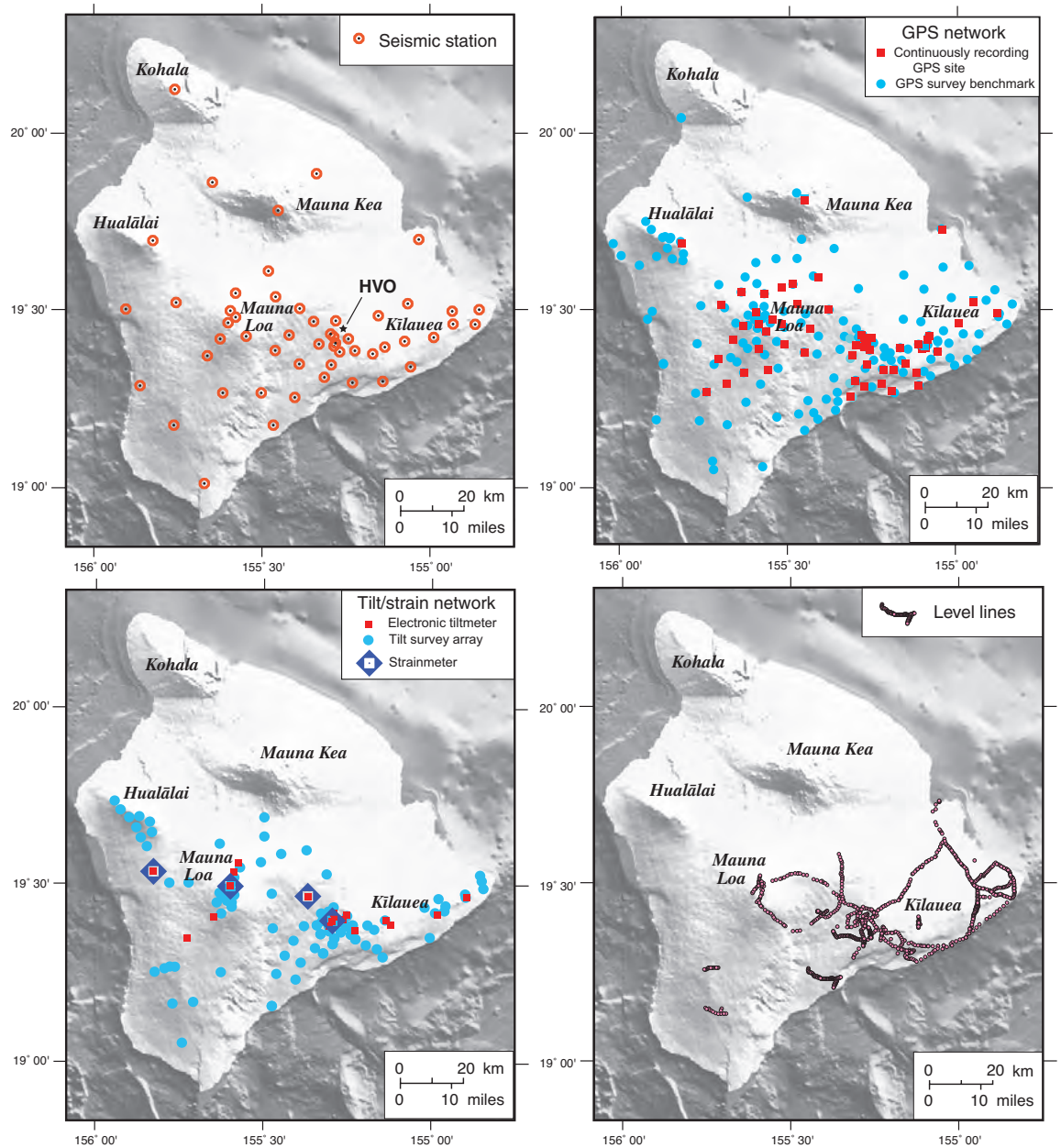




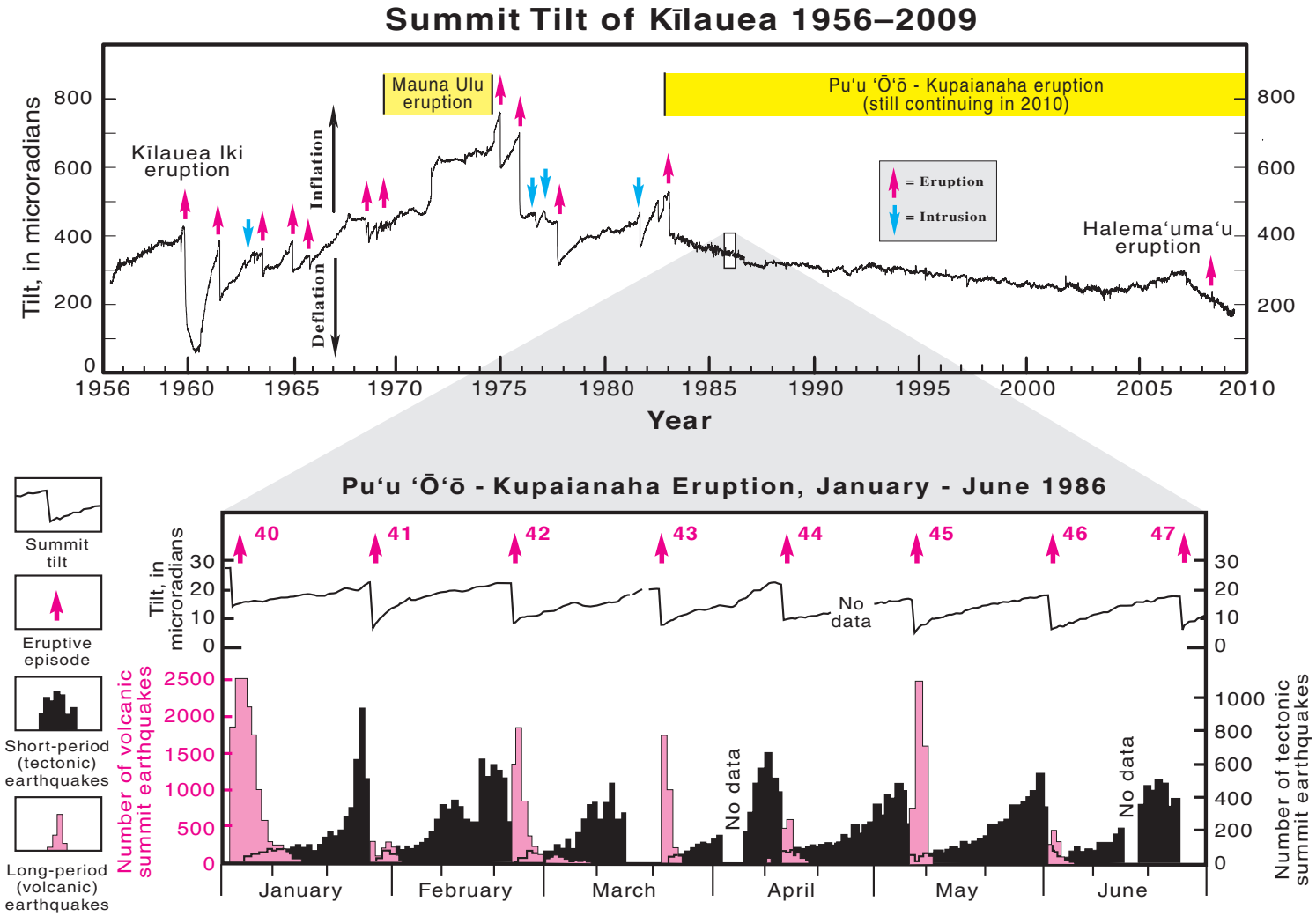


Above center: *On this seismograph, a sharp-needle pen "writes" the seismic signatures with a hot stylus on heat-sensitive paper wrapped around a recording drum. (USGS photograph by J.D. Griggs.) For modern-day precise monitoring, however, HVO records and analyzes seismic activity with computer recording and processing systems.* ***Left:*** *Examples of common seismic signatures typically recorded before and during eruptions.* ***Above right:*** *An example of a computer display of digital traces of seismic signals recorded by the network of broadband seismometers around Kīlauea summit. Here, we see the seismic signals produced by the explosions on the morning of March 19, 2008, that initiated the eruption within Halemau'ma'u Crater, which still continues in 2010. (Modified from image of Phillip B. Dawson, USGS.)*

Volcano-Monitoring Networks on Hawai‘i



Principal volcano-monitoring networks operated by the Hawaiian Volcano Observatory. The configurations of the networks evolve with time—to adapt to new technologies, to upgrade systems, and to meet changing needs dictated by eruptive activity.



Above: *The common pattern of gradual inflation, followed by abrupt deflation, is well demonstrated by changes in "tilt" of the volcano's slopes associated with major eruptions and intrusions at Kīlauea. A change in tilt of 1 microradian equals an angle of 0.00006 degree. With the onset of the Pu'u 'Ō'ō-Kupaianaha eruption in 1983, Kīlauea summit underwent long-term net deflation until late 2003, when this trend reversed for several years. Summit deflation resumed in 2007 and has continued through 2010. (Tilt data plotted by Asta Miklius, USGS.)* ***Below:*** *A detailed look at a 6-month segment of the tilt record reveals similar inflation-deflation patterns for the high-lava-fountaining episodes of the Pu'u 'Ō'ō-Kupaianaha eruption, even though the tilt changes and time intervals involved are much smaller (compare scales of the two diagrams). Also shown are variation patterns of the two types of earthquakes that commonly precede and accompany Kīlauea eruptions.*

Anatomy of an Eruption: The Inflation-Deflation Cycle

Kīlauea's behavior during and between eruptions is remarkably regular. Monitoring instruments placed at the volcano's summit can be used to trace the cycles of gradual inflation, during which the reservoir fills with magma, and abrupt deflation, when the reservoir partially empties to deliver magma to an eruption. These recurring inflation-deflation cycles are precisely recorded by tiltmeters and seismometers, as is well displayed during the 1983-to-present Pu‘u ‘Ō‘ō-Kupaianaha eruption.

During inflation, rocks surrounding the magma reservoir become stressed. This stress is partly relieved by increasing numbers of earthquakes that are too small to be felt but are easily recorded by seismometers at Kīlauea’s summit. These earthquakes (called *short-period* or *tectonic*) are recorded as high-frequency features on a seismograph. During deflation the stress is completely relieved. The short-period earthquakes stop, but their place is taken by low-frequency earthquakes (called *long-period* or *volcanic*), which reflect adjustments related to the exit of magma from the summit reservoir to feed the eruption. Long-period earthquakes are related to harmonic tremor, the continuous vibration of the ground associated with underground magma or fluid movement.

Kīlauea’s distinctive inflation-deflation pattern is seen in nearly every eruption, regardless of the size of the observed tilt changes. For example, the pattern is dramatically apparent for the Kīlauea Iki eruption in 1959, which involved the largest tilt change recorded to date (nearly 300 microradians). The same pattern is also well seen in activity involving smaller tilt changes (20 microradians or less), as observed during the continuous eruption of the Pu‘u ‘Ō‘ō vent in January–June 1986.

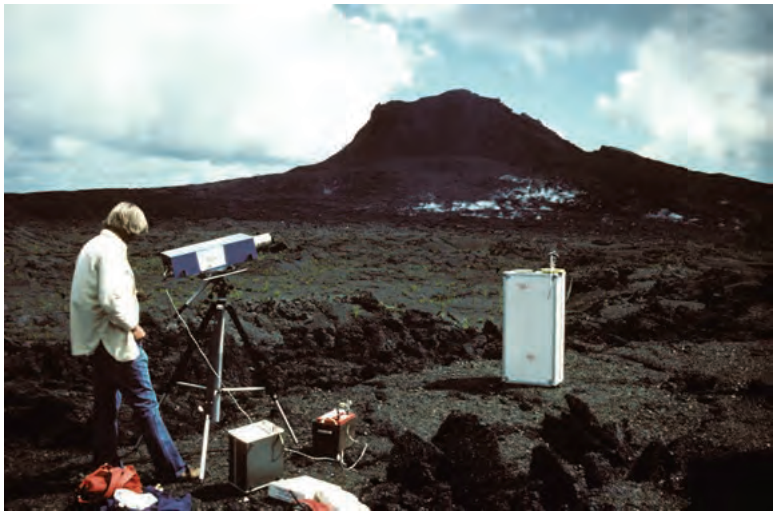
Less commonly observed at Kīlauea in the summit tilt record, and sometimes also recorded by a tiltmeter at Pu‘u ‘Ō‘ō, is a *deflation-inflation* pattern (called a “DI tilt event”) that typically lasts less than a week. A DI event is characterized by an abrupt deflation as large as a few microradians lasting several hours to 2–3 days, which is followed by a sharp inflation of about equal tilt change over several days. This type of tilt pattern was first recognized in August 2000, but it has become increasingly more common since 2004, especially after 2008. The eruption dynamics of DI events are not yet understood. However, these events tend to correlate with lava pulses and (or) pauses during activity at the Pu‘u ‘Ō‘ō vent since July 2007 and are thought to reflect variations in magma supply to a shallow storage zone just east of Halemau‘uma‘u Crater.

Forecasting Eruptions

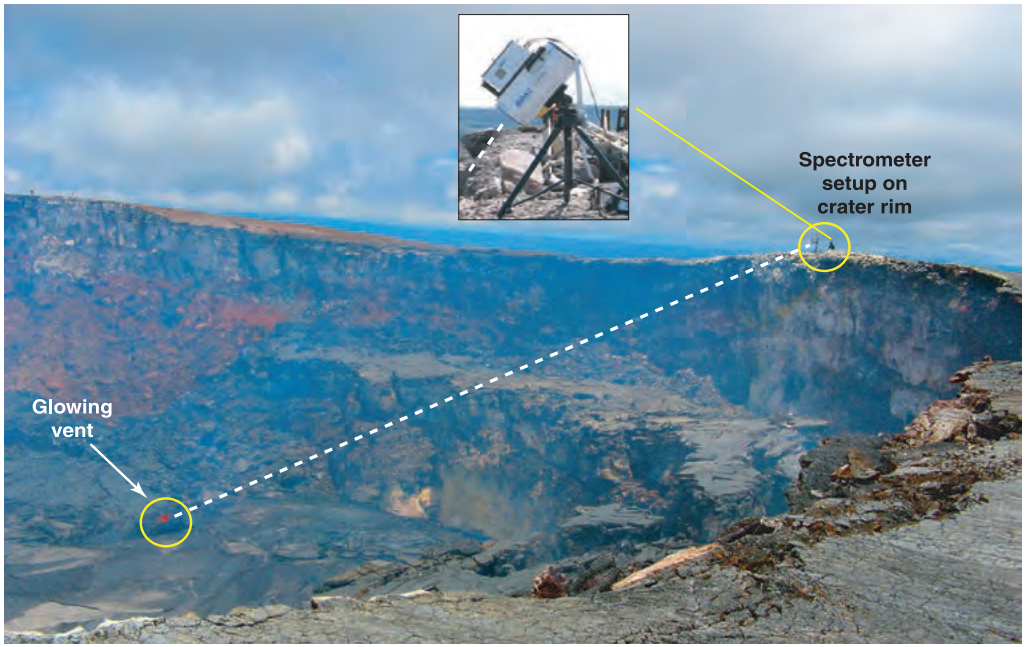
A prime objective of volcano monitoring is to detect the early signs of possible eruptive activity and to make reliable eruption forecasts. Although considerable advances have been made in volcano monitoring in Hawai‘i, accurate long-term forecasts (one year or longer) still elude scientists. However, the capability for short-term forecasts (hours to months), especially of Kīlauea’s activity, is much better.

Accurate short-term forecasts of Hawaiian eruptions are based primarily on analyses of inflation-deflation patterns, made possible through decades of study of ground deformation (tilt) and seismicity (earthquakes and volcanic tremor). When the level of inflation and the short-period earthquake counts are high, the volcano is ready to erupt. Sometimes there is a delay of days or even weeks before eruption occurs, but scientists are alerted by the patterns and are ready to study the eventual outbreak when it does occur. Eruption is signaled by the beginning of sharp deflation accompanied by either harmonic tremor or earthquakes close to the site of eruptive outbreak. These signals are usually seen an hour to several hours before lava breaks the surface, allowing scientists enough time to travel to the likely site of activity and issue warnings.

The combination of seismic and ground-deformation monitoring has proved to be the most useful and reliable method in the short-term forecasting of Kīlauea eruptions. However, some other techniques being developed or tested show promise and should increase future forecasting capabilities. These newer methods include the monitoring of changes in the composition and volume of volcanic gas emissions, such as sulfur dioxide, carbon dioxide, hydrogen, helium, and radon; magnetic and gravitational fields of the volcano; and various geoelectrical properties of the volcano. Some of the gas-monitoring techniques can make measurements with parts-per-million (ppm) precision. For gases and fluids, one ppm can pictured in terms of a very dry martini—1 drop of vermouth in 16 gallons of gin!



*A scientist uses a correlation spectrometer (**COSPEC**) to measure the emission of sulfur dioxide gas from the Pu‘u ‘Ō‘ō vent. This instrument—originally developed to monitor atmospheric pollution by measuring sulfur dioxide discharge from industrial smokestacks—has largely been replaced by instruments that are more sensitive, lighter in weight, less cumbersome, and of lower cost. (USGS photograph by J.D. Griggs.)*



*A **F**ourier **T**ransform **I**nfra**R**ed (**FTIR**) spectrometer is used to analyze volcanic gases emitted from a glowing vent. This instrument (closeup in inset) is capable of analyzing many other species of volcanic gases in addition to sulfur oxide and carbon dioxide. (USGS photograph by A.J. Sutton.)*

In recent decades, great strides have been made in gas monitoring using satellite- and ground-based remote-sensing instrumentation and techniques. With various types of field-portable spectrometers, HVO scientists continuously measure the emission of sulfur dioxide and carbon dioxide at the summit calderas of Kīlauea and Mauna Loa. They also make repeated, though not continuous, measurements of gas output at eruptive vents and other specific sites. HVO’s near-real-time monitoring of volcanic-gas emissions from the ongoing eruptions at Pu‘u ‘Ō‘ō and Halema‘uma‘u provides key information to the National Park Service and Hawai‘i County for assessment of potential hazards to visitors and residents from volcanic air pollution (discussed later).

Other monitoring techniques are also proving useful—data from magnetic, gravity, and geoelectrical studies provide diagnostic information about the subsurface configuration and workings of a volcanic system. So far, data from the nonseismic and nongeodetic monitoring techniques have not revealed definitive short-term precursors to possible eruptions. However, they have identified underground movement of magma from one place to another, sometimes unaccompanied by measurable ground deformation or earthquakes. Experience on well-studied active volcanoes in Hawai‘i and elsewhere has shown that the best volcano monitoring is achieved by using a combination of approaches rather than relying on any single method.

At present, HVO scientists generally can identify an increased potential for Kīlauea or Mauna Loa eruptions and the likely locations of lava outbreaks, but they cannot make specific forecasts of the exact timing or size of an expected eruption. However, for a number of Kīlauea eruptions in recent decades, the HVO staff has been able to warn officials of Hawai‘i Volcanoes National Park and (or) the County of Hawai‘i, hours to days in advance, to take safety measures, if deemed necessary.

Kīlauea's Volcanic "Plumbing System"

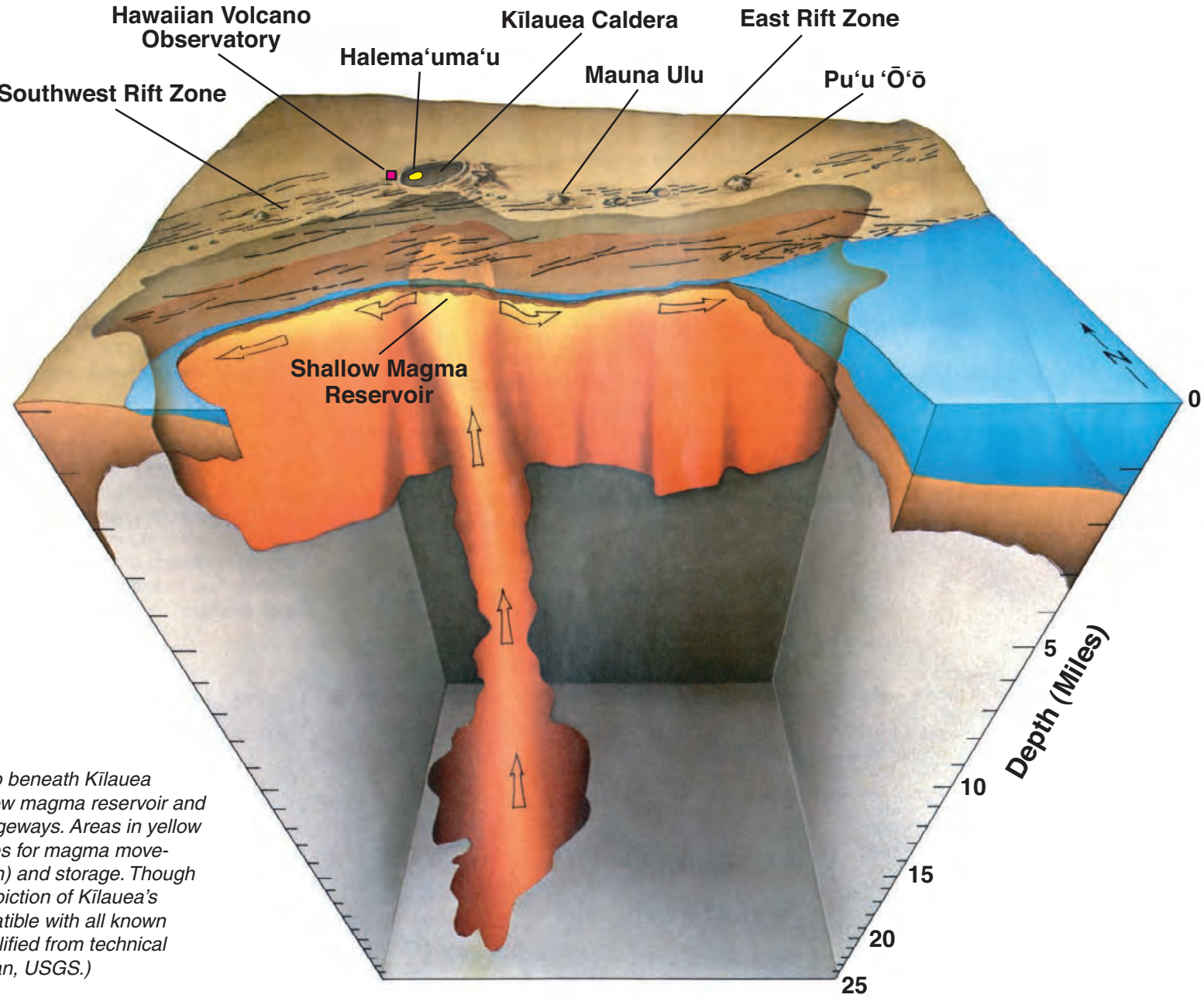
From decades of monitoring and research at HVO, Kīlauea's volcanic "plumbing system" is now relatively well understood. This system links the processes involved in the formation, transport, storage, and, ultimately, eruption of magma to sustain Hawai'i's active volcanoes.

Kīlauea's plumbing system is believed to extend deep beneath the Earth's surface, where magma is generated by partial melting of material beneath the Pacific Plate as it passes over the Hawaiian hot spot. This belief is based on the persistent recurrence of earthquakes 30 miles or more beneath Hawai'i. Earthquakes occurring 20–30 miles beneath the surface are probably related to the accumulation and upward movement of magma. Seismic data for levels shallower than 20 miles can be interpreted to define diffuse zones of continuous magma rise, one leading to Kīlauea and another to Mauna Loa.

Before Kīlauea erupts, most of the magma entering the volcano is stored temporarily within a shallow reservoir. Earthquake data and ground-deformation patterns suggest that this reservoir is located 1 to 4 miles beneath the summit and consists of pockets of magma concentrated within a crudely spherical space about 3 miles across. Earthquakes do not occur within the reservoir, because liquid magma does not rupture to generate seismic waves.

Kīlauea eruptions occur either at its summit or within two well-defined swaths (called *rift zones*) that radiate from the summit. During summit eruptions, the magma reservoir deflates only slightly, if at all. This relation implies that the rate at which magma is erupted nearly equals that at which the reservoir is refilled by new magma from depth. During an eruption in a rift zone, called a rift or flank eruption, however, the summit region undergoes a significant and abrupt deflation as magma moves quickly from the summit reservoir into the rift zone. Similar summit deflation occurs during a rift intrusion, in which magma injected into the rift zone remains stored underground there rather than breaking the ground surface in an eruption. When the rift eruption or rift intrusion ends, the summit region reinflates as the shallow reservoir is refilled by magma from depth. Small pockets of summit-fed magma may be stored for a while within a rift zone and form transient secondary reservoirs.

The volcanic plumbing system for Mauna Loa is less well known. Analysis of data from the well-monitored 1975 and 1984 eruptions, however, suggests that the essential features of Mauna Loa's plumbing system are similar to Kīlauea's, despite the difference in size between the two volcanoes. Mauna Loa's magma reservoir also may be larger than Kīlauea's, which would be consistent with the observations that Mauna Loa eruptions tend to be characterized by higher lava-output rates, longer eruptive fissures, and larger lava flows.



Cut-away view looking deep beneath Kīlauea Volcano, showing the shallow magma reservoir and the principal magma passageways. Areas in yellow are the most favorable zones for magma movement (arrows show direction) and storage. Though greatly generalized, this depiction of Kīlauea's "plumbing system" is compatible with all known scientific information. (Simplified from technical illustration of Michael P. Ryan, USGS.)

Hawaiian Eruptive Style—Powerful but Usually Benign

By definition, the adjective *eruptive* describes any object or phenomenon associated with processes of "bursting forth," "breaking out," or "issuing forth suddenly and violently." Strictly speaking, no eruption is truly nonexplosive, but most Hawaiian eruptions closely approach being such. Indeed, volcanologists worldwide use the term "Hawaiian" to characterize similar, relatively gentle eruptive style at other volcanoes.

Typical Activity: "Nonexplosive" or Weakly Explosive

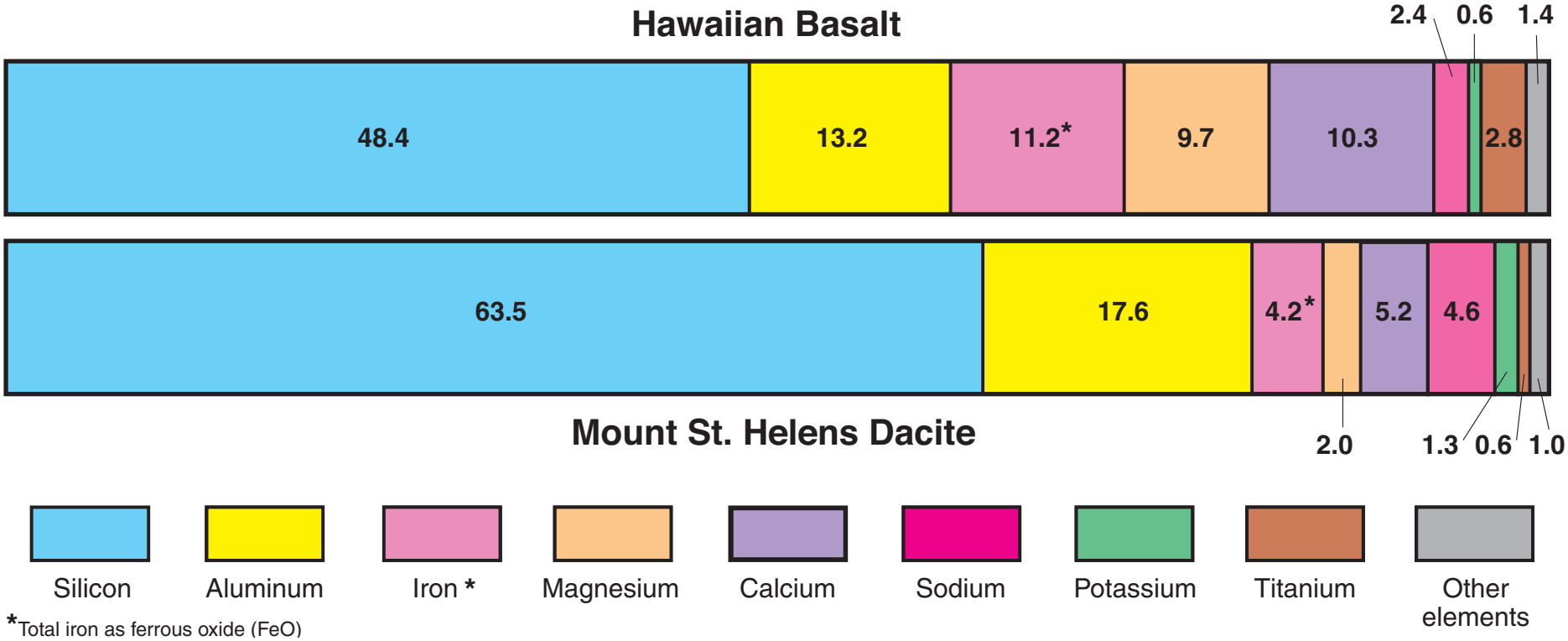
With infrequent exceptions, eruptions of Hawaiian volcanoes generally are weakly explosive or nonexplosive and relatively benign. Hawaiian eruptions are typically gentle because their lava is highly fluid and thus tends to flow freely both beneath the surface and upon eruption. In contrast, lava of volcanoes located along plate margins, such as Mount St. Helens, generally is more *viscous* (less fluid) and tends to fragment, often very explosively, during eruption. Highly fluid lava favors the nonviolent release of the expanding volcanic gases that drive eruptions. In contrast, viscous magma suppresses easy escape of volcanic gases, which results in pressure buildup underground and ultimately in explosive gas release and magma fragmentation.

Lava viscosity ("stiffness" or "resistance to flow") is largely determined by the chemical composition and temperature of the magma, the amount of crystals in the magma, and the gas content. The low viscosity (high fluidity) of Hawaiian lavas derives mainly from its *basaltic* composition, characterized by more iron (Fe), magnesium (Mg), calcium (Ca), and titanium (Ti), and less silicon (Si), aluminum (Al), sodium (Na), and potassium (K), compared to viscous lavas, such as the *dacite* erupted explosively at Mount St. Helens in 1980. In the graph (page 26) showing compositional differences between Hawaiian basalt and Mount St. Helens dacite, the chemical elements are given as oxides [(for example, calcium as calcium oxide (CaO)]. Basalt is a dark volcanic rock composed of small crystals and glass, whereas dacite, also fine-grained or glassy, is generally much lighter in color.

Hawaiian eruptions typically begin with *lava fountains* spouting from a series of nearly continuous fissures, evoking colorful popular descriptions such as "curtains of lava" or "curtains of fire." As most eruptions progress, lava-fountain activity becomes localized at a single *vent* (an opening from which lava erupts), generally within hours of the initial outbreak. Depending on the shape of the vent and other eruptive conditions, lava fountains can vary widely in form, size, and duration.

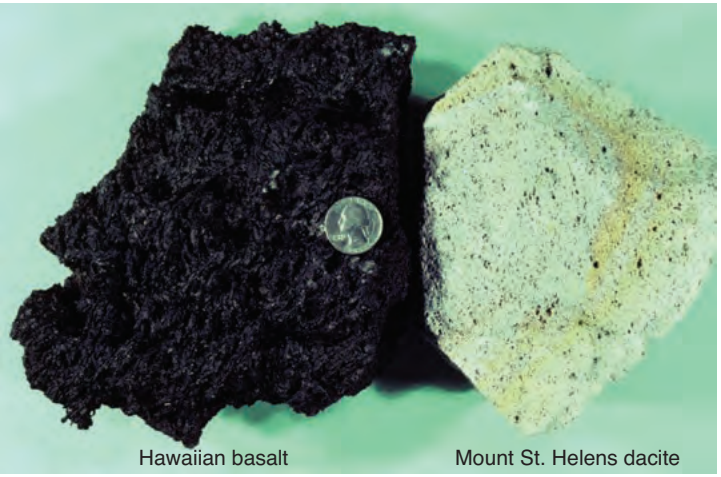
It should not be forgotten, however, that Kīlauea also can be violently explosive. Each of the last two periods of significant historical explosive activity, in 1790 and 1924, was probably driven by expanding steam from heated ground or surface water, and each produced fatalities. Three smaller explosive bursts have even occurred at Pu‘u ‘Ō‘ō, one in 1987 and two in the 1990s, peppering the surface of the cone with heavy rocks. Since 2008, several small explosive events at Halema‘uma‘u Crater have showered the nearby ground with ash and blocky debris. In fact, Kīlauea erupts explosively about as often as does Mount St. Helens, and in the past 1,500 years ash from Kīlauea has risen into or above the jet stream at least six times. Should such a powerful explosive eruption occur today,

Above: *Mount St. Helens, a typical steep-sided composite volcano, shortly before its decapitation by the May 18, 1980, eruption. (Photograph courtesy of D.R. Pevear, Western Washington University, Bellingham.)* ***Below:*** *Snow-capped Mauna Loa, an excellent example of a shield volcano, viewed from the Hawaiian Volcano Observatory. (USGS photograph by Robert I. Tilling.)*



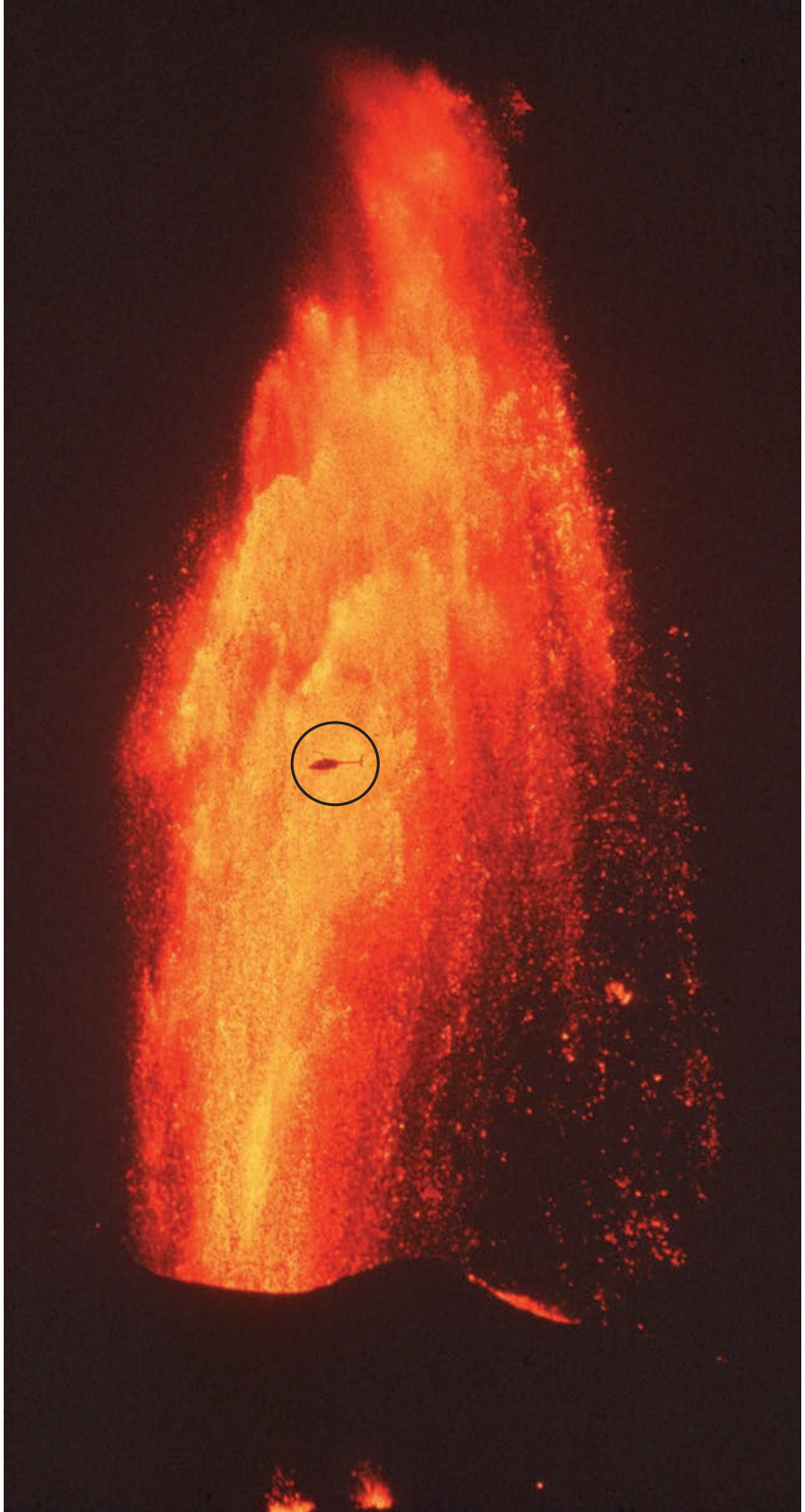
the resulting ash cloud could severely disrupt trans-Pacific air traffic.

An explosive eruption at Mauna Loa never has been witnessed in recorded history, but field mapping has shown ample geologic evidence for prehistoric explosive eruptions. Around its summit caldera, Moku‘āweoweo, lie several deposits of ancient explosive debris, including a few blocks as large as about 7 feet across found near the summit. Smaller blocks were thrown out to distances as great as 2 miles. Preliminary studies suggest that at least three separate explosive events occurred, taking place about a thousand years ago or perhaps earlier.



Above: *This graph illustrates the differences in average chemical compositions of lava erupted by Hawaiian volcanoes and during the 1980 eruption of Mount St. Helens. The number for each chemical element gives the amount (in weight percent) of that element (expressed as oxide) contained in the lava.* ***Left:*** *Note the contrast in color and texture between Hawaiian basalt and Mount St. Helens dacite. (USGS photograph by J.D. Griggs).*

Lava fountains can vary widely in size and form. ***Center:*** *A 1,500-foot-high fountain jets from the Pu‘u ‘Ō‘ō vent in 1984; note silhouette of helicopter for scale. (Photograph by Mardie Lane, National Park Service.)* ***Top right:*** *An aerial view of a discontinuous row of lava fountains 50–100 feet high during the August 1971 Kīlauea summit eruption. (Photograph courtesy of the National Park Service.)* ***Bottom right:*** *A line of lava fountains during the 1984 Mauna Loa eruption; two scientists (left center) give scale. (USGS photograph by Richard B. Moore.)*



Above: *Mildly explosive entry of lava into the ocean, after traveling about 7 miles from the Pu‘u ‘Ō‘ō vent in February 1988. (USGS photograph by Taeko Jane Takahashi.)* ***Left below:*** *A 40-foot arching "hose" fountain spurts from Pu‘u ‘Ō‘ō vent in February 1983. (USGS photograph by J.D. Griggs.)* ***Right below:*** *A "dome" fountain, about 45 feet high, plays continuously for hours during the 1969–71 Mauna Ulu eruption of Kīlauea. (USGS photograph by Jeffrey B. Judd.)*

During the 1959 Kīlauea Iki eruption, one lava fountain shot up 1,900 feet, the record height for historical Hawaiian eruptions. A fountain in 1969 from Mauna Ulu rose 1,770 feet. More recently, some of the vigorous eruptive episodes of the 1983–1986 Pu‘u ‘Ō‘ō vent produced lava fountains at least 1,500 feet high. However, when the rate of gas release is too low to cause high fountaining, lava merely wells up nonexplosively and flows quietly or oozes from the vent. Though impressive, even these spectacularly high lava fountains are products of relatively weak explosive activity. By comparison, the May 1980 explosive eruption of Mount St. Helens sent ash more than 64,000 feet up into the atmosphere.

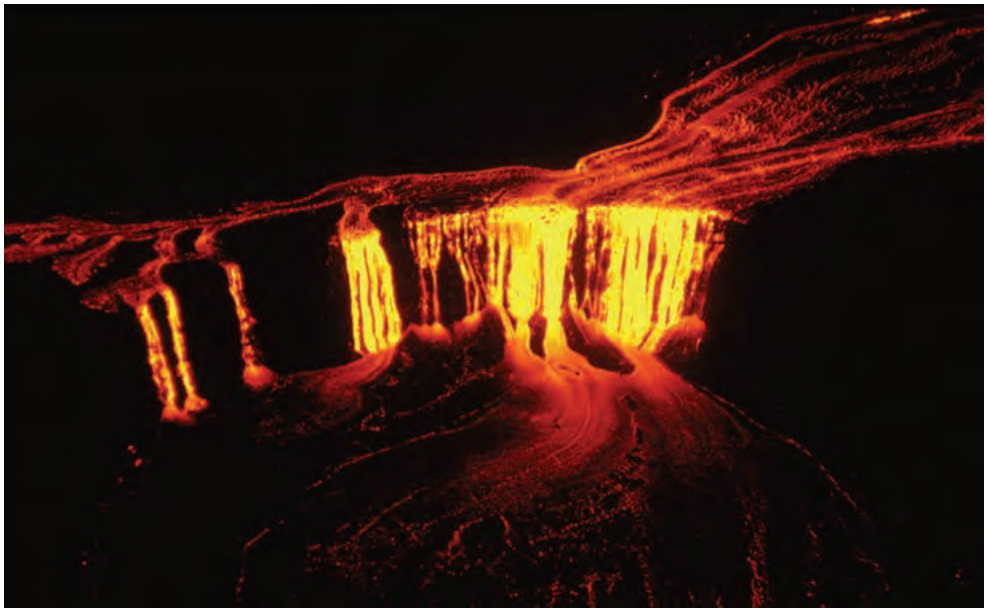
Molten lava falling from fountains and quietly erupting from vents often forms long incandescent *lava streams* or *lava flows*, giving rise to the popular but misleading term "rivers of fire." This colorful term is misleading because the lava flows are molten rock and hence do not burn: “fire” is involved only if the flows ignite and burn vegetation and wooden structures along their paths. Hawaiian lava flows generally advance at average speeds of a few miles per hour—a pace slower than that of a person walking quickly or running. However, if a lava flow is confined within a channel or lava tube, it can advance more quickly, especially if the ground is steep. For short periods of time during some Mauna Loa and Kīlauea eruptions, several lava flows have been clocked rushing down steep slopes at 35 miles per hour! But this is unusual.

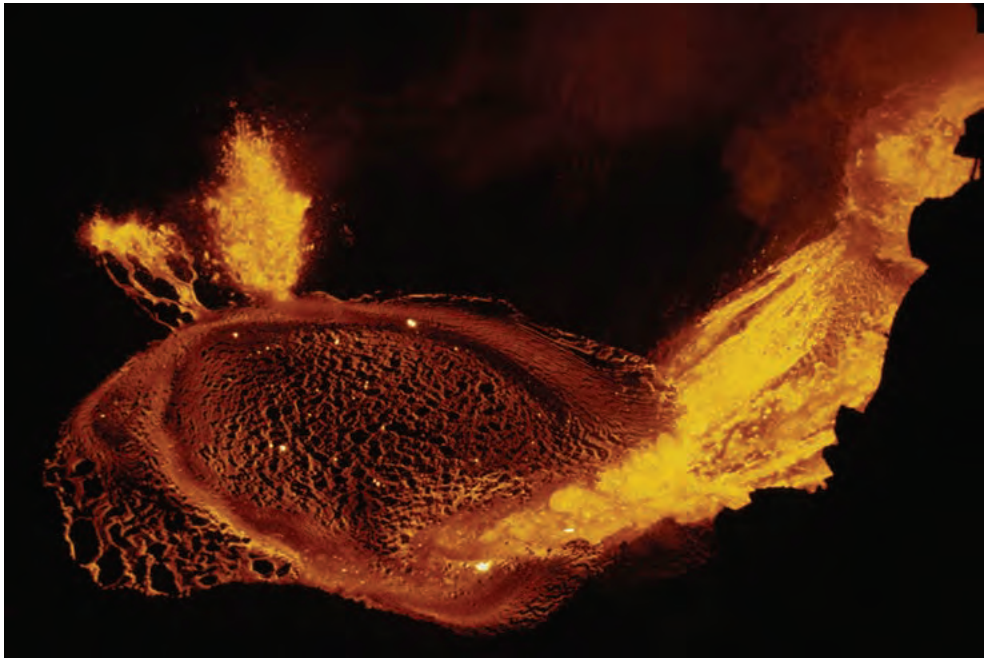
During long-lived eruptions, lava flows tend to become "channeled" into a few main streams. Overflows of lava from these streams solidify quickly and plaster on to the channel walls, building natural levees or ramparts that allow the level of the lava to rise. Lava streams that flow steadily in a confined channel for many hours to days may develop a solid crust or roof and thus change gradually into streams within *lava tubes*. Because the walls and roofs of such tubes are good thermal insulators, lava flowing through them can remain hot and fluid much longer than surface flows. Tube-fed lava can be transported for great distances from the eruption sites. For example, during both the 1969–74 Mauna Ulu eruption and the 1983–present Pu‘u ‘Ō‘ō-Kupaianaha eruption, many lava flows traveled underground through lava-tube systems more than 7 miles long to enter the ocean. In fact, lava transported through tubes has entered the ocean 75 percent of the time since 1986, with the longest lived of these entries lasting 22 months (May 2005–March 2007) at East Lae‘apuki.

A 1,500-foot-high lava fountain erupts from Pu‘u ‘Ō‘ō in September 1984. Red-hot blobs of liquid lava ejected high into the air are rapidly cooled in flight, forming a billowing black cloud of cinders and Pele’s hair and Pele’s tears that can be carried many miles downwind from the vent. Low lava fountains play from fissures at the base of the cone (foreground). (USGS photograph by Christina Heliker.)

Center: *Aerial view of a braided lava flow during the 1984 Mauna Loa eruption. With imagination, some people see in this flow pattern the figure of Pele, Goddess of Volcanoes, with her arms raised. (Photograph by Katia Krafft, Centre de Volcanologie, Cernay, France.)* ***Top right:*** *This view into a "skylight" (collapsed roof) of a lava tube during the Pu'u 'Ō'ō eruption shows how Thurston Lava Tube might have looked when it was "active" a few hundred years ago. Here, geologists sample molten lava flowing through the tube using a sledgehammer head attached to a steel cable. The lava-coated hammer is dangling at the edge of the skylight, above the surface of the reddish flowing lava stream. (USGS photograph by J.D. Griggs.)* ***Bottom right:*** *Inside the Thurston Lava Tube (Nāhuku), Hawai'i Volcanoes National Park. (Photograph by Peter Mouginis-Mark, University of Hawai'i.)*

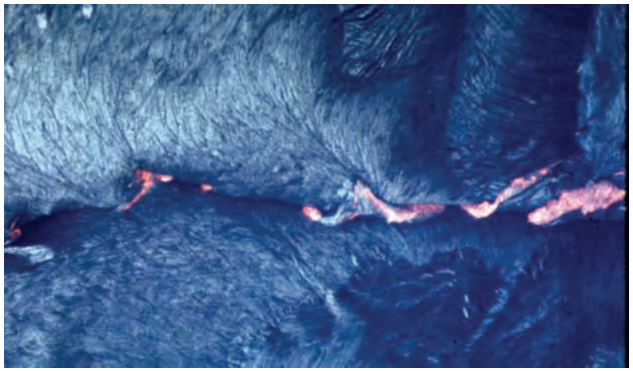
Lava streams that plunge over cliffs or the steep walls of craters form impressive *lava cascades* or *lava falls*. Where cascades spill into preexisting craters, *lava lakes* or *lava ponds* may form. Such lakes are considered inactive and generally form a solid crust within hours or a few days. The still-molten lava beneath this crust can take weeks to years, depending on the lake size and depth, to cool and solidify completely. Lava lakes formed at the site of, and sustained by, active eruptive vents are considered active. The crust formed on these active lakes is not permanent and repeatedly breaks up in response to circulation and sloshing of the underlying still-molten lava. Repeated overflows from active lava lakes raise lake level by rampart construction similar to overflowing lava streams. By this process of levee growth, lakes may become perched many feet above their surroundings.

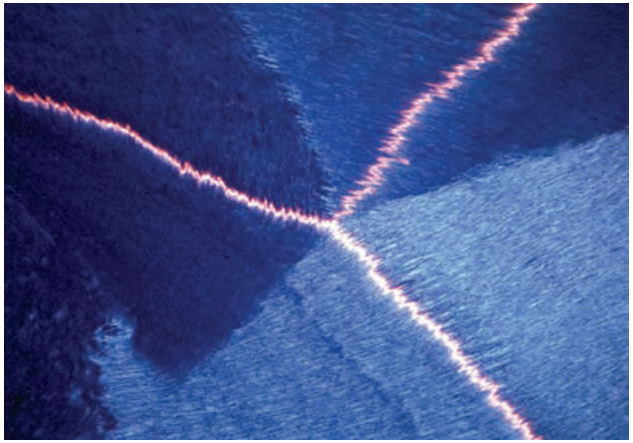




Above: *Lava cascades plunge 160 feet into Lua Hou Crater on the upper part of Mauna Loa's southwest rift zone during the volcano's July 1975 eruption. (USGS photograph by Robin T. Holcomb.)* ***Left:*** *A clockwise-circulating lava lake (nearly 500 feet across) formed in the west pit of Pauahi Crater, on Kīlauea's upper east rift zone, during the November 1973 eruption. Small bright spots seen on the lake surface are caused by floating trees bursting into flames. (USGS photograph by Robert I. Tilling.)*

At Kīlauea's summit, the century-long lava-lake activity in Halema‘uma‘u Crater ceased after the 1924 explosive eruption. However, a lava lake was active in the crater for about 8 months during a 1967–68 eruption. It was not until the 1969–74 Mauna Ulu eruptions on Kīlauea's upper east rift zone, however, that scientists had an opportunity to observe the development and behavior of a long-lived active lava lake outside the summit region of a Hawaiian volcano. The lava-lake behavior at Mauna Ulu, including movement and collision of thin plates of surface crust floating on circulating molten lava, provided a small-scale version of the Earth's global plate tectonics (see images this page). Lava-lake flow dynamics have been observed during Kīlauea's 1983–present Pu‘u ‘Ō‘ō-Kupaianaha eruption, mostly recently within the pit vent at Halema‘uma‘u.





Surface movements of active lava lakes on Kīlauea's east rift zone provide a very small scale analogy to movements of Earth's tectonic plates. ***Upper left:*** *Vigorous currents within the active 1987 Kupaianaha lava lake break the crust into separate slabs. (USGS photograph by J.D. Griggs.)* ***Lower left:*** *In the 1971 Mauna Ulu lava lake, moving slabs, ranging in size from a few feet to several tens of feet across but only a few inches thick, are rafted by circulating lava beneath. (USGS photograph by Wendell A. Duffield.)* ***Right:*** *Close-up views of the Mauna Ulu lava lake surface to show small-scale analogs to the three common types of tectonic plate boundaries: convergent boundary between two slabs of crust (**upper**); divergent or spreading boundaries between three slabs (**middle**); and transform fault offsetting a spreading boundary between two slabs (**lower**). (USGS photographs by Wendell A. Duffield.)*

Infrequent Explosive Activity

Explosive eruptions that deposit large volumes of *pyroclastic debris* over large areas—like the May 1980 eruption of Mount St. Helens—are relatively rare at Hawaiian volcanoes. The term "pyroclastic"—derived from Greek *pyro* (fire) and *klastos* (broken)—is a general term to describe all types of fragmented new magma or old rock ejected during explosive eruptions. Relatively few Hawaiian eruptions have been violently explosive, based on the scarcity of pyroclastic deposits. In contrast, some volcanic chains formed along the convergent boundaries of the Earth's tectonic plates contain 90 percent or more pyroclastic material. Nonetheless, explosive eruptions occur at Hawaiian volcanoes every few decades to centuries—as often as at many "explosive" volcanoes. In Hawai‘i, however, explosive events tend to be overlooked, because gentle *effusive* eruptions are by far the most common.

This footprint and thousands of others are preserved in two muddy ash deposits of Kīlauea's explosive eruptions in the 18th centuries. The prints in the younger deposit were left by Hawaiians who survived the explosions in 1790 from the summit of Kīlauea, several miles away. (Photograph by James F. Martin, National Park Service.)

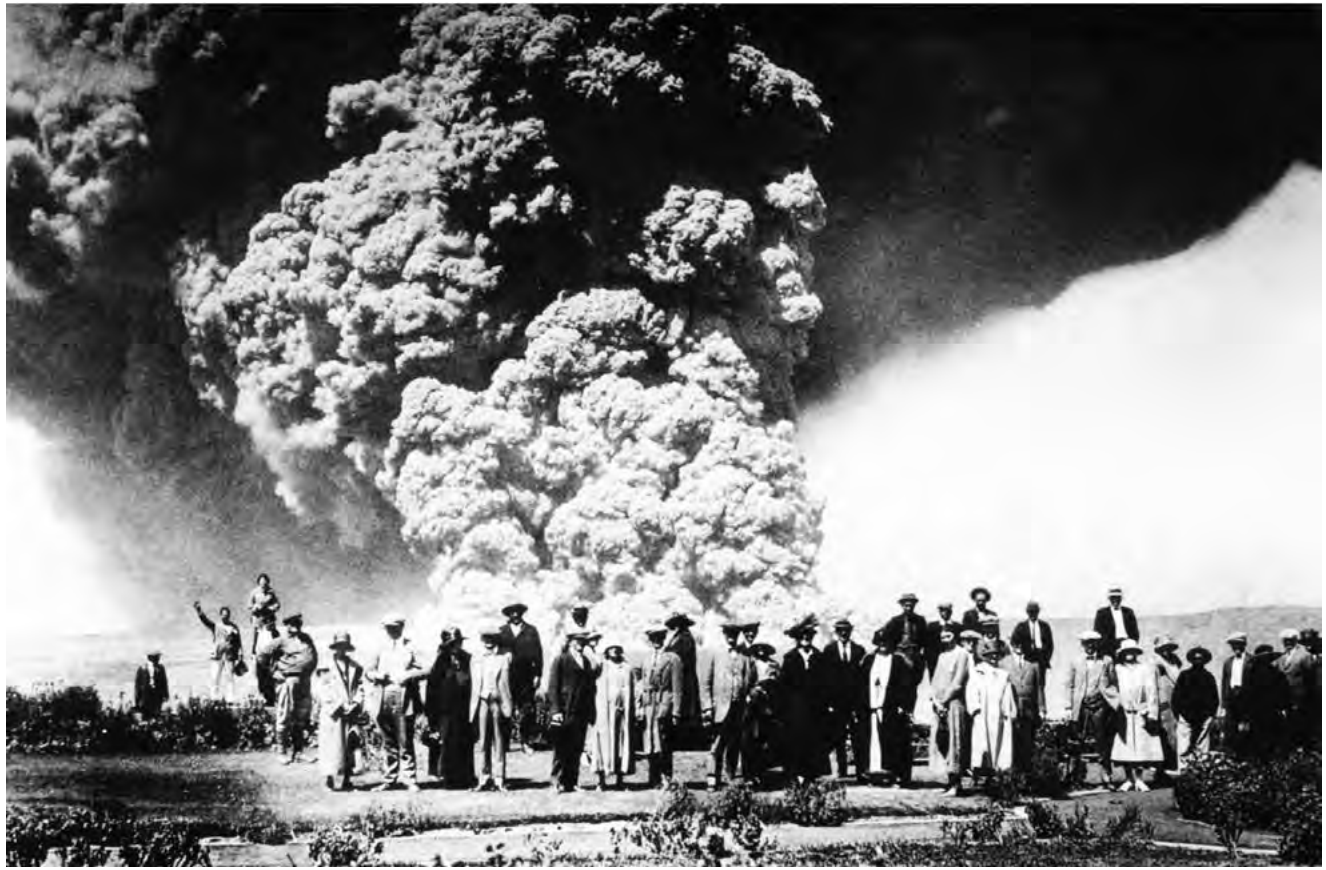
In 1790, a series of major explosive eruptions, which probably lasted a few days to a few weeks, culminated three centuries of intermittent explosive activity that deposited a blanket of pyroclastic debris as much as 35 feet thick in and around Kīlauea's summit. At the time of the 1790 eruptions, a band of Hawaiian warriors, led by Keōua, chief of the Ka‘ū district, was marching across the summit region of Kīlauea to battle the army of a cousin and rival chief, Kamehameha. Some of Keōua's warriors were caught in a hot, high-velocity explosion cloud, composed mainly of volcanic steam and other gases and hot ash. This cloud, termed a *pyroclastic surge*, moved swiftly along the ground surface and killed a number of people, estimates ranging widely, from about 80 to 5,400. Had the Hawaiian Volcano Observatory been at its present location on the summit of Kīlauea in 1790, it almost certainly would have been destroyed. An eyewitness account indicates that an ash column probably rose at least 30,000 feet into the sky, as has occurred in five other explosive eruptions in the past 1,500 years. Such high-rising ash columns from Kīlauea could pose a volcanic hazard to today's jet aircraft flying at cruise-level altitudes (around 30,000 feet).

A much less energetic explosive eruption took place at Halema‘uma‘u Crater in May 1924. Three months before the eruption, the long-lived lava lake in Halema‘uma‘u played actively about 150 feet below the crater rim. Beginning in February, the lake surface began to drop rapidly, and before long the lake drained entirely, exposing the crater floor. Throughout March and April, the crater floor itself subsided, apparently in response to magma moving out of the summit reservoir into the east rift zone. By May 6, the floor of Halema‘uma‘u had dropped more than 600 feet below the crater rim.

A series of steam-blast explosions began during the night of May 10–11, 1924, at Halema‘uma‘u and continued vigorously for more than two weeks. Each explosive pulse lasted from a few minutes to 7 hours; the most powerful ones sent ash plumes more than a mile high and hurled large blocks, some weighing several tons, more than a half mile from Halema‘uma‘u. Many of these blocks were red hot. A photographer, who ventured too close to the crater, was struck by a falling block during the largest explosion on May 18 and died that evening from his injuries. When the explosions ended, Halema‘uma‘u was about twice as wide and eight times as deep as 3 months earlier.

The 1790 and 1924 eruptions were explosive because they involved the violent mixing of groundwater and magma or hot rocks. During both eruptions, as the magma column subsided

Guests at a wedding reception pose in May 1924 at Kīlauea Volcano as a large explosion cloud rises thousands of feet into the air above Halemaʻumaʻu Crater. Given the data from recent studies, their location would now be considered too close for safety. (Photograph courtesy of the Bishop Museum, Honolulu.)



in the vent, groundwater circulating around the vent came into sudden contact with hot material and flashed explosively to steam. Both eruptions ejected mainly chunks of solid, hot older rocks—only a few of the fragments were formed from new magma. Explosions before 1790 expelled fragments of solid, older rocks and new magmatic material, suggesting that groundwater mixed with both. Though impressive, the 1924 explosions produced only about one-tenth of 1 percent of the volume of the explosions during the period 1500–1790.

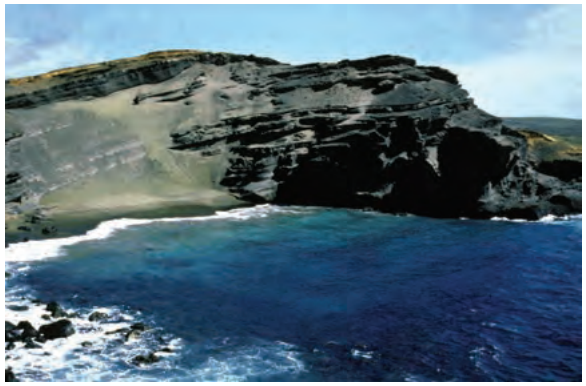
Pyroclastic deposits exposed at Kīlauea indicate that about two dozen major explosive eruptions have occurred during the past 50,000 years. Mauna Loa apparently has had less frequent explosive eruptions during the same time interval. Judging by their distribution and thickness, Kīlauea's prehistoric pyroclastic deposits had to be produced by explosive eruptions at least as strong as the 1790 eruption. One explosion about 1,000–1,300 years ago was even several times more powerful.

A special type of explosive activity, called a *littoral explosion*, occasionally results when active lava flows enter the ocean. Seawater comes into contact with the hot inner parts of the lava flow and flashes into steam, triggering an explosive spray of fragments derived from both the solidified outer part of the lava flow

as well as its still-molten core. Once formed, these chilled fragments quickly begin to disintegrate into smaller bits because of wave action. Because of their surf-zone locations, most small fragmental deposits from littoral explosions are quickly removed by erosive wave action. Larger deposits, however, can be more permanent and form *littoral cones*. About 50 such cones, prehistoric and historical, dot the shores of Mauna Loa and Kīlauea volcanoes. A well-studied example of a littoral cone is the 240-feet-high Pu‘u Hou, located 5 miles northwest of the southernmost point of the Island of Hawai‘i; it formed when lava from the 1868 eruption of Mauna Loa entered the ocean.

Fragmental deposits from littoral explosions and from surf breaking up streams of flowing lava can be reworked and concentrated along shorelines by wave action to quickly form *black-sand beaches*, composed of sand-size grains of the shattered black glassy lava. Many of these “instant” beaches, particularly if small, are ephemeral features, soon to be eroded by surf or covered by younger lava flows from ongoing eruption. Larger beaches, however, can form longer lasting landscapes that become popular visitor destinations. One of Hawai‘i’s most beautiful and photographed black-sand beaches was at Kaimū Bay, on the Puna coast along Kīlauea Volcano’s southeastern flank. Unfortunately, Kaimū beach met its demise when it was completely buried by lava erupted from the Kupaianaha vent in mid-1990.

Pu‘u o Mahana, a small prehistoric cone on the coast 3 miles northeast of the island’s south tip, is the site of Hawai‘i's famous "green-sand beach." This beach obtains its color from the shiny green mineral *olivine* (a magnesium-iron silicate) eroded from the cone and concentrated by wave action. *Peridot*, a gem-quality variety of olivine, is the birthstone for the month of August. Pu‘u o Mahana was believed to have originated from littoral explosions, but recent studies suggest that it probably formed inland, at an elevation more than 300 feet above current sea level. This cone’s present-day position at the water’s edge reflects the gradual sinking of the Island of Hawai‘i after Pu‘u o Mahana formed tens of thousands of years ago.



Center: *Molten lava is shredded by littoral explosions upon entry into the ocean during the 1969–71 Mauna Ulu eruption. (USGS photograph by Donald W. Peterson.)* ***Top right:*** *Pu‘u o Mahana, originally thought to be a prehistoric littoral cone of Mauna Loa (see text), is the site of the Island of Hawai‘i's green-sand beach. (USGS photograph by Robert I. Tilling.)* ***Bottom right:*** *Closeup of the green sand, which obtains its color from wave-concentrated grains of the mineral olivine. (USGS photograph by Robert I. Tilling.)*

Night-time view of the vigorous and spectacular littoral explosions that occurred during July 2008, when lava from the Pu‘u ‘Ō‘ō vent entered the ocean at Waikupanaha. The size of the explosions can be appreciated from the silhouettes of the unwary onlookers (bottom left), who are much too close to the action for their safety. (USGS photograph by Michael Poland.)

Hawaiian Volcanic Products, Landforms, and Structures

The volcanic mountains of Hawai‘i have been built by the accumulation of basaltic lava flows erupted, mostly nonexplosively, over hundreds of thousands of years, as the Pacific Plate moved northwestward over the Hawaiian hot spot. In contrast, volcanic mountains in the zones where tectonic plates converge (subduction zones), such as Mount St. Helens and the other Cascade Range volcanoes, have been built primarily by pyroclastic debris produced by explosive eruptions. Even though they both form linear mountain ranges, Hawaiian volcanoes differ greatly from Cascade volcanoes in mode of origin and types of volcanic rocks.

Molten lava can solidify in a variety of ways, depending on eruption dynamics and gas content of the erupting magma. Volcanic products of Hawaiian eruptions are mostly dark in color but vary widely in form and texture.

Lava Flows

Lava flows form more than 99 percent of the above-sea parts of Hawaiian volcanoes. *Pāhoehoe* (pronounced "PAH-hoy-hoy") and *‘a‘ā* (pronounced "ah-AH") are the two main types of Hawaiian lava flows, and these two Hawaiian names, introduced into the scientific literature in the early 19th century, are now used by volcanologists worldwide to describe similar lava-flow types. Pāhoehoe is lava that in solidified form is characterized by a smooth, billowy, or ropy surface, while ‘a‘ā is lava that has a rough, jagged, spiny, and generally clinkery surface. In thick ‘a‘ā flows, the rubbly surface of loose block and clinkers hides a massive, relatively dense interior.

The contrast between the surfaces of pāhoehoe and ‘a‘ā flows is immediately obvious to anyone hiking Hawaiian lava fields. Walking on dense pāhoehoe can be almost as easy as strolling on a paved sidewalk. But walking across ‘a‘ā is like scrambling over a building-demolition site or battle zone, strewn with loose, unstable debris of all shapes and sizes. The jagged rubble of ‘a‘ā flows quickly destroys field boots and, should the hiker stumble or fall (not at all uncommon), it can tear clothing and flesh.

An active clinkery ‘a‘ā flow advances over the smooth surface of an earlier erupted pāhoehoe flow in 1993. Both flows originated from the Pu‘u ‘Ō‘ō eruption. (USGS photograph by Christina Heliker.)

*Closer views of the surfaces of an ‘a‘ā flow (**above**) and a pāhoehoe flow (**below**). (USGS photographs by J.D. Griggs and Taeko Jane Takahashi, respectively.)*

Scuba divers film an underwater lava flow during the Pu‘u ‘Ō‘ō-Kupaianaha eruption. As the flow advances, incandescent lava breaks through the solidified shell of a pillow-lava lobe to form another tongue of lava. (Copyrighted photograph courtesy of Sharkbait World Pictures, Kailua-Kona, Hawai‘i.)

*A piece of pillow lava is collected by a mechanical arm of a **R**emotely **O**perated **V**ehicle (**ROV**) from great water depths on the submerged southern slope of Kīlauea Volcano. To collect the sample of choice, the mechanical arm is precisely manipulated by scientists aboard the ROV's mother ship on the ocean surface. (USGS photograph by Peter W. Lipman.)*

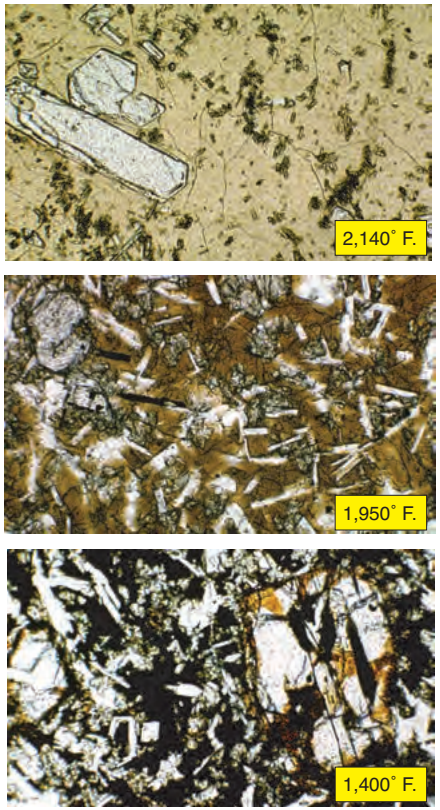
Many Hawaiian lava flows solidify as pāhoehoe throughout their length, and a few flows solidify completely as ‘a‘ā. Most flows, however, consist of both pāhoehoe and ‘a‘ā in widely varying proportions. Strictly speaking, the terms *pāhoehoe* and *‘a‘ā* should be used to describe completely solidified flows and not to moving lava. Yet, many scientists find it convenient to apply these terms to describe different parts and aspects of still-moving lava flows. In a given active flow, pāhoehoe upstream commonly changes to ‘a‘ā downstream, but, under certain circumstances, ‘a‘ā-crusted lava flows can also change into pāhoehoe flows. The explanation for changes in flow type depends on the delicate balance between the initial gas content of the lava, the changes in lava viscosity, the rate of deformation ("shear strain"), and increasing amounts of crystals in lava as it flows and cools. Once this critical balance is upset, pāhoehoe-crusted flows can change to ‘a‘ā, or ‘a‘ā-crusted flows can change to pāhoehoe.

Hawaiian lava is fluid enough to travel great distances, especially if it is transported through lava tubes. Excellent thermal insulation provided by tubes conserves the heat and fluidity needed for lava to flow long distances. The long-distance transport of lava through tube systems makes possible the development of the gently sloped volcanic shields. Some flows produced during the past 200 years are longer than 30 miles; in general, pāhoehoe flows tend to be longer than ‘a‘ā flows. Lava tubes may be preserved when an eruption ends and the lava drains away to leave open tunnels. They may be as much as several tens of feet in width, and one has been followed by *spelunkers* (cave explorers) for about 18 miles. Ancient Hawaiians used lava tubes as places of shelter, burial caves, and water-collection sites (by catching drips through the tube roof). Visitors to Hawai‘i Volcanoes National Park can walk through Thurston Lava Tube (Nāhuku), which formed in a pāhoehoe flow 500–600 years ago.

Fluid lava erupted or flowing under water can produce *pillow lava*, which forms when molten lava breaks through the thin walls of underwater tubes, squeezes out like toothpaste, and quickly solidifies as irregular, tongue-like lobes or protrusions (similar structures can result from the formation of multiple pāhoehoe toes from tube-fed flows). These processes are repeated countless times, and the resulting protrusions stack one upon another as the lava flow advances underwater. The term pillow comes from the observation that these stacked protrusions are sack- or pillow-shaped in cross section. Typically ranging from less than a foot to several feet in diameter, each pillow has a glassy outer skin formed by the rapid cooling of lava by water. Much pillow lava is erupted under relatively high pressure created by the weight of the overlying water, so there is little or no explosive interaction between the hot lava and cold water. The bulk of the submarine part of a Hawaiian volcano is composed of pillow lavas.

Abundant studies, by remotely controlled deep-sea cameras as well as by small, manned research submarines, have demonstrated the widespread occurrence of pillow lavas in areas of submarine volcanism. It was not until 1970, however, that the underwater formation of pillow lava was first directly observed. During the 1969–74 Mauna Ulu and the 1983–present Pu‘u ‘Ō‘ō-Kupaianaha eruptions of Kīlauea, teams of scuba-diving observers watched and filmed lava pillows being formed as lava flows entered the sea. Well-formed pillows have been studied on the submarine parts of Kīlauea and Mauna Loa, as well as the submerged parts of the 1800–1801 lava flows of Hualālai Volcano off the west coast of Hawai‘i.

Decreasing temperatures



Left: *Three specimens from the 1965 lava lake in Makaopuhi Crater (about 5 miles west of Pu‘u ‘Ō‘ō), sampled by drilling, as seen under the microscope (field of view about 0.05 inch). They were collected at three different times during drilling, as the lava-lake crust solidified and thickened with cooling. The samples represent the still-molten portion of the lava lake at the time of sampling and in-hole temperature measurement. The amount and kinds of crystals in these specimens increase with decreasing temperatures as the lava lake gradually cools. The fine brownish material between the crystals was liquid at the time of sampling and chilled to a glass when the sample solidified completely upon rapid cooling. (USGS photomicrographs by Thomas L. Wright.)*

Another common lava feature is the ponded flow or *lava lake*, the formation of which has been described earlier in connection with the eruptive style of Hawaiian volcanoes. Upon solidification, the surface of ponded lava is smooth, broken only by polygonal cooling cracks, formed in much the same way as shrinkage cracks in mud that has been dried by the sun. Many lava lakes have formed and been well observed during Kīlauea eruptions, the most recent of which were lakes at Kupaianaha (1986–90) and Pu‘u ‘Ō‘ō (1988–2006). The now completely solidified deep lava lake (443 feet) formed during the November–December 1959 eruption at Kīlauea Iki Crater is the only one of these still visible and easily accessible; most other lava lakes have been covered by younger lava flows or are not safely accessible.

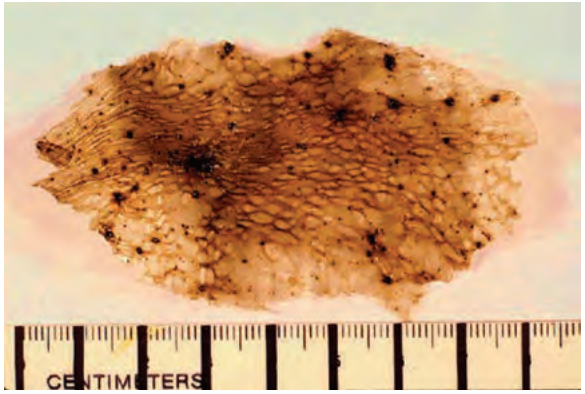
Hawaiian lava lakes have been investigated in detail because they furnish natural crucibles to study the cooling, crystallization, and chemical change of basaltic lava. These studies have included drilling holes through the solid crust of the lake to measure temperature and other properties and to sample the still-molten lava in the interior. In physical terms, the formation of the lava lake's solid crust by cooling can be compared to the formation of a sheet of ice on top of a body of water during a winter freeze. Holes drilled in 1988 at Kīlauea Iki indicated that parts of the deep interior of the lake still contained some molten 1959 lava (as much as 15 percent). The internal temperatures of the deep, hottest zones of the now completely solid lava lake (1,100–1,800°F) will remain hundreds of degrees hotter than the surface temperature for many more years.

Far left: *Looking about 400 feet down from the rim of Kīlauea Iki Crater to the surface of the lava lake formed in the 1959 eruption and a site of drilling studies in 1975 (oval).* ***Left:*** *Closeup of the Kīlauea Iki drilling operations. HVO scientists wore asbestos gloves to handle hot drilling steel. (USGS photographs by Robin T. Holcomb.)*

Drilling of lava lakes can be risky. When the Mauna Ulu eruption began on May 24, 1969, lava poured into ‘Alae Crater and quickly buried a drill rig and related equipment before they be could be lifted out by helicopter! A more common risk during drilling is posed by occasional minor steam explosions in drillholes caused by contact of molten lava with the cooling water used in drilling.

Fragmental Volcanic Products

Fragmental volcanic debris is formed during mildly explosive activity, such as lava fountaining, and, less commonly, during the infrequent violently explosive eruptions, such as those during 1500–1790 at Kīlauea. *Tephra* is the general term now used by volcanologists for airborne volcanic ejecta of any size. Additionally, various terms have been used to describe ejecta of different sizes. Fragmental volcanic products between 0.1 and about 2.5 inches in diameter are called *lapilli*; material finer than 0.1 inch is called *ash*. In a major explosive eruption, most of the pyroclastic debris would consist of lapilli and ash. Fragments larger than about 2.5 inches are called *blocks* if they were ejected in a solid state and *volcanic bombs* if ejected in semisolid, or plastic, condition. Volcanic bombs undergo widely varying degrees of aerodynamic shaping, depending on their fluidity, during the flight through the atmosphere. Based on their shapes after they hit the ground, bombs are variously described, in graphic terms, as "spindle or fusiform," "ribbon," "bread-crust," or "cow-dung.”

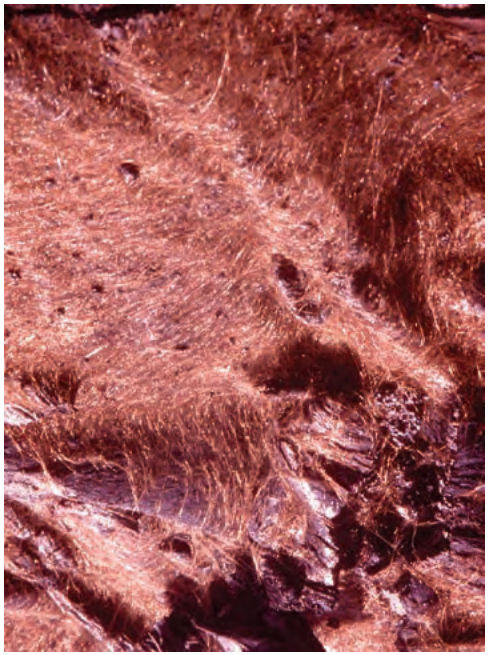


*Some common Hawaiian fragmental volcanic products: (**Left, top to bottom**): reticulite; Pele's tears; and limu o Pele (see text) (USGS photographs by J.D. Griggs); (**Right, top to bottom**): volcanic bombs and accretionary lapilli, spherical accumulations of volcanic ash, generally formed during explosive eruptions in presence of moisture. (USGS photographs by John P. Lockwood.)*

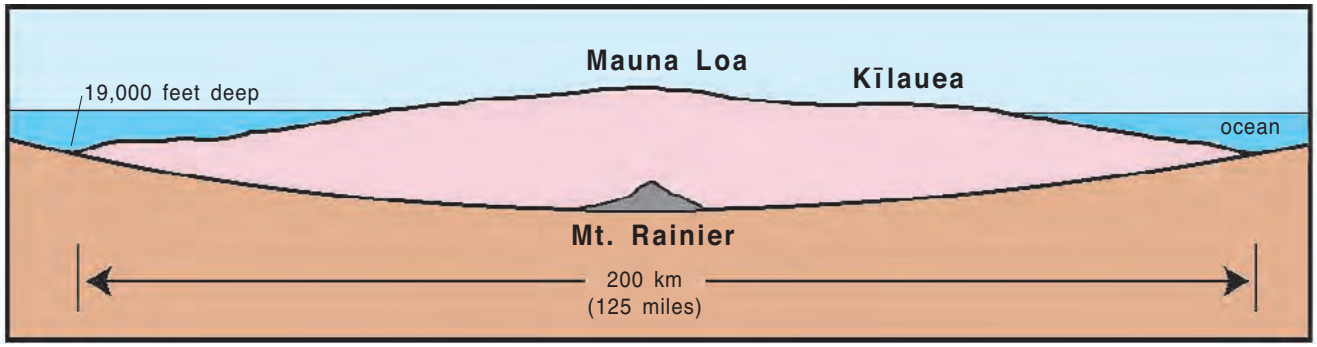
Another category of ejecta far more common than volcanic bombs is *scoria* or *cinder*, which refers to lapilli- or bomb-size irregular fragments of frothy lava. If the cinder contains abundant vesicles (gas-bubble cavities), it is called *pumice*, which can be light enough to float on water if the vesicles are closed to rapid filling by water. In Hawai‘i, these fragments share a common mode of origin: all result from sudden chilling of frothy lava from which gases were escaping during fountaining. During the exceptionally high fountaining episodes of some eruptions—such as at Kīlauea Iki in 1959, Mauna Ulu in 1969, or Pu‘u ‘Ō‘ō during 1983–1986—an extremely vesicular, feathery light pumice, called *reticulite* or *thread-lace scoria*, can form and be carried many miles downwind from the high lava fountains. Even though reticulite is the least dense kind of tephra, it does not float on water, because its vesicles are open and interconnected. Consequently, when it falls on water, it becomes easily waterlogged and sinks.

If scoria or pumice clots are sufficiently soft to flatten or splash as they strike the ground, they are called *spatter*. The still-molten character of spatter fragments can cause them to stick together to form *welded spatter* or *agglutinate*. Droplets of lava ejected in a very fluid condition and solidified in flight can form air-streamlined spherical, dumbbell, and irregular shapes. Drop-shaped lapilli are called *Pele's tears*, after the Hawaiian goddess of volcanoes. In streaming through the air, Pele's tears usually have trailing behind them thin threads of liquid lava, which are quickly chilled to form lustrous filaments of golden brown volcanic glass, called *Pele's hair*. Pele's hair can form thick mats downwind from high lava fountains near a vent, or it can be blown many miles from the vent. Even in the absence of high fountaining, thick mats of Pele’s hair can form near lava ponds and long-lived skylights, where swirling thermal air currents pluck strands from lava surfaces and deposit them on the walls and rim of the lava tube or pond. On some occasions, thin flakes of basaltic glass, called *limu o Pele* (“Seaweed of Pele”), form during explosive activity when hot lava enters the sea. These flakes are fragments of the glassy walls of exploding steam-filled bubbles of lava; though extremely fragile, the largest flakes can be several inches across.

Top: *Spattering at a vent, fed by tube-fed lava actively flowing beneath it, begins to form a hornito during the Pu‘u ‘Ō‘ō eruption in 2002. (USGS photograph by Donald A. Swanson.)* ***Below****: With continued spattering, the same hornito grew into an unusually high spire-like object before collapsing; a person (circled) gives scale. The top of the Pu‘u ‘Ō‘ō cone is visible on skyline left of spire. (USGS photograph by James Kauahikaua.)*



Top: *Shiny strands of volcanic glass, called Pele's hair, are commonly found downwind from active eruptive vents, skylights of lava tubes, or ocean-entry points and form matlike deposits.* ***Below:*** *Volcanic spatter sometimes becomes tightly welded to form mounds around active vents. (USGS photographs by Margaret T. Mangan and Richard B. Moore, respectively.)*



Profile of Hawaiian shield volcanoes compared with the profile of Mount Rainier, one of the larger composite volcanoes of the Cascade Range, drawn at the same approximate horizontal and vertical scale. The ocean floor beneath Mauna Loa and neighboring Kīlauea is downwarped many thousands of feet because of their immense weight. In size, Hawaiian shield volcanoes dwarf composite volcanoes.

Volcanic Landforms and Structures

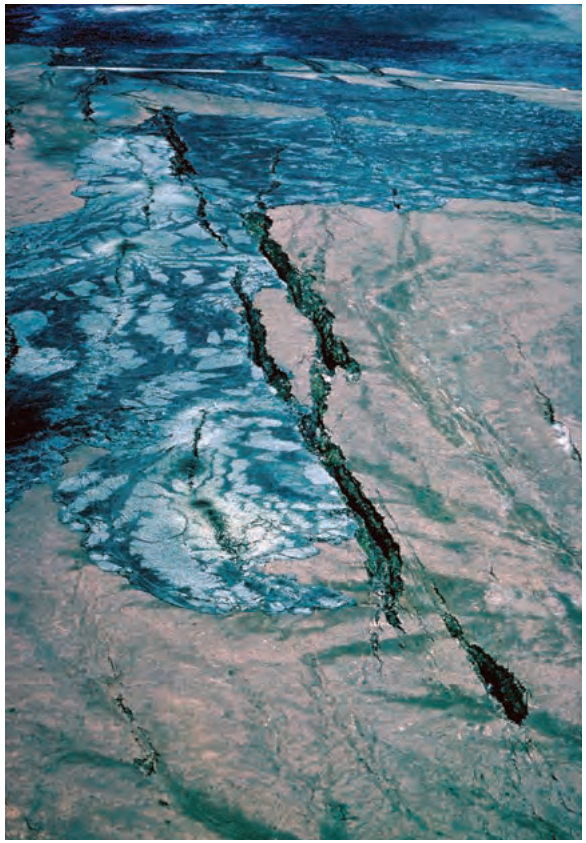
Hawaiian volcanoes exemplify a type of volcano known as a *shield volcano* built by countless outpourings of fluid lava flows that advance great distances from a central summit vent or group of vents. The successive piling up of these flows results in a broad, gently sloping, convex-upward landform, whose profile resembles that of a Roman warrior's shield.

Hawaiian shield volcanoes are the highest and largest mountains on Earth. For example, Mauna Kea Volcano rises 13,796 feet above sea level (a.s.l.) but extends tens of thousands of feet below sea level to meet the deep ocean floor. Mauna Loa Volcano (13,679 feet a.s.l.) is slightly lower than Mauna Kea, but it is much larger in volume, comprising about 19,000 cubic miles. Measured from its base resting on the deepest part of the bowed seafloor, the total height of Mauna Loa is about 56,000 feet—almost twice the height of the tallest mountain on land, Mount Everest (*Chomolungma* in Tibetan) in the Himalaya (29,028 feet a.s.l.). The profile of the Mauna Loa shield appears smooth, whereas the shield profile of Mauna Kea has a more uneven appearance, reflecting the growth of numerous small cinder cones on its upper slopes after shield formation.

Hawaiian and other shield volcanoes characteristically have a broad summit, indented with a *caldera*, a term commonly used for a large depression of volcanic origin. Most calderas form by collapse because of removal of magma from the volcano's reservoir by eruption and/or intrusion. Kīlauea's summit caldera is about 2.5 miles long and 2 miles wide. Moku‘āweoweo, the summit caldera complex of Mauna Loa, is more elongate, measuring about 3 by 1.5 miles. The terms *crater* or *pit crater* are applied to similar but smaller collapse features.

Aerial view in February 1973 of two prominent volcanic shields that formed during the 1969–1974 eruption on Kīlauea's upper east rift zone (see text). Both the Mauna Ulu shield (background) and the somewhat smaller ‘Alae shield (foreground) were built by repeated overflows from active lava lakes. In this view, the active ‘Alae lava lake with its silvery crust is brim full and overflowing. (USGS photograph by Robert I. Tilling.)

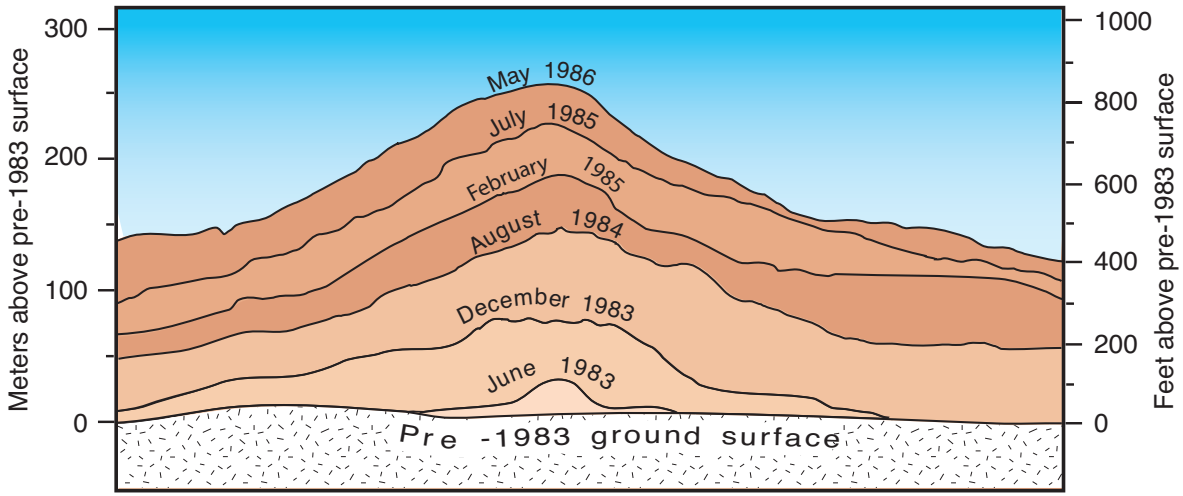
Aerial view from the south of snow-covered Moku'āweoweo, Mauna Loa Volcano's summit caldera, and several pit craters along its southwest rift zone. Mauna Kea Volcano, which last erupted about 4,000 years ago, can be seen in the distance. (USGS photograph by Donald W. Peterson.)



Aerial view of prominent fissures within the southwest rift zone of Kīlauea Volcano. The shiny dark lava was erupted from these fissures in September 1971. (USGS photograph by J.D. Griggs.)

Rift zones radiate from the summit calderas of both Mauna Loa and Kīlauea and extend down the volcanic flanks into the sea. They are elongate tapering ridges featuring prominent open fissures (see image upper right), pit craters, cinder and spatter cones, and small volcanic shields. The orientation of rift zones is influenced by the gravitational stresses and buttressing effects of preexisting neighboring volcanoes. Most Hawaiian eruptions take place either within summit calderas or along rift zones.

Repeated forceful intrusions of magma from the summit reservoir into the rift zones, together with continuous gravity-driven creep of the south side of the volcano, have pushed Kīlauea's south flank toward the sea. This seaward movement is readily measurable at rates as high as 4 inches per year. Eventually the accumulated seaward movement causes the south flank to become unstable, ultimately resulting in a large earthquake. Such earthquakes occur occasionally and are accompanied by substantial and sudden movements along faults cutting the south flank (the Hilina Fault System), as well as by slip



Growth profiles of Kīlauea's newest volcanic cone, built during the first three years of the Pu'u 'Ō'ō-Kupaianaha eruption.

Aerial view of some scarps of the Hilina Fault System, expressed as sharp cliffs on the south flank of Kīlauea Volcano. (USGS photograph by Donald A. Swanson.)

along a nearly horizontal fault zone at the base of the volcano. For example, in response to a magnitude 7.2 earthquake beneath the area on November 29, 1975, points on Kīlauea's south flank dropped as much as 11 feet and shifted southward as much as 24 feet. The *scarps* (steep slopes) of the Hilina faults are observable as *pali* (Hawaiian for cliffs) on Kīlauea's south flank.

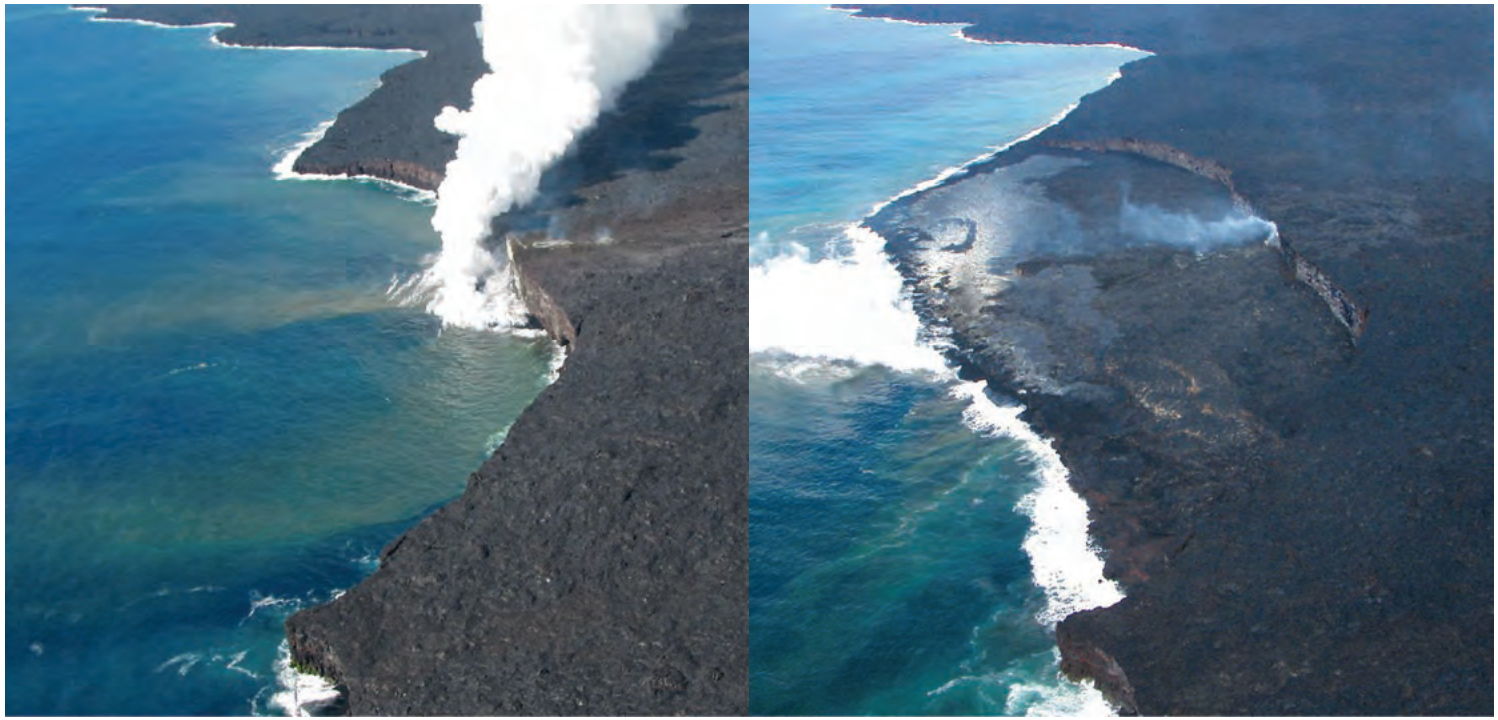
Prolonged eruptions on Kīlauea's east rift zone during the past four decades have given scientists unprecedented opportunities to observe the growth of Hawaiian volcanic landforms. The 1969–74 eruptions created two prominent volcanic shields: a symmetrical 397-foot-high mound at Mauna Ulu (Hawaiian for "growing mountain") and, abutting it, a more irregular shield, 328 feet high, over the site of buried 'Alae Crater. Another lava pond and 180-foot-high shield developed during the 4.5 years (July 1986–February 1992) when the Kupaianaha vent was active.

The highest volcanic landform constructed in Hawai'i during the past two centuries is the cinder-and-spatter cone built by eruptions at the Pu'u 'Ō'ō vent during 1983–86. By mid-July 1986, it had grown to its maximum height of about 835 feet above the pre-1983 surface. Since 1987, however, the form of this cone has been modified by eruption-related collapses, creating a large central crater and lowering its height by about 225 feet.

Above: *Pu‘u ‘Ō‘ō cone is one of the most recently created landforms in the United States; it began to grow in January 1983 and attained its maximum size in mid-1986 (see text). As seen here, a flank-vent eruption on Pu‘u ‘Ō‘ō’s west slope lights up the night sky in February 1992. This activity began the building of a new lava shield against the cone (see photographs to right). (Time-exposure photograph by Peter Mouginis-Mark, University of Hawai‘i).* ***Above right:*** *The Pu‘u ‘Ō‘ō cone in June 1992; within four months, the lava shield (middle ground) had become well developed. (USGS photograph by Tari Mattox.)* ***Below right:*** *Same view of Pu‘u ‘Ō‘ō in August 1997, after a large collapse of its top in January 1997. By then, the lava shield had become even larger by additional lava flows from flank vents, marked by spatter cones on top of the shield. (USGS photograph by Christina Heliker.)*

Above: *Aerial view in November 1992 of a lava delta, only four days old, formed at Kamoamoa Bay as flows from Pu‘u ‘Ō‘ō entered the sea, producing steam clouds and extending the shoreline 600 feet seaward. A much larger delta was active at East Lae‘apuki during 2005–2007 (see text).* ***Right:*** *A scientist looks at a large block of solidified lava that was hurled more than 50 feet inland during a littoral explosion. The blast was triggered by collapse of an active lava bench in 1989. (USGS photographs by Christina Heliker.)*

The Pu‘u ‘Ō‘ō-Kupaianaha eruption of Kīlauea Volcano also has produced to date more than 540 acres of surviving new land on the south coast of the Island of Hawai‘i. New land is created when hot lava—in a surface flow or fed by a lava tube—streams into the ocean and is shattered by explosive interaction with the cold seawater, forming a pile of fragmental volcanic products at the ocean edge. With sustained entry of lava into the ocean, over time this pile of loose debris enlarges and extends the shoreline seaward to form *lava deltas*—analogous to sediment deposition forming deltas at the mouths of large rivers. Actively growing lava deltas appear to be solid, especially if veneered with a surface of smooth lava. However, they in fact are highly unstable, because they are constructed on weak foundations of unconsolidated volcanic rubble. Active lava deltas can collapse unexpectedly—in part or completely—with little or no warning. Such collapses may occur catastrophically or piecemeal over several hours. The collapse-caused scar forms a new sea cliff, and the ocean area in front of it can again be filled with lava continuing to spill into the ocean, thereby sustaining the rebuilding of the delta. Some scientists call this newest extension of the active lava delta a *lava bench*. The development of lava benches shows that lava deltas have already collapsed and may do so again in the future.



Left: *Aerial view (on December 2, 2005) of the newly exposed sea cliff at the ocean lava entry at East Lae‘apuki, four days after the major collapse of the actively growing lava delta at the site (see text) (USGS photograph by James Kauahikaua.)* ***Right:*** *With continued lava entry into the ocean, by late-April 2006 the lava delta had grown back to more than its precollapse size. By mid-2007, this delta reached its maximum size to become the largest one observed to date. (USGS photograph by Tim Orr.)*

The 1983–present eruption at Kīlauea has provided unparalleled opportunities to study the evolution of lava deltas, the largest of which to date was constructed at the East Lae‘apuki ocean lava entry during 2005–2007. This delta had grown to about 34 acres in area by mid-November 2005 before suddenly collapsing on November 28 to produce the largest collapse observed to date. A time-lapse camera onshore (see http://gallery.usgs.gov/videos/136) captured the piecemeal collapse, which removed the entire delta as well as 10 acres of land behind it in less than 5 hours. With continued lava entry into the ocean at the same site, this delta quickly rebuilt and, by March 2007, had developed into the largest one observed to date—covering about 64 acres in area (48 football fields!). Then, the lava delta became inactive and was mostly removed several months later by two huge collapses, one in May and another in August 2007. Its final few remaining acres collapsed over the next three years. Today, none of the originally huge East Lae‘apuki lava delta remains.

Collapses involving lava deltas can trigger strong steam-blast explosions that hurl lava and large rock fragments more than 300 feet inland and send waves of scalding water onshore, thereby posing serious hazards to too-close observers of lava entry into the ocean. Since the early 1990s, one person has been killed during a lava-bench collapse, and three others have died in accidents related to bench or delta collapse.

Lō‘ihi: Hawai‘i’s Newest Volcano

Above: *The manned research submarine Pisces V of the Hawai‘i Undersea Research Lab (HURL) of the University of Hawai‘i, Mānoa, being launched by its mother ship R/V Ka‘imikai-o-Kanaloa. (HURL photograph by Alexander Malahoff, University of Hawaii.)* ***Below:*** *A closeup view of the Pisces V on shore. (HURL photograph by Brian P. Midson, University of Hawai‘i.)*

If the hot-spot theory is correct, the next volcano in the Hawaiian chain should form east or south of the Island of Hawai‘i. Abundant evidence indicates that such a new volcano exists at Lō‘ihi, a seamount (or submarine peak) located about 20 miles off the south coast. Lō‘ihi rises 10,100 feet above the ocean floor to within 3,100 feet of the water surface. Recent detailed mapping shows Lō‘ihi to be similar in form to Kīlauea and Mauna Loa. Its relatively flat summit apparently contains a caldera about 3 miles across; two distinct ridges radiating from the summit are probably rift zones.

Photographs taken by deep-sea cameras show that Lō‘ihi's summit area has fresh-appearing, coherent pillow-lava flows and talus blocks. Pillow-lava fragments dredged from Lō‘ihi have fresh glassy crusts, indicative of their recent formation. The exact ages of the sampled Lō‘ihi flows are not yet known, but certainly some cannot be more than a few hundred years old. In fact, since 1959 the HVO seismic network has recorded large earthquake swarms at Lō‘ihi during 1971–1972, 1975, 1984–1985, 1990–1991, and 1996, suggesting major submarine eruptions or magma intrusions into the upper part of Lō‘ihi. The July–August 1996 swarm was by far the most energetic seismic activity at Lō‘ihi recorded to date, involving more than 4,200 earthquakes. Ninety-five of these earthquakes had magnitudes of 4.0 or larger, and three of these were felt onshore by residents of Hawai‘i’s Ka’ū District.

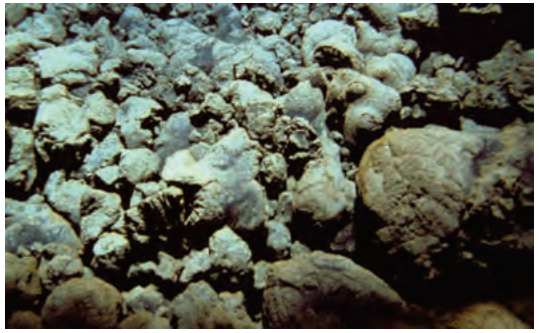
The intense 1996 earthquake activity at Lō‘ihi launched two “rapid-response” expeditions in August–September by University of Hawai‘i scientists to conduct onsite observations of the activity. This included surface-ship bathymetric surveys and a series of manned-submersible dives to make closeup observations and collect lava samples. These rapid-response and followup studies indicated that part of Lō‘ihi’s summit had collapsed to form a new pit crater (called Pele’s Pit), about 1,800 feet across and 900 feet deep.

Within this new crater, several new hydrothermal vents were observed, issuing the hottest waters ever measured at Lō‘ihi (about 390°F). Also, the observations showed the deposition of large quantities of glassy sand and gravel. While not conclusive, dating of two samples of young lava flows by an experimental isotopic technique has been interpreted by some scientists to suggest at least one, possibly two eruptions slightly preceded the 1996 earthquake swarm. Thus, from the periodic earthquake swarms and associated changes in structure, Lō‘ihi appears to be a dynamic, actively growing, but still submarine, volcano.

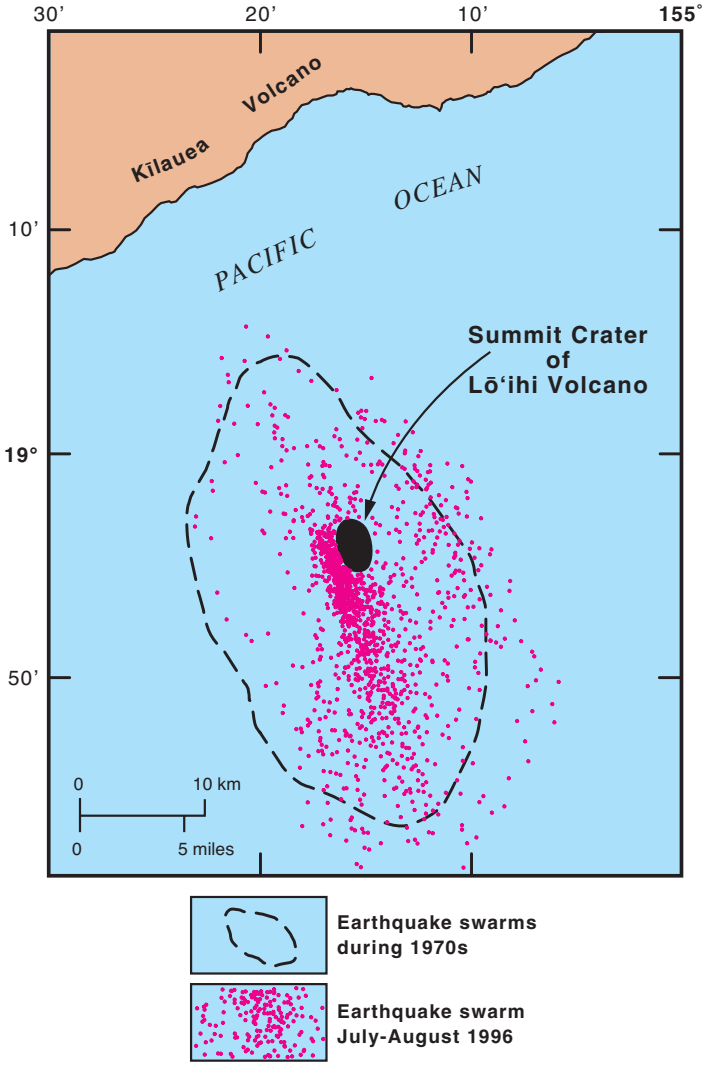
Seismic data also indicate that the deepest earthquakes beneath Lō‘ihi merge with the deep earthquakes beneath neighboring Kīlauea. This downward convergence implies that Lō‘ihi, Kīlauea, and Mauna Loa all tap the same deep magma supply. The triangular zone defined by the summits of these three active volcanoes perhaps can be taken to lie over the postulated Hawaiian hot spot.

Studies of Lō‘ihi provide a unique opportunity to decipher the youthful submarine stage in the formation and evolution of Hawaiian volcanoes. Scientists wonder when the still-growing Lō‘ihi will emerge above the surface of the Pacific to become Hawai‘i's newest volcano island. It will almost certainly take several tens of thousands of years, if the growth rate for Lō‘ihi is comparable to that of other Hawaiian volcanoes (about 0.1 foot per year averaged over geologic time). It is also possible that Lō‘ihi will never emerge above sea level and that the next link in the island chain has not yet begun to form.

The Shinkai 6500 of the Japan Agency for Marine Science and Technology (JAMSTEC) is the world's deepest manned research submersible, capable of operating at ocean depths down to 4 miles. It was used in 1999 by Japanese and U.S. scientists to study Lō‘ihi Volcano. (Photograph courtesy of JAMSTEC.)



The flank of Lō‘ihi, showing broken pillow lava of a fresh flow, as seen from about 7 feet above the volcano's surface at a water depth of about 4,200 feet. (Photograph by Alexander Malahoff, University of Hawai‘i.)



Map showing the locations of earthquakes that occurred during the 1970s and in the July–August 1996 period in the vicinity of Lō‘ihi. These earthquake swarms, plus similar occurrences in 1984–85 and the early 1990s, provide seismic evidence that Lō‘ihi is an active submarine volcano.

Volcanic Hazards and Benefits

Left: *A house is consumed by advancing lava during Kīlauea's 1960 Kapoho eruption. (Photographer unknown.)* ***Below:*** *View of Kapoho village during the 1960 eruption before it was entirely destroyed (Photograph by Gordon Morse)* ***Bottom****: A posteruption scene showing the remnants of corrugated iron roofs to mark the site of the lava-buried village. (USGS photograph by Robert I. Tilling).*

In the short term—on a human time scale—some Hawaiian eruptions can be extremely destructive, causing major disruptions in the daily lives of the people affected by them. On a geologic time scale (hundreds to millions of years), however, the eruptions have been beneficial. The benefits directly or indirectly derive from the volcanic formation of the island chain itself and include: scenic beauty, fertile soils, comfortable climate, and exploitable volcanic (geothermal) energy.

Volcanic Hazards

About 300,000 people have been killed directly or indirectly by volcanic activity worldwide during the past 500 years. Nearly all of those deaths have been caused by explosive eruptions of composite volcanoes along the convergent boundaries of the Earth's tectonic plates. The worst recent volcanic disaster was in November 1985, when mudflows triggered by a relatively small explosive eruption of glacier-capped Nevado del Ruiz Volcano, Colombia, buried the town of Armero and killed about 25,000 people. In contrast, fewer than about 5,000 people have been killed directly by eruptions in the recorded history of Hawai'i and only 5 of them since the beginning of the 20th century.

Although the usually gentle Hawaiian eruptions generally pose little danger to people, their lava flows and the building of ejecta cones can be highly destructive to populated and cultivated areas. For example, the villages of Kapoho in 1960 and Kalapana in 1990 were destroyed by eruptions on the east rift zone of Kīlauea. Flows from the ongoing Pu‘u ‘Ō‘ō-Kupaianaha eruption have buried a total of 211 buildings, including several residential areas in addition to Kalapana village and the Waha‘ula Visitor Center in Hawai‘i Volcanoes National Park.

Above right: *Lava flows from the Kupaianaha vent on Kīlauea's east rift zone cross the highway to enter Kalapana in December 1989. By late 1990, the community lay buried beneath 50–80 feet of lava. (USGS photograph by J.D. Griggs.)* ***Below right:*** *Lava flows from Pu‘u ‘Ō‘ō ignite the Waha‘ula Visitor Center, Hawai‘i Volcanoes National Park, in June 1989. (USGS photograph by J.D. Griggs.)*

Night view of the lava flows of the 1984 Mauna Loa eruption, with the lights of downtown Hilo in foreground. (USGS photograph by David Little.)

Parts of Hilo, the largest city on the Island of Hawai‘i, with a population of about 40,000, are built on the pāhoehoe lava flows of the 1881 Mauna Loa eruption. During the March–April 1984 eruption of Mauna Loa, Hilo was again threatened. Lava flows advanced nearly 16 miles in about 5 days, and a bright red glow in the sky above the incandescent flows could be seen on clear nights. The citizens and officials of Hilo became increasingly concerned as the eruption continued. Fortunately, the flows stopped about 4 miles short of the city's outskirts.

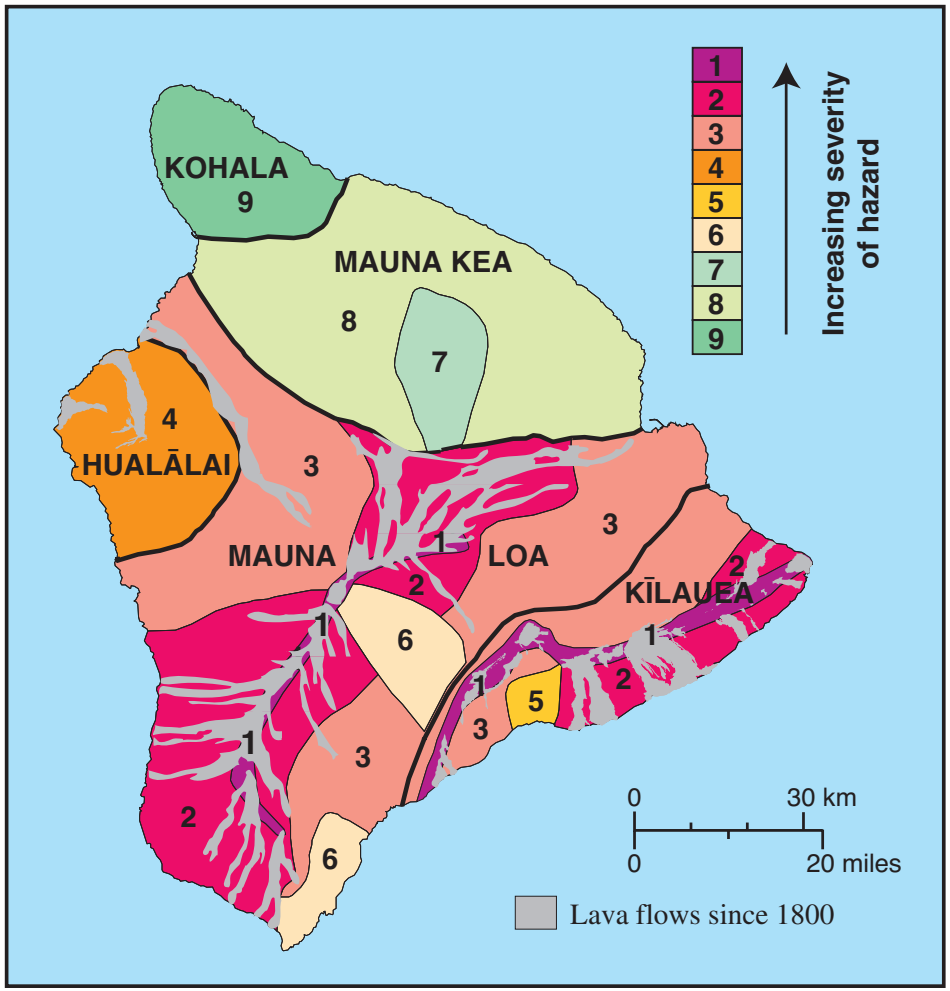
Because of the frequent Kīlauea and Mauna Loa eruptions, the Hawaiian Volcano Observatory conducts round-the-clock monitoring to detect early signs of impending activity and to advise local officials on a timely basis. A key component in reducing volcanic hazards is the preparation of volcanic-hazards zonation maps. These maps, which delineate the zones of relative severity of volcanic hazards, are based on an assessment of eruption frequency, nature of expected activity, and likely vent areas and lava-flow paths.

The infrequent explosive eruptions can pose a potential hazard to people in the area of ash fallout. Nearly all of the volcanic-caused fatalities in Hawai‘i in the past 220 years were caused by explosive activity. In 2008, small explosions in Halema‘uma‘u hurled blocks weighing more than 200 pounds onto a visitor overlook, fortunately closed by Hawai‘i Volcanoes National Park officials several weeks earlier. An explosive eruption is an example of a low-frequency but highly hazardous volcanic event.

It is useful to distinguish between the terms *hazard* and *risk*. Evaluation of hazards is based on geologic information only and considers the likelihood of destructive volcanic phenomena and products in a given area. Assessment of *risks* evaluates the likelihood of loss of life and property in the area being considered. Thus, volcanic "risk" increases as the zones defined as hazardous become cultivated, populated, or otherwise developed. Even areas with a very low severity of volcanic hazards may be classified as high risk if they are densely populated. Hazard-zonation maps provide government officials and the public with critical information that allows them to assess the risks of volcanic hazards and apply the results in long-term land-use planning, estimates of the socioeconomic and political impact of eruptions, and preparation of contingency plans in case of volcanic emergencies.

A volcanic-hazards map has been prepared for the Island of Hawai‘i, in which the areas of increasing relative severity of lava-flow hazards are designated "9" through "1." Related maps have been prepared for hazards from ash fall, ground failures, and subsidence. Similar volcanic hazards-assessment studies have been made for the islands of Maui and O‘ahu, although the expected frequency of future eruptions on those islands is much lower. Boundaries drawn between the hazard zones are necessarily gradational and reflect the judgment of experienced volcanologists. Hazards-assessment studies assume that probable future eruptive behavior is most likely to be similar to a given volcano's past behavior. As a volcano's eruptive history becomes better documented by additional studies, the hazards-zonation maps for it need to be revised and updated to reflect the incorporation of new and better information.

Mention should be made of another type of volcanic hazard—highly destructive but very, very infrequent—that has affected the Hawaiian Islands in the geologic past. Since the mid-1960s, mapping studies of the sea floor around the islands have recognized deposits of debris from more than fifteen gigantic landslides, covering many hundreds of square miles. Such underwater landslides, which have also been identified at other volcanic islands in the world [for example, Canary Islands (Atlantic Ocean), Cape Verde Islands (Atlantic Ocean), and La Réunion Island (Indian Ocean)], are among the largest known on Earth. They result from catastrophic collapses of the unstable flanks of active volcanoes, which can suddenly remove huge chunks of land and trigger towering waves (“mega-tsunamis”) that have carried rocks and sediments as high as 1,000 ft above sea level. The youngest giant Hawaiian submarine landslide, produced by a widespread collapse of Mauna Loa’s west flank, occurred about 120,000 years ago. Subsequent smaller landslides from both Mauna Loa and Kīlauea have been recognized, but their precise geologic ages are not well known. It is important to study Hawai‘i’s giant submarine landslides, despite their infrequency, because the devastating potential hazards they pose can cause enormous loss of life, property, and resources. However, the close monitoring of the measurable flank movement of Hawaiian volcanoes by the Hawaiian Volcano Observatory should detect any sudden acceleration in movement that may provide earning warning for any possible flank collapse.



Map of Island of Hawai‘i showing the volcanic hazards from lava flows. Severity of the hazard increases from zone 9 to zone 1. Shaded areas show land covered by flows erupted in the past two centuries from three of Hawai‘i’s five volcanoes (Hualālai, Mauna Loa, and Kīlauea).

Volcanic Air Pollution

Since mid-1986, in addition to the lava erupted and associated lava-flow hazards, the continuous activity at Pu‘u ‘Ō‘ō-Kupaianaha has also emitted on average about 2,000 tons of polluting sulfur dioxide gas (SO_2) per day. This emission rate is not trivial—considerably higher than that of the single dirtiest coal-fired power plant in the mainland U.S. Keep in mind, however, that most volcanic gases, including those from active Hawaiian volcanoes, are composed primarily of water vapor (H_2O, 70–90 percent), with decreasing abundances of carbon dioxide (CO_2), sulfur dioxide (SO_2), and trace amounts of other gases. Also, it be must emphasized that SO_2 and other gases generated by all the world's volcanoes pale by comparison with the total output of gases produced by human activity (mostly the combustion of fossil fuels). For example, the world's volcanoes spew about 200 million tons of CO_2 annually, while human activities worldwide produce some 24 *billion* tons of CO_2 each year—about 120 times more!

Above: *View on a day free of vog (see text) looking northwest from the Island of Hawai‘i toward the island of Maui; flank of Kohala Volcano is seen upper right. Haleakalā Volcano (east Maui), about 80 miles away, is clearly visible on the horizon, attesting to exceptional atmospheric clarity. (USGS photograph by Christina Heliker).* ***Below:*** *View from same spot on a day with heavy vog. Haleakalā cannot be seen, and even Kohala is barely visible. (USGS photograph by Tamar Elias).*

Nevertheless, Kīlauea's high and steady output of SO_2 poses a persistent natural hazard for Hawai‘i residents and visitors: volcanic air pollution, commonly called "volcanic smog," or *vog*. Vog is a visible haze comprising gas and an aerosol of tiny particles and acidic droplets, created when SO_2 and other gases emitted from Kīlauea interact chemically with sunlight and atmospheric oxygen, moisture, and dust. Depending on wind patterns (primarily) and other atmospheric conditions, vog can drift 100 miles or more from the eruption site. Near Kīlauea's active vents, vog consists mostly of SO_2 gas, but, by the time it reaches the Kona coast on the west side of the island, vog is mostly an aerosol of sulfuric acid and other sulfate compounds. When the prevailing northeasterly trade winds are disrupted, vog is dispersed more widely, affecting the entire Island of Hawai‘i and, sometimes, other Hawaiian islands.

In mid-2008, because of the new vent in Halema‘uma‘u Crater, SO_2 emissions from Kīlauea's summit increased from about 150 tons per day to as much as 2,000 tons per day. During late 2009, summit emissions were fluctuating between about 400 and 1,500 tons per day. High vog levels result in regionally hazy sky conditions that degrade air clarity and reduce visibility for motorists and air traffic. Exposure to vog is known to exacerbate existing respiratory problems and can produce symptoms such as headaches and eye irritation in some otherwise healthy individuals. Several studies to determine the effects of vog on human health have been conducted on the island and others are underway (see the Hawaiian Volcano Observatory's website for links to vog studies: http://hvo.wr.usgs.gov/hazards/). Hawai‘i Volcanoes National Park maintains an up-to-date website on current SO_2 conditions inside the park: http://www.nature.nps.gov/air/webcams/parks/havoso2alert/havoalert.cfm. In addition, the Department of Health of the State of Hawaii maintains another useful website about SO_2 levels for the southern half of the Island of Hawai‘i: http://www.hiso2index.info/.

The droplets of sulfuric acid suspended in vog combine with atmospheric moisture to form acid rain, which damages agricultural crops and accelerates rusting and corrosion of metal. Acid rain can also contaminate household drinking water by leaching lead from the roofing and plumbing materials of rooftop water-catchment systems used in many homes on the Island of Hawai‘i.

Volcanic air pollution is also caused when molten lava spills into the ocean and reacts with the chlorides in seawater, creating large steam plumes laden with hydrochloric acid (HCl). The impacts of these highly acidic coastal plumes—sometimes called *laze* (abbreviated from "lava haze")—are limited to within a few miles downwind of their source; thus, laze mainly poses a hazard to people who visit sites of lava entry into ocean. Although

awareness of the environmental hazards of volcanic air pollution has increased greatly since the mid-1980s, more studies are needed to better understand how vog and laze affect human health.

Volcanic Benefits

First of all, the Hawaiian Islands would not exist were it not for volcanic activity. Equally important, many factors that combine to make the islands an attractive place to live or visit depend directly or indirectly on the results of past and present eruptions.

Hawai‘i's majestic volcanic mountains, beautiful beaches, and pleasant climate combine to make the islands a popular tourist destination, which includes two heavily visited national parks. Haleakalā National Park on Maui, founded in 1961, features the spectacularly eroded summit crater of 10,023-foot-high Haleakalā Volcano, last active in the 15th or 16th century. Hawai‘i Volcanoes National Park, created by Congress in 1916, contains the two historically active Hawaiian volcanoes, Mauna Loa and Kīlauea. This park is one of the few places in the world where the processes and products of active volcanism can be viewed in relative safety by both scientists (volcanologists) and nonscientists (general public). Indeed, millions of park visitors have personally experienced the sights, sounds, and smells of volcanic eruptions and gained a firsthand appreciation of the phenomena that created and shaped these beautiful Hawaiian Islands.

Given enough rainfall, areas buried by new lava recover quickly; revegetation can begin less than one year after the eruption. Erosion and breakdown of the volcanic material can form fertile soils over periods of tens to thousands of years. These rich soils fostered the agricultural development of the Hawaiian Islands, as represented principally by the sugar, pineapple, coffee, and macadamia nut industries. Some volcanic products provide an abundant local source of raw materials for landscaping, housing and construction, and road building.

In recent decades, volcanic energy has been harnessed by a geothermal power plant on Kīlauea’s east rift zone. As of 2009, 30 megawatts of electricity were being produced and fed into the grid of the local utility company. However, it should be mentioned that the exploitation of Kīlauea’s geothermal potential also has generated controversy among Hawai‘i’s residents, particularly those living near the geothermal plant. Thus, the increased production envisaged in this century will need to be balanced by fuller consideration of environmental and cultural concerns.

Left: *Pressure testing in 1976 of a geothermal well drilled into Kīlauea’s lower east rift zone. A power plant later constructed in this area produces about 30 megawatts of electricity, about 30 percent of the island’s needs. (Photograph courtesy of the Hawai‘i Geothermal Project.)* ***Right:*** *Some of the power-generating equipment at this plant, the only commercial producer of geothermal energy in the State of Hawai‘i. (Photograph courtesy of Puna Geothermal Venture.)*

Above: *A luxuriant crop of burdock—a root vegetable widely used in Japanese cuisine—growing in the fertile volcanic soils derived from products of past Hawaiian eruptions. Mauna Kea Volcano is visible in the distance. (USGS photograph by Taeko Jane Takahashi.)*

Benefits of Research at the Hawaiian Volcano Observatory

Hawai‘i is both a natural laboratory for the study of eruptive processes and a volcanic wonderland for visitors. The huge challenge facing scientists and government officials is clear: Work to reduce the adverse impact of eruptions in the short term, so that residents and visitors can continue to enjoy the long-term benefits of volcanism. Toward this end, the Hawaiian Volcano Observatory (HVO) will continue to give timely warnings of anticipated volcanic activity, reliable and current progress reports once an eruption starts, and the best possible technical information on volcanic hazards posed by any eruption, present or future.

In addition, the high eruption frequency of its volcanoes and the availability of state-of-the-art research facilities at HVO combine to make Hawai‘i an excellent training ground for volcanologists from around the world. HVO and other scientists are striving to improve volcano-monitoring and eruption-forecasting techniques, in order to reduce the risks associated with eruptions of active volcanoes in Hawai‘i and elsewhere. Along with HVO, the U. S. Geological Survey operates four other volcano observatories: Alaska Volcano Observatory (in Anchorage, in cooperation with the Geophysical Institute of the University of Alaska-Fairbanks and the State of Alaska Division of Geological and Geophysical Surveys); Cascades Volcano Observatory (in Vancouver, Washington, in cooperation with the Geophysics Program of the University of Washington-Seattle); Long Valley Observatory (monitoring Long Valley Caldera, east-central California); and Yellowstone Volcano Observatory (monitoring Yellowstone Caldera, Wyoming, in cooperation with University of Utah-Salt Lake City and the National Park Service).

Below left: *Park visitors safely watch spectacular lava cascades and fountains during the August 1971 eruption at Kīlauea's summit. (Photograph courtesy of the National Park Service.)*
Below right: *Some of many thousands of visitors who in recent years have safely observed the slow advance of pāhoehoe lava erupted from Kīlauea's east-rift zone. (USGS photograph by Steven R. Brantley.)*

Selected Readings

The publications listed below furnish additional information on topics not covered, or only briefly discussed, in this booklet. Some of the listed publications are accessible on the Internet.

Decker, Robert, and Decker, Barbara, 2005, Volcanoes (4th ed.): San Francisco, W.H. Freeman and Company, 320 p. [An information-packed introduction to the study of volcanoes written in an easy-to-read style.]

Decker, R.W., Wright, T.L., and Stauffer, P.H., editors, 1987, Volcanism in Hawai‘i: U.S. Geological Survey Professional Paper 1350, 1,667 p. Online version: http://pubs.usgs.gov/pp/1987/1350/.

Dzurisin, Daniel, 2007, editor, Volcano deformation; geodetic monitoring techniques: Chichester, U.K.,Springer-Praxis Publishing, 441 p. [An authoritative treatment of the geodetic techniques used to monitor active and potentially active volcanoes.]

Heliker, Christina, 1997 (revised), Volcanic and seismic hazards on the island of Hawaii: U.S. Geological Survey general-interest publication, 48 p. [A nontechnical, well-illustrated summary of the natural hazards affecting the Island of Hawai‘i.] Online version: http://pubs.usgs.gov/gip/hazards/.

Heliker, Christina, and Brantley, S.R., 2004, The ongoing Pu‘u ‘Ō‘ō-Kupaianaha eruption of Kīlauea Volcano, Hawai‘i: U.S. Geological Survey Fact Sheet 2004–3085, 2 p. [A single-sheet, nontechnical summary of the first 20 years of this prolonged and continuing eruption.] Online version: http://pubs.usgs.gov/fs/2004/3085/.

Heliker, Christina, Stauffer, P.H., and Hendley, J.W., II, 2000 (revised), Living on active volcanoes—the Island of Hawai‘i: U.S. Geological Survey Fact Sheet 074–97, 2 p. [A single-sheet, nontechnical summary of Hawaiian volcanoes and their associated hazards.] Online version: http://wrgis.wr.usgs.gov/fact-sheet/fs074-97.

Heliker, Christina, Swanson, D.A., and Takahashi, T.J., 2003, editors, The Pu‘u ‘Ō‘ō-Kupaianaha eruption of Kīlauea Volcano, Hawai‘i; the first 20 years: U.S. Geological Survey Professional Paper 1676, 206 p. [A collection of 12 scientific papers—richly illustrated by many maps, diagrams, and photographs—that summarizes all aspects of the first two decades of this ongoing eruption, the longest and largest rift-zone activity at Kīlauea in more than 600 years.] Online version: http://pubs.usgs.gov/pp/pp1676/.

Helz, R.L., 2005, Monitoring ground deformation from space: U.S. Geological Survey Fact Sheet 2005–3025, 4 p. [A well-illustrated, simple-to-read summary of a satellite-based technique increasingly being used to monitor the active volcanoes of Hawai‘i and elsewhere: Interferometric Synthetic Aperture Radar (InSAR).] Online version: http://pubs.usgs.gov/fs/2005/3025/.

Johnson, Jenda, Brantley, S.R., Swanson, D.A., Stauffer, P.H., and Hendley, J.W., II, 2004, Viewing lava safely—common sense is not enough: U.S. Geological Survey Fact Sheet 152–00, 4 p. [A nontechnical summary of potential hazards associated with closeup viewing of Kīlauea eruptive activity, with emphasis on safety measures observers should take.] Online version: http://geopubs.wr.usgs.gov/fact-sheet/fs152-00.

Juvik, S.P., and Juvik, J.O., 1998, editors, Atlas of Hawai‘i (3d ed.): Honolulu, University of Hawai‘i Press, 333 p. [A very handy reference volume compiled by the Department of Geography, University of Hawai‘i, describing the natural, cultural, and social environment of Hawai‘i, the 50th State.]

Kious, W.J., and Tilling, R.I., 1996, This dynamic Earth—the story of plate tectonics: U.S. Geological Survey general-interest publication, 77 p. [A beautifully illustrated, jargon-free introduction to explain the theory of plate tectonics for nonscientists. This booklet nicely complements the world map “This dynamic planet” (Simkin and others, 2006).] Online version: http://pubs.usgs.gov/publications/text/dynamic.html.

Klein, F., and Wright, T.L., 2000, Catalog of Hawaiian earthquakes, 1823–1959: U.S. Geological Survey Professional Paper 1623, 97 p. [A comprehensive compilation of Hawaiian earthquakes through 1959, including events that occurred before availability of modern seismic data.] Online version: http://pubs.usgs.gov/pp/pp1623.

Lipman, P.W., and Mullineaux, D.R., editors, 1981, The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, 844 p. [The most comprehensive collection of scientific articles on Mount St. Helens' spec-

tacular 1980 eruption; it contains 62 reports on many aspects of this best-known U.S. explosive volcano. This volume provides an instructive comparison with U.S. Geological Survey Professional Paper 1350, edited by Decker and others, which summarizes present knowledge on Hawaiian volcanoes, the best-known U.S. (usually) nonexplosive volcanoes.]

Macdonald, G.A., Abbott, A.T., and Peterson, F.L., 1983, Volcanoes in the sea; the geology of Hawai‘i (2d ed.): Honolulu, University of Hawai‘i Press, 517 p. [A handsome book that provides an excellent overview of the eruptive and other geologic processes that have shaped the Hawaiian Islands.]

Mastin, L.G., Christiansen, R.L., Swanson, D.A., Stauffer, P.H., and Hendley, J.W., II, 1998, Explosive eruptions at Kīlauea Volcano, Hawai‘i: U.S. Geological Survey Fact Sheet 132–98, 2 p. [A single-sheet nontechnical summary of the occasional explosive eruptions of Kīlauea Volcano, which usually erupts nonexplosively.] Online version: http://geopubs.wr.usgs.gov/fact-sheet/fs132-98.

Sherrod, D.R., Sinton, J.M., Watkins, S.E., and Brunt, K.M., 2007, Geologic Map of the State of Hawai‘i: U.S. Geological Survey Open-File Report 2007–1089. [Contains a series of geologic maps of the Hawaiian Islands (scale of 1:250,000 for the Island of Hawai‘i and scale of 1:100,000 for the other islands) and an 85-page explanatory pamphlet. The geologic maps and pamphlet can be downloaded as pdf files.] Online version: http://pubs.usgs.gov/of/2007/1089/.

Sherrod, D.R., Scott, W.E., and Stauffer, P.H., editors, 2008, A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750, 856 p. [After being dormant during 1986–2003, Mount St. Helens came back to life in 2004. This collection of 37 papers, which provides a comprehensive summary of the renewed 2004–2006 eruptive activity, complements USGS Professional Paper 1250 (1981).] Online version: http://pubs.usgs.gov/pp/1750/.

Sigurdsson, Haraldur, Houghton, B.F., McNutt, S.R., Rymer, Hazel, and Stix, John, editors, 2000, Encyclopedia of volcanoes: San Diego, Academic Press, 1,417 p. [Perhaps the most comprehensive review of the state-of-the-art knowledge about volcanoes, volcano hazards, and volcano monitoring, as the relatively young science of volcanology entered the 21st century.]

Simkin, Tom, Tilling, R.I., Vogt, P. R., Kirby, S., Kimberly, Paul, and Stewart, D.B., compilers, 2006, This dynamic planet; world map of volcanoes, earthquakes, impact craters, and plate tectonics (3d ed.): U.S. Geological Survey Geologic Investigations Map I–2800, Mercator projection with scale 1:30,000,000 at equator. Online version: http://mineralsciences.si.edu/tdpmap/.

Sutton, Jeff, Elias, Tamar, Hendley, J.W., II, and Stauffer, P.H., 1997, Volcanic air pollution—a hazard in Hawai‘i: U. S. Geological Survey Fact Sheet 169–97, 2 p. [A single-sheet, nontechnical summary of the hazards posed by volcanic air pollution created by the recent prolonged eruptions of Kīlauea Volcano.] Online version: http://wrgis.wr.usgs.gov/fact-sheet/fs169-97.

Tilling, R.I., 1993 (reprinted), Volcanoes: U.S. Geological Survey general-interest publication, 45 p. [A general introduction to the study of volcanoes for the nonspecialist, with focus on the nature, types, workings, products, and hazards of volcanoes.] Online version: http://pubs.usgs.gov/gip/volc/.

Tilling, R.I., Topinka, Lyn, and Swanson, D.A., 1990 (revised), Eruptions of Mount St. Helens— past, present, and future: U.S. Geological Survey general-interest publication, 46 p. [A nontechnical summary, illustrated by many color photographs and diagrams, of the abundant scientific data available for the volcano, with emphasis on the catastrophic eruption of May 18, 1980, which caused the worst volcanic disaster in U.S. history.] Online version: http://pubs.usgs.gov/publications/msh/.

Trusdell, F.A., Wolfe, E.W., and Morris, Jean, 2005, Digital database of the geologic map of the Island of Hawai‘i: U.S. Geological Survey Data Series 144, version 1.0. Online at: http://pubs.usgs.gov/ds/2005/144/.

Westervelt, W.D., 1963, Hawaiian legends of volcanoes: Rutland, Vermont, Charles E. Tuttle Company, 205 p. [An interesting collection of legends and stories about Pele, Hawaiian goddess of volcanoes, and her volcanic exploits and deeds.]

Wolfe, E.W., and Morris, Jean, 1996 (reprinted 2009), Geologic map of the island of Hawai‘i: U.S. Geological Survey Miscellaneous Investigations Series Map I–2524–A and I–2524–B (three map sheets, scale

1:100,000). [These maps summarize a half-century of new geological knowledge gained since the classic geologic map of the island published by Harold T. Stearns and Gordon A. Macdonald in 1946. This monumental work is the first to show in detail the age and distribution of both prehistoric lavas and those erupted during written history (that is, the past two centuries), including a compilation of the sample locations and chemical analyses of hundreds of Hawaiian lavas.] Digital version: see Trusdell and others (2005).

Wright, T.L., Takahashi, T.J., and Griggs, J.D., 1992, Hawai‘i volcano watch; a pictorial history, 1779–1991: University of Hawai‘i Press and Hawai‘i Natural History Association, 162 p. [A highly readable, richly illustrated account of “volcano monitoring” in Hawai‘i, from the earliest observations to modern scientific studies.]

Selected Viewings

The best way to see Hawaiian eruptive activity is to visit Hawai‘i Volcanoes National Park—at the right time and place. The next best thing is to view videos or DVDs of Hawaiian eruptions, some of which are listed here. Some school and public libraries might have them in their collections.

Videos and (or) DVDs

Eruption of Kīlauea, 1959–60: U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025. [Originally an award-winning movie jointly produced (in 1961) by the USGS and the National Park Service that contains spectacular footage of the highest lava fountains ever recorded in Hawai‘i and of the formation of Kīlauea Iki lava lake. This classic film has been beautifully restored and is now available as a 28-minute DVD created by Michael M. Moore (USGS Library, Menlo Park). The DVD can be accessed online at: http://education.usgs.gov/common/video_animation.htm]

Fire Under the Sea—The Origin of Pillow Lava: Moonlight Productions, 73-1132 Ahikawa Street Kailua-Kona, Hawaii 96740. [Originally a 20-minute movie that first captured the actual sights and sounds of underwater movement of red-hot lava and formation of pillow lava, as filmed by scuba-diving scientists during the 1969–1974 Mauna Ulu eruptions of Kīlauea. A 10-minute excerpt from this classic original film can be seen on YouTube at: http://www.youtube.com/watch?v=H7DPL0YYGL4.

Inside Hawaiian Volcanoes: Department of Mineral Sciences, Smithsonian Institution, NHB-119, Washington, DC 20560. [A 25-minute video jointly produced by the USGS and the Smithsonian Institution showing the geologic settings and structures of Hawaiian volcanoes and the methods used to monitor volcanic behavior.]

Rivers of Fire: Hawai‘i Natural History Association, Ltd., P.O. Box 74, Hawai‘i Volcanoes National Park, HI 96718. [A 25-minute videotape of the March–April 1984 eruption of Mauna Loa Volcano that contains some of the best footage of Hawaiian lava flows ever filmed.]

The Hawaiian Volcanoes: a Force for Creation: Harada Productions, 22 Malanai Street, Hilo, HI 96720. [A 30-minute videotape containing dramatic scenes of the Pu‘u ‘Ō‘ō-Kupaianaha activity of Kīlauea through 1989 and of the 1984 eruption of Mauna Loa Volcano.]

Volcanoscapes V: Hawai‘i Volcanoes National Park: Tropical Visions, Inc., 62 Halaulani Place, Hilo, HI 96720. [A 70-minute video, the latest in a series featuring not only Kīlauea’s current eruption at Pu‘u ‘Ō‘ō-Kupaianaha, but also other major Hawaiian eruptions. It also covers flora and fauna of the National Park and historical information and images about the Big Island of Hawai‘i.]

A Firsthand Account of the Current Eruption of Kīlauea Volcano: Winter 2010 Eruption Update: Volcano Video Productions, P.O. Box 909, Volcano, HI 96785. [A 60-minute videotape summarizing the course of the 1983–present Pu‘u ‘Ō‘ō-Kupaianaha eruption of Kīlauea Volcano through 2009, including the perspective of, and narration by, a former staff member of the USGS Hawaiian Volcano Observatory.]

Lava Flows and Lava Tubes: What they are, how they form: Volcano Video Productions, P.O. Box 909, Volcano, HI 96785. [Award-winning 42-minute video.]

Kīlauea: Mountain of Fire: Public Broadcast System. [This 50-minute video, produced in March 2009, contains excellent footage

of the current activity at Kīlauea along with informative commentary. It also shows scientists of the Hawaiian Volcano Observatory making studies of the eruption. This video can be seen in its entirety at: http://video.pbs.org/video/1133372360/.]

Selected Websites

The following websites provide national and worldwide information on volcanoes, eruptions, and volcano hazards.

http://hvo.wr.usgs.gov

[Maintained by the USGS Hawaiian Volcano Observatory (HVO), this site provides the most comprehensive and authoritative online information about the volcanoes and associated hazards in Hawai‘i and how HVO scientists monitor them.]

http://volcanoes.usgs.gov

[The official site of the USGS Volcano Hazards Program, this site contains much useful information about the volcanoes of the United States and the hazards they pose; it also provides links to the websites of the other volcano observatories operated by the USGS in Alaska, the Cascades (California, Oregon, Washington), Long Valley (California), and Yellowstone (Wyoming-Montana).]

http://www.nmnh.si.edu/gvp

[Maintained by Global Volcanism Program of the Smithsonian Institution, Washington, D.C., this site is the best source for information about volcanoes of the world and their eruptive activity; it is the “telephone book” of the world’s volcanoes.]

http://www.geology.sdsu.edu/how_volcanoes_work

[Supported NASA as part of Project **ALERT** (**A**ugmented **L**earning **E**nvironment and **R**enewable **T**eaching), this site has a wealth of educational materials about volcanoes and their eruptive processes and products. It is intended for use by college-level students of geology and volcanology and by teachers of earth science.]

http://www.swisseduc.ch/stromboli/index-en.html

[Developed and maintained by Italian and Swiss volcanologists, this site provides abundant materials and use links to volcanoes and eruptions. Although it emphasizes Etna and Stromboli volcanoes, the site also contains great photographs and video clips of many other volcanoes in the world, including those of Hawai‘i.]

http://www.photovolcanica.com/index.html

[This commercial website, which is maintain by Dr. Richard Roscoe (Munich, Germany), contains many excellent photo galleries of volcanoes and eruption scenes (mostly non-Hawaiian), in addition to a diverse collection of nonvolcanic photographs.]

Conversion of Units

Metric units of measurement are the standard in virtually every country in the world. However, the United States still adheres to English units, as used in this booklet. For readers in countries that use Metric units and for U.S. students learning the Metric system, a conversion table is given below.

	To convert English units	To Metric units	Calculation
			Multiply by:
Length	inch	centimeter	2.5
	foot	centimeter	30.5
	yard	meter	0.91
	miles (statute)	kilometer	1.61
			Multiply by:
Area	square inch	square centimeter	6.4
	square foot	square meter	0.09
	square yard	square meter	0.84
	square mile	square kilometer	2.6
			Multiply by:
Volume	gallon (U.S.)	liter	3.8
	cubic foot	cubic meter	0.03
	cubic yard	cubic meter	0.76
	cubic mile	cubic kilometer	4.0
Temperature	degree Fahrenheit (°F)	degree Centigrade (°C)	*Subtract 32, then multiply by 0.56*

Glossary

Terms shown in **bold type** within definitions are separately defined in this listing. Some terms (for example, ash and dome) have other meanings, but only their use in volcanology is covered in these definitions. For more information, the interested reader should consult the website "USGS Photo Glossary of volcanic terms": http://volcanoes.usgs.gov/images/pglossary/index.php

Agglutinate. A welded **pyroclastic** deposit; term is commonly used for deposits of volcanic ejecta fused while hot and viscous. Agglutinate typically occurs in **spatter cones**.

Andesite. Volcanic rock, typically dark gray to black, with about 57–63 percent **silica**.

Ash. Fine fragments, less than 2 millimeters (about 0.1 inch) across, of volcanic rock erupted during an explosive eruption.

Basalt. Volcanic rock with about 47–53 percent **silica**, typically gray to black. Basaltic **lavas** are more fluid than **andesites** or **dacites**, which contain more silica.

Caldera. A large, basin-shaped volcanic depression, more or less circular in form; typically more than 1 to 2 miles (several kilometers) across. Commonly formed by collapse during withdrawal or ejection of a large volume of **magma** that leaves the roof of the **magma** reservoir unsupported.

Dacite. Volcanic rock, commonly light colored, with about 64–69 percent **silica**. Dacite lavas are viscous and tend to form thick blocky **lava** flows or steep-sided piles of lava called lava **domes**. Dacitic **magmas** tend to erupt explosively, thus also ejecting abundant **ash** and **pumice**.

Dome. A steep-sided mass of viscous and often blocky **lava** extruded from a **vent**; typically has a rounded top and covers a roughly circular area. Typically **silicic** (**rhyolite** or **dacite**) in composition.

Ejecta. Material explosively ejected from a volcano.

Lava. Molten rock (**magma**) that reaches the earth's surface by explosive or effusive volcanic activity.

Magma. Molten rock beneath the Earth's surface. All magmas and **lavas** consist mainly of a liquid, along with smaller and variable amounts of solid and gaseous matter.

Pumice. Highly **vesicular** volcanic **ejecta**, typically **silicic** in composition. It is essentially **magma** that has been frothed up by escaping gases and then cooled and solidified during eruption.

Pyroclastic. General term applied to volcanic products or processes that involve explosive ejection and fragmentation of **lava**. Literally means "fire-broken" (from the Greek *pyro*=fire, *klastos*=broken).

Pyroclastic flow. A hot (typically >1,450°F or 800°C), turbulent, ground-hugging mixture of rock fragments, gas, and **ash** that travels very rapidly (hundreds of miles per hour) away from a volcanic **vent** or collapsing lava **dome**. Commonly associated with an overriding less dense flow component called **pyroclastic surge**.

Pyroclastic surge. The less dense component of a **pyroclastic flow**, with a low concentration of solids and a density much less than that of the resulting deposit. Pyroclastic surges flow mostly above rather than hugging the ground.

Rhyolite. Volcanic rock, typically light colored, with 70–77 percent **silica**. Rhyolite lavas are viscous and tend to form thick blocky **lava** flows or steep-sided piles of lava called lava **domes**. Rhyolite **magmas** tend to erupt explosively, commonly also producing abundant **ash** and **pumice**.

Scoria. Vesicular volcanic **ejecta**, essentially **magma** that has been frothed up by escaping gases. It is a textural variant of **pumice**, with scoria typically being less **vesicular**, denser, and usually andesitic or basaltic in composition.

Silica. Silica is silicon dioxide (SiO_2) the predominant molecular constituent of volcanic rocks and **magmas**. It tends to polymerize into molecular chains, increasing the viscosity of the magma. **Basalt** magma, having relatively low content of SiO_2, is fairly fluid, but with increasing SiO_2, **andesite**, **dacite**, and **rhyolite** magmas are progressively more viscous. Because it is more difficult for dissolved gas to escape from more viscous magma, higher silica magmas generally erupt more explosively.

Silicic. Describes magma that contains more than ~63 percent **silica** and is generally viscous, gas-rich, and tends to erupt explosively. Includes **rhyolite** and **dacite**.

Spatter cone. A steep-sided cone constructed of **agglutinate** at a **vent**. Most spatter cones are small, typically 30 feet (10 meters) or less in height, and commonly form in linear groups along a fissure.

Tephra. A general term for any airborne **pyroclastic** material, regardless of the shape or size of the fragments. Most commonly applied to smaller size volcanic ejecta (such as **ash** and **scoria**).

Vent. Any opening at the Earth's surface through which **magma** erupts or volcanic gases are emitted.

Vesicular. Describes **lava** whose texture is marked by conspicuous cavities, which represent volcanic-gas bubbles trapped in **magma**.

Volcanic glass. A natural glass formed by the rapid cooling (quenching) of the liquid component of **magma**.

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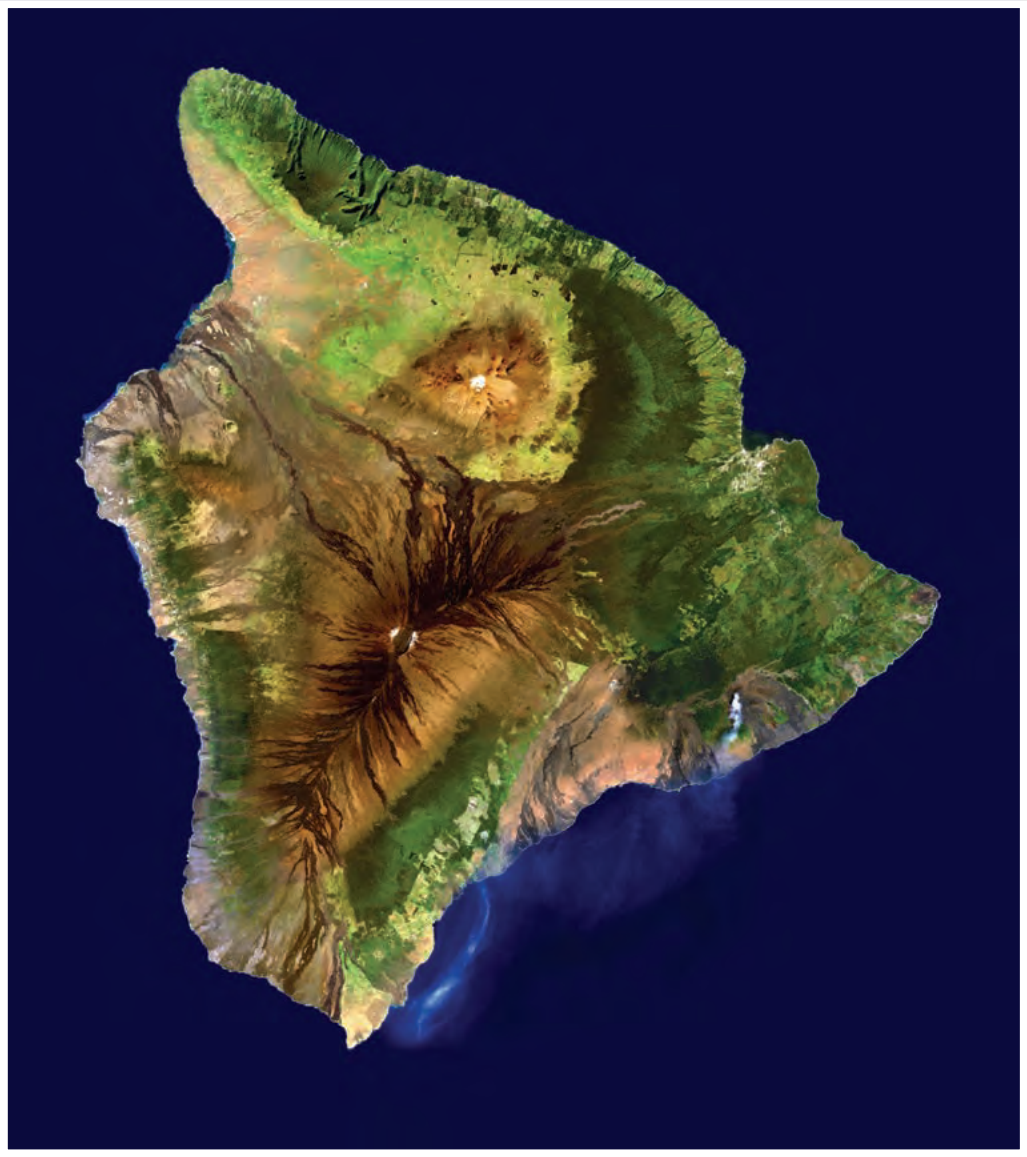
Modified from original graphics and design by Bobbie Myers and Martha Kiger

Sunrise view in August 2002 of lava from the Pu‘u ‘Ō‘ō-Kupaianaha eruption cascading into the ocean on the south coast of the Island of Hawai‘i. (USGS photograph by Donald A. Swanson.)

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.



Mosaic of the Island of Hawai‘i by Pamela Owensby (Hawai‘i Institute of Geophysics, Honolulu) from 20 NASA Landsat images taken between July 1999 and June 2000. Note the fume cloud at the Pu‘u ‘Ō‘ō vent and the trail of volcanic smog (vog) drifting along the southeastern coast of the island. (Image courtesy of Peter Mouginis-Mark, Hawai‘i Institute of Geophysics.)