Eruptions of Hawaiian Volcanoes—Past, Present, and Future

General Information Product 117

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

Aerial view of the Kīlauea summit eruption that began in December 2020 and filled the deepest part of Halemaʻumaʻu, a crater within the summit caldera that collapsed during 2018. The eruption eventually focused on one vent and continued until May 2021. Photograph by Matthew Patrick, U.S. Geological Survey.

Cover. Fissure 8 erupts on July 29, 2018, during Kīlauea's lower East Rift Zone eruption. Photograph by Matthew Patrick, U.S. Geological Survey.

Back cover. Aerial view of fissures erupting high on the Northeast Rift Zone of Mauna Loa in 2022. A plume of volcanic gases and fine volcanic ash and Pele's hair are wafted nearly vertically above the vents. Photograph by Matthew Patrick, U.S. Geological Survey.

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By Katherine M. Mulliken, Robert I. Tilling, and Donald A. Swanson

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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 U.S. Geological Survey Hawaiian Volcano Observatory (HVO), then located on the caldera rim of Kīlauea, celebrated its 75th anniversary. To honor this anniversary, the U.S. Geological Survey (USGS) published Professional Paper 1350 (see Selected Readings section, page 62), 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 the State of Hawaii's active volcanoes—Kīlauea and Mauna Loa. A second edition of the booklet was published in 2010 to commemorate the Centennial of HVO (which occurred in January 2012), summarizing abundant new information gained since the January 1983 onset of Kīlauea's middle East Rift Zone eruption at Puʻuʻōʻō and the March 2008 beginning of Kīlauea's summit lava-lake activity within Halemaʻumaʻu. In this third edition, we include highlights from Kīlauea's subsequent activity, including the 2018 eruption in the lower East Rift Zone—the largest and most destructive in at least 200 years—and associated summit-collapse events, the eruptions at Kīlauea's summit since 2018, and the 2022 eruption of Mauna Loa, which occurred after 38 years of quiescence. It also considers new data leading to an improved history of Kīlauea's explosive activity in the recent geologic past.

This general-interest booklet is a companion to the one on Mount St. Helens volcano (southwestern Washington) first published in 1984, revised in 1990 (see Selected Readings section). Together, these publications illustrate the contrast between the two main types of volcanoes: shield volcanoes, such as those in the State of Hawaii, which generally are nonexplosive to weakly explosive; and composite volcanoes, such as Mount St. Helens in the Cascade Range, which generally erupt explosively.

Fissures erupt spatter and produce lava flows during the 2011 Kamoamoa eruption of Kīlauea volcano. Photograph by Matthew Patrick, U.S. Geological Survey.

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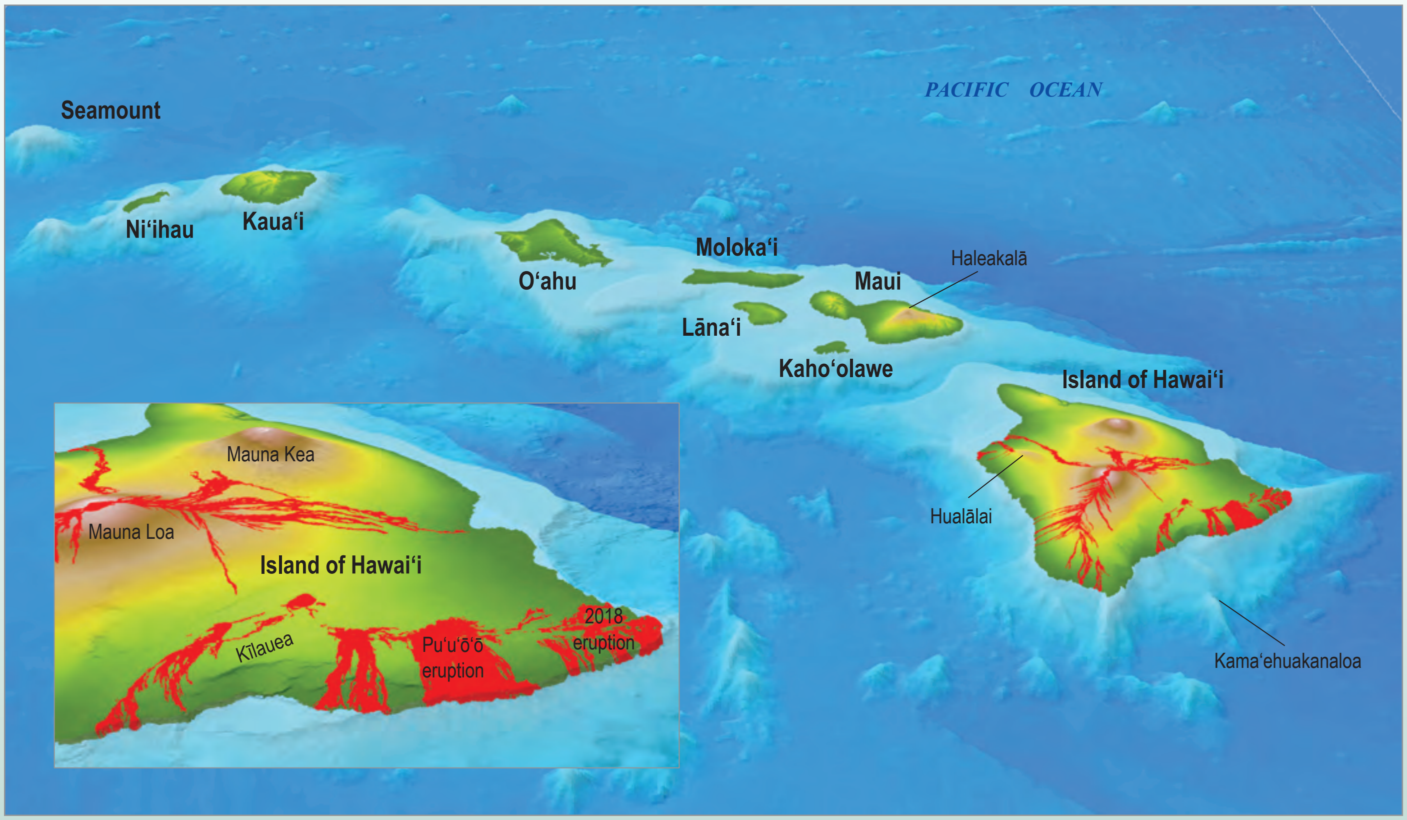
Introduction

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

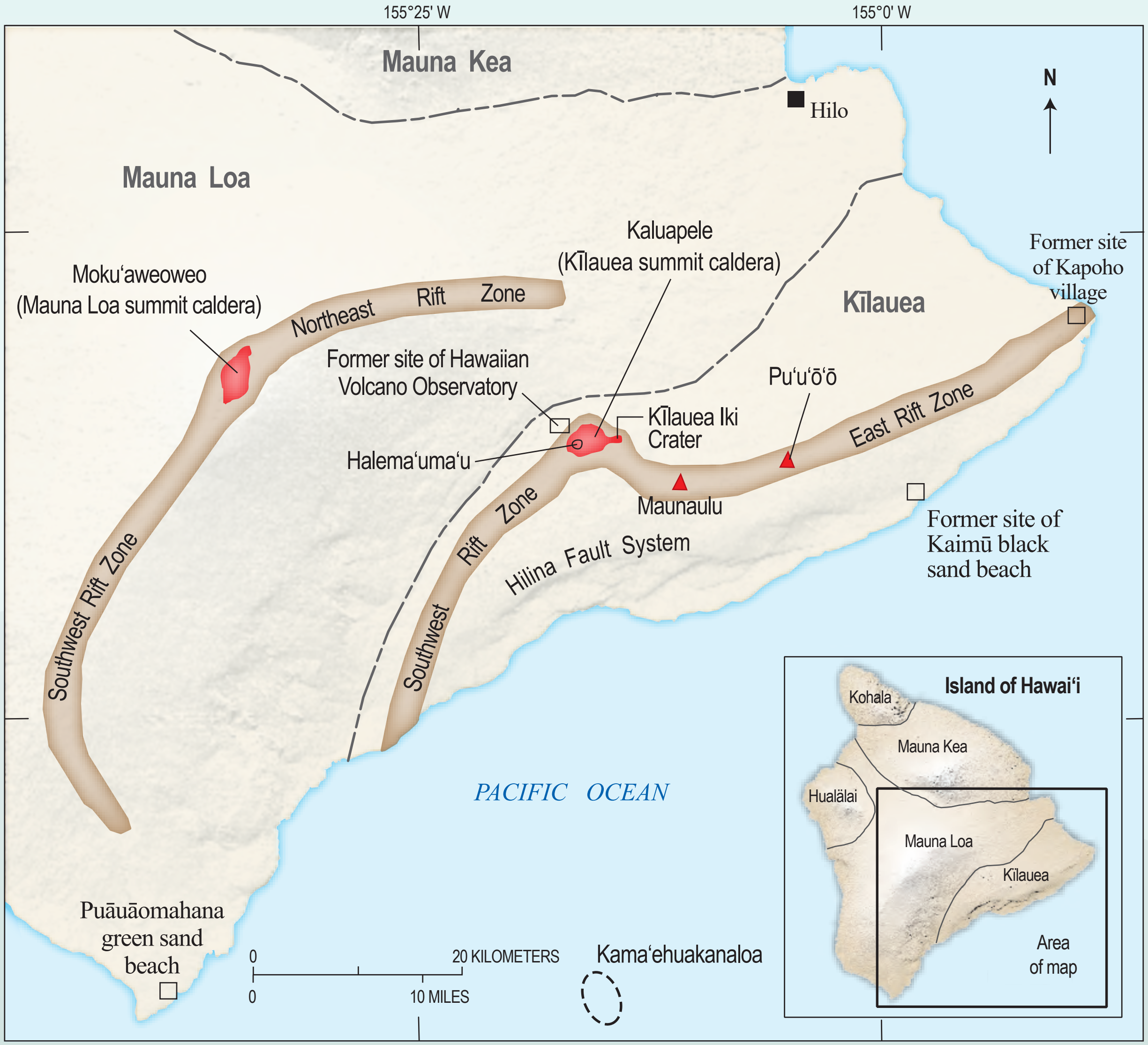
Few would quarrel with Mark Twain's vivid description of the Hawaiian Islands, written after his 4-month stay in 1866. Many archeologists believe that the Hawaiian Islands were discovered and settled in the late first millennium C.E.[1] or a little later by Polynesians sailing from islands, possibly the Marquesas Islands, in the southern tropical Pacific. Subsequently, nearly a thousand years passed before the first documented visit to the Hawaiian Islands by non-Polynesians. On January 18, 1778, during his third major voyage in the Pacific Ocean, the famous British navigator and explorer, Captain James Cook, sighted the Polynesians' remote home. Cook named his discovery the "Sandwich Islands," in honor of the Earl of Sandwich, then First Lord of the British Admiralty. The Hawaiian Islands are 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.

Hawaii, which in 1959 became the 50th State of the United States of America, is now home to about 1.5 million people and hosts many times that number of visitors each year. The Hawaiian Islands' 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 Le‘ahi (Diamond Head) on O‘ahu, Haleakalā on Maui, and the huge mountains of Mauna Loa and Mauna Kea on the Island of Hawai‘i—are volcanic.

[1]C.E. denotes "Common Era," the secular equivalent of "Anno Domini" (A.D.). B.C.E. denotes "Before Common Era."



The principal Hawaiian Islands, stretching about 400 miles (more than 600 kilometers) from Ni‘ihau in the northwest to the Island of Hawai‘i in the southeast, are the exposed tops of volcanoes that rise thousands of feet (thousands of meters) 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. Volcanoes that have erupted in the past 5,000 years are labeled, including Kama‘ehuakanaloa (formerly called Lō‘ihi Seamount), the State of Hawaii's newest (and still submarine) volcano, the top of which lies nearly 3,000 feet (1,000 meters) beneath the ocean surface. Modified from map on reverse side of "This Dynamic Planet" by Simkin and others (2006).



Base map from U.S. Geological Survey 10-meter digital data

Shaded relief map of the southeastern part of the Island of Hawai'i, showing the principal features and localities of Mauna Loa, Kīlauea, and Kama'ehuakanaloa volcanoes discussed in the text.

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 Kama'ehuakanaloa (previously called Lō'ihi Seamount), off the island's south coast, is the newest Hawaiian volcano, actively growing on the seafloor deep beneath the ocean surface.

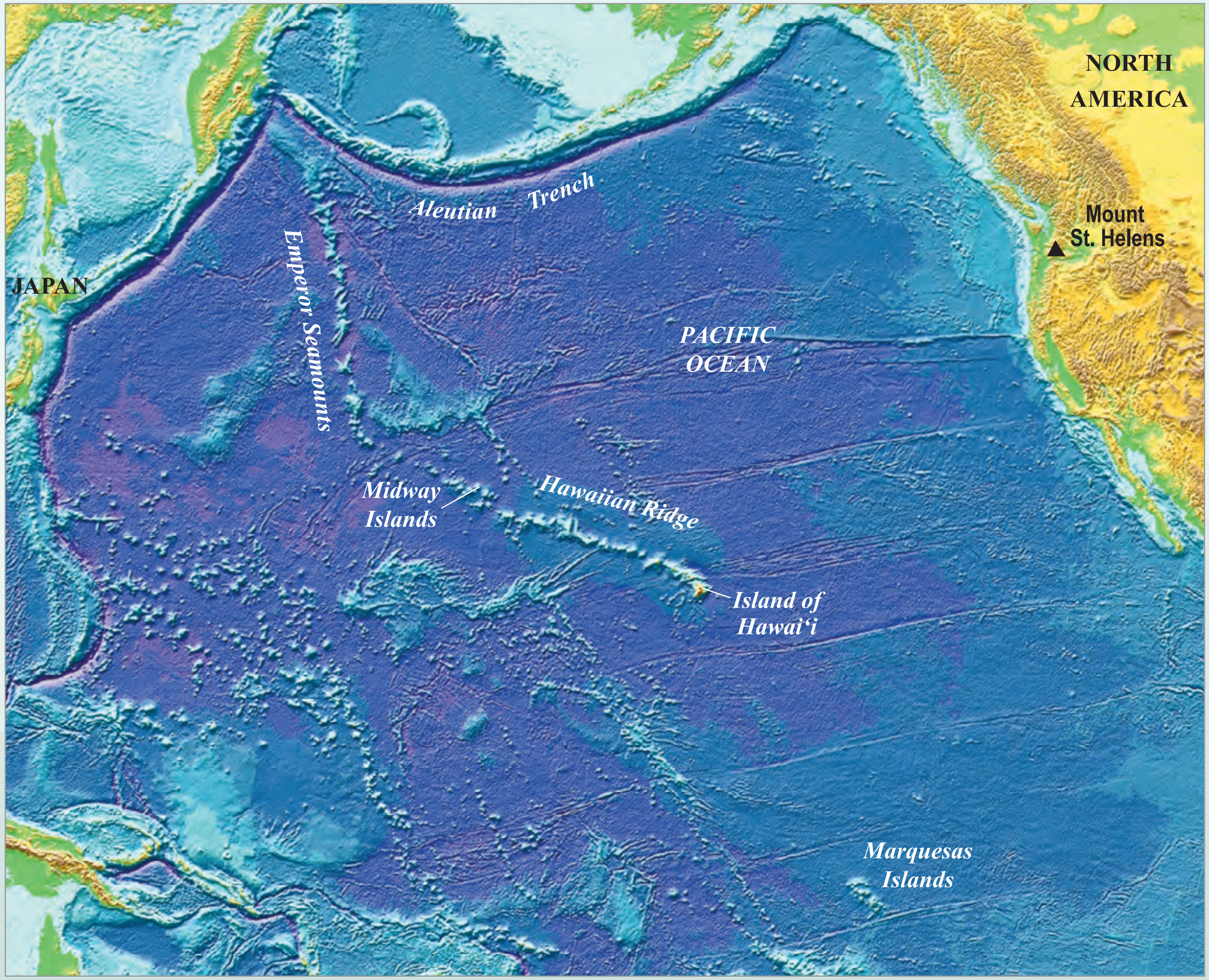
Both Mauna Loa and Kīlauea are readily accessible, such that scientists generally can study them at close range in relative safety. As a result, these are two of the most intensely observed and best understood volcanoes on our planet. Research on these active volcanoes provides a basis for understanding 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.

Lili'uokalani Park, in the city of Hilo on the Island of Hawai'i, typifies the tropical beauty and serenity of the Hawaiian Islands. Photograph by Katherine Mulliken, U.S. Geological Survey.

Origin of the Hawaiian Islands

The Hawaiian Islands are the tops of gigantic volcanic mountains formed by countless eruptions of fluid *lava*[2] over several million years; some tower more than 30,000 feet (9,140 meters) 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 Seamounts, 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 Islands to the northwest, is about 1,600 miles (2,600 kilometers), approximately the distance from Washington, D.C., to Denver, Colorado. The amount of lava erupted to form this huge ridge, about 186,000 cubic miles (776,000 cubic kilometers), is more than enough to cover the State of California with a layer about 6,000 feet (1.8 kilometers) thick.

[2]Most of the italicized terms in the text are defined and explained as an integral part of the discussion. For those terms perhaps not fully explained, a glossary at the back of this booklet (p. 66) provides supplementary information or broader context.



Map of the Pacific Ocean basin showing the location of the Hawaiian Ridge and Emperor Seamounts in relation to some other features and localities mentioned in the text. Modified from the third edition of “This Dynamic Planet” map by Simkin and others (2006).

Hawaiian Legends and Early Scientific Work

The distinctive northwest-southeast alignment of the Hawaiian Islands 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, and other indicators of the relative ages of the islands. Oral traditions suggest that early Hawaiians recognized that the islands become younger from the northwest to the southeast.

Polynesians arrived in the Hawaiian Islands from the South Pacific Ocean 1,200–800 years ago, according to several archaeological studies. Modern geologic studies show that during this time, both Mauna Loa and Kīlauea experienced eruptions, and oral traditions metaphorically describe some of this activity.

The deity ʻAilāʻau controlled volcanic activity during early Polynesian occupation, especially at Kīlauea. Today, most volcanic activity is considered to be manifestations of Pele, a revered deity who oversees active volcanism in the Hawaiian Islands. It is common to see offerings left for Pele at viewpoints in the summit area of Kīlauea. She is tempestuous, possibly gaining this reputation from the many explosive eruptions between 1500 and the early 1800s C.E. Perhaps not surprisingly, the Hawaiian word for lava, lava flow, volcano, and eruption is *pele*.

Pele, the goddess of Hawaiian volcanoes, as portrayed by artist D. Howard Hitchcock. Photograph by J.D. Griggs, U.S. Geological Survey, with permission of the Volcano House Hotel, owner of the original painting.

Night view (time exposure) of Pele's home during the 2022 eruption within Halemaʻumaʻu at the summit of Kīlauea. Photograph by Janice Wei, National Park Service.

Many oral traditions describe feats of Pele in the islands. One oral tradition and its recent volcanological interpretation follows.

Pele arrived on Kauaʻi into a culture led by the chieftain Lohiʻau. Some traditions state that Pele came to Kauaʻi directly from southern Polynesia, but others say she arrived (perhaps in a dream?) from her already established home at Kīlauea. The hula chants describe metaphorically an intense love affair between Pele and Lohiʻau. Pele then left Kauaʻi moving down the island chain toward Kīlauea, either returning home or using her *pāoa* (digging stick) to find hot ground for her residence. At Kīlauea, Pele displaced ʻAilāʻau, who had fled in fear of her power and was little heard of again until the large eruption in the lower East Rift Zone in 2018.

Pele had fond memories of Lohiʻau and asked her sisters to return to Kauaʻi to fetch the chieftain and bring him to Kīlauea for her. Her youngest sister, Hiʻiaka-i-ka-poli-o-Pele (generally referred to simply as Hiʻiaka), agreed, and after a series of misadventures with her traveling companion, Wahineʻōmaʻo—including the revival of a dead Lohiʻau—finally ended up back at Kīlauea. Hiʻiaka was late returning from Kauaʻi, however, and a much-upset Pele set fire to a forest along the East Rift Zone that was favored by Hiʻiaka and her friend Hōpoe. This angered Hiʻiaka, who in spiteful response took Lohiʻau as a lover in full view of Pele. Furious, Pele killed Lohiʻau and threw his body into the crater. Hiʻiaka dug to retrieve the body, stopping just short of breeching a rock barrier that kept water from drowning Pele.

These events have been interpreted to describe the two largest volcanic crises at Kīlauea since Polynesian settlement—the eruption of a giant lava flow in the 15th century that covered most of Kīlauea north of the East Rift Zone and the formation of Kīlauea caldera in about 1500 C.E.

Some interpretations of the oral traditions directly link Pele's migration from Kauaʻi to Kīlauea to the actual successive creation of the islands. The islands are far older than Hawaiian settlement, but the various accounts of migration of volcanic activity from Kauaʻi to the Island of Hawaiʻi in Hawaiian legends are in accord with modern scientific studies and they testify to the keen observational skills of the Native Hawaiians.

A painting titled "Pele Searches for a Home" by renowned Hawaiian artist Herb Kawainui Kāne depicting a fierce battle between Pele and her older sister and nemesis Namakaokahaʻi (Hawaiian goddess of the sea) from the legends of Pele's migration along the Hawaiian Island chain. Copyrighted by Herb K. Kāne, LLC; used with permission.

Starting in 1823, missionaries and other Westerners witnessed and provided important written descriptions of eruptions at Kīlauea and Mauna Loa, speculating as they did about the nature of Hawaiian volcanoes. The first formal geologic study of the Hawaiian Islands was conducted during 6 months in 1840–41, as part of the U.S. Exploring Expedition of 1838–42, 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, as shown by 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 middle 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.

Aerial view in July 2022 of Halemaʻumaʻu, the crater within Kīlauea's summit caldera; lava from the 2021–22 eruption forms the crater floor. Mauna Loa is in the background. The boundary between Hawaiʻi Volcanoes National Park (gray vegetation) and a private ranch (lighter green) is visible in the upper right corner of the image. Photograph by Katherine Mulliken, U.S. Geological Survey.

The deeply eroded Koʻolau volcano on Oʻahu is 2 to 3 million years older than Mauna Loa on the Island of Hawaiʻi (visible on the skyline in image on p. 6), whose profile is unscarred by erosion. Photograph by Katherine Mulliken, U.S. Geological Survey.

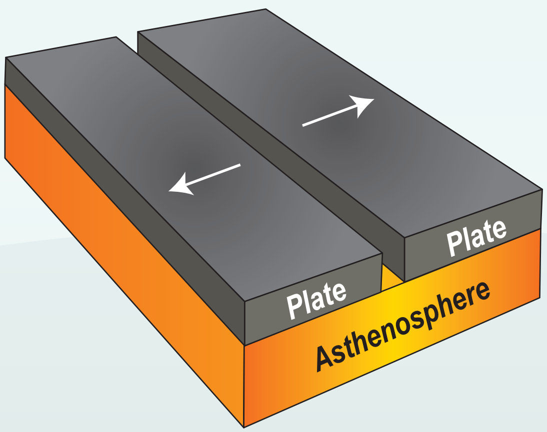
Plate Tectonics and the Hawaiian Hot Spot

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 (80 to 160 kilometers) thick. These plates move relative to one another at average speeds of several inches (7–11 centimeters) per year—about as fast as human fingernails grow. Scientists recognize three common types of boundaries between these moving plates (see diagrams below).

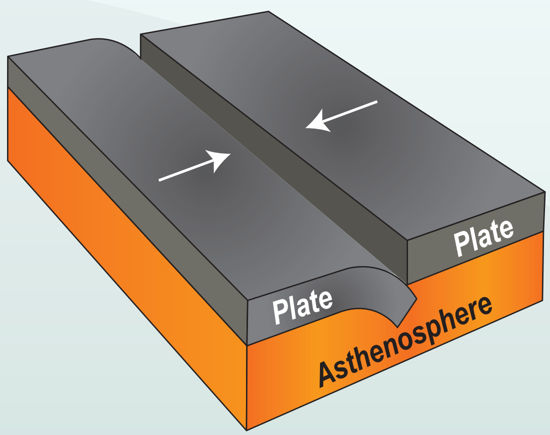
1. *Divergent or spreading.*—Adjacent plates pull apart, such as along the Mid-Atlantic Ridge, which separates the North America and South America Plates from the Eurasia and Africa Plates. This pulling apart causes seafloor spreading as new magma ascending from the underlying less rigid layer, or *asthenosphere*,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

2. *Convergent.*—Two plates move toward each other, 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 subducts beneath 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.

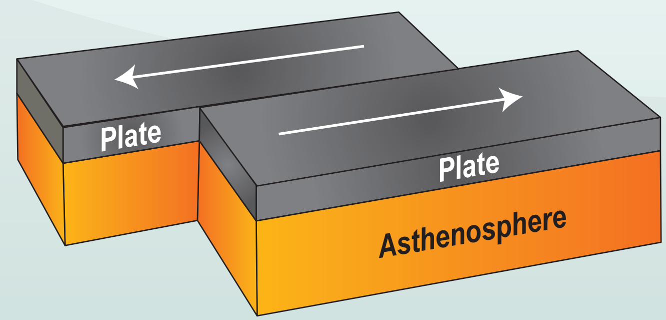
3. *Transform fault.*—One plate slides horizontally past another. The best-known example is the earthquake-prone San Andreas Fault Zone of California, which marks the boundary between the Pacific and North America Plates.



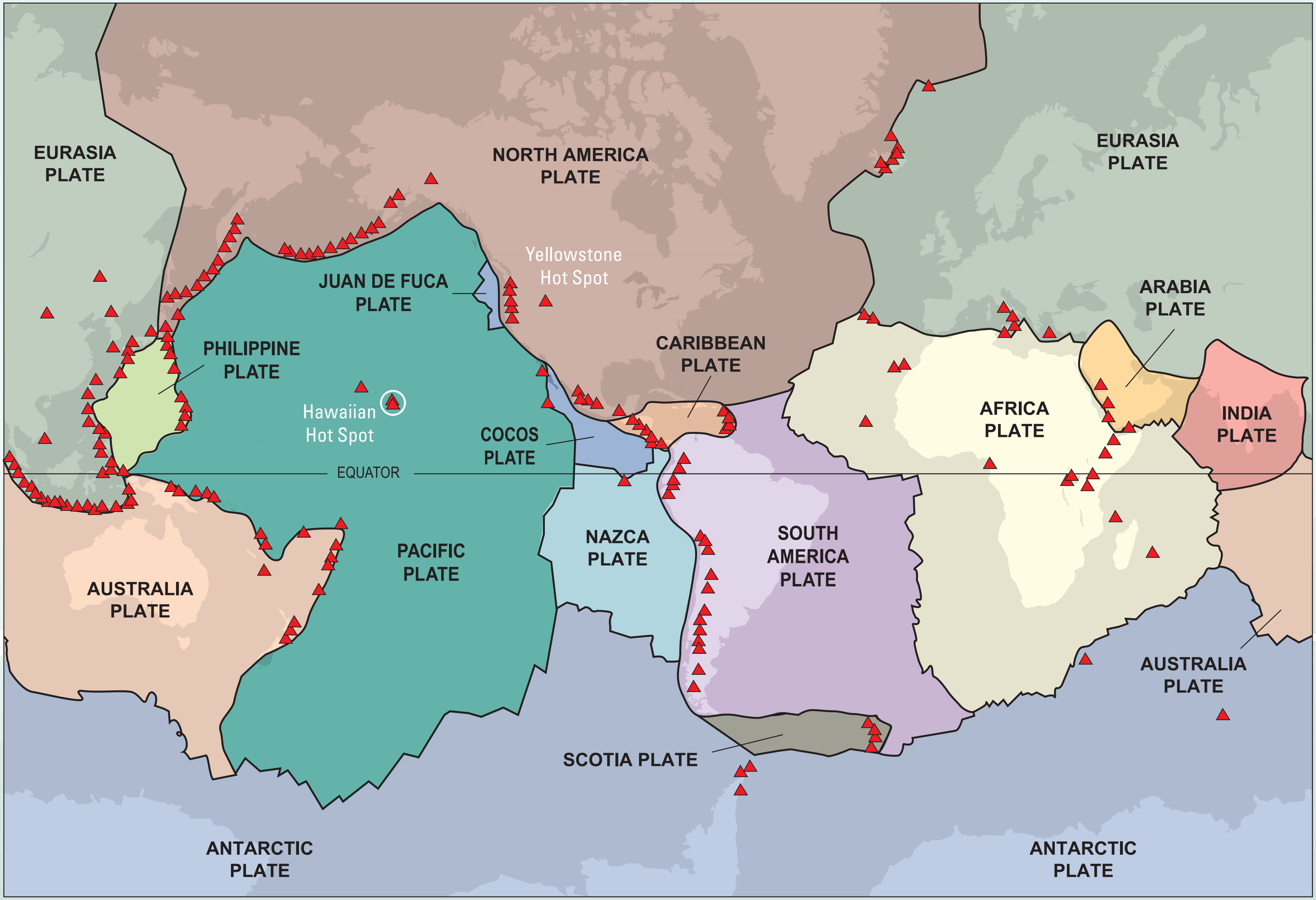
Divergent plate boundary



Convergent plate boundary



Transform fault plate boundary



Map showing 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. Only some of the Earth's more than 500 active volcanoes (triangles) are shown here. Map modified from Kious and Tilling (1996).

Nearly all 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 (3,200 kilometers) 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 (called *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 Ridge–Emperor Seamounts 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 (kilometers) beneath the lithosphere? Or do they extend down thousands of miles (kilometers), perhaps to Earth’s core-mantle boundary? Also, although scientists generally 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.

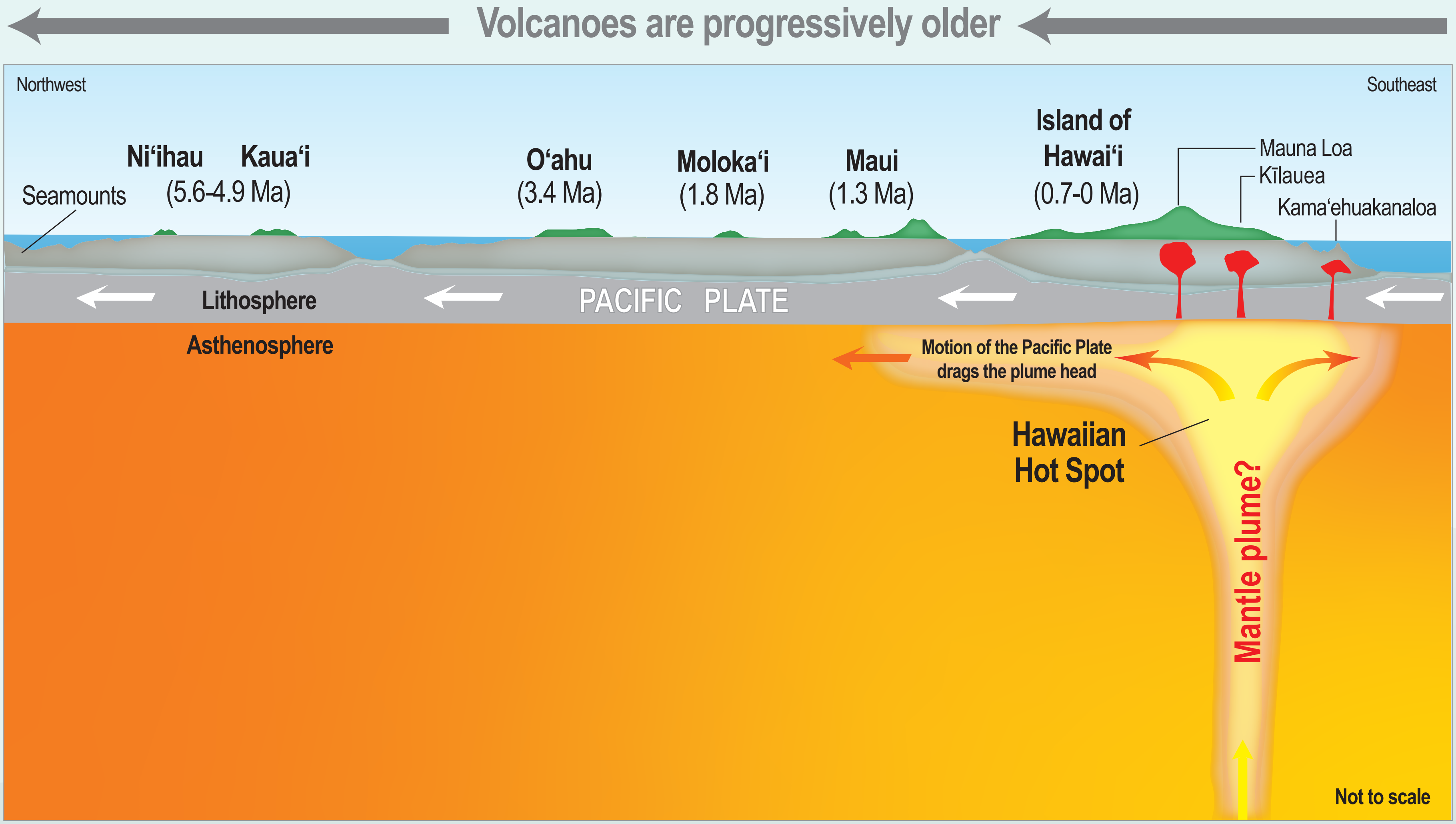
Over a span of about 70 million years, the combined processes of magma formation, eruption, and continuous movement of the Pacific Plate over the stationary hot spot have left the trail of volcanoes across the ocean floor that we now call the Hawaiian Ridge–Emperor Seamounts. A sharp bend in the chain about 2,200 miles (3,500 kilometers) northwest of the Island of Hawai‘i was previously interpreted as a major change in the direction of plate motion around 45–43 million years ago, as suggested by the ages of the volcanoes bracketing the bend. However, recent studies suggest that the northern segment (Emperor Seamounts) formed as the hot spot moved southward until about 45 million years ago, when it became fixed in its current location. Thereafter, northwesterly plate movement prevailed, resulting in the formation of the Hawaiian Ridge “downstream” from the hot spot.

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 Kama‘ehuakanaloa, off the Island of Hawai‘i’s south coast, marks the zone of magma upwelling at the southeast edge of the hot spot. With the possible exception of Maui, the other Hawaiian Islands have moved northwestward beyond the hot spot—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): Ni‘ihau and Kaua‘i, 5.6 to 4.9 million years old; O‘ahu, 3.4 to 2.2 million years old; Moloka‘i, 1.8 to 1.3 million years old; Maui, 1.3 to 0.8 million years old; and the Island of Hawai‘i, less than 0.7 million years old 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 northwest 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 southeast flank of Mauna Loa, Kīlauea is thought 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, Kama‘ehuakanaloa, and, possibly, also Hualālai and Haleakalā. Some scientists have estimated the Hawaiian Hot Spot to be about 200 miles (320 kilometers) wide, with much narrower vertical passageways that feed magma to the individual 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 (given in million years ago [Ma]) are progressively older to the northwest, consistent with the hot spot model for the origin of the Hawaiian Ridge–Emperor Seamounts. Modified from “This Dynamic Planet” map by Simkin and others (2006).

Hawaiian Eruptions in Written History

The Hawaiian Islands have a brief written history, extending back less than 300 years, compared to such volcanic regions as Iceland, Indonesia, Italy, and Japan. Written accounts exist for most Hawaiian eruptions since 1823, when the first missionaries visited the Island of Hawaiʻi. Descriptions of earlier eruptions are based only on interpretations of ancient Hawaiian chants and stories told to the missionaries by Hawaiian elders and early European residents, augmented by more recent geologic studies.

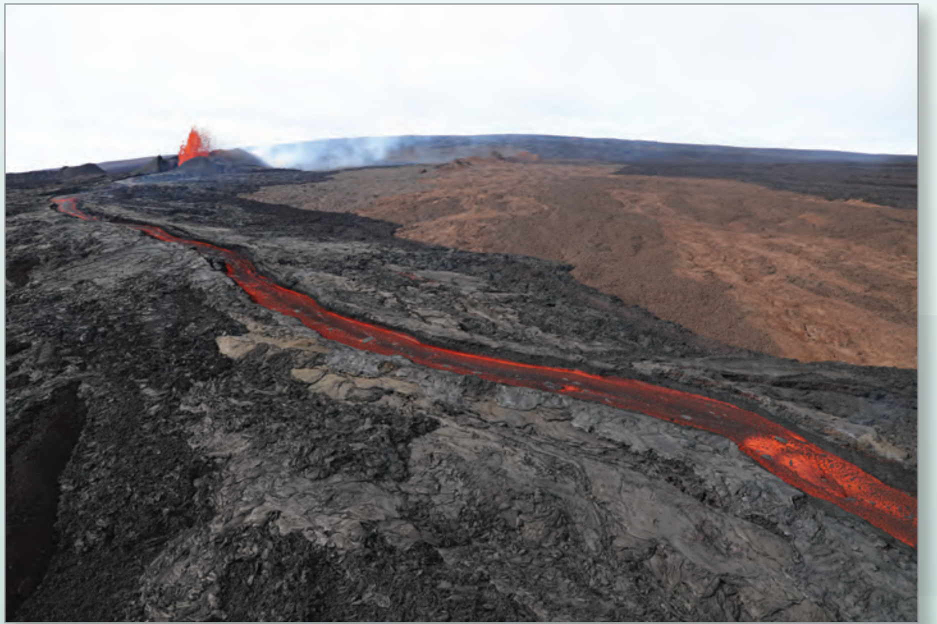
All the known Hawaiian eruptions since Captain Cook's arrival in 1778 have been at Mauna Loa and Kīlauea, except for the 1800–1801 eruption of Hualālai on the west coast of the Island of Hawaiʻi. Exceptions to the overall northwest-southeast shift of volcanic activity include a series of minor submarine eruptions that probably occurred in 1955–56 between the islands of Oʻahu and Kauaʻi and near Necker Island, about 350 miles (560 kilometers) northwest of Kauaʻi. These eruptions perhaps represent rejuvenated volcanism that does not follow the general northwest-southeast progression of volcanic activity reflected in the age of the Hawaiian Islands.

For the past 200 years, Mauna Loa and Kīlauea have tended to erupt on average every 5–10 years, placing them among the most frequently active volcanoes of the world. At each volcano, some intervals of repose between eruptions have been much longer than the long-term average. The individual Kīlauea eruptions recorded since 1778 are in addition to the nearly continuous eruptive activity within or near Halemaʻumaʻu, extending throughout the 19th century and into the early 20th century.

Simultaneous eruption of both volcanoes has been rare, except at times when Kīlauea was continuously active before 1924. In March 1984, activity at both volcanoes overlapped for one day, and in late 2022, activity at both volcanoes overlapped for nearly 2 weeks. 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, and from 1985 to the present, only Kīlauea was (is) active (except the brief eruption of Mauna Loa in 2022).

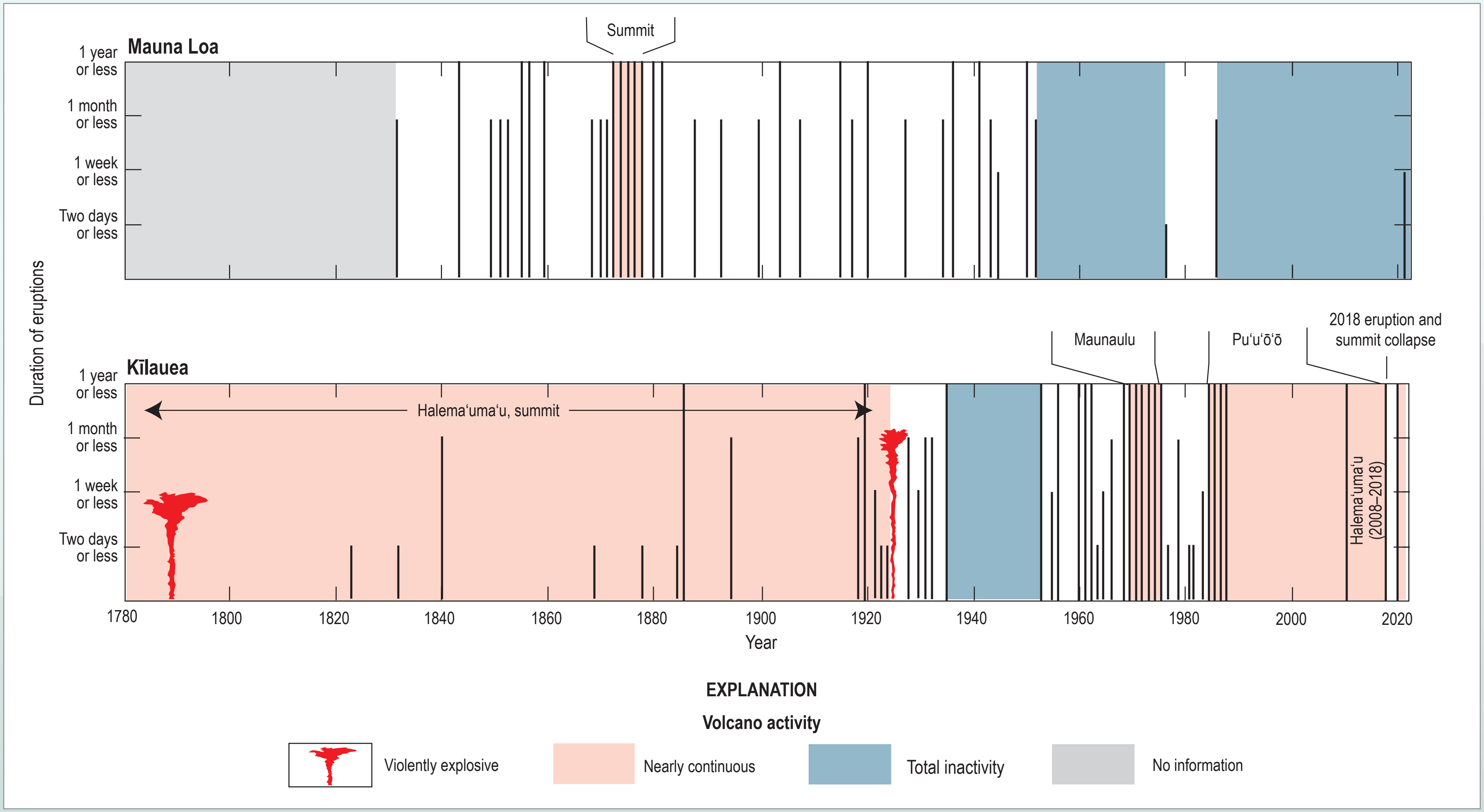
Since July 1950, Hawaiian eruptive activity has been dominated by frequent and sometimes prolonged eruptions at Kīlauea, whereas only three short-lived eruptions have occurred at Mauna Loa (July 1975, March–April 1984, and November–December 2022).

On March 30, 1984, Kīlauea and Mauna Loa were in simultaneous eruption, the first time since 1924. Kīlauea's Puʻuʻōʻō vent during its 17th high-fountaining episode. Photograph by Edward W. Wolfe, U.S. Geological Survey.



Aerial view of a channelized lava flow during the 2022 Mauna Loa eruption. This eruption fed a lava flow that advanced 12 miles (19 kilometers), stopping 1.7 miles (2.8 kilometers) away from the Daniel K. Inouye Highway (Saddle Road). Photograph by Tim Orr, U.S. Geological Survey.

The November–December 2022 eruption of Mauna Loa ended a 38-year-long period without eruptive activity—the longest time between Mauna Loa eruptions since at least 1823. Despite this long repose period, the eruption itself was a typical Mauna Loa eruption. Like most observed eruptions, it began within Moku‘āweoweo—the summit caldera—and later migrated to a rift zone, where the eruption continued for nearly 2 weeks. Fortunately, the vents, which opened at high elevations on Mauna Loa’s Northeast Rift Zone, generated lava flows that traveled primarily in north and northeast directions, toward the largely undeveloped Humu‘ula Saddle region between Mauna Loa and Mauna Kea. Thus, impact to infrastructure was minimal. The National Oceanic and Atmospheric Administration’s Mauna Loa Observatory was closed because lava flows crossed the access road; however, the eruption ended before lava flows reached the Daniel K. Inouye Highway (Saddle Road), a major thoroughfare across the Island of Hawai‘i. During the 2022 Mauna Loa eruption, lava flows extended 12 miles (19 kilometers) from the vents and reached to within 1.7 miles (2.8 kilometers) of the highway. The event is a reminder that Mauna Loa remains an active volcano with the potential to affect Island of Hawai‘i residents.



Graphs summarizing the eruptions of Mauna Loa and Kīlauea that occurred during written history. Information is limited for eruptions before 1823, when the first missionaries arrived on the Island of Hawai‘i. The total duration of eruptive activity in a given year, shown by the length of the vertical bar, may reflect a single eruption or a combination of several separate eruptions.

Aerial image of a lava flow that erupted from Mauna Loa’s Northeast Rift Zone in late 2022 as it advanced downslope toward the Daniel K. Inouye Highway in the Humuʻula Saddle region. Photograph by Lis Gallant, U.S. Geological Survey volunteer.

Kīlauea’s Puʻuʻōʻō eruption began in January 1983 and became the volcano’s largest and longest lasting flank eruption in more than 500 years before it abruptly ended in early May 2018. This eruption was primarily fed from the Puʻuʻōʻō *vent* (an opening from which lava erupts), above which a tall cone was built. This cone partly collapsed in 1997 and never regained its former height before a subsequent collapse that marked the end of the eruption. Lava flows destroyed 215 structures and covered 8.4 miles (13.5 kilometers) of road. Sustained flows that entered the ocean built lava deltas that added 440 acres (178 hectares) to the island. In 2014, a narrow lava flow entered the outskirts of Pāhoa town and stopped just short of severing the highway to Hilo. By the end of the Puʻuʻōʻō eruption, approximately 1.1 cubic miles (4.4 cubic kilometers) of lava had erupted, covering an area of about 105 square miles (273 square kilometers).

On March 19, 2008, a new vent opened explosively on the southeast side of Halemaʻumaʻu in the summit caldera of Kīlauea. The small explosion—the first substantial explosive activity at Kīlauea’s summit since 1924—opened a crater 115 feet (35 meters) in diameter (informally called the Overlook crater) and hurled ballistic blocks as large as a meter in diameter over about 74 acres (30 hectares) outside the crater, covering a stretch of Crater Rim Drive. A dusting of ash was reported more than 20 miles (30 kilometers) farther southwest. Overlook crater continued to erupt for 10 years—the longest summit eruption since 1924. Although Kīlauea erupted simultaneously from two different areas previously (over brief periods lasting several days and during the 1919–20 Maunaiki eruption on the Southwest Rift Zone), the decade-long overlap of eruptions at Overlook crater in Halemaʻumaʻu at the summit and Puʻuʻōʻō on the East Rift Zone represents the longest time in recorded history that Kīlauea was erupting from two different areas.

A lava lake began to form in Overlook crater in late 2008 and continued to the end of the eruption. The crater and lava lake gradually enlarged, mainly by repeated wall collapses that sometimes triggered small explosions, reaching a size of about 920 by 660 feet (280 by 200 meters) before lava drained away at the end of the eruption in early May 2018. At night, glow from the lake mesmerized visitors at Hawaiʻi Volcanoes National Park’s Jaggar Museum overlook. The lava lake emitted large amounts of sulfur dioxide, frequently causing serious downwind volcanic air pollution, also referred to as volcanic smog or

An active lava lake within Halemaʻumaʻu overflowing its levee, as painted by D. Howard Hitchcock in 1894. Snow-capped Mauna Loa forms the far horizon. Photograph by J.D. Griggs, U.S. Geological Survey, with permission from the Volcano House Hotel, owner of the original painting.

vog (see p. 58). Notably, the summit eruption had no appreciable effect on the continuing eruption near Puʻuʻōʻō except that the amount of sulfur dioxide emitted at Puʻuʻōʻō dropped drastically, since magma lost much of its gas through the summit lava lake before being erupted from Puʻuʻōʻō.

Having two active eruptions—on the East Rift Zone and at the summit—at the same time achieved a certain false “normality” at Kīlauea between 2008 and 2018. Two simultaneous eruptions no longer seemed unusual and, in the spring of 2018, there was no clear indication that a substantial change was approaching.

In mid-April 2018, the area around Puʻuʻōʻō was inflating (pressurizing) strongly, and the U.S. Geological Survey Hawaiian Volcano Observatory (HVO) issued a warning for a possible eruption at another location along Kīlauea’s East Rift Zone. The inflation soon affected the summit enough to cause the lava lake in Overlook crater to overflow onto the floor of Halemaʻumaʻu. The crater floor of the Puʻuʻōʻō cone collapsed on April 30, and earthquakes migrated into the lower East Rift Zone. On May 1, HVO issued another warning—this one emphasizing the potential for an eruption along the populated lower East Rift Zone. An eruption began in the residential community of Leilani Estates on May 3. Lava in the lake in Overlook crater began to drain in early May and disappeared by May 10. Within these remarkable 11 days (April 30–May 10), both the Puʻuʻōʻō and Overlook crater eruptions ceased, and the largest Kīlauea rift zone eruption and summit collapse in more than 200 years had begun.

Sunset view of the Kīlauea summit lava lake in 2017. Photograph by Matthew Patrick, U.S. Geological Survey.

This roiling plume of ash and rockfall debris marks a major collapse within Puʻuʻōʻō following the magnitude 6.9 earthquake on May 4, 2018. Photograph by Tina Neal, U.S. Geological Survey.

Adding to the turmoil, a magnitude 6.9 earthquake shook the Island of Hawai‘i on May 4. Centered under the south flank of Kīlauea, it was presumably triggered by the intrusion of magma into the East Rift Zone. Such a large earthquake—the largest in Hawaii since 1975—would usually have commanded the news, but lava flows destroying homes and roads in Leilani Estates were of greater public concern.

Between May 3 and May 8, 24 fissures (numbered in order of formation) opened and erupted lava fountains and flows along the lower East Rift Zone. Some of these fissures remained active for less than a day, but others erupted—either continuously or intermittently—for several to many days. Fissure 8 (cover image), active for about 91 days with six brief interruptions, was by far the most productive, accounting for more than 90 percent of all the erupted lava. Fissure 8 built a spatter cone that was such an important new feature that it was eventually named Ahu‘ailā‘au by the Hawai‘i Board on Geographic Names in honor of the deity ‘Ailā‘au, thought by some to have presided over the eruption.

Lava flows from these vents eventually covered about 13.7 square miles (35.5 square kilometers) and added about 875 acres (354 hectares) of new land along the shoreline as lava-built deltas into the ocean. Lava covered about 30 miles (48 kilometers) of roads and destroyed 716 structures. Thousands of people were displaced. About 2.0 billion cubic yards (1.5 billion cubic meters) of lava erupted, including that which entered the ocean. Moreover, air quality was badly degraded because of the large volume of sulfur dioxide emitted during the eruption and the laze plume generated where lava entered the ocean.

Studies of the composition of lava erupted early in the 2018 eruption show that it was a mixture of magma from Pu‘u‘ō‘ō and cooler magma that had been stored in the subsurface for decades beneath the lower East Rift Zone. Most of the lava throughout the eruption, however, came from the magma storage areas in the summit region, traveling down the rift zone to the lower elevation eruption area. The lava from fissure 17 had a chemical composition of *andesite*, which is different from the predominantly basaltic compositions of Hawaiian lava. Scientists infer that the andesitic composition resulted from the fresh magma entering and interacting with, and forcing the eruption of, differentiated magma long stored in the rift zone (see discussion on lava viscosity and composition, p. 28). During Kīlauea’s 2018 eruption, a large clot of viscous andesitic spatter was hurled from fissure 17 and struck a man on the porch of his house, causing one of the most serious injuries of the eruption.

Part of Kīlauea’s caldera, centered at Halema‘uma‘u, subsided as magma that was stored under it moved into the East Rift Zone in 2018. By May 14, new cracks cut the parking lot near Halema‘uma‘u as the crater started to widen. Weak explosions took place during the last 2 weeks of May, as the floor of Halema‘uma‘u collapsed around the vent that had formerly supplied the 2008–18 lava lake. The caldera floor adjacent to Halema‘uma‘u started to collapse noticeably in late May. At first, the collapse occurred slowly for hours, dropping only a few inches (several centimeters). Then, every 20–30 hours, the ground suddenly dropped a meter or more in a few seconds, accompanied by an earthquake with an equivalent magnitude of 5.0–5.3. These events, felt throughout the

Comparative views of Kīlauea’s summit show the dramatic changes in the volcanic landscape since 2008. At left is a photograph taken on November 28, 2008, with a distinct plume of gas rising from the vent that had opened within Halema‘uma‘u about 8 months earlier. At middle is a photograph from a similar vantage taken on July 13, 2018, showing the effect of caldera-collapse events. At right is a photograph taken on July 19, 2022, showing how eruptions in Halema‘uma‘u since 2018 have filled the deepest part of the caldera that collapsed in 2018. The (former) U.S. Geological Survey Hawaiian Volcano Observatory buildings are visible in the lower right corner or center of each image. Photographs by Tim Orr, Janet Babb, and Katherine Mulliken, U.S. Geological Survey.

summit area, triggered rockfalls from the caldera wall and within the collapsing area itself. Sixty-two such collapse events took place during the eruption, the last on August 2, 2018.

By the time the partial collapse of Kīlauea caldera ended in early August, the floor of Halemaʻumaʻu had dropped more than 1,600 feet (500 meters), and adjacent parts of the caldera floor had subsided more than 490 feet (150 meters). The changes in the caldera, coupled with those caused by the eruption on the lower East Rift Zone, left the volcano more visibly altered than at any time in the past 200 years.

The long Puʻuʻōʻō eruption—lasting from 1983 to 2018—may have set the scene for the 2018 eruption and summit collapse. During those 35 years, a magma-storage reservoir developed and expanded under the Puʻuʻōʻō area. When that reservoir was breached during the April 2018 inflation, a large volume of stored magma was then injected into the lower East Rift Zone, initiating the eruption. Magma stored in the summit area then moved into the East Rift Zone to replace that removed from Puʻuʻōʻō, and the summit collapsed as its support was removed.

Kīlauea began to reinflate soon after the end of the 2018 eruption, but incoming magma from the hot spot source was stored within the volcano rather than erupting. Starting in late July 2019, a lake of water formed in the deepest part of Halemaʻumaʻu, the largest body of standing water in the caldera in at least the past 200 years. The water lake appeared as the water table began to recover its pre-2008 level, which had been disrupted by the dynamics and heat related to the 2008–18 eruption. The water lake deepened steadily, and by late December 2020 was about 170 feet (51 meters) deep, more than 980 feet (300 meters) long, and had a surface area of 8.2 acres (3.3 hectares).

On the evening of December 20, 2020, lava began to erupt from short fissures that cut the north and west wall of Halemaʻumaʻu above the water lake. Lava flowed down the crater wall into the water, which evaporated within 90 minutes, forming in its place a steadily deepening lava lake (see inside cover image). The eruption continued until May 23, 2021, when the lava lake was 732 feet (223 meters) deep. This eruption was short lived and small but provided visual evidence that Kīlauea was still active. It was followed by an intrusion in the south caldera in August 2021, without eruption, and several ensuing eruptions within Halemaʻumaʻu that continued to fill the deepest areas of Kīlauea caldera affected by the 2018 collapse. An intrusion in the Southwest Rift Zone in early 2024 was followed by a brief eruption there on June 6, 2024. Several subsequent intrusions to the southeast and a 5-day eruption in and near Nāpau Crater in September 2024 indicate that magma has reestablished a pathway into Kīlauea's East Rift Zone.

Studies of Hawaiian eruptions over the past two centuries demonstrate a pattern of dominant activity alternating between Mauna Loa and Kīlauea, implying that both volcanoes, in some complicated manner, may alternately tap the same deep magma source. Whether this is actually happening is a topic of scientific debate and continuing research. Abundant data suggest that the lavas of the two volcanoes are chemically and isotopically distinct. Geodetic and seismic evidence indicates that each volcano has its own shallow magma reservoir that operates independently of the other.

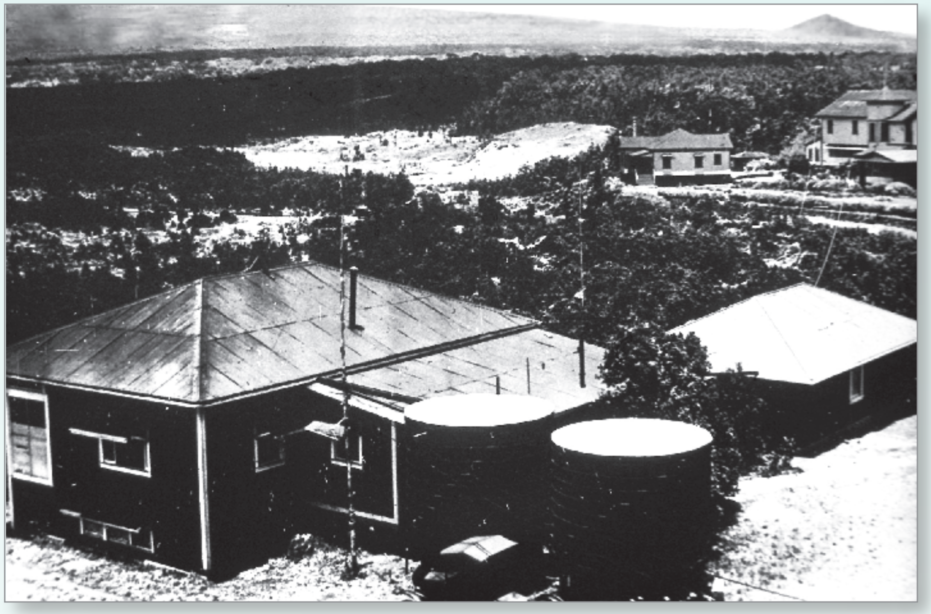
The average volume of lava erupted at Kīlauea since 1952 is 139 million cubic yards (106 million cubic meters) per year. In contrast, the average rate of lava output along the entire Hawaiian Ridge–Emperor Seamounts chain during its 70-million-year life is only about 20 million cubic yards (15.3 million cubic meters) 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.

Comparative views of Kīlauea's summit water lake from the east rim of Halemaʻumaʻu. On December 18, 2019, the lake had a surface area of 2.7 acres (1.1 hectares). By September 23, 2020, the lake had risen approximately 80 feet (25 meters) and had a surface area of 8.2 acres (3.3 hectares). Photographs by Katherine Mulliken and Matthew Patrick, U.S. Geological Survey.

Volcano Monitoring and Research

Before the 20th century, most scientific studies of volcanoes were conducted during short-lived expeditions, generally undertaken in response to a major eruption. 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 Saint-Pierre and killed about 30,000 people.

Spurred by a stimulating lecture delivered by Jaggar and recognizing the importance of studies of Kīlauea begun by American volcanologist Frank A. Perret, a group of Hawaiian residents founded the Hawaiian Volcano Research Association (HVRA) in 1911. 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.



The first Hawaiian Volcano Observatory, located near the site of the present Volcano House Hotel, as it appeared around 1922. Photograph courtesy of the Bishop Museum, Honolulu, Hawaii, photographer unknown; used with permission.

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, and the National Park Service. Since 1948, HVO has been operated by the U.S. Geological Survey. Over more than 100 years of research, HVO scientists have developed and refined many of the surveillance techniques now commonly employed by volcano observatories worldwide.

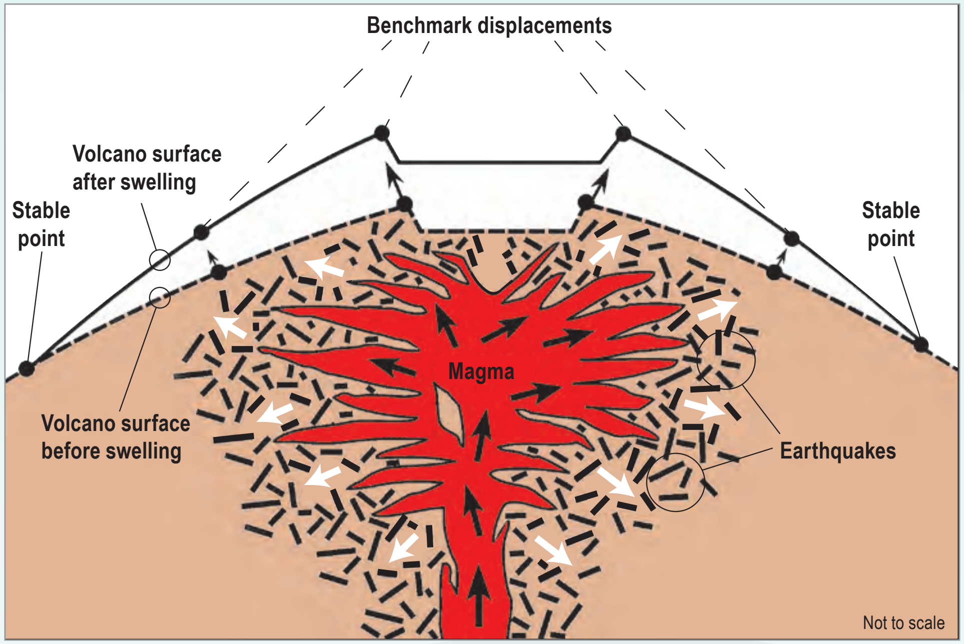
View of the U.S. Geological Survey Hawaiian Volcano Observatory at its former location on the west edge of Kaluapele, the summit caldera of Kīlauea. In the background, lava erupts from the caldera floor during the September 2023 eruption. These buildings were removed because of damage caused by the 2018 Kīlauea summit collapse events. Photograph by Cheryl Gansecki, U.S. Geological Survey.

Volcano Monitoring

The term *volcano monitoring* refers to the observations and measurements—visual and instrumental—scientists make to document changes in the state of 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 Kīlauea's shallow summit reservoir, the volcano swells or inflates as it is pressurized (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 (but not always), 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 relieved—a process like deflating a balloon. During deflation, changes in tilt and in vertical and horizontal distances between benchmarks are opposite to those during inflation.

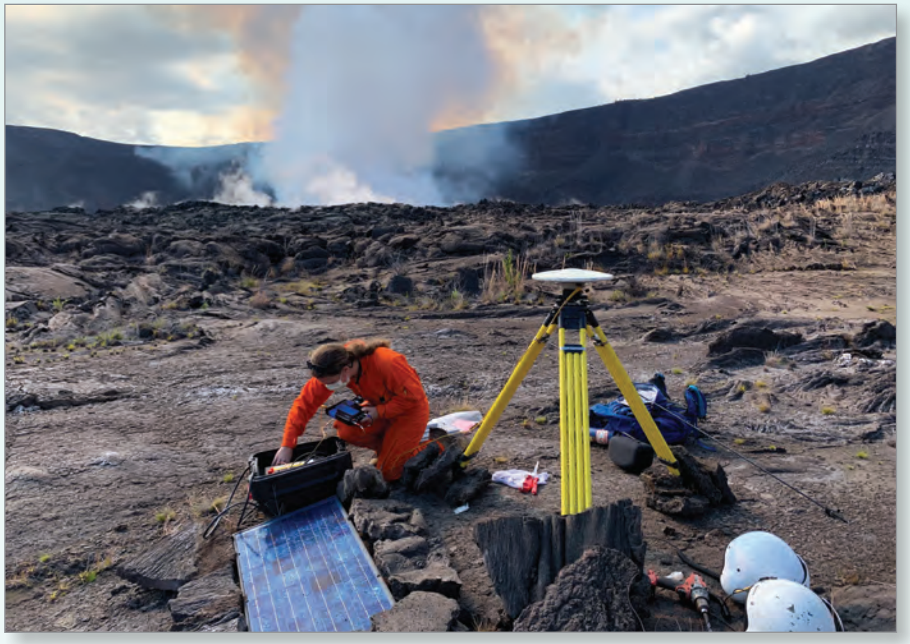
Changes in the shape of the volcano during inflation and deflation are determined by ground-deformation measurements. Tilt changes can be measured continuously and extremely precisely with instruments called tiltmeters, which can detect a change in angle of less than 1 microradian (about 0.00006 degree). A 1-microradian increase in tilt would be equivalent to steepening the slope of a 0.62-mile-long (1-kilometer-long) board by placing a dime under one end of it.

Methods for monitoring horizontal and vertical changes have evolved over the years. Since the 1990s, the Global Positioning System (GPS)—a satellite-based technology—has become the principal means by which the ground movements at active volcanoes are monitored.



Hypothetical slice through Kīlauea showing pre-eruption inflation. 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.

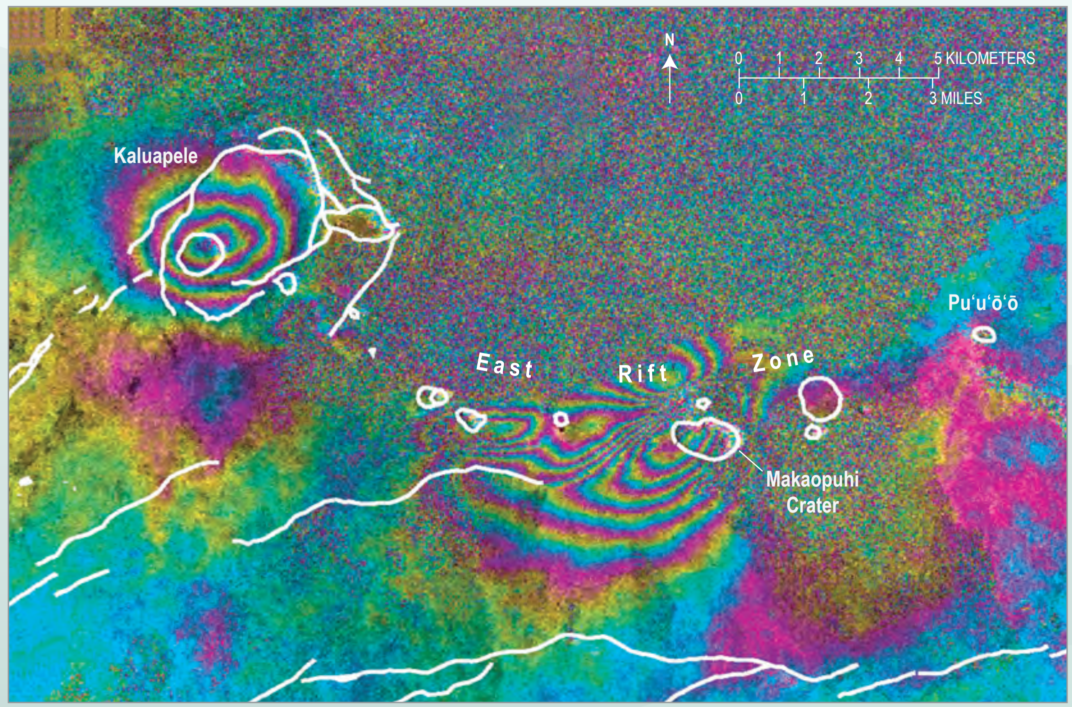
U.S. Geological Survey Hawaiian Volcano Observatory scientists used a laser-ranging instrument from the late 1960s to the mid-1980s to make an electronic distance measurement; however, this technique is no longer used by the observatory. Snow-capped summit of Mauna Loa is visible in the background. Photograph by J.D. Griggs, U.S. Geological Survey.



A U.S. Geological Survey Hawaiian Volcano Observatory scientist services a Global Positioning System (GPS) measurement site at the summit of Kīlauea while an antenna receiver (on tripod centered over a benchmark) acquires signals emitted from several GPS satellites. Repeated measurements at the same benchmark will reveal changes to the horizontal and vertical position of that point on the volcano. An eruption plume is visible in the background. Photograph by Kevan Kamibayashi, U.S. Geological Survey.

Originally deployed for military purposes by the Department of Defense, the GPS involves an array of about 30 satellites (orbiting about 12,000 miles or 19,300 kilometers above the Earth) that continuously send 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 programs to process 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*) to the nearest millimeter (one thousandth of a meter). Repeated measurements of a GPS network of many benchmarks make it possible to monitor an entire volcano. In addition to monitoring inflation and 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 centimeters per year. GPS measurements can be made around the clock regardless of the weather and do not require one benchmark to be seen from another, offering advantages over older methods of ground-deformation measurement.

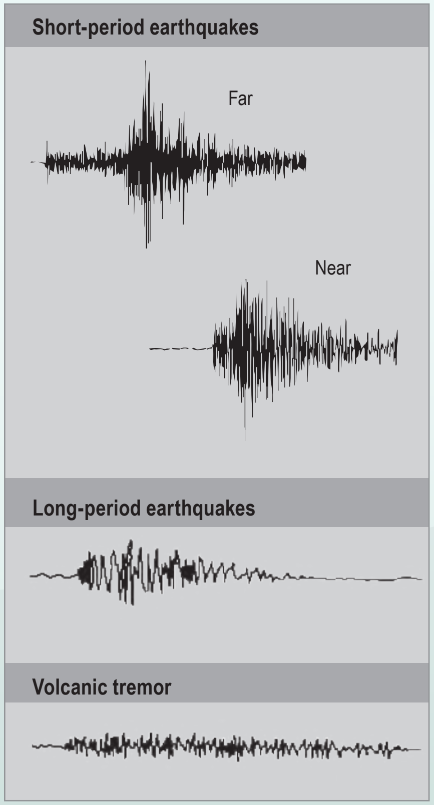
Over the past 15 years, another satellite-based tool has been used to track ground deformation at Hawaiian and other volcanoes—Interferometric Synthetic Aperture Radar (**InSAR**). This technique involves processing radar signals sent by



Areas of color bands, or "fringes," in this InSAR image show subsidence at Kaluapele, Kīlauea's summit caldera, and a combination of uplift and subsidence centered near Makaopuhi Crater. The 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 inch (2.5 centimeters) 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. White lines mark faults and outline craters. This image was produced by Michael Poland, U.S. Geological Survey, from a pair of satellite radar images acquired 35 days apart in 2007 by the European Space Agency's ENVISAT satellite.

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 by 60 miles or 48 by 96 kilometers). 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 more complete view of the overall ground deformation than measurements obtained through either technique alone.

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 seismometers are converted into electronic signals, which are transmitted by radio to the volcano observatory, for recording and analysis by scientists. Seismic signals were historically recorded on mechanical instruments called *seismographs*, which have been replaced by advanced computer systems and programs. 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.



Examples of common earthquake seismic signatures typically recorded before and during eruptions.

U.S. Geological Survey Hawaiian Volcano Observatory scientists examine a wall of screens displaying volcano-monitoring datasets including earthquake activity, visual and thermal (infrared) web cameras, and ground deformation. These monitoring datasets are telemetered to the observatory and available in near real time. Photograph by Don Becker, U.S. Geological Survey.

Scientists collect volcanic gas data using a Fourier transform infrared spectrometer (FTIR). During the 2011 Kamoamoa eruption, sulfur dioxide emission rates from Kīlauea's East Rift Zone averaged about 8,000 metric tons per day, with a peak value of about 11,000 metric tons per day. Photograph by A.J. Sutton, U.S. Geological Survey.

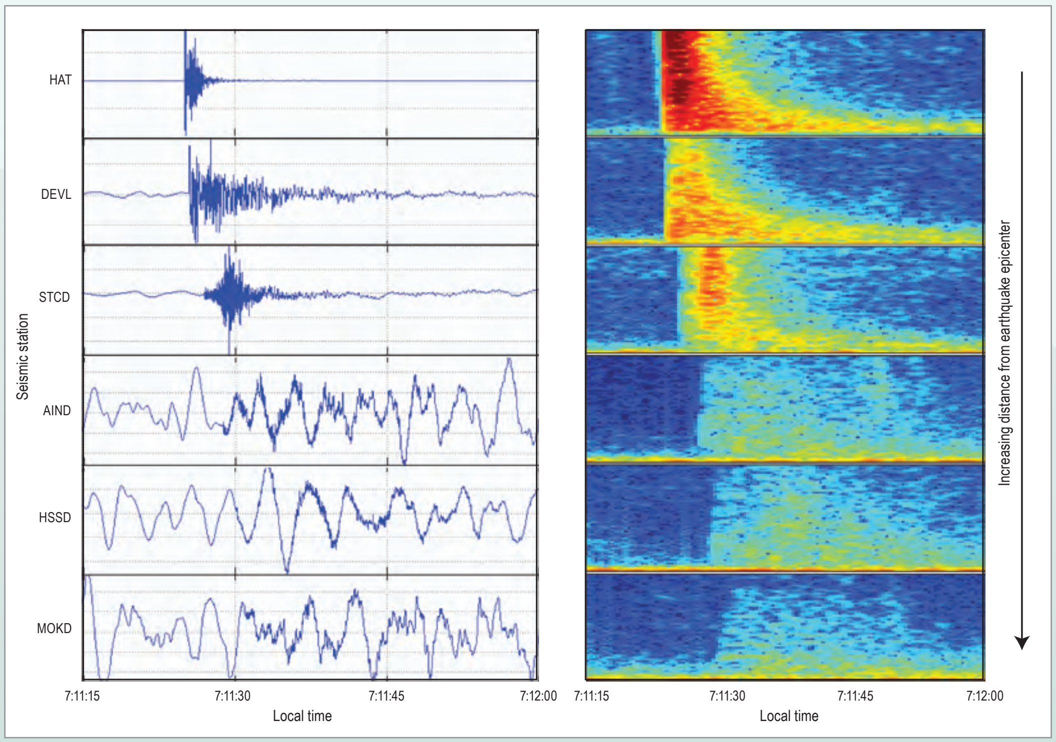
HVO operates nearly 100 seismic stations, principally of two types. The older type (short period) records local earthquakes and is especially useful for locating where an earthquake occurred. The second, newer type (broadband), more capable than the short-period instruments, records a broader range of frequencies and is commonly used for research purposes. Broadband instruments are slowly replacing short-period seismometers.

A third type of instrument, an infrasound sensor, measures sound waves in the air generated by earthquakes and eruptions. At other volcano observatories, this technique allows for rapid detection of eruptions, particularly those that are explosive.

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 (8 kilometers) from an eruption site.

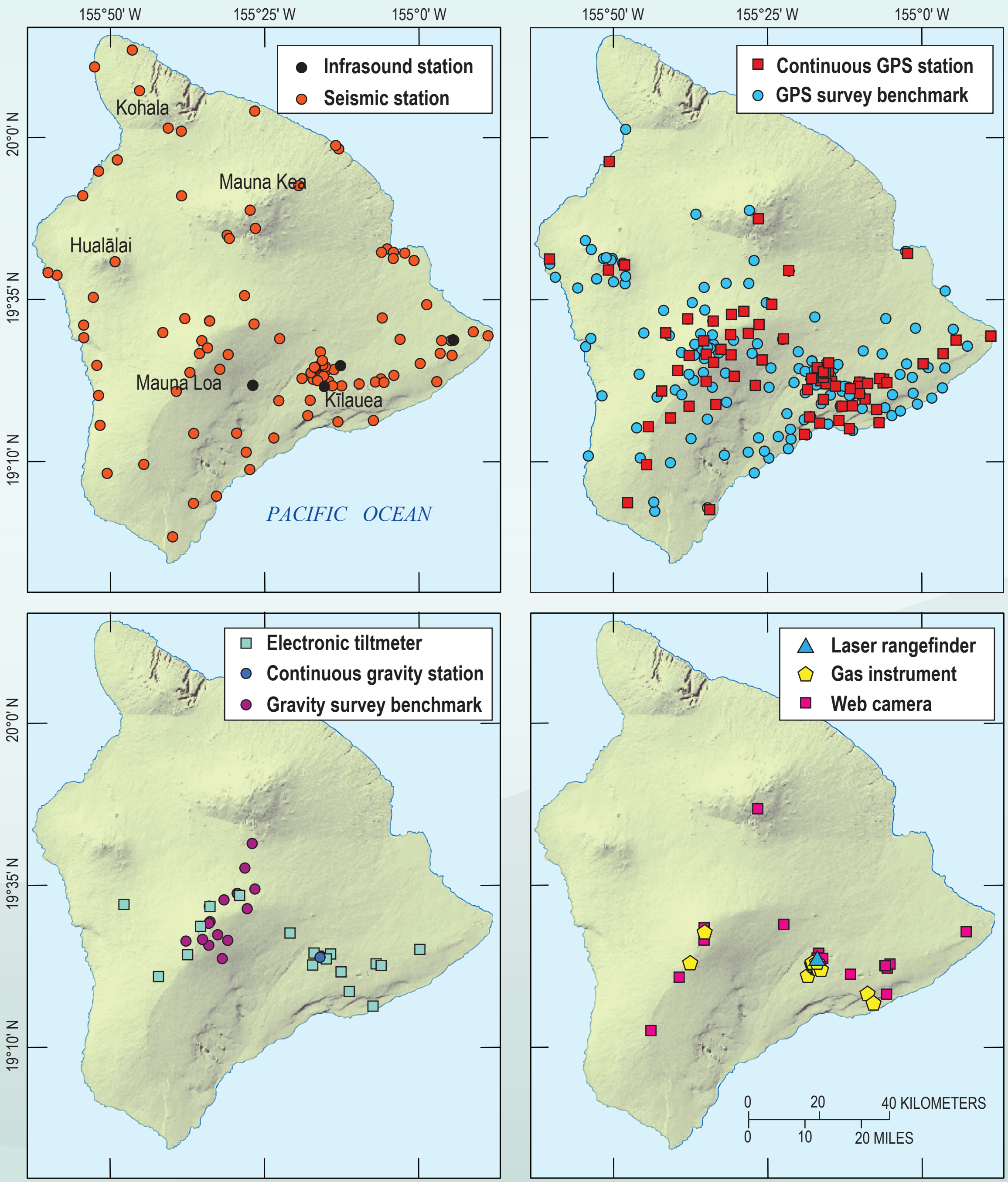
In recent decades, great strides have been made in gas monitoring using satellite and ground-based remote-sensing instrumentation and techniques. With various types of field-portable spectrometers, HVO scientists frequently measure the emission of sulfur dioxide and carbon dioxide at the summit calderas of Kīlauea and Mauna Loa. They also make repeated, though not continuous, measurements of gas output at eruptive vents and other specific sites. One technique uses a Fourier transform infrared spectrometer (FTIR), an instrument that can analyze many other species of volcanic gases in addition to sulfur dioxide and carbon dioxide. HVO's near-real-time monitoring of volcanic-gas emissions from the recent eruptions at Puʻuʻōʻō and Halemaʻumaʻu has provided key information to the National Park Service and Hawaii County for assessment of potential hazards to visitors and residents from volcanic air pollution (discussed on p. 58).

One of the greatest recent advancements in volcano monitoring, particularly of eruptions, is the application of camera technologies, which allow remote areas to be monitored for volcanic activity. At HVO, geologists have deployed time-lapse cameras that record changes over time and telemetered web cameras—both visual and thermal—which provide near-real-time views of remote or erupting areas. Thermal imagery, in particular, can see through fume, providing a clear picture of where lava is on the surface. Likewise, the use of unoccupied aircraft systems (**UAS** or drones) for aerial surveys of erupting areas has allowed for observations of inaccessible areas, which can be particularly useful in hazardous eruptions, such as Kīlauea's 2018 lower East Rift Zone eruption. Aerial imagery collected via UAS surveys can be used to generate three-dimensional models and refine eruptive volume estimates.



Left, Helicorder plots showing six digital traces of seismic signals from a magnitude 2.3 earthquake that occurred 2.1 miles (3.3 kilometers) below the surface on August 11, 2021, recorded on seismic stations at varying distances from the earthquake epicenter. Right, Spectrograms showing frequency content recorded by the same seismic stations for the same earthquake. Colors show increasing values from dark blue to dark red.

Maps of the principal volcano-monitoring networks operated by the U.S. Geological Survey Hawaiian Volcano Observatory in 2022. The configurations of the networks evolve with time—to adapt to new technologies, upgrade systems, and meet changing needs dictated by eruptive activity.



Base from U.S. Geological Survey 10-meter digital data

A web camera (left) and thermal camera (right) provide views of the summit of Kīlauea. Photograph by Matthew Patrick, U.S. Geological Survey.

Two U.S. Geological Survey pilots of unoccupied aircraft systems (UAS) perform a routine inspection of an aircraft prior to a flight at the summit of Kīlauea in June 2018. The UAS for this particular flight was outfitted with a multi-gas sensor to identify any new degassing sources within the collapsing summit caldera. All UAS flights inside Hawai‘i Volcanoes National Park were conducted with explicit permission of the National Park Service. Photograph by Patricia Nadeau, U.S. Geological Survey.

Volcano Inflation and Deflation During Eruptions

Kīlauea's behavior during and between many eruptions is often remarkably regular. Monitoring instruments placed at the volcano's summit measure the episodes 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 patterns are precisely recorded by tiltmeters and seismometers, as is well displayed during the 1983–2018 Pu'u'ō'ō eruption.

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

Kīlauea's distinctive inflation-deflation pattern is seen in most eruptions, regardless of the size of the observed tilt changes. The pattern was first well documented for the Kīlauea Iki eruption in 1959, which involved the largest tilt change recorded (nearly 300 microradians) until the off-scale change associated with the 2018 deflationary trend. 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.

Also 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 event* that typically lasts less than a week. A deflation-inflation event is characterized by an abrupt deflation as large as a few microradians and lasts 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 deflation-inflation events are not yet fully understood, but it is clear that they are relatively shallow events affecting the high-level magma storage zone beneath Halema'uma'u.

Anticipating Eruptions

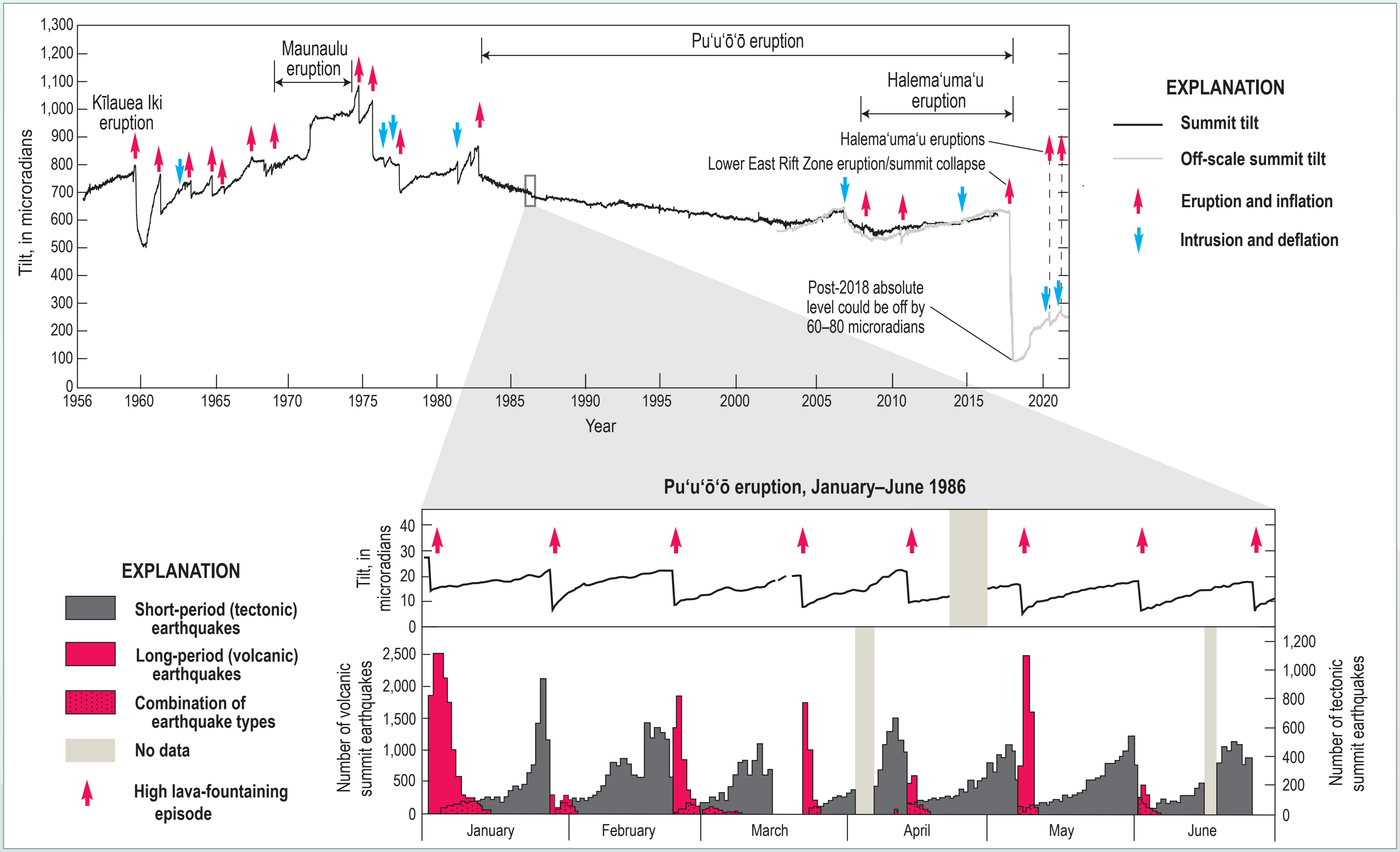
A prime objective of volcano monitoring is to detect the early signs of possible eruptive activity and to make reliable eruption forecasts. Although considerable advances have been made in volcano monitoring in the State of Hawaii, accurate long-term forecasts (1 year or longer) still elude scientists. However, the capability for short-term forecasts (hours to days), especially of Kīlauea's activity, is much better.

Accurate short-term forecasts of Hawaiian eruptions are based primarily on analyses of seismicity (earthquakes and volcanic tremor) and on inflation-deflation patterns, made possible through decades of study of ground deformation (tilt). When the level of inflation and short-period earthquake counts are high, the volcano may be 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, if and when it does occur. Increased seismicity and ground deformation accompany movement of magma, but whether this magma will stay underground as an intrusion or appear at the surface as an eruption cannot be forecast accurately. There are many more intrusions than eruptions. Eruption, or sometimes magma intrusion without eruption, is signaled by the beginning of sharp deflation accompanied by either volcanic 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 could 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 precision at the parts per million level. For gases and fluids, one part per million can be pictured in terms of an Olympic-sized swimming pool—half a gallon of dye in the 500,000 gallons of water that fill the pool!

Other monitoring techniques are also proving useful. Data from magnetic, gravity, and geoelectrical studies can provide diagnostic information about the subsurface configuration and inner workings of a volcanic system. So far, data from nonseismic and nongeodetic monitoring techniques have not revealed definitive short-term precursors to possible eruptions. However, gravity measurements have identified possible underground movement of magma from one place to another, sometimes unaccompanied by measurable ground deformation or earthquakes. Experience on well-studied active volcanoes on the Island of 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, size, or duration of an expected eruption. However, for several Kīlauea eruptions in recent decades, HVO staff have been able to warn officials of Hawai'i Volcanoes National Park and (or) Hawaii County hours to days in advance to take safety measures, if deemed necessary.



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 (top plot). A change in tilt of 1 microradian equals an angle of 0.00006 degree. During 1956–2017, a water-tube tiltmeter measured long-term changes of ground deformation in the summit region of Kīlauea (black line) and, since 1999, a modern digital tiltmeter has tracked short-term changes (gray line). In 2017, the water-tube tiltmeter was damaged and became dysfunctional. With the onset of the Pu'u'ō'ō 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 continued through 2010. A large deflationary trend in 2018 marks elastic deflation that accompanied the summit collapse events associated with the large lower East Rift Zone eruption that year. During the 2018 deflation event, the digital tiltmeter went off-scale resulting in the post-2018 Kīlauea summit absolute level potentially being off by 60–80 microradians, but deflation during that event totaled more than 800 microradians. Following 2018, the summit of Kīlauea has inflated with brief pulses of deflation associated with intrusions or eruptions in the summit region. A detailed look at a 6-month segment of the tilt record (bottom plot) reveals similar inflation-deflation patterns for the high lava-fountaining episodes of the early Pu'u'ō'ō 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 (short and long period) that commonly precede and accompany Kīlauea eruptions.

Kīlauea's Volcanic "Plumbing System"

From decades of monitoring and research at HVO, a picture of Kīlauea's volcanic "plumbing system" is coming into focus. This system links the processes involved in the formation, transport, storage, and, ultimately, eruption of magma to sustain the State of Hawaii's active volcanoes.

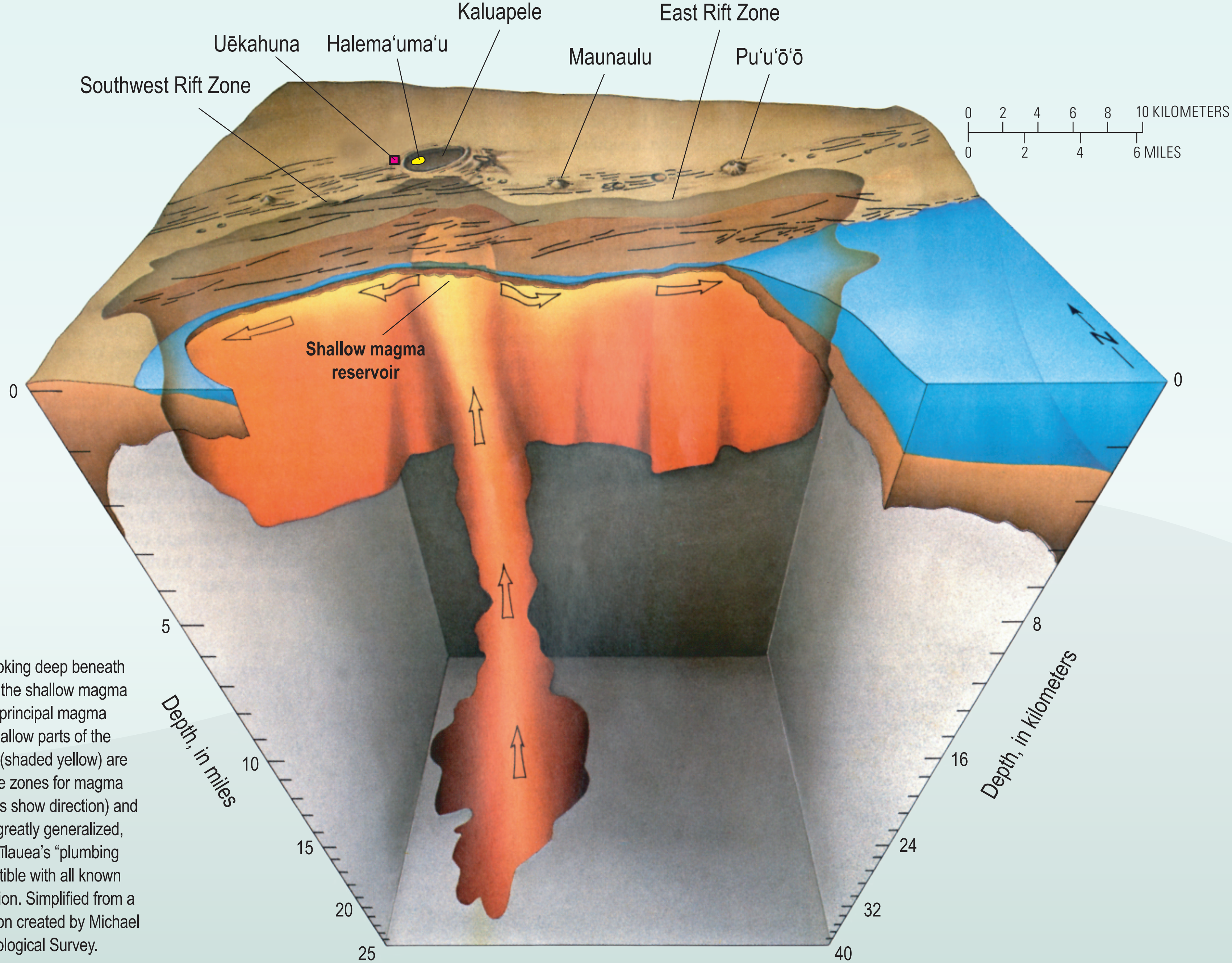
Kīlauea's plumbing system is thought to extend about 60 miles (100 kilometers) beneath the Earth's surface, where magma is generated by partial melting of material beneath the Pacific Plate as it passes over the Hawaiian Hot Spot. This idea is based on geochemical study of the lava composition and on the persistent recurrence of earthquakes 30 miles (50 kilometers) or more beneath the Island of Hawaiʻi. Earthquakes occurring 20–30 miles (32–48 kilometers) beneath the surface are probably related to the accumulation and upward movement of magma. Seismic data for levels shallower than 20 miles (32 kilometers) 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 one or two reservoirs 0.6–3 miles (1–5 kilometers) below the surface of the summit region. Earthquake data and ground-deformation patterns suggest that two reservoirs are present, a shallower one just northeast of Halemaʻumaʻu and a deeper one 1.2–1.9 miles (2–3 kilometers) away in the southern part of the caldera. Earthquakes do not occur within the reservoir because liquid magma does not rupture to generate seismic waves. It is important to emphasize that scientists do not yet know whether each reservoir is a single compartment or a zone of smaller interconnected rooms and narrow passageways.

Nearly all 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 usually 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 can be stored for a while within a rift zone and form transient secondary reservoirs.

Occasionally, part or all of the summit caldera collapses, hundreds of feet (or hundreds of meters) at times, when one or more reservoirs empties. Such a collapse affected part of the caldera in 2018, when magma left the Halemaʻumaʻu reservoir and entered the East Rift Zone. Even larger collapses, involving the entire summit area, occurred about 500 and 2,200 years ago. Caldera collapses, whether partial or whole, probably last several weeks to months as magma leaves the reservoirs. Rather than the summit simply deflating like a balloon, rocks are broken and faulted, creating cliffs such as those that are evident in the summit area today.

The volcanic plumbing system for Mauna Loa is less well known. Analysis of data from the well-monitored 1975, 1984, and 2022 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. And importantly, Mauna Loa's caldera also undergoes collapse just like at Kīlauea. Since a telemetered tiltmeter was installed at Mauna Loa's summit in 1999, Mauna Loa has undergone several periods of inflation (2002–05, 2014–17, and 2020–22), thought to represent an influx of magma.



Cut-away view looking deep beneath Kīlauea, showing the shallow magma reservoir and the principal magma passageways. Shallow parts of the magma chamber (shaded 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 a technical illustration created by Michael P. Ryan, U.S. Geological Survey.

Hawaiian Eruptive Style— Lava Flows to Powerful Explosions

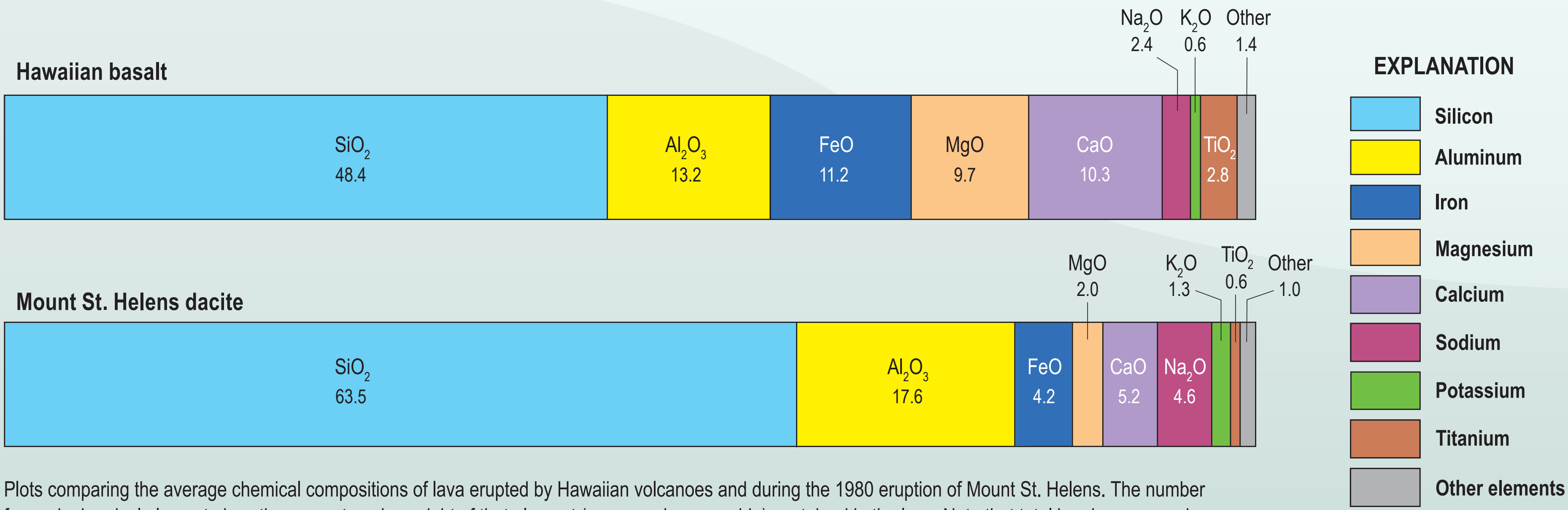
By definition, the adjective *eruptive* describes any object or phenomenon associated with processes of "bursting forth," "breaking out," or "issuing forth suddenly and violently." Strictly speaking, no eruption is truly nonexplosive; even weak spattering is explosive, as are the towering lava fountains so famous at Kīlauea. Nonetheless, volcanologists worldwide use the term "Hawaiian" to mean a similar, relatively gentle eruptive style at other volcanoes. But, as we shall see, both Kīlauea and Mauna Loa have their violent sides.

"Nonexplosive" or Weakly Explosive Eruptions

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, sometimes very explosively, during an eruption. Highly fluid lava favors the nonviolent release of gas from bubbles that form as pressure drops when the liquid rises toward the surface; such bubbles help drive an eruption. In contrast, viscous magma suppresses easy escape of bubbles, which commonly results in pressure buildup underground and ultimately in explosive gas release and magma fragmentation. In addition, viscous magma tends to contain more gas, further augmenting its explosive potential.

Lava *viscosity* (stiffness or resistance to flow) is largely determined by the chemical composition and temperature of the magma. Strictly speaking, viscosity only refers to the fluidity of a pure liquid, and the fluidity of an impure liquid containing crystals and bubbles should be called effective viscosity. Here, however, we use the term viscosity to refer to the "real-world" fluidity with crystals and gas bubbles in the liquid.

The low viscosity (high fluidity) of most Hawaiian lava 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 lava, such as the *dacite* erupted explosively at Mount St. Helens in 1980. In the figure below 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, which also can be fine grained or glassy, is generally much lighter in color. *Andesite* is intermediate in composition and color between basalt and dacite. Basaltic lavas overwhelmingly predominate at Hawaiian volcanoes, but there are rare occurrences of lavas with nonbasaltic compositions. Recent examples include the eruption of some andesite in 2018 at Kīlauea (previously mentioned on p. 16), and the penetration into molten dacite in 2005 during the drilling of a geothermal well into Kīlauea's lower East Rift Zone.

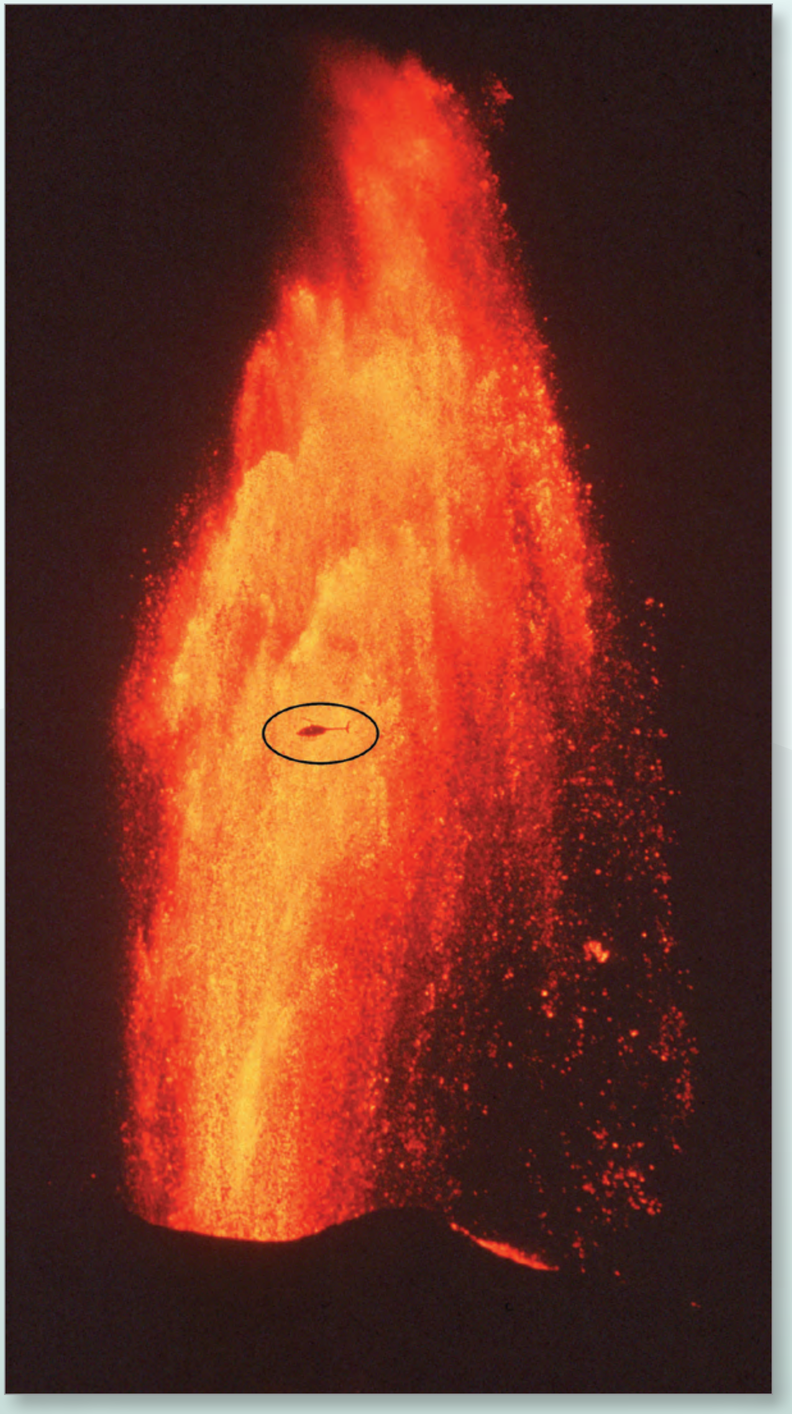


Plots comparing the average chemical compositions of lava erupted by Hawaiian volcanoes and during the 1980 eruption of Mount St. Helens. The number for each chemical element gives the percentage by weight of that element (expressed as an oxide) contained in the lava. Note that total iron is expressed as ferrous oxide (FeO).

Note the contrast in color and texture between Hawaiian basalt (left) and Mount St. Helens dacite (right). Photograph by J.D. Griggs, U.S. Geological Survey.

Hawaiian eruptions typically begin with lava fountaining from a series of nearly continuous fissures, evoking colorful popular descriptions such as "curtains of lava." As most eruptions progress, lava fountain activity, itself weakly explosive, typically becomes localized at a single vent, generally within hours of the initial outbreak. Depending on the shape of the vent and other eruptive conditions, lava fountains can range widely in form, size, and duration.

During the 1959 Kīlauea Iki eruption, one lava fountain shot up 2,200 feet (680 meters), the record height for historical Hawaiian eruptions. A fountain in 1969 from Maunaulu rose 1,800 feet (540 meters). More recently, some of the vigorous fountains during the 1983–86 Pu‘u‘ō‘ō eruption reached at least 1,500 feet (460 meters) high. Rarely, 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 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 12 miles (19.5 kilometers) up into the atmosphere.



Lava fountains can vary widely in size and form. A 1,500-foot-high (460-meter-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.

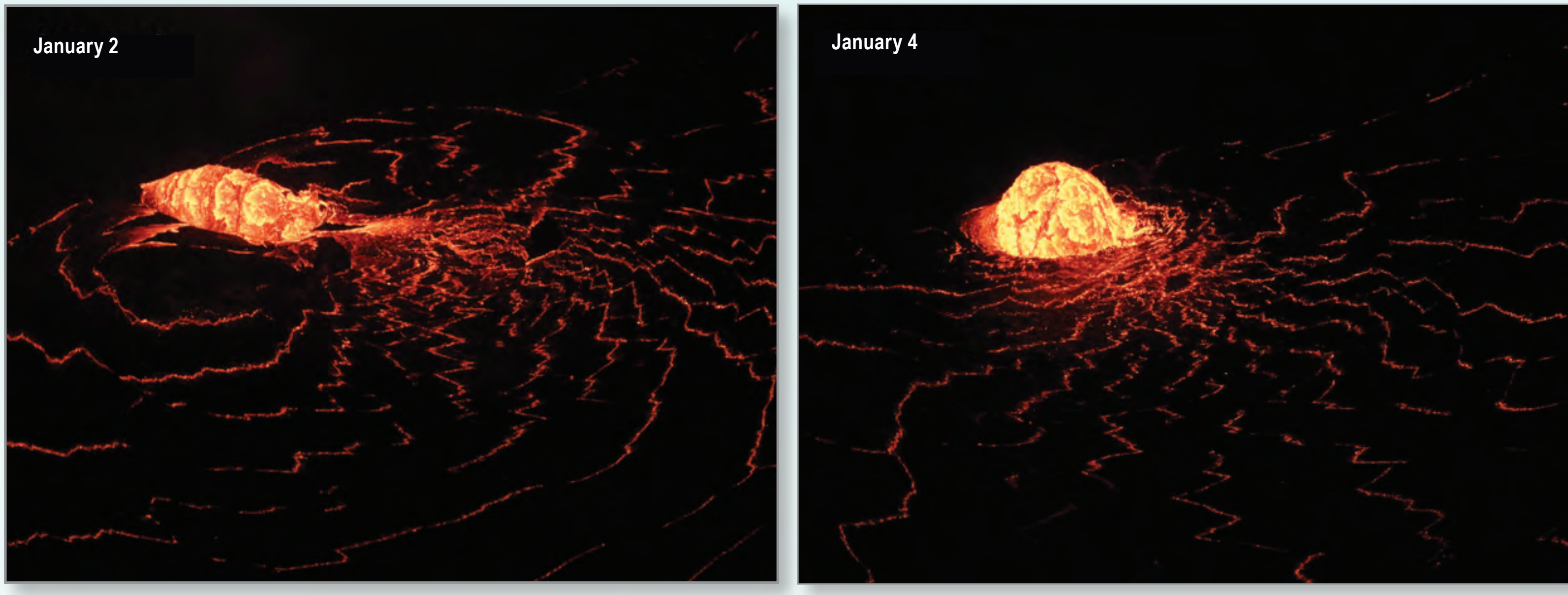
Molten lava falling from fountains and quietly erupting from vents commonly forms long incandescent *lava flows*, giving rise to the popular but misleading term "rivers of fire." This colorful term is inaccurate because flowing lava is molten rock and hence does not burn; "fire" is involved only if the flows ignite and burn vegetation, wooden structures, and other combustibles along their paths. Hawaiian lava flows generally advance at average speeds of a few miles (several kilometers) 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, or if the eruption rate is very high, 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 measured at about 20 miles per hour (35 kilometers per hour)! But this is unusual.

During long-lived eruptions, lava flows tend to become channelized into a few main streams. Overflows of lava from these streams solidify quickly and plaster on to the channel walls, building natural levees that allow the level of the lava flow 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

A line of lava fountains during the 2018 Kīlauea lower East Rift Zone eruption; fountains reached heights of about 160 feet (50 meters). Photograph by Matthew Patrick, U.S. Geological Survey.

Aerial view of an erupting fissure during the March 2011 Kamoamoa eruption of Kīlauea's East Rift Zone. Spattering lava fountains feed lava flows that cascade into a nearby crack. Photograph by Tim Orr, U.S. Geological Survey.

Mildly explosive entry of lava into the ocean, after traveling about 6.8 miles (11 kilometers) from the Puʻuʻōʻō vent in February 1988. Photograph by Taeko Jane Takahashi, U.S. Geological Survey.



A lava fountain formed a dome, about 20 feet (6 meters) tall, that lasted for days in January 2021 during the summit eruption of Kīlauea in Halemaʻumaʻu. Photograph by Matthew Patrick, U.S. Geological Survey.

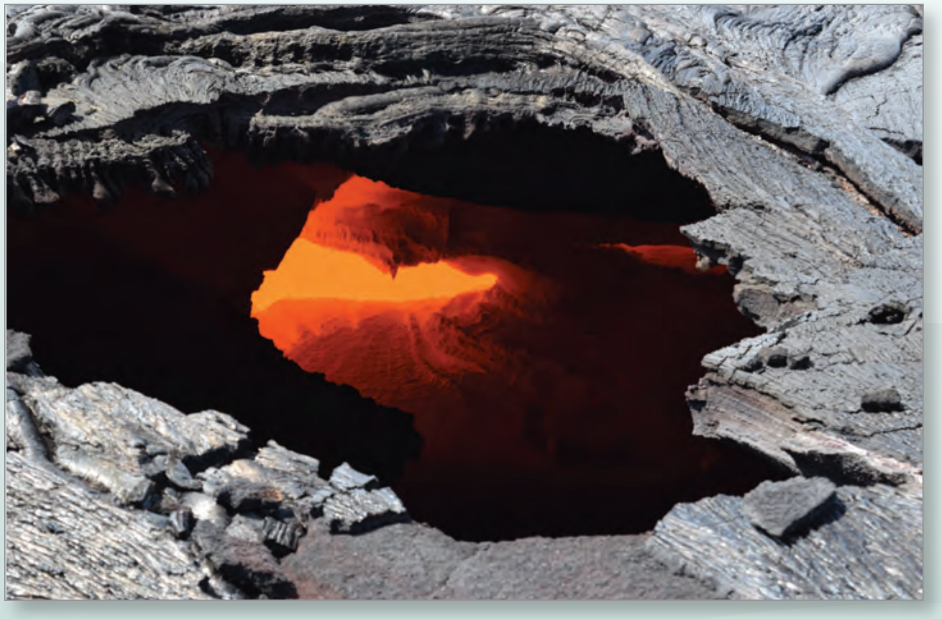
In 2017, the end of a lava tube fed by Kīlauea's Puʻuʻōʻō eruption was sheared off when part of the coastline collapsed. This allowed the lava to gush like a firehose and enter the ocean 69 feet (21 meters) below. Photograph by Liliana DeSmither, U.S. Geological Survey.

A perched lava pond within Puʻuʻōʻō in June 2011. Fresh lava flows (with silver sheen) that have spilled out over this perched pond raised the elevation of the crater floor. Photograph by Tim Orr, U.S. Geological Survey.

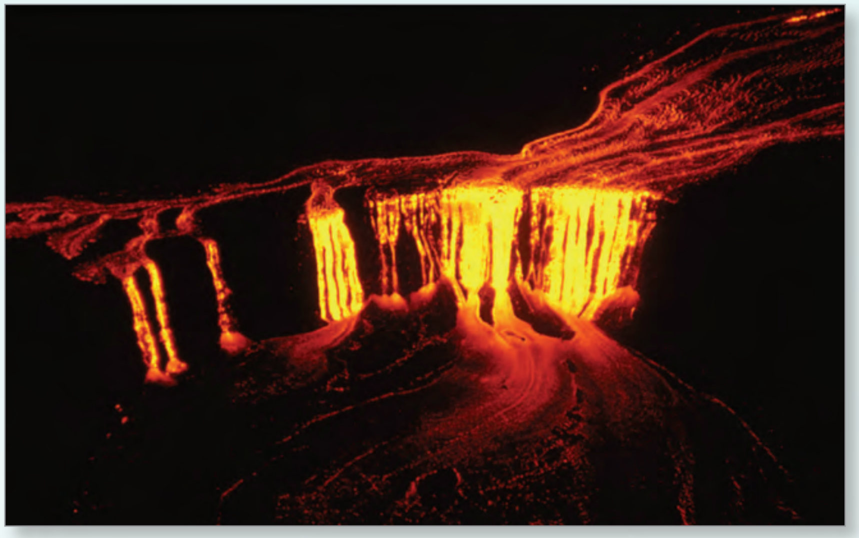
lava can be transported for great distances from the eruption sites. For example, during both the Maunaulu and Puʻuʻōʻō eruptions on Kīlauea, many lava flows traveled underground through lava-tube systems more than 6.8 miles (11 kilometers) long before entering the ocean. Lava flowing for weeks in tubes can erode downward, a process called thermal erosion, resulting in a tube whose height is much greater than the depth of the lava flowing through it.

Lava streams that plunge over cliffs or the steep walls of craters form impressive lava cascades or 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. In contrast, lava lakes formed at the site of, and sustained by, active 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 can raise the lake level by levee construction similar to overflowing lava streams. Through this process of levee growth, lakes may become perched many feet (several meters) above their surroundings.

Aerial view of lava flowing through a branching channel during the 2022 eruption of Mauna Loa on the Island of Hawaiʻi. Flow direction is from right to left across the image. Lava was flowing 8–11 miles per hour (13–18 kilometers per hour) at this location, close to the vents high on Mauna Loa's Northeast Rift Zone. Farther downslope, on flatter ground, the wide lava flow fronts were advancing slower, at an average rate of 20 feet per hour (6 meters per hour). Photograph by Mike Zoeller, U.S. Geological Survey.



This view into a "skylight" (collapsed roof) of a lava tube during the Puʻuʻōʻō eruption shows how Nāhuku (Thurston Lava Tube) might have looked when it was active about 550 years ago. Photograph by Liliana DeSmither, U.S. Geological Survey.



Lava cascades plunge 160 feet (50 meters) into Luahou, a crater on the upper part of Mauna Loa's Southwest Rift Zone, during the volcano's July 1975 eruption. Photograph by Robin T. Holcomb, U.S. Geological Survey.

A clockwise-circulating lava lake (nearly 500 feet or 150 meters 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. Photograph by Robert I. Tilling, U.S. Geological Survey.

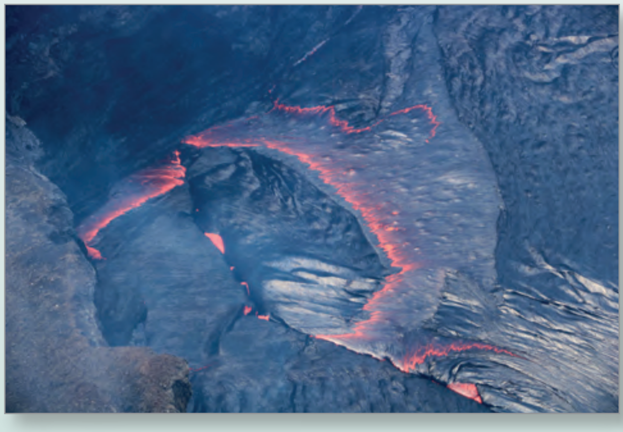
Inside Nāhuku (Thurston Lava Tube), Hawai‘i Volcanoes National Park. Photographs by Katherine Mulliken, U.S. Geological Survey.

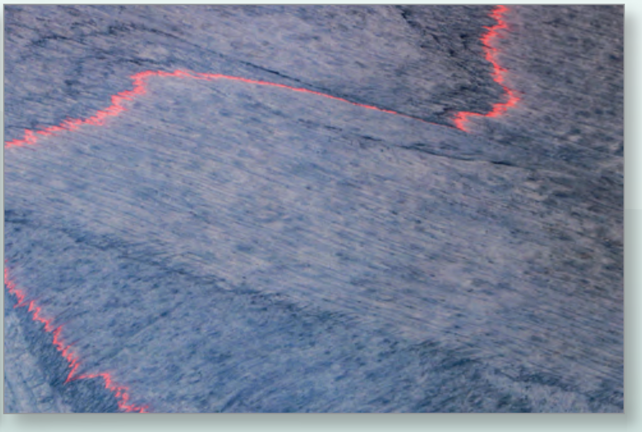
At Kīlauea's summit, the nearly continuous, century-long lava-lake activity in Halema‘uma‘u ceased after the 1924 explosive eruption. However, a lava lake was active in the summit crater for about 8 months during the 1967–68 eruption, then for 10 years in 2008–18, and again intermittently during 2020–23. It was not until the 1969–74 Maunaulu 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 Maunaulu, 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 and p. 35). Similar lava-lake flow dynamics were also observed during the Pu‘u‘ō‘ō eruption.

A well-studied example of an inactive lava lake—formed when lava cascades into a preexisting crater—is the one produced during the 1959 Kīlauea Iki eruption. Today, thousands of visitors to Hawai‘i Volcanoes National Park can walk across the crust of this now solidified lava lake that is more than 365 feet (111 meters) deep.

In the 2008–18 Kīlauea summit lava lake, moving slabs of surface crust, ranging in size from a yard (about a meter) to several yards (several meters) across but only inches (several centimeters) thick, are rafted by circulating lava beneath. Photograph by Matthew Patrick, U.S. Geological Survey.

Surface movements of active lava lakes on Kīlauea provide a very small-scale analogy to movements of Earth's tectonic plates. Vigorous spattering within the active summit lava lake in March 2018 break the crust into separate slabs. Photograph by Liliana DeSmither, U.S. Geological Survey.





U.S. Geological Survey Hawaiian Volcano Observatory staff scientist Wendell Duffield was the first to recognize that the surface of an active lava lake, as observed during the 1969–74 Maunaulu eruption, provides small-scale analogs to global plate tectonics. Shown here are closeup views of the 2008–18 Kīlauea summit Halema‘uma‘u lava-lake surface to show analogs to the three common types of tectonic plate boundaries: convergent boundary between two slabs of crust (left), divergent or spreading boundaries between two slabs (middle), and transform fault offsetting a spreading boundary between slabs (right). Photographs by Matthew Patrick, U.S. Geological Survey.

Explosive Eruptions

Explosive eruptions far more powerful than lava fountains characterize the history of both Kīlauea and Mauna Loa. Once thought to be rare, research over the past two decades documents that such explosions have taken place repeatedly at both volcanoes in the geologically recent past. Explosive eruptions form *tephra*, a word for any solid fragmented material (lava or rock) that results from an explosive eruption. It is usually restricted to fragments that fall to the ground rather than traveling as a surge across the ground (the infamous lateral blast at Mount St Helens in 1980 was such a surge). Another term, *pyroclastic*—derived from Greek *pyro* (fire) and *klastos* (broken)—means essentially the same thing but today is usually applied to the eruption itself or for fragmented lava or rocks in a surge. A pyroclastic eruption deposits tephra.

Relatively few Hawaiian eruptions are violently explosive, and none reached the size of famous pyroclastic eruptions from volcanoes that form along the convergent boundaries of the Earth's tectonic plates, such as those at Mount St. Helens in 1980 and Vesuvius in 79 C.E. Some volcanoes of this type contain 90 percent or more tephra, whereas Kīlauea and Mauna Loa contain less than a few percent. These observations led volcanologists to overlook the importance of powerful explosions on Hawaiian volcanoes. Another reason that powerful explosions were overlooked until recently is that, during the time of written history in the Hawaiian Islands, gentle effusive eruptions are by far the most common.

Recent research estimates that more than 50 powerful explosions took place at Kīlauea between about 1500 and the early 1800s C.E. At least four of these powerful explosions sent volcanic ash high into the subtropical jet stream to heights of 6 miles (10 kilometers) or more, and the tephra was distributed toward the northeast, east, and southeast. Ash from most of the explosions, however, did not reach such heights and was spread southwestward by the prevailing trade winds. Consequently, the cumulative thickness of tephra deposits during the 300 years of frequent powerful explosions is about 36 feet (11 meters) on the downwind south rim of Kīlauea but only 6 feet (2 meters) on the upwind north rim.

The most famous powerful explosions occurred in 1790, when several hundred people were killed, apparently by a surge of hot ash and gas, on the northwest flank of Kīlauea. This lethal stage of the eruption accompanied, or immediately followed, a powerful explosion that generated a plume visible from Kawaihae in the northern part of the island. Just before this explosion, muddy ash falling on the ground in the Ka'ū District left a deposit that hundreds of people (mostly women and children) walked on, leaving footprints that are still visible today. The fatalities were warriors and their families led by Keōua, on the way to battle his cousin Kamehameha for supremacy of the island. For more information on the interpretation of these events, see the "Selected Readings" section.

Available evidence suggests that powerful explosions can dominate eruptive activity at Kīlauea for periods lasting several centuries. Two such periods, 200 B.C.E. to 1000 C.E. and 1500 C.E. to the early 1800s C.E., have been identified. If an eruption occurred during these periods, it was more likely to be explosive than effusive. During intervening periods, such as 1000 to 1500 C.E. and the early 1800s to the present, effusive eruptions dominated, and powerful explosions were rare and smaller than those during the dominantly explosive periods. The cause of this cyclicity—centuries of mostly powerful explosions alternating with centuries of mostly effusive lava flows—is the subject of intense current research. Importantly, work is also underway to ascertain if the transition from an effusive to an explosive period can be anticipated; obviously, public safety would benefit from such a capability.

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

A crowd of visitors poses in May 1924 at Kīlauea volcano as a large explosion cloud rises hundreds of feet (hundreds of meters) into the air above Halema'uma'u. In fact, Ruy H. Finch, acting Scientist-in-Charge at the Hawaiian Volcano Observatory at the time, warned them that it was "unwise to remain there." Given the data from recent studies, their location would now be considered too close for safety. Photograph by Tai Sing Loo, courtesy of the Bishop Museum, Honolulu, Hawaii; used with permission.

Even with increased studies, the cause(s) of the powerful explosions remain(s) uncertain. Some were almost certainly driven by pressurized steam resulting from heating of groundwater below the water table. Others were likely powered by rapidly expanding gas effervescing from magma, and still others may have involved both steam and magmatic gas processes.

A notable characteristic of deposits of many powerful Kīlauea explosions is that they generally contain few if any *juvenile* (freshly erupted magma) products. Instead, fragments of preexisting rocks from the walls of the eruption conduit dominate. For example, the 1790 deposits contain only trace amounts of what may have been fresh magma. However, in other powerful explosive deposits, fresh material dominates.

For the public, the most obvious signs of past powerful explosions at Kīlauea are large heavy blocks that were hurled ballistically from the caldera when it was much deeper than it is today. Such huge ballistic blocks were ejected in or around 1790, in 1924, and during a small explosion in 2008. The collapse of part of the caldera in 2018, however, engulfed most of the younger blocks, but visitors to Kīlauea Overlook in Hawai‘i Volcanoes National Park can still walk past a large block ejected around 1790.

Deposits of powerful ancient explosions, dating back more than 50,000 years, occur near Pāhala, in cliffs in the Hilina fault system, and at scattered other places. They indicate that explosive activity is not a relatively recent phenomenon at Kīlauea. Mauna Loa likewise has evidence of at least five powerful explosions in the summit area during the past 1,500 years, indicated by explosive deposits. Large ballistic blocks dot the summit landscape, including near the summit cabin. The youngest explosion, which produced some of these ballistic blocks, took place after 1840, perhaps in 1877.

A special type of explosive activity, called a *littoral explosion*, occasionally results when active lava flows enter the ocean. When seawater comes into contact with the hot inner parts of the lava flow, it flashes into steam, triggering an explosive spray of lava fragments derived from both the solidified outer part of the lava flow as well as its still-molten inner 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 subsequent erosive wave action. Larger deposits, however, can be more permanent and form littoral cones. About 50 such cones, both prehistoric and historical, dot the shores of Mauna Loa and Kīlauea volcanoes. A well-studied example of a littoral cone is the 240-foot-tall (73-meter-tall) Pu‘uhou, located 5 miles (8 kilometers) 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.

Ballistic block at Kīlauea Overlook. In the background, visitors look into the caldera, from which the block, about 5 feet (1.5 meters) wide, was ejected in about 1790. The caldera was several hundred feet (hundreds of meters) deep at the time. Photograph by Donald A. Swanson, U.S. Geological Survey.

Molten lava erupted by Kīlauea’s Pu‘u‘ō‘ō vent on the East Rift Zone is shredded by littoral explosions upon entry into the ocean during January 2017. Photograph by Janet Babb, U.S. Geological Survey.

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 quickly formed beaches, which—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 the Island of Hawai‘i's most beautiful and photographed black-sand beaches was at Kaimū Bay, on the Puna coast along Kīlauea's southeast flank. Unfortunately, Kaimū Beach met its demise when it was completely buried by lava erupted from the Kupaianaha vent in early fall of 1990.

Puāuāomahana, a small prehistoric cone on the coast 3 miles (5 kilometers) northeast of the island's south tip, is the site of the Island 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. Puāuāomahana was once believed to have originated from littoral explosions, but recent studies suggest that it probably formed inland, at an elevation originally more than 300 feet (90 meters) above sea level. This cone's present-day position at the water's edge reflects the gradual sinking of the Island of Hawai‘i and rising sea level as Earth's glaciers have melted after Puāuāomahana formed tens of thousands of years ago.

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. Photograph by Michael Poland, U.S. Geological Survey.

Puāuāomahana, once thought to be a prehistoric littoral cone of Mauna Loa, is the site of the Island of Hawai‘i's green-sand beach. Photograph by Katherine Mulliken, U.S. Geological Survey.

Closeup of the green sand at Puāuāomahana, which obtains its color from wave-concentrated grains of the mineral olivine. Photograph by Robert I. Tilling, U.S. Geological Survey.

Hawaiian Volcanic Products, Landforms, and Structures

The volcanic mountains of the Hawaiian Islands have been built by the accumulation of basaltic lava flows erupted 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 and Alaska's Aleutian volcanoes, have been built by a combination of lava flows and pyroclastic debris produced by explosive eruptions; accordingly, they are commonly termed "composite" volcanoes. Even though they both form linear mountain ranges, Hawaiian volcanoes differ greatly from Cascade Range composite 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-level parts of Hawaiian volcanoes. *Pāhoehoe* (pronounced "PAH-hoy-hoy") and *ʻaʻā* (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, whereas ʻaʻā is solidified lava that has a rough, jagged, spiny, and generally clinkery surface. In thick ʻaʻā flows, the rubbly surface of loose blocks and clinkers hides a massive, relatively dense interior.

The contrast between the surfaces of pāhoehoe and ʻaʻā 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 ʻaʻā is like scrambling over a building demolition site, strewn with loose, unstable debris of all shapes and sizes. The jagged rubble of ʻaʻā flows quickly destroys field boots and, should the hiker stumble or fall (not at all uncommon), it can tear clothing and flesh.

Many Hawaiian lava flows solidify as pāhoehoe throughout their length, and a few flows solidify completely as ʻaʻā. Some flows, however, consist of both pāhoehoe and ʻaʻā in widely varying proportions. Strictly speaking, the terms pāhoehoe and ʻaʻā should only 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. For a given active flow, pāhoehoe upstream commonly changes to ʻaʻā downstream, but, under certain circumstances, ʻaʻā-crusted lava flows can also transition into pāhoehoe flows. The explanation for changes in flow type depends on the delicate balance between the initial gas content of the lava, the

In 2016, an active ʻaʻā lava flow from Puʻuʻōʻō advanced over the smooth surface of a previous Puʻuʻōʻō pāhoehoe lava flow on the slope near the top of the Pūlama pali, one of the steep escarpments on Kīlauea's southeast flank. Photograph by Tim Orr, U.S. Geological Survey.

Closeup view of the surface of a pāhoehoe flow. Photograph by Matthew Patrick, U.S. Geological Survey.

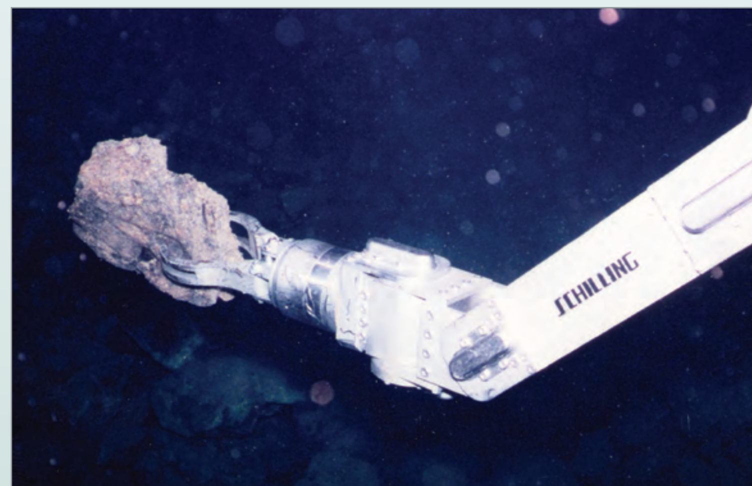
Closeup view of the surface of an ‘a‘ā flow. Photograph by Liliana DeSmither, U.S. Geological Survey.

When lava flows underwater, it quickly forms a solidified exterior shell, resulting in bulbous shapes called pillow lava, as shown here. Photograph by the Hawai‘i Undersea Research Laboratory at the University of Hawai‘i; used with permission.

changes in lava viscosity, the rate of deformation (shear strain), and the increasing amounts of crystals in the 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 landforms called *shields* (see discussion on p. 45). Some flows produced during the past 200 years are longer than 30 miles (48 kilometers); in general, pāhoehoe flows tend to be longer than ‘a‘ā flows, but there are many exceptions. 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 (several meters) in width, and one has been followed by speleologists (cave explorers) for about 18 miles (29 kilometers). 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 Nāhuku (Thurston Lava Tube), which formed in a pāhoehoe flow about 550 years ago.

Fluid lava erupted or flowing underwater 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 on land). 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



A piece of pillow lava is collected by a mechanical arm of a Remotely Operated Vehicle (ROV) from great water depths on the submerged south slope of Kīlauea. To collect the sample of choice, the mechanical arm is precisely manipulated by scientists aboard the ROV’s mother ship on the ocean surface. Photograph by Peter W. Lipman, U.S. Geological Survey.

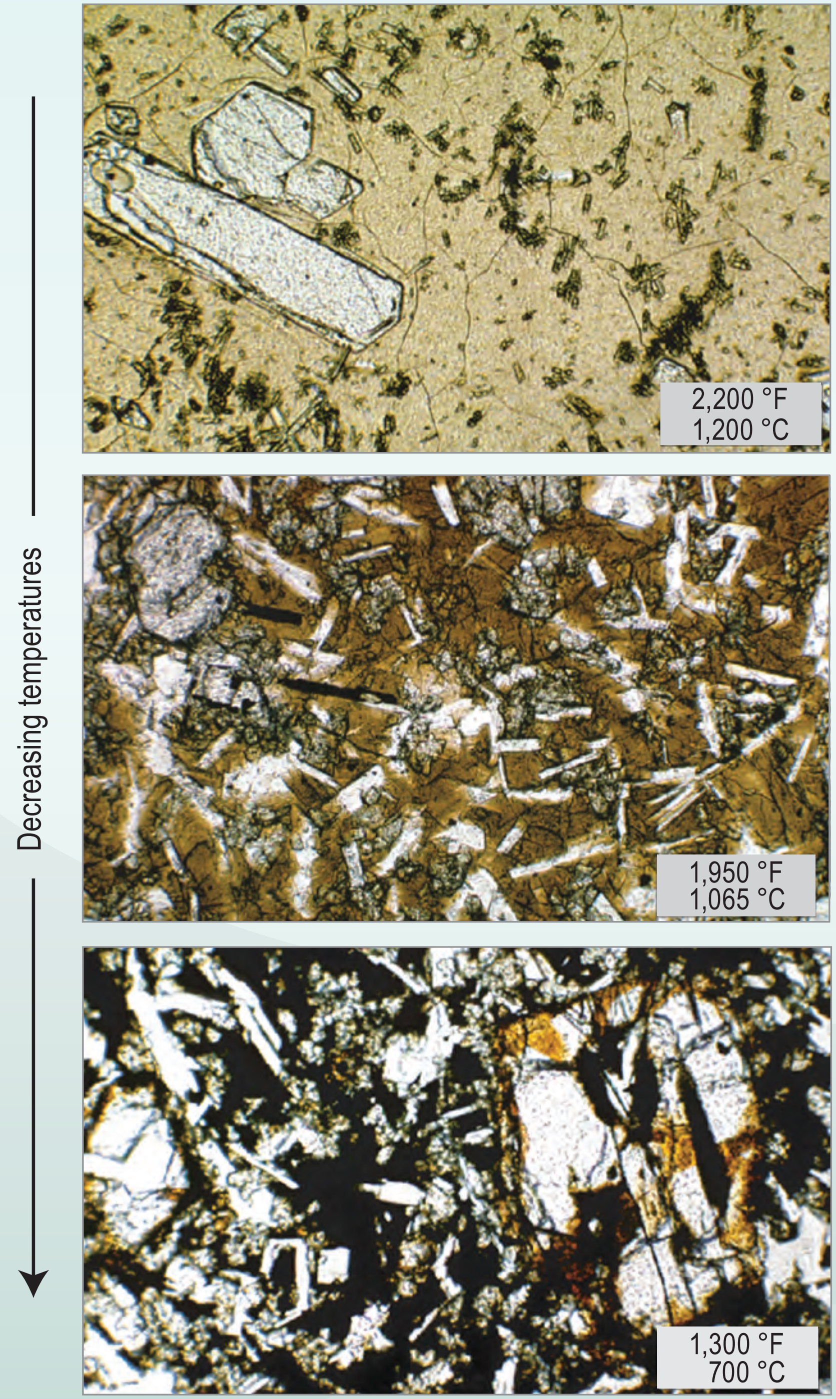
section. Typically ranging from less than one to several feet (about a meter) in diameter, each pillow has a glassy outer skin formed by the rapid cooling of lava by water. Much pillow lava is erupted under relatively high pressure created by the weight of the overlying water, so there is little or no explosive interaction between the hot lava and cold water. Most 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, crewed 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 Maunaulu and the 1983–2018 Puʻuʻōʻō eruptions of Kīlauea, teams of scuba-diving observers 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 off the west coast of the Island of Hawaiʻi.

Another common lava feature is the ponded flow or *lava lake*, the formation of which is described in the previous section. Lava lakes can be either active or passive. An active lava lake is one that directly overlies the vent that continually supplies lava to it during the eruption. In contrast, a passive lava lake is simply a pool of lava that has ponded within a preexisting crater or depression—physically separated from the vent—and proceeds to cool and solidify.

Upon complete 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 active lava lakes have formed and been well observed during Kīlauea eruptions, the most recent of which were lakes at Kupaianaha (1986–90), Puʻuʻōʻō (1988–2018), and Halemaʻumaʻu (2008–18 and 2020–23). The now completely solidified 365-foot-deep (111-meter-deep) lava lake formed during the November–December 1959 eruption at Kīlauea Iki Crater is the only one still visible and easily accessible; most other lava lakes have been covered by younger lava flows or otherwise destroyed.

Hawaiian lava lakes have been investigated in detail because they furnish natural crucibles to study the cooling, crystallization, and chemical change of basaltic lava at low pressure. 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.



Three specimens from the 1965 lava lake in Makaopuhi Crater (about 5 miles or 8 kilometers west of Puʻuʻōʻō), sampled by drilling, as seen under the microscope (field of view is about 0.04 inch or 0.1 centimeter). Samples 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 (given in degrees Fahrenheit and Celsius). 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. Photomicrographs by Thomas L. Wright, U.S. Geological Survey.

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). However, all molten lava had completely crystallized by the mid-1990s. The internal temperatures of the deep, hottest zones of the solidified lava lake (590–980 °C or 1,100–1,800 °F) will remain hundreds of degrees hotter than the surface temperature for many more years.

Drilling of lava lakes can be risky. When the Maunaulu eruption began on May 24, 1969, lava flowed into ‘Alae Crater, covering the surface of a lava lake formed 3 months earlier and quickly burying a drill rig and related equipment before they 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.

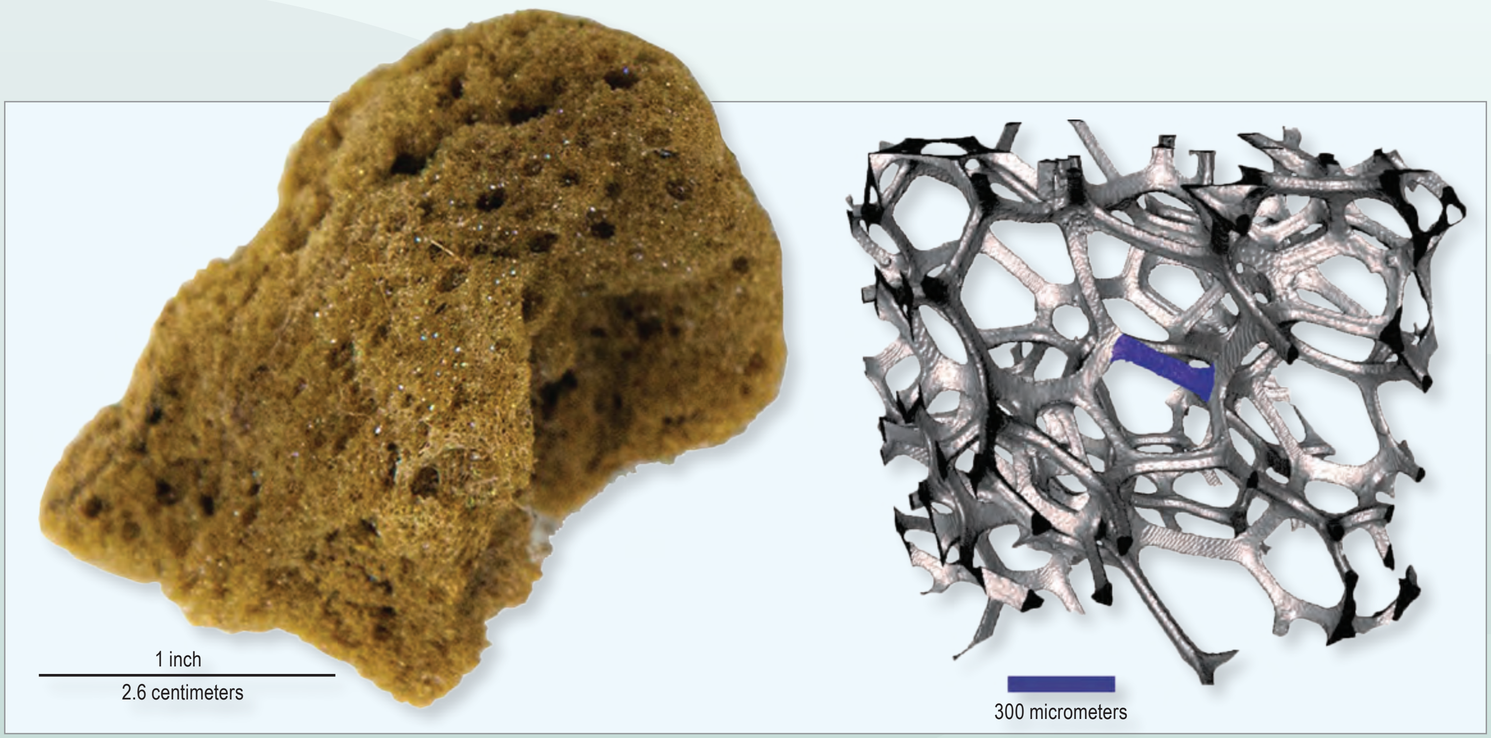
View looking about 390 feet (120 meters) down from the rim of Kīlauea Iki Crater to the surface of the lava lake formed in the 1959 eruption and a site of drilling studies in 1975 (circled). Photograph by Robin T. Holcomb, U.S. Geological Survey.

Closeup view of the Kīlauea Iki drilling operations in 1975. U.S. Geological Survey Hawaiian Volcano Observatory scientists wear asbestos gloves to handle hot drilling steel. Photograph by Robin T. Holcomb, U.S. Geological Survey.

Fragmental Volcanic Products

Fragmental volcanic debris is formed during mildly explosive activity, such as lava fountaining, and during the violently explosive eruptions, such as those that occurred between 1500 and the early 1800s C.E. at Kīlauea. *Tephra* is the general term used by volcanologists for airborne volcanic ejecta of any size but various terms can be used to describe ejecta of different sizes. Fragmental volcanic products between 2 and 64 millimeters in diameter are called *lapilli*; material finer than 2 millimeters is called *ash*. In a major explosive eruption, most of the pyroclastic debris would generally consist of lapilli and ash. Fragments larger than about 64 millimeters 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 air. 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.”

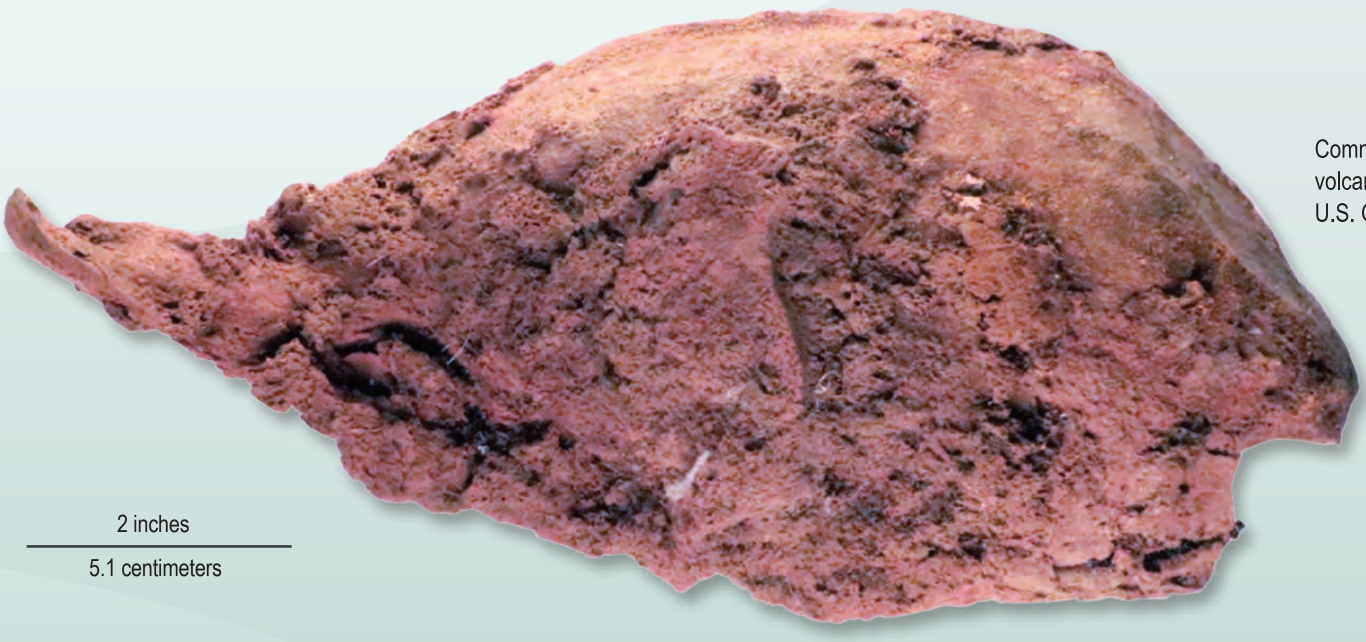
Common Hawaiian fragmental volcanic products: Pele’s tears. Photograph by Katherine Mulliken, U.S. Geological Survey.



Left, Fragment of reticulite erupted about 500 years ago at Kīlauea. Right, X-ray computed microtomography (XRCT) image of this fragment. Note the honeycomb-like structure. Photograph and image by Laura L. Schepp, Institution for Energy Infrastructures and Geothermal Systems, Bochum, Germany; used with permission.

Common Hawaiian fragmental volcanic products called limu o Pele, which refers to the way this product resembles seaweed. Photograph by Katherine Mulliken, U.S. Geological Survey.

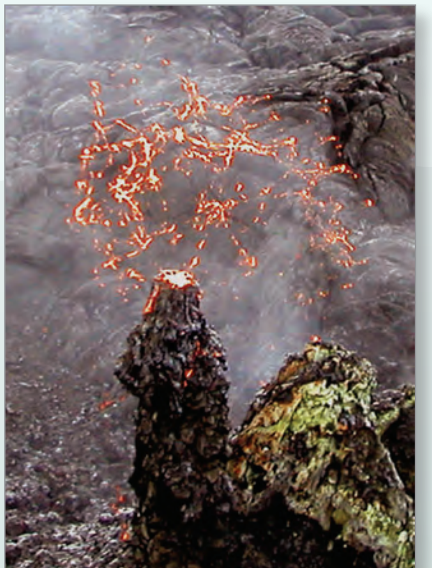
Common Hawaiian fragmental volcanic products: accretionary lapilli, spherical accumulations of volcanic ash, generally formed during explosive eruptions in presence of moisture. Photograph by John P. Lockwood, U.S. Geological Survey.



Common Hawaiian fragmental volcanic products: volcanic bomb. Photograph by Katherine Mulliken, U.S. Geological Survey.

Another category of ejecta 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 Hawaiian eruptions, these fragments share a common mode of origin: all result from sudden chilling of frothy lava from which gases were escaping during fountaining. During exceptionally high fountaining episodes of some eruptions—such as at Maunaulu in 1969 and Puʻuʻōʻō during 1983–86—an extremely vesicular frothy lava called *reticulite* or *thread-lace scoria* can form and be carried many miles (many kilometers) downwind from the high lava fountains. Even though reticulite is the least dense kind of inorganic material known, it does not float on water because its vesicles are open and interconnected. Consequently, when it falls on water, it becomes quickly waterlogged and sinks.

If scoria or pumice clots are sufficiently fluid 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 deity 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 (many kilometers) 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 (several centimeters) across.



Spattering at a vent, fed by tube-fed lava actively flowing beneath it, begins to form a hornito during the Puʻuʻōʻō eruption in 2002. Photograph by Donald A. Swanson, U.S. Geological Survey.

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 mat-like deposits. This photograph shows Pele's hair that drifted 0.6 miles (1 kilometer) south of the lava lake in Halemaʻumaʻu. Photograph by Donald A. Swanson, U.S. Geological Survey, on November 16, 2016).

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 Puʻuʻōʻō cone is visible on the skyline left of the spire. Photograph by James Kauahikaua, U.S. Geological Survey.

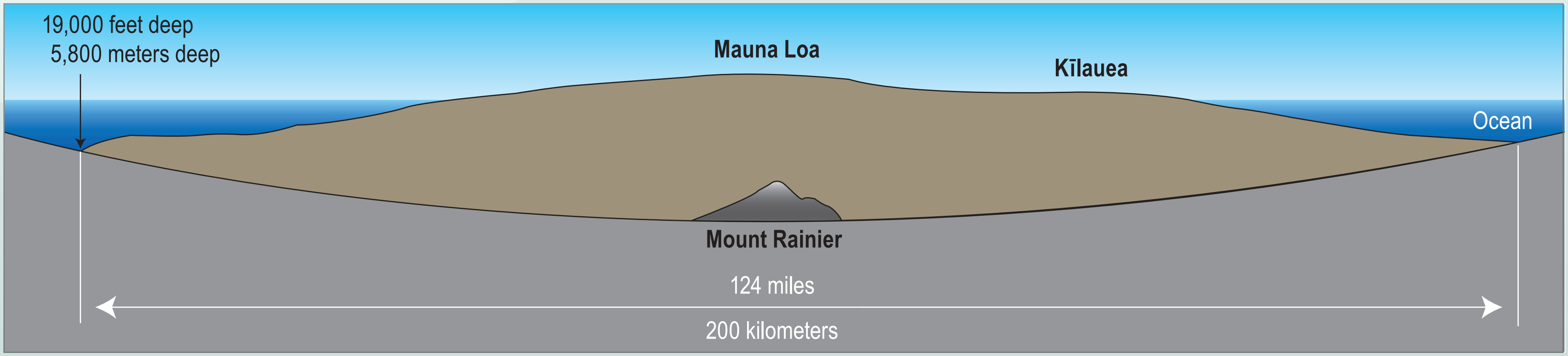
Volcanic spatter sometimes becomes tightly welded to form mounds around active vents. Photograph by Richard B. Moore, U.S. Geological Survey.

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.

Mount St. Helens, a typical steep-sided composite volcano, before its decapitation during the May 18, 1980, eruption. Photograph by Rick Hoblitt, U.S. Geological Survey.

Snow-capped Mauna Loa, an excellent example of a shield volcano, viewed from the Uēkahuna bluff area of Kīlauea, within Hawaiʻi Volcanoes National Park. Photograph by Robert I. Tilling, U.S. Geological Survey.



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 down-warped many hundreds of feet (hundreds of meters) because of their immense weight. In size, Hawaiian shield volcanoes dwarf composite volcanoes.

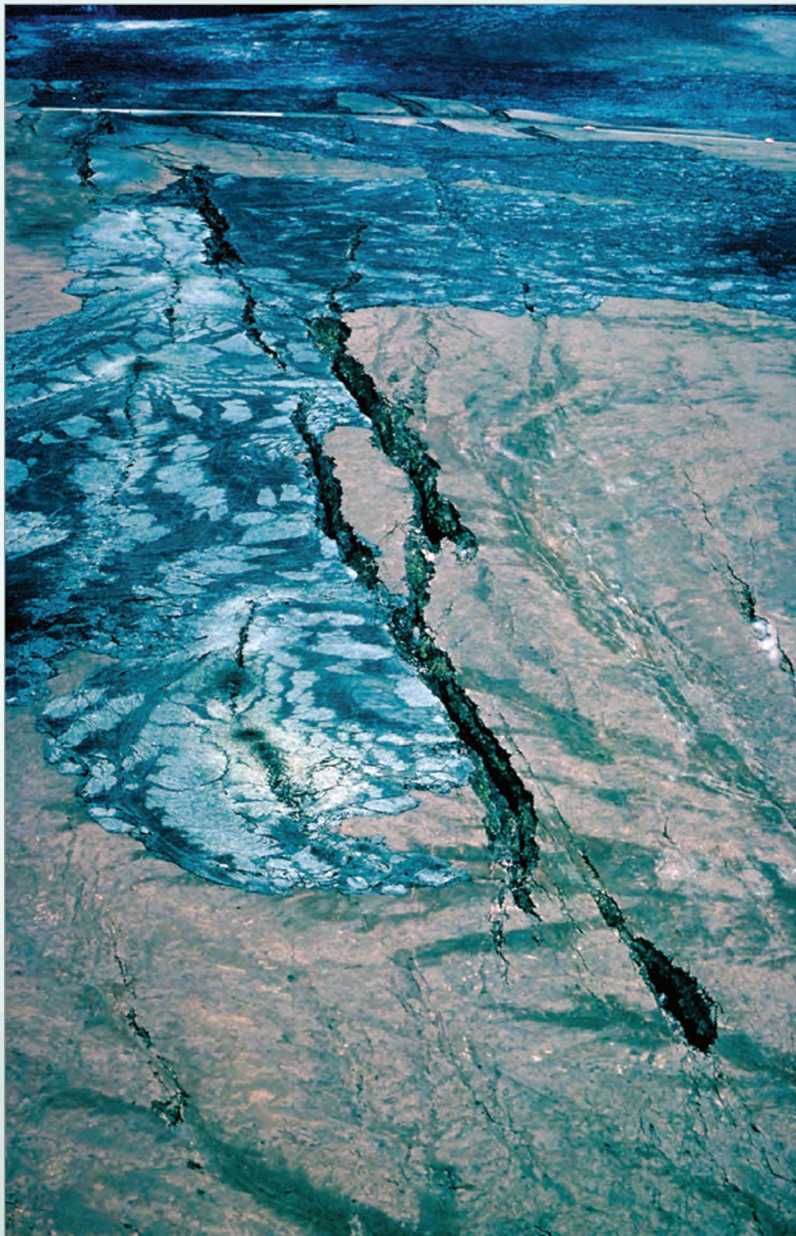
Hawaiian shield volcanoes are the tallest and largest mountains on Earth. For example, Mauna Kea rises 13,803 feet (4,205 meters) above sea level but extends more than 33,000 feet (10,000 meters) below sea level to meet the deep ocean floor. Mauna Loa (13,670 feet or 4,169 meters above sea level) is slightly lower than Mauna Kea, but it is much larger in volume, comprising nearly 19,000 cubic miles (80,000 cubic kilometers). Measured from its base resting on the deepest part of the bowed seafloor, the total height of Mauna Loa is about 10 miles (17 kilometers)— almost twice the height of the tallest mountain on land, Mount Everest in the Himalaya (29,032 feet or 8,848 meters above sea level). The profile of the Mauna Loa shield appears smooth, whereas the shield profile of Mauna Kea has a steeper, 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. Kaluapele, Kīlauea's summit caldera, is about 2.5 miles (4 kilometers) long and 1.9 miles (3 kilometers) wide. Moku'āweoweo, the summit caldera complex of Mauna Loa, is more elongate, measuring about 3 by 1.5 miles (4.8 by 2.4 kilometers). The terms *crater* or *pit crater* are applied to similar but smaller collapse features.

Aerial view in September 1972 of two prominent volcanic shields that formed during the 1969–74 eruption on Kīlauea's upper East Rift Zone. Both the Maunaulu Lava 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. Photograph by Robert I. Tilling, U.S. Geological Survey.

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 on next page), 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 prominent rift zones. However, for Mauna Loa, recent studies have identified more than 30 radial vents on the northern and western sectors of the volcano from which lava has been erupted in addition to vents in the main rift zones and the summit caldera.

Aerial view from the south of snow-covered Moku'āweoweo, Mauna Loa's summit caldera, and several pit craters along its Southwest Rift Zone. Mauna Kea, which last erupted about 4,000 years ago, can be seen in the distance. Photograph by Donald W. Peterson, U.S. Geological Survey.



Aerial view of prominent fissures within the Southwest Rift Zone of Kīlauea. The shiny dark lava was erupted from these fissures in September 1971. Photograph by J.D. Griggs, U.S. Geological Survey.

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 (10 centimeters) 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 that cut the south flank (the Hilina Fault System), as well as by slip along a nearly horizontal fault zone at the base of the volcano. For example, in response to a moment magnitude 7.7 earthquake beneath the area on November 29, 1975, points on Kīlauea's south flank dropped as much as 11 feet (3.4 meters) and shifted southward as much as 24 feet (7.3 meters). The scarps (steep slopes) of the Hilina Fault System are observable as *pali* (Hawaiian for cliff) on Kīlauea's south flank.

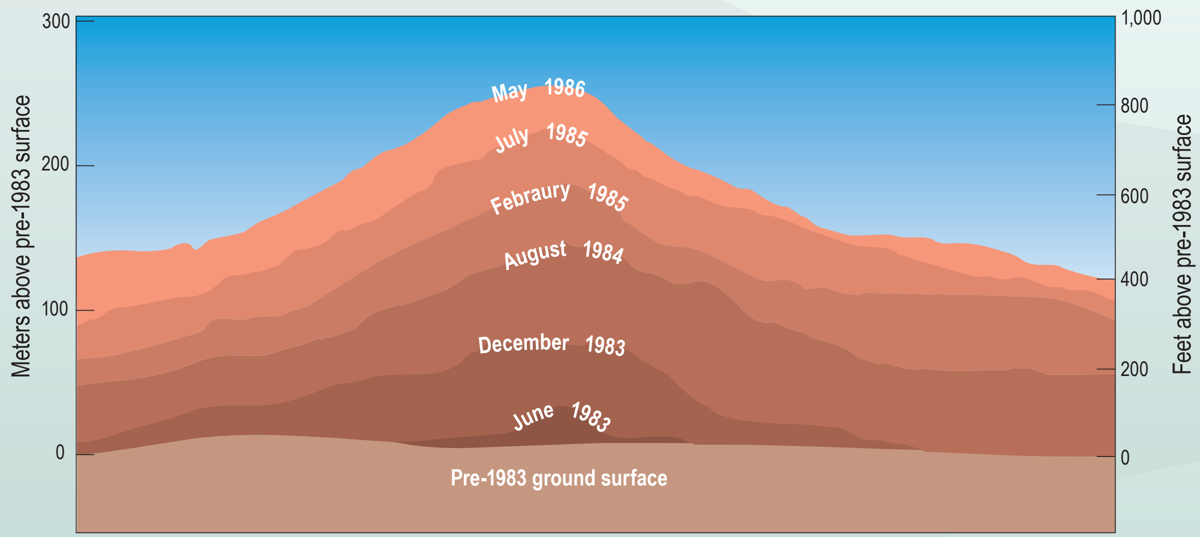
Aerial view of some scarps of the Hilina Fault System, expressed as sharp cliffs on the south flank of Kīlauea. Photograph by Donald A. Swanson, U.S. Geological Survey.

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-tall (121-meter-tall) mound at Maunaulu (Hawaiian for "growing mountain") and, abutting it, a more irregular shield, 320 feet (100 meters) tall, over the site of the buried ʻAlae Crater. Another lava pond and 180-foot-tall (55-meter-tall) shield developed during the 4.5 years (July 1986–February 1992) when the Kupaianaha vent was active.

The tallest volcanic landform constructed in the Hawaiian Islands during the past two centuries is the cinder-and-spatter cone built by eruptions at the Puʻuʻōʻō vent during 1983–86. By mid-July 1986, it had grown to its maximum height of about 833 feet (254 meters) 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 300 feet (90 meters). The most prominent landform built during the 2018 eruptions was the 180-foot-tall (55-meter-tall) spatter cone formed at fissure 8.

Puʻuʻōʻō cone is one of the most recently created prominent landforms in the United States; it began to grow in January 1983 and attained its maximum size in July 1986. This image was taken about a month later, on August 19, 1986. Photograph by J.D. Griggs, U.S. Geological Survey.

Growth profiles of Puʻuʻōʻō cone on Kīlauea's middle East Rift Zone, during the first 3 years of the Puʻuʻōʻō eruption.



The Puʻuʻōʻō cone in June 1992; a flank-vent eruption that began on Puʻuʻōʻō's west slope in February 1992 built a new lava shield against the cone and, within 4 months, the lava shield (middle ground) had become well developed. Photograph by Tari Mattox, U.S. Geological Survey.

Same view of Puʻuʻōʻō 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. Photograph by Christina Heliker, U.S. Geological Survey.

The 1983–2018 Puʻuʻōʻō eruption of Kīlauea also produced 440 acres (178 hectares) of new land along the south coast of the Island of Hawaiʻi. The much shorter 2018 lower East Rift Zone eruption created even more new land—875 acres (354 hectares) erupted over 3 months. 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. Sustained flows of lava form a smooth veneer on top of the rubble. Over time this pile of loose debris and capping flows enlarges and extends the shoreline seaward to form a *lava delta*—analogous to sediment deposits forming deltas at the mouths of large rivers. Although lava deltas appear to be solid, they in fact are highly unstable, because they are constructed on 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 1983–2018 eruptions at Kīlauea have provided unparalleled opportunities to study the evolution of lava deltas, the largest of which to date was constructed at the East Laeʻapuki ocean

A scientist looks at a large block of solidified lava that was hurled more than 50 feet (15 meters) inland during a littoral explosion triggered by collapse of an active lava delta in 1989. Photograph by Christina Heliker, U.S. Geological Survey.

Aerial view in November 1992 of a lava delta, only 4 days old, formed at Kamoamoa Bay as flows from Puʻuʻōʻō entered the sea, producing steam clouds and extending the shoreline 600 feet (183 meters) seaward. A much larger delta was active at East Laeʻapuki in 2005–07. Photograph by Christina Heliker, U.S. Geological Survey.

lava entry during 2005–07. This delta grew to about 34 acres (13.8 hectares) in area by mid-November 2005 before suddenly collapsing on November 28 in the largest delta failure observed to date. A time-lapse camera onshore captured the piecemeal collapse, which removed the entire delta as well as 10 acres (4 hectares) 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 (26 hectares) in area (48 football fields!). Over the next 3 years, this huge lava delta was entirely removed by a series of large collapses.

View the lava delta collapse here.

Collapses involving lava deltas can trigger strong steam-blast explosions that hurl lava and large rock fragments more than 300 feet (90 meters) inland and send waves of scalding water onshore, thereby posing serious hazards to observers who are too close to lava entering the ocean. In 1993, a photographer standing on a lava delta was swept out to sea and lost when it collapsed suddenly. In recent decades, several other too-close observers have suffered injuries or death from incidents related to such collapses.

Aerial view (on December 2, 2005) of the newly exposed sea cliff at the ocean lava entry at East Lae‘apuki, 4 days after the major collapse of the actively growing lava delta at the site. Photograph by James Kauahikaua, U.S. Geological Survey.

With continued lava entry into the ocean, by late-April 2006 the East Lae‘apuki lava delta had grown back to more than its pre-collapse size. By mid-2007, the delta reached its maximum size to become the largest one observed to date. Photograph by Tim Orr, U.S. Geological Survey.

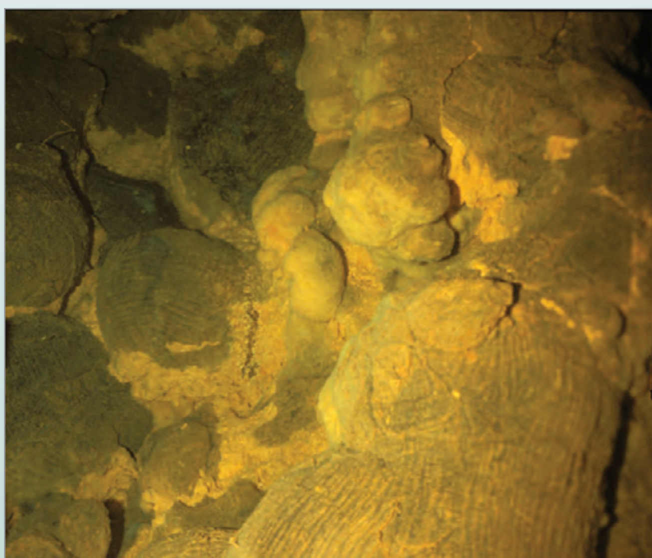
Kamaʻehuakanaloa—The Newest Hawaiian Volcano

If the hot-spot theory is correct, the next volcano in the Hawaiian Islands chain should form southeast of the Island of Hawaiʻi. Indeed, such a new volcano exists at Kamaʻehuakanaloa (formerly called Lōʻihi), a seamount (or submarine peak) located about 20 miles (32 kilometers) off the south coast. Kamaʻehuakanaloa rises 10,100 feet (3,078 meters) above the ocean floor but is still 3,110 feet (949 meters) below the water surface. Recent detailed mapping shows Kamaʻehuakanaloa to be similar in form to Kīlauea and Mauna Loa. Its relatively flat summit apparently contains a caldera about 3 miles (4.8 kilometers) across; two distinct ridges radiating from the summit are probably rift zones.

Photographs taken by deep-sea cameras show that the summit area of Kamaʻehuakanaloa has fresh-appearing, coherent pillow-lava flows and talus blocks. Pillow-lava fragments dredged from Kamaʻehuakanaloa have fresh glassy crusts, indicative of their recent formation. The exact ages of the sampled Kamaʻehuakanaloa 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 Kamaʻehuakanaloa during 1971–72, 1975, 1984–85, 1990–91, 1996, and 2020, suggesting major submarine eruptions or magma intrusions into the upper part of the volcano. The July–August 1996 swarm was by far the most energetic seismic activity at Kamaʻehuakanaloa 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 the Island of Hawaiʻi's Kaʻū District.

The crewed research submarine Pisces V of the Hawaiʻi Undersea Research Lab (HURL) of the University of Hawaiʻi, Mānoa, is launched by its mother ship research vessel Kaʻimikai-O-Kanaloa. Photograph by HURL; used with permission.

A closeup view of the Pisces V research submarine. Photograph by the Hawaiʻi Undersea Research Laboratory at the University of Hawaiʻi, Mānoa; used with permission.



The flank of Kamaʻehuakanaloa, showing broken pillow lava of a fresh flow, as seen from about 6 feet (2 meters) above the volcano's surface at a water depth of about 4,200 feet (1,280 meters). Photograph courtesy of the Hawaiʻi Undersea Research Laboratory at the University of Hawaiʻi; used with permission.

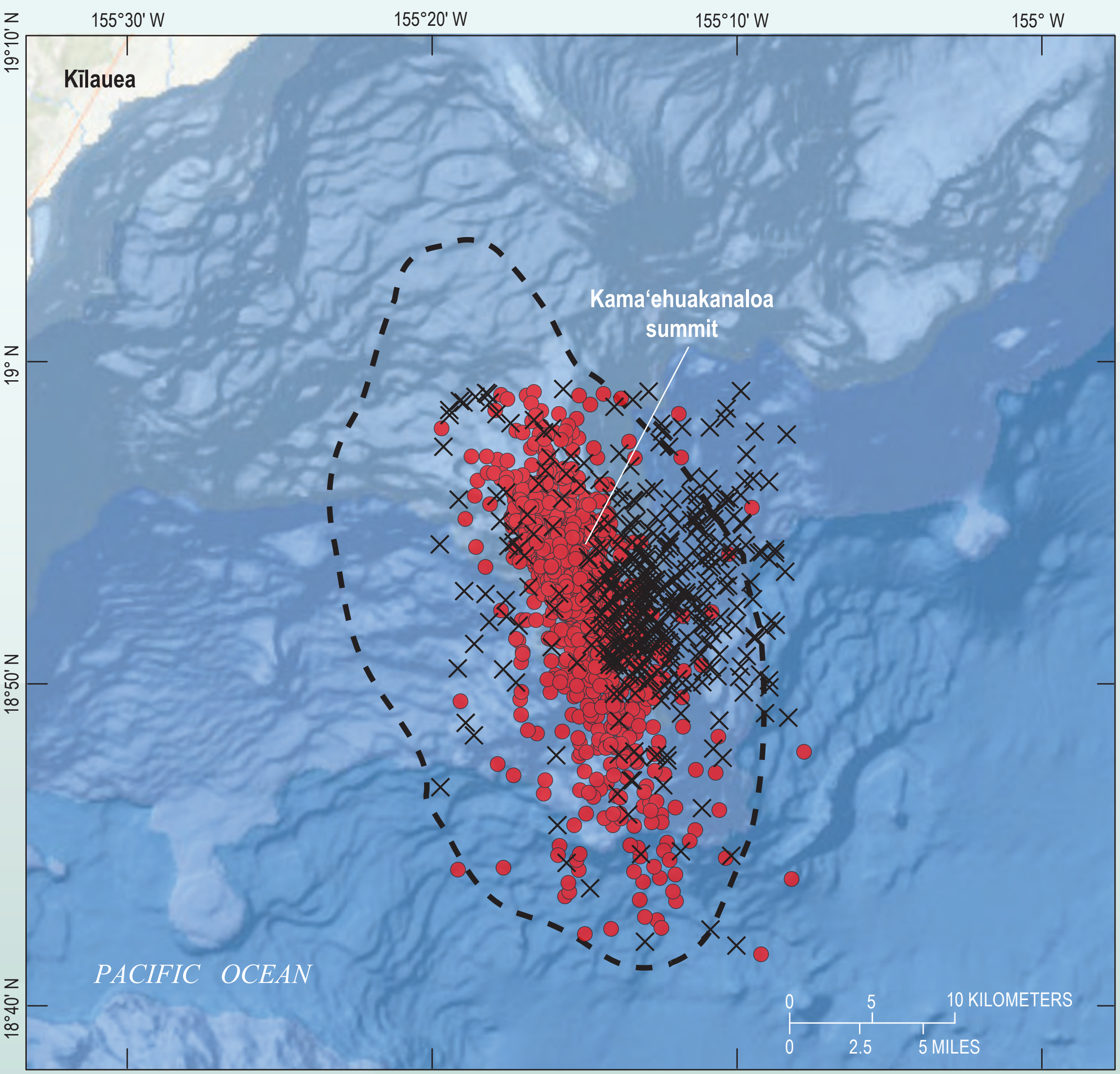
The Shinkai 6500 of the Japan Agency for Marine Science and Technology (JAMSTEC) is one of the world's deepest crewed research submersible, capable of operating at ocean depths down to 3.7 miles (6 kilometers). It was used in 1999 by Japanese and U.S. scientists to study Kamaʻehuakanaloa. Copyrighted by JAMSTEC; used with permission.

The intense 1996 earthquake activity at Kama‘ehuakanaloa launched two rapid-response expeditions in August–September 1996 by University of Hawai‘i scientists to conduct onsite observations of the activity. This included surface-ship bathymetric surveys and a series of crewed-submersible dives to make closeup observations and collect lava samples. These rapid-response and follow-up studies indicated that part of Kama‘ehuakanaloa’s summit had collapsed to form a new pit crater, called Pele’s Pit, about 341 feet (549 meters) across and 170 feet (274 meters) deep.

Within this new crater, scientists observed several new hydrothermal vents issuing the hottest waters ever measured at Kama‘ehuakanaloa (about 199 °C or 390 °F). Also, the observations showed the deposition of large quantities of glassy sand and gravel that could have formed by explosions. Though not conclusive, dating of two samples of young lava flows by an experimental isotopic technique has been interpreted by some scientists to suggest that at least one eruption, and possibly two, slightly preceded the 1996 earthquake swarm. Thus, from the periodic earthquake swarms and associated changes in structure, Kama‘ehuakanaloa appears to be a dynamic, actively growing, but still submarine, volcano.

Seismic data also indicate that the deepest earthquakes beneath Kama‘ehuakanaloa merge with the deep earthquakes beneath neighboring Kīlauea. This downward convergence implies that Kama‘ehuakanaloa, Kīlauea, and Mauna Loa all tap the same deep magma supply, and recent work suggests that they are connected by a complex of sills (nearly horizontal tabular bodies of magma) 19–25 miles (30–40 kilometers) beneath the surface. The triangular zone defined by the summits of these three active volcanoes perhaps overlies the postulated Hawaiian Hot Spot.

Studies of Kama‘ehuakanaloa provide a unique opportunity to decipher the youthful submarine stage in the formation and evolution of Hawaiian volcanoes. Scientists wonder if, and when, the still-growing Kama‘ehuakanaloa will emerge above the surface of the Pacific Ocean to become the newest Hawaiian volcano island and later expand the southern coast of the Island of Hawai‘i. It will almost certainly take several tens of thousands of years, if the growth rate for Kama‘ehuakanaloa is comparable to that of other Hawaiian volcanoes (about 1 inch or 3 centimeters per year averaged over geologic time). It is also possible that Kama‘ehuakanaloa will never emerge above sea level and that the next link in the island chain has not yet begun to form.



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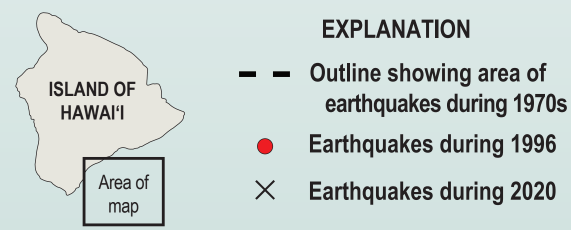


Map showing the locations of earthquakes that occurred during the 1970s, in 1996, and in 2020 in the vicinity of Kama‘ehuakanaloa. These earthquake swarms, plus similar occurrences in 1984–85 and the early 1990s, provide seismic evidence that Kama‘ehuakanaloa is an active submarine volcano.

Volcanic Hazards and Benefits

In the short term—on human timescales—some Hawaiian eruptions can be extremely destructive, causing major disruptions in the daily lives of the people affected by them. On a geologic timescale (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, and exploitable volcanic (geothermal) energy.

Hazards and Risks

Worldwide, about 300,000 people have been killed directly or indirectly by volcanic activity during the past 500 years. Nearly all 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 the glacier-capped Nevado del Ruiz volcano, Colombia, buried the town of Armero and killed about 25,000 people. In contrast,

Houses and agricultural plots are covered by advancing lava, erupted from fissures 16–20, during Kīlauea’s 2018 lower East Rift Zone eruption. Photograph by Elise Rumpf, U.S. Geological Survey.

Image from DigitalGlobe, copyright 2014

Image from Planet Labs, Inc., copyright 2018

Satellite images of Kapoho Crater and Kapoho Bay before and after the 2018 lower East Rift Zone eruption of Kīlauea.

fewer than 1,000 people have been killed directly by eruptions during the written history of the Hawaiian Islands, and only a very small handful of these since the beginning of the 20th century. As discussed in the "Explosive Eruptions" section (p. 35), a few hundred fatalities were caused by a deadly pyroclastic surge during Kīlauea's explosive summit eruption in 1790.

Although gentle Hawaiian eruptions generally pose little danger to people, flowing lava 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 1983–2018 Puʻuʻōʻō eruption buried a total of 215 buildings, including several residential areas in addition to Kalapana and the Wahaʻula Visitor Center in Hawaiʻi Volcanoes National Park. The effects of Hawaiian volcanic hazards are epitomized by Kīlauea's lower East Rift Zone eruption and associated summit collapses in 2018, during which lava destroyed 716 structures and covered about 30 miles (48 kilometers) of road. In addition, the associated summit collapse in 2018 forced the closure of Hawaiʻi Volcanoes National Park and the abandonment of HVO's buildings on Uēkahuna bluff.

Aerial view of a lava flow from Puʻuʻōʻō, on Kīlauea's middle East Rift Zone, encroaching on Pāhoa Village Road (lower right corner) in 2014. This lava flow stalled before crossing the road. Photograph by Kyle Anderson, U.S. Geological Survey.

Lava flows from the 2018 eruption of Kīlauea's lower East Rift Zone cross Kaupili Street in Leilani Estates, burying the road and igniting power poles and lines. Photograph by Matthew Patrick, U.S. Geological Survey.

Parts of Hilo, the largest city on the Island of Hawaiʻi, with a population of over 45,000, are built on 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 (26 kilometers) 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 3.7 miles (6 kilometers) short of the city's outskirts.

Lava flows from Puʻuʻōʻō ignite the Wahaʻula Visitor Center, Hawaiʻi Volcanoes National Park, in June 1989. Photograph by J.D. Griggs, U.S. Geological Survey.

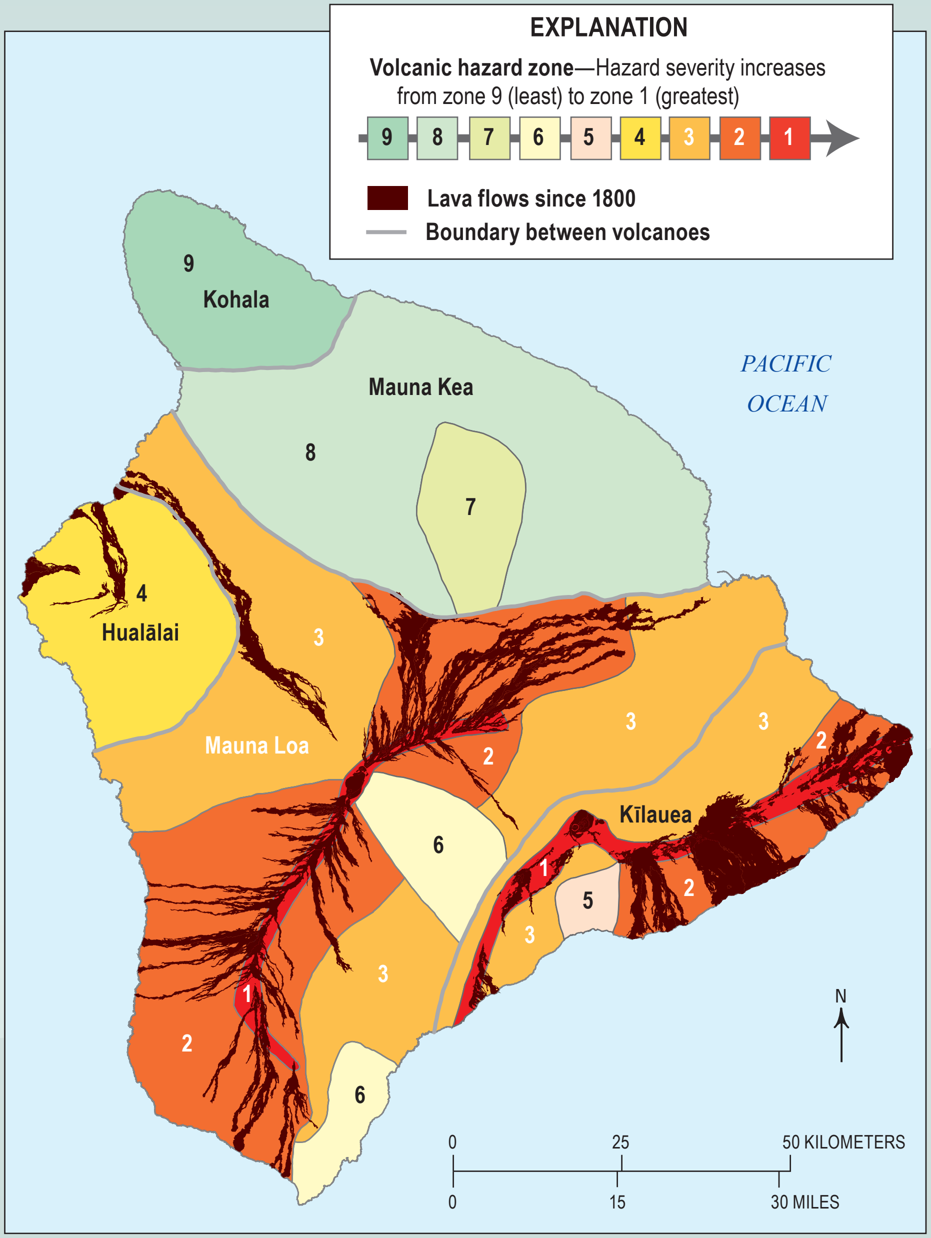
Night view of the lava flows of the 1984 Mauna Loa eruption, with the lights of downtown Hilo in foreground. Photograph by David Little, U.S. Geological Survey.

During a volcanic crisis, when an eruption and associated seismicity pose a potential or ongoing threat to people and populated areas, HVO plays a pivotal role in meeting the U.S. Geological Survey's congressionally mandated responsibility to provide timely warnings of volcanic disasters. Accordingly, because of the frequent Kīlauea and Mauna Loa eruptions, HVO conducts 24/7 monitoring to detect early signs of impending eruptions and to effectively communicate hazards information to Federal and local government agencies tasked with emergency management and to the public. For example, during 2014–15, advancing lava flows from Puʻuʻōʻō encroached on populated areas of Pāhoa town and Highway 130, posing a major threat to thousands of people. This dire situation lasted for several months and required HVO scientists to work nearly around-the-clock to provide up-to-date information—via news releases, daily volcano updates, partner-agency briefings, community meetings, website posts, and so on—regarding the rate of flow advance, the specific areas most likely to be affected, and other hazards-related questions. Most effective of the various communication means utilized, however, were several public meetings organized by the Hawaii County Mayor's Office and led by the Administrator of Hawaii County Civil Defense Agency. These well-attended meetings during the 2014–15 Pāhoa lava-flow crisis provided abundant opportunities for HVO scientists to interact directly with affected residents, business owners, and other stakeholders and address their concerns as the crisis progressed. Luckily, direct effects of advancing lava flows ultimately proved to be limited, and only one home was lost. A positive side benefit of these public meetings was that both the Hawaii County government officials and the HVO staff earned credibility with, and trust of, the affected populace throughout the crisis. Moreover, HVO's effective response to the Pāhoa crisis afforded invaluable experience that later was put to good use during the more destructive 2018 Kīlauea eruption and the 2022 eruption of Mauna Loa, by providing a blueprint of how to communicate public information.

Infrequent explosive eruptions also can pose a potential hazard to people present in the area of tephra fallout. Nearly all of the eruption-related fatalities in the Hawaiian Islands since the year 1790 were caused by explosive activity. In 2008, small explosions in Halemaʻumaʻu hurled blocks weighing more than 90 kilograms onto a visitor overlook, which, fortunately, had been closed by Hawaiʻi Volcanoes National Park officials several weeks earlier. An explosive eruption is an example of a low-frequency but high-hazard volcanic event.

It is useful to distinguish between the terms *hazard* and *risk*. Evaluation of volcanic hazards is based on geologic information only and considers the likelihood of destructive volcanic processes and products in a given area. Assessment of volcanic risks evaluates the likelihood of loss of life and property in the given area. A hazard creates a risk, and the risk of the same hazard can change depending on how vulnerable the threatened population and its infrastructure might be. Thus, volcanic "risk" increases as land zones defined as hazardous become cultivated, populated, or otherwise developed. Even areas where the severity of volcanic hazards is low 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 to planning for long-term land use, estimating socioeconomic and political impacts of eruptions, and preparing contingency plans in case of volcanic emergencies.

Community meetings in 2014 were well-attended and an effective means of sharing the latest hazards information with the public as lava flows from Puʻuʻōʻō encroached on Pāhoa town and Highway 130. Photograph by Steven Brantley, U.S. Geological Survey.



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

A key component in reducing volcanic risk 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. A lava-flow hazards map has been prepared for the Island of Hawai‘i in which areas of relative severity of lava-flow hazards are designated with numerals 1 (most hazardous) through 9 (least hazardous). 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 eruptions are 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 may 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 extremely 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 15 gigantic landslides, covering many hundreds of square miles (hundreds of square kilometers). Similar 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 feet (300 meters) 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 Mauna Loa have been recognized, but their precise geologic ages are not well known. It is important to study giant submarine landslides in the Hawaiian Islands, despite their infrequency, because the devastating potential hazards they pose could cause enormous loss of life, property, and resources. However, monitoring of measurable flank movements of Hawaiian volcanoes by the Hawaiian Volcano Observatory may detect any sudden acceleration in movement, which may provide early warning for possible flank collapse.

Volcanic Air Pollution

Between mid-1986 and 2008, in addition to the erupted lava and its associated hazards, the continuous activity at Pu‘u‘ō‘ō also emitted on average about 2,000 metric tons of polluting sulfur dioxide gas (SO_2) per day. This emission rate is not trivial—it is considerably higher than that of the highest emitting coal-fired power plant in the United States. 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. Notably, 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 metric tons of CO_2 annually, whereas human activities worldwide produce some 32 billion metric tons of CO_2 each year—about 160 times more.

Nevertheless, Kīlauea's high and steady output of SO_2 poses a persistent natural hazard for State of Hawaii 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 volcanoes interact chemically with sunlight and atmospheric oxygen, moisture, and dust. Depending on wind patterns (primarily) and other atmospheric conditions, vog can drift hundreds of miles (hundreds of kilometers) or more from an 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, islands throughout the State of Hawaii.

In mid-2008, because of the new vent in Halema‘uma‘u, SO_2 emissions from Kīlauea's summit increased from about 150 metric tons per day to as much as 12,000 metric tons per day. During the summit lava-lake period from 2008–18, summit emissions were on average 4,500–5,000 metric tons per day, whereas the emission rate from Pu‘u‘ō‘ō dropped to a few hundred metric tons per day in 2010. Record-high SO_2 emissions were measured during Kīlauea's 2018 lower East Rift Zone eruption, during which an average of nearly 200,000 metric tons of SO_2 were emitted per day. The onset of recent eruptions within Halema‘uma‘u in 2020 and 2021 were associated with high SO_2 emissions of about 50,000–85,000 metric tons per day; in both eruptions, emissions decreased to hundreds or thousands of metric tons of SO_2 per day as lower levels of eruptive activity continued.

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. In addition, the Hawaii Interagency Vog Information Dashboard offers comprehensive information and data on vog and its effects, as well as vog and wind forecast maps, at https://vog.ivhhn.org.

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. The Ka‘ū Desert, near the summit of Kīlauea, lacks much vegetation because rain that falls there contains sulfuric acid supplied by Halema‘uma‘u, a classic example of an acid-rain desert.

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 effects of these highly acidic coastal plumes—sometimes called *laze* (abbreviated from "lava haze")—are typically limited to within a few miles (several kilometers) downwind of their source. Thus, laze mainly poses a hazard to people who visit or live near sites where lava is actively entering the 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.

A side-by-side comparison of the northwest wall of Kīlauea caldera on a clear day (left) and a day with thick vog (right). The former U.S. Geological Survey Hawaiian Volcano Observatory can be seen near the center in each photo. Photographs by U.S. Geological Survey.

Visit the U.S. Geological Survey Hawaiian Volcano Observatory's website at https://www.usgs.gov/observatories/hvo/hazards for links to vog studies

Volcanic Benefits

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. The majestic volcanic mountains, beautiful beaches, and pleasant climate combine to make the Hawaiian 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-tall (3,055-meter-tall) Haleakalā, 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. Hawai‘i Volcanoes National 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. 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 the beautiful islands.

Given enough rainfall, areas buried by new lava recover quickly; revegetation can begin less than 1 year after an 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. Lava from Kīlauea’s 2018 eruption damaged several production wells, forcing the plant to shut down temporarily. Power production was restored in November 2020, and, as of 2022, about 30 megawatts of electricity were being produced and fed into the grid of the local utility company.

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. Photograph by Taeko Jane Takahashi, U.S. Geological Survey.

Aerial view of some of the power-generating equipment at the only commercial producer of geothermal energy in the State of Hawaii. Photograph by Rick Hazlett, U.S. Geological Survey.

Lava encroached on the geothermal plant in lower Puna District during Kīlauea’s lower East Rift Zone eruption in 2018, damaging some production wells. This image shows channelized lava flows originating from the 2018 lower East Rift Zone fissures; green geothermal plant structures are visible nearby (right, center). Photograph by Matthew Patrick, U.S. Geological Survey.

Pressure testing in 1976 of a geothermal well drilled into Kīlauea’s lower East Rift Zone. A power plant later constructed in this area has the capacity to produce almost 40 megawatts of electricity, nearly 30 percent of the Island of Hawai‘i’s needs. Photograph courtesy of the Hawai‘i Geothermal Project; used with permission.

Benefits of Research at the U.S. Geological Survey Hawaiian Volcano Observatory

The Hawaiian Islands are 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 effect 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 U.S. Geological Survey 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. This is achieved by careful monitoring of Hawaiian volcanoes and continuing research to better understand them.

In addition, the high eruption frequency of its volcanoes and the availability of state-of-the-art research facilities at HVO combine to make the Island of Hawaiʻi an excellent training ground for volcanologists from around the world. A cooperative agreement with the University of Hawaiʻi allows the Center for the Study of Active Volcanoes to offer a training program for volcano scientists and technicians from other countries. With funding from the Volcano Disaster Assistance Program (a partnership of the U.S. Geological Survey and the U.S. Agency for International Development), course participants travel first to the Island of Hawaiʻi, where they receive training at HVO by U.S. Geological Survey and University of Hawaiʻi staff, followed by travel to the Pacific Northwest, where they receive training at the Cascades Volcano Observatory by U.S. Geological Survey staff. HVO and other scientists strive to improve volcano-monitoring and eruption-forecasting techniques to reduce the risks associated with eruptions of active volcanoes in the State of Hawaii 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 Pacific Northwest Seismic Network, headquartered at the University of Washington-Seattle); California Volcano Observatory (monitoring volcanoes in California and Nevada); and Yellowstone Volcano Observatory (which, in cooperation with eight other organizations, monitors Wyoming’s Yellowstone Plateau volcanic field and its caldera, and other volcanic activity in Wyoming, Montana, Idaho, Colorado, Utah, New Mexico, and Arizona).

Some of the many thousands of visitors who safely observed the slow advance of pāhoehoe lava erupted from Kīlauea’s East Rift Zone in 2016. Photograph by Janet Babb, U.S. Geological Survey.

Hawaiʻi Volcanoes National Park visitors safely watch spectacular lava-lake activity during the 2022 eruption within Halemaʻumaʻu at Kīlauea’s summit. Photograph by Janice Wei, National Park Service.

Selected Readings

In addition to references cited in this report, 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 online.

Babb, J.L., Kauahikaua, J.P., and Tilling, R.I., 2011, The story of the Hawaiian Volcano Observatory—A remarkable first 100 years of tracking eruptions and earthquakes: U.S. Geological Survey General Information Product 135, 62 p., https://doi.org/10.3133/gip135. [A summary of the history of the Hawaiian Volcano Observatory.]

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Wolfe, E.W., and Morris, J., 1996a, Geologic map of the Island of Hawai‘i (reprinted 2009): U.S. Geological Survey Miscellaneous Investigations Series Map I–2524–A, 3 sheets, scale 1:100,000, https://doi.org/10.3133/i2524A. [These maps summarize a half-century of new geological knowledge gained since the classic geologic map of the island published by Stearns and Macdonald (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).]

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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 Hawaii, from the earliest observations to modern scientific studies.]

Selected Videos and DVDs

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 online videos, web-camera images, or DVDs of Hawaiian eruptions, some of which are listed here. Some school and public libraries might have them in their collections, and some are available online.

Kīlauea summit eruption—Lava returns to Halema‘uma‘u: U.S. Geological Survey General Information Product 182. [The video briefly recounts the eruptive history of Halema‘uma‘u and describes the formation and continued growth of the summit vent and lava lake that was active from 2008 to 2018; available to view online at https://doi.org/10.3133/gip182.]

Eruption of Kīlauea, 1959–60: U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025. [Originally an award-winning video jointly produced (in 1961) by the U.S. Geological Survey and the National Park Service that contains spectacular footage of the highest lava fountains ever recorded in the State of Hawaii and of the formation of Kīlauea Iki lava lake. This classic film has been beautifully restored by Michael M. Moore (U.S. Geological Survey Library, Menlo Park) and is now available as a 28-minute video that can be accessed online at https://www.youtube.com/watch?v=gGPC77Wvd70.]

Fire Under the Sea—The Origin of Pillow Lava: Moonlight Productions, 73-1132 Ahikawa Street Kailua-Kona, Hawaii 96740. [Originally a 20-minute video 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 1969–74 Maunaulu eruptions of Kīlauea. A 10-minute excerpt from this classic original film can be viewed 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 U.S. Geological Survey and the Smithsonian Institution showing the geologic settings and structures of Hawaiian volcanoes and the methods used to monitor volcanic behavior.]

Selected Websites

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

https://www.usgs.gov/observatories/hvo
[Maintained by the U.S. Geological Survey Hawaiian Volcano Observatory (HVO), this site provides the most comprehensive and authoritative online information about the volcanoes and associated hazards in the State of Hawaii and how HVO scientists monitor them.]

https://www.usgs.gov/programs/VHP
[The official site of the U.S. Geological Survey 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 four other U.S. Geological Survey volcano observatories.]

- Alaska Volcano Observatory: https://avo.alaska.edu
- California Volcano Observatory: https://www.usgs.gov/observatories/calvo
- Cascades Volcano Observatory: https://www.usgs.gov/observatories/cvo
- Yellowstone Volcano Observatory: https://www.usgs.gov/observatories/yvo

https://volcanoes.usgs.gov/vsc/glossary
[Maintained by the U.S. Geological Survey Volcano Hazards Program, this site contains definitions for volcanology terms, many of which are illustrated with photographs.]

https://volcano.si.edu
[Maintained by the 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.]

https://volcanoes.sdsu.edu
[Maintained by San Diego State University and supported by the National Aeronautics and Space Administration as part of Project ALERT (Augmented Learning Environment and Renewable Teaching), this site—How Volcanoes Work—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.]

https://www.swisseduc.ch/stromboli
[Developed and maintained by Italian and Swiss volcanologists, this site provides abundant materials and useful 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 the State of Hawaii.]

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 U.S. Geological Survey Volcano Hazards Program Glossary website at https://volcanoes.usgs.gov/vsc/glossary.

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 several 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. All Hawaiian calderas were formed by withdrawal of magma from an underlying reservoir.

Crater A small (typically less than 1.0 mile or less than 1.6 kilometer diameter), approximately circular depression in the ground associated with volcanic activity, whether formed explosively or by collapse. Craters commonly are co-located with one or more active eruptive **vents**, but they also can simply form by collapse in response to draining of supporting underlying **magma**. A *pit crater* forms by collapse without explosion. The term *crater* also is applied to depressions of planetary surfaces produced by meteorite impacts.

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 commonly blocky **lava** extruded from a **vent**; typically has a rounded top, covers an approximately circular area, and is **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. It has lost much of the gas that magma contains below the surface.

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 but basaltic in the Hawaiian Islands. 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* for fire and *klastos* for broken).

Pyroclastic flow A hot (typically greater than 1,500 °F or greater than 800 °C), turbulent, ground-hugging mixture of rock fragments, gas, and **ash** that travels very rapidly (hundreds of miles per hour or hundreds of kilometers 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. Pyroclastic surges have erupted from Hawaiian volcanoes, but no pyroclastic flows have been recognized.

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 being less vesicular, denser, and usually andesitic or basaltic in composition.

Silica 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 SiO_2 content, is fairly fluid. 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, magmas with higher silica 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 32 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 **lapilli**).

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 amorphous (uncrystallized) product formed by the rapid cooling (quenching) of the liquid component of **magma**.

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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.

Sunrise view in August 2002 of lava from the Puʻuʻōʻō eruption cascading into the ocean and constructing a lava delta on the south coast of the Island of Hawaiʻi. Photograph by Donald A. Swanson, U.S. Geological Survey.

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