Department of the Interior / U.S. Geological Survey

Eruptions of Hawaiian Volcanoes:

Past, Present, and Future

Special thanks go to Taeko Jane Takahashi and J.D. Griggs, Hawaiian Volcano Observatory, for assistance with photography selection and to Martha Penman for graphics design.

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

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Past, Present, and Future

by
Robert I. Tilling
Christina Heliker and
Thomas L. Wright

Cover Photograph: Lava cascades fed by fountains at vent (skyline) fall more than 75 feet to fill Aloi Crater during the 1969-71 Mauna Ulu eruption of Kilauea Volcano. *(Photograph by 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 throughout the history of mankind. 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 can be viewed and studied with relative ease and safety.

In January 1987, the Hawaiian Volcano Observatory (HVO), located on the rim of Kilauea Volcano, celebrated its 75th Anniversary. In honor of HVO's Diamond Jubilee, the U.S. Geological Survey (USGS) published *Professional Paper 1350*, an up-to-date summary of the many studies on Hawaiian volcanism by the USGS and other scientists. Drawing from the wealth of data contained in that volume, this booklet focuses on selected aspects of the eruptive history, style, and products of two of Hawaii's active volcanoes, Kilauea and Mauna Loa.

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

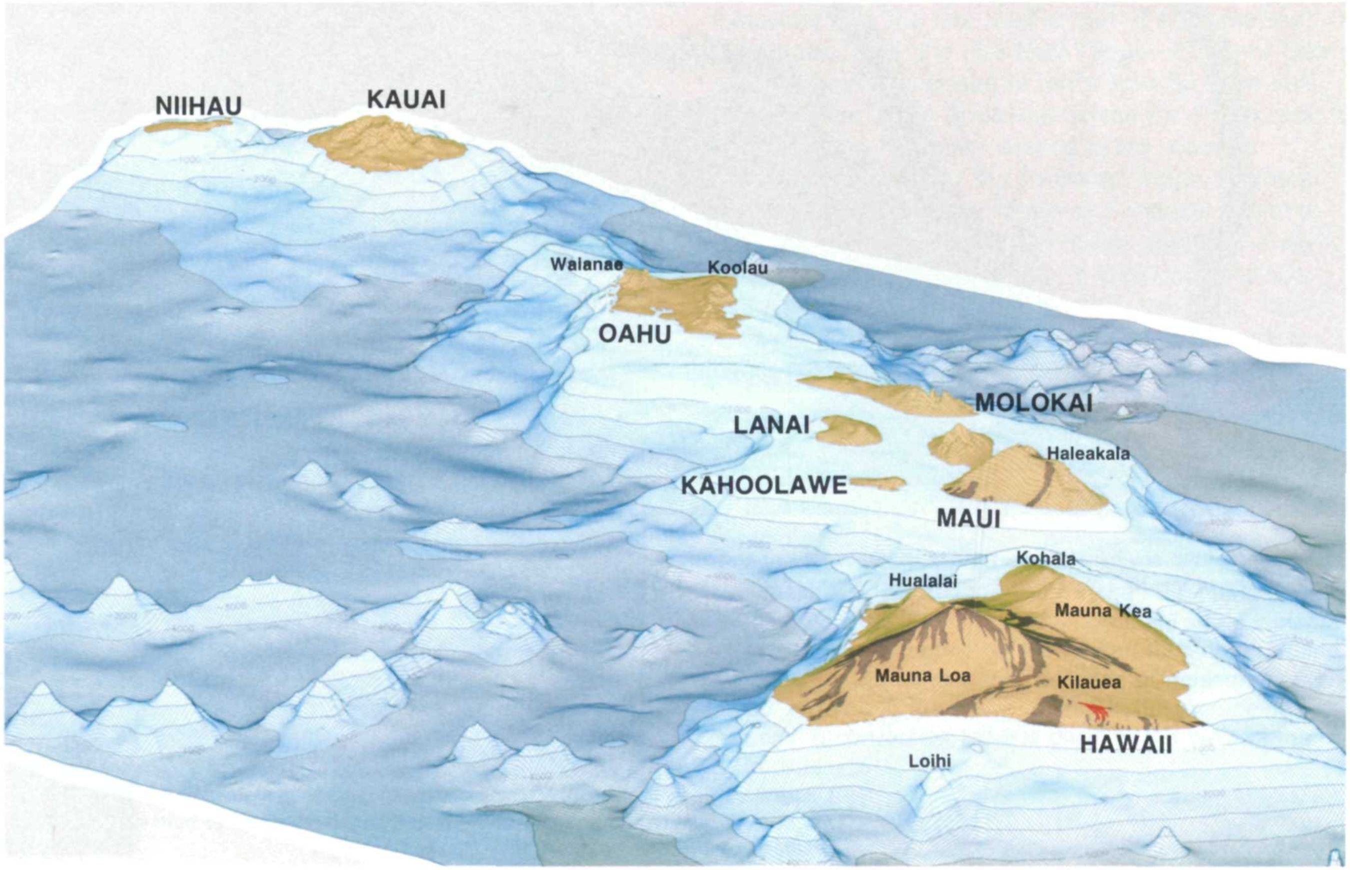
Lava shoots 1,000 feet into the air during a high-fountaining episode of the 1983-to-present Pu'u 'O'o eruption of Kilauea Volcano. *(Photograph by J.D. Griggs.)*

Introduction

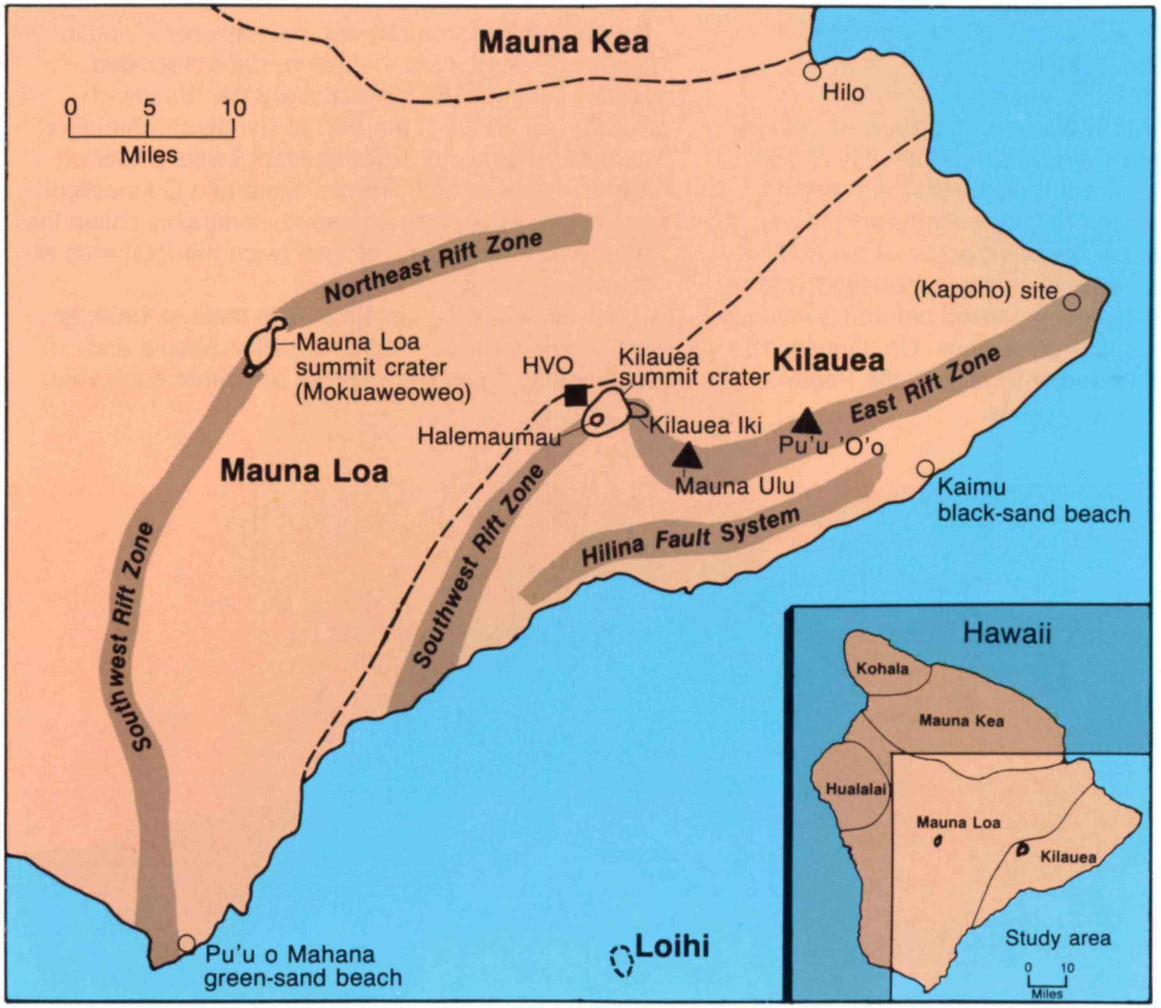
"The loveliest fleet of islands that lies anchored in any ocean." —Mark Twain

Few would quarrel with Mark Twain's vivid description of Hawaii, written after his 4-month stay in 1866. The Hawaiian Islands were discovered and settled around the 6th century A.D. by Polynesians sailing from islands, probably the Marquesas, in the southern tropical Pacific. Subsequently, a thousand years or more of cultural isolation passed before Hawaii was first visited by non-Polynesians. On January 18, 1778, during his third major voyage in the Pacific, the famous British navigator and explorer, Captain James Cook, sighted the Polynesians' secluded home. Cook named his discovery the "Sandwich Islands," in honor of the Earl of Sandwich, then First Lord of the British Admiralty. Mark Twain's fleet of islands is larger than Rhode Island and Connecticut combined. The island of Hawaii, commonly called the "Big Island," covers more than twice the total area of the other islands.

Hawaii, which became our 50th state in 1959, is now home for more than one million people and hosts many times that number of visitors each year.



The principal Hawaiian islands (all capital letters) are the exposed tops of volcanoes that rise tens of thousands of feet above the ocean floor. Some islands are made up of two or more volcanoes. Loihi Seamount, Hawaii's newest volcano, still lies about 3,100 feet beneath the sea. *(Modified by permission from a map published by Dynamic Graphics, Inc., Berkeley, California.)*



Sketch map of the southeastern part of the island of Hawaii and adjacent offshore, showing the principal features and localities of Mauna Loa, Kilauea, and Loihi Volcanoes discussed in the text.

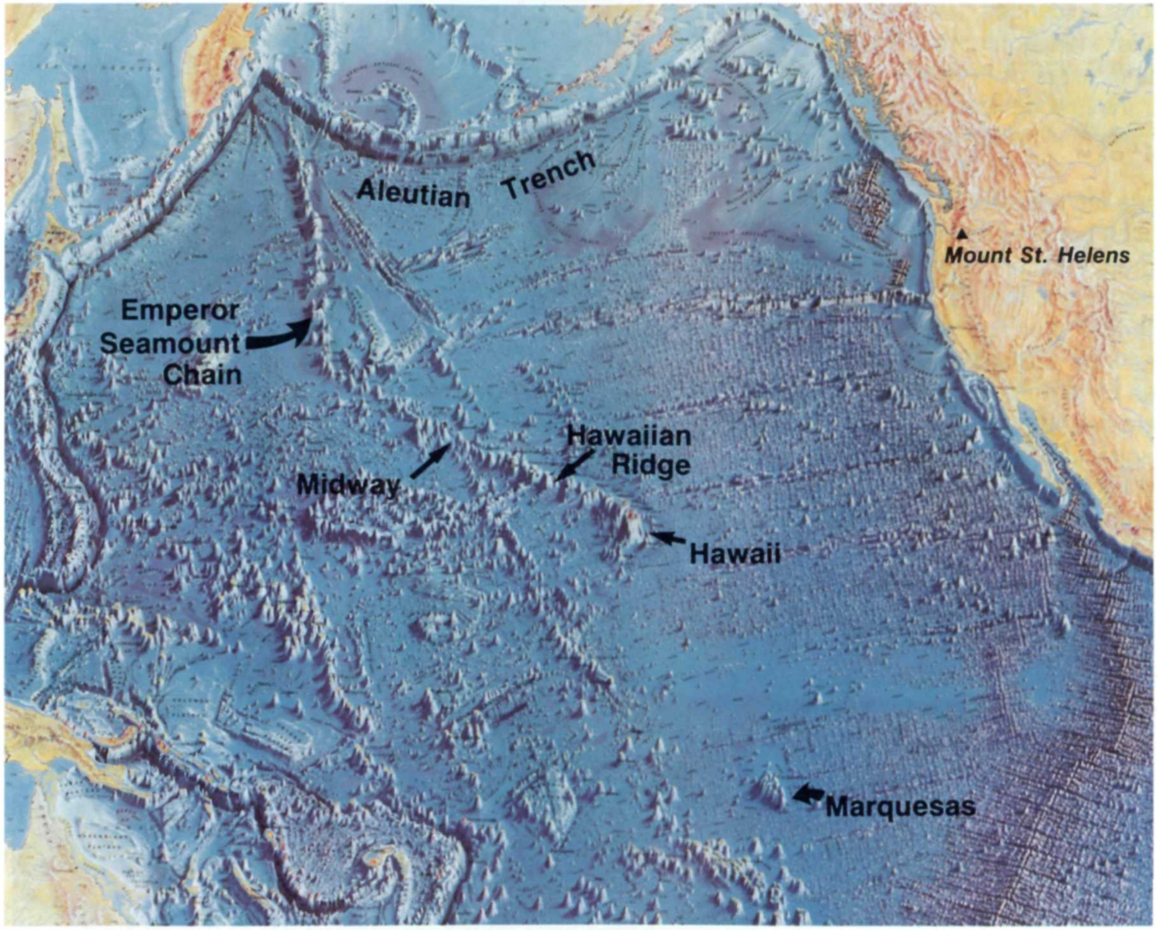
Hawaii's worldwide image as an idyllic tropical paradise is well deserved. What is less well-known, however, is that the islands exist only because of nearly continuous volcanic activity. All of the prominent features of the Hawaiian Islands, such as Diamond Head on Oahu, Haleakala Crater on Maui, and the huge masses of Mauna Loa and Mauna Kea on the Big Island, are volcanic.

Since the beginning of a historical record early in the 19th century, eruptions have occurred frequently at Mauna Loa and Kilauea; these two volcanoes on the Big Island are among the most active in the world. Nearby Loihi Seamount, off the Big Island's south coast, is the newest Hawaiian volcano, not yet visible above the ocean surface.

Most eruptions of Mauna Loa and Kilauea are nonexplosive, and both volcanoes are readily accessible; scientists 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. Hawaii serves as a superb natural laboratory for the study of volcanic eruptions.

Liliuokalani Park, in the city of Hilo on the Big Island, typifies the tropical beauty and serenity of the Hawaiian Islands. *(Photograph by John Penisten, Hilo, Hawaii.)*

Origin of the Hawaiian Islands



Map of the Pacific basin showing the location of the Hawaiian Ridge-Emperor Seamount Chain in relation to some other features and localities mentioned in the text. *(Base map reprinted by permission from World Ocean Floor Panorama by Bruce C. Heezen and Marie Tharp, Copyright 1977.)*

The Hawaiian Islands are the tops of gigantic volcanic mountains formed by countless eruptions of fluid *lava*[1] over several million years; some tower more than 30,000 feet above the sea floor.[2] These volcanic peaks rising above the ocean surface represent only the tiny, visible part of an immense submarine ridge, the Hawaiian Ridge—Emperor Seamount Chain, composed of more than 80 large volcanoes. This range stretches across the Pacific sea floor from the Hawaiian Islands to the Aleutian Trench. The length of the Hawaiian Ridge segment alone, between the Big Island and Midway Island to the northwest, is about 1,600 miles, roughly the distance from Washington, D.C., to Denver, Colorado. The amount of lava erupted to form this huge ridge, about 186,000 cubic miles, is more than enough to cover the State of California with a mile-thick layer.

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[1] Scientists use the term *lava* for molten rock (and contained gases) that breaks through the Earth's surface, and the term *magma* for the molten rock underground.

[2] The United States uses *English* units of measurements. For readers in the many countries that use *metric* units, a conversion table is given in the back of the booklet.

Hawaiian legends and early scientific work

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

Hawaiian legends tell that eruptions were caused by Pele, the beautiful but tempestuous Goddess of Volcanoes, during her frequent moments of anger. Pele was both revered and feared; her immense power and many adventures figured prominently in ancient Hawaiian songs and chants. She could cause earthquakes by stamping her feet and volcanic eruptions and fiery devastation by digging with the *Pa'oa*, her magic stick. An oft-told legend describes the long and bitter quarrel between Pele and her older sister Namakaokahai that led to the creation of the chain of volcanoes that form the islands.

Pele first used her Pa'oa on Kauai, where she subsequently was attacked by Namakaokahai and left for dead. Recovering, she fled to Oahu, where she dug a number of "fire pits," including the crater we now call Diamond Head, the tourist's landmark of

Above: Pele, the Goddess of Volcanoes, as portrayed by artist D. Howard Hitchcock. *(Photograph by J.D. Griggs with permission of the Volcano House Hotel, owner of the original painting.)* *Below:* Night view (time exposure) of Pele's home during the 1967-68 eruption within Halemaumau Crater. *(Photograph by Richard S. Fiske.)*

modern Honolulu. Pele then left her mark on the island of Molokai before traveling further southeast to Maui and creating Haleakala Volcano, which forms the eastern half of that island. By then Namakaokahai realized that Pele was still alive and went to Maui to do battle with her. After a terrific fight, Namakaokahai again believed that she had killed her younger sister, only to discover later, however, that Pele was very much alive and busily working at Mauna Loa Volcano on the island of Hawaii. Namakaokahai then conceded that she could never permanently crush her sister's indomitable spirit and gave up the struggle. Pele dug her final and eternal fire pit, Halemaumau Crater, at the summit of Kilauea Volcano, where she is said to reside to this day. The migration of volcanic activity from Kauai to Hawaii described by this Hawaiian legend is confirmed by modern scientific studies.

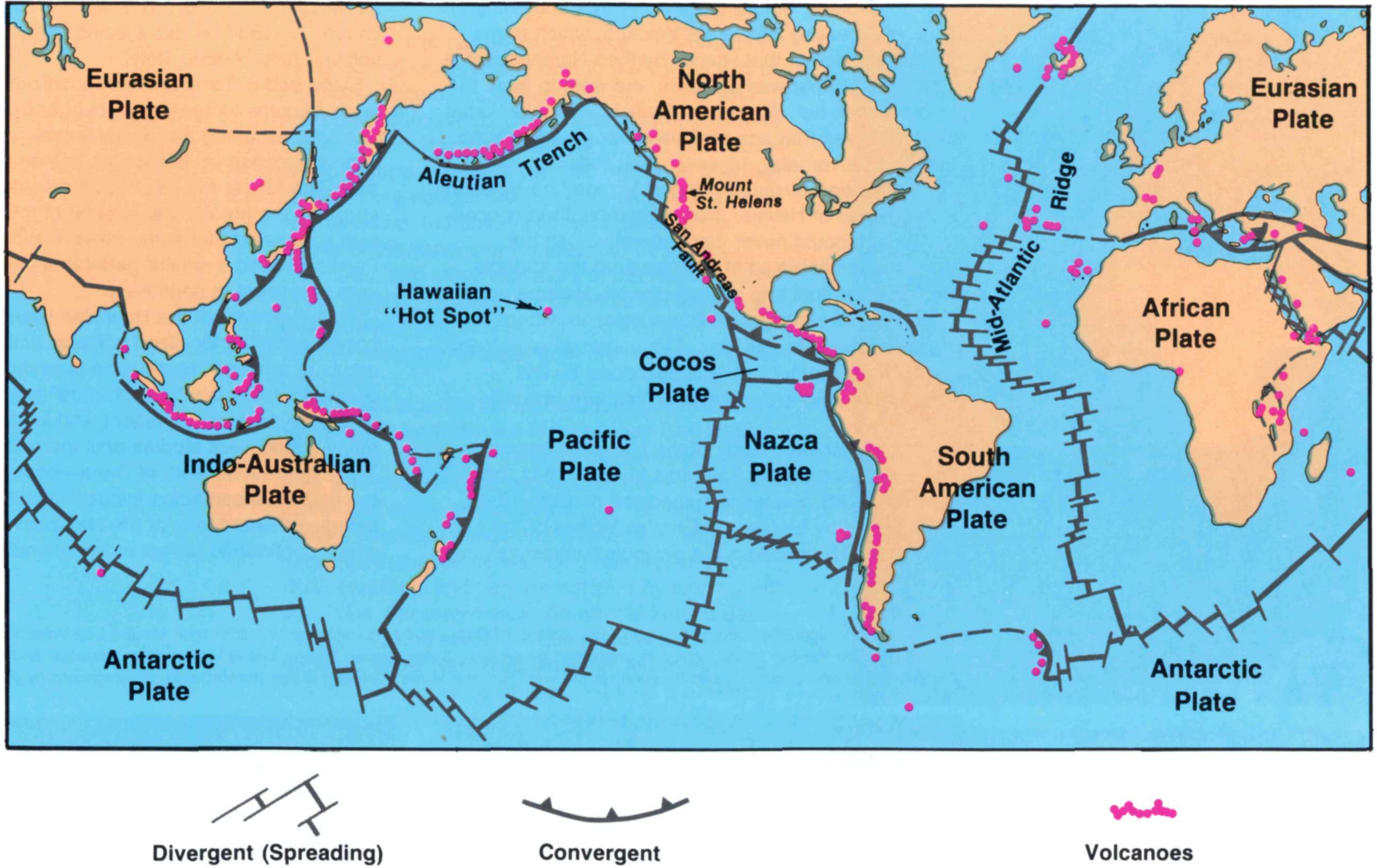
The first geologic study of the Hawaiian Islands was conducted during 6 months in 1840-1841, as part of the U.S. Exploring Expedition of 1838-1842, commanded by Lieutenant Charles Wilkes of the U.S. Navy. The expedition's geological investigations were directed by James Dwight Dana. Though only 25 years old in 1838, Dana was no stranger to volcanoes. In 1834 he had studied Vesuvius, the active volcano near Naples, Italy.

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

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

Deeply eroded Koolau Volcano (left photograph), island of Oahu, is 2 to 3 million years older than Mauna Loa Volcano (right photograph), on the Big Island, which is unscarred by erosion. Snow-capped Mauna Loa is viewed from the east, and the Hawaiian Volcano Observatory (circled) can be seen on the west rim of Kilauea's summit crater (foreground). *(Photographs by Richard S. Fiske.)*

Active volcanoes of the world



Most active volcanoes are located along or near the boundaries of the Earth's shifting tectonic plates. Hawaiian volcanoes, however, occur in the middle of the Pacific Plate. Not all of the Earth's more than 500 active volcanoes are shown.

Plate tectonics and the Hawaiian "Hot Spot"

In the early 1960's, the related concepts of "sea-floor 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-tectonics theory, the Earth's surface consists of about a dozen rigid slabs or *plates*, each averaging at least 50 miles thick. These plates move relative to one another at average speeds of a few inches per year—about as fast as human fingernails grow. Scientists recognize three common types of boundaries between these moving plates:

(1) *Divergent* or *spreading*—adjacent plates pull apart, such as at the Mid-Atlantic Ridge, which separates the North and South American Plates from the Eurasian and African Plates. This pulling apart causes "sea-floor spreading" as new material is added to the oceanic plates.

(2) *Convergent*—plates moving in opposite directions meet and one is dragged down (or *subducted*) beneath the other. Convergent plate boundaries are also called *subduction zones* and are typified by the Aleutian Trench, where the Pacific Plate is being subducted under the North American Plate.

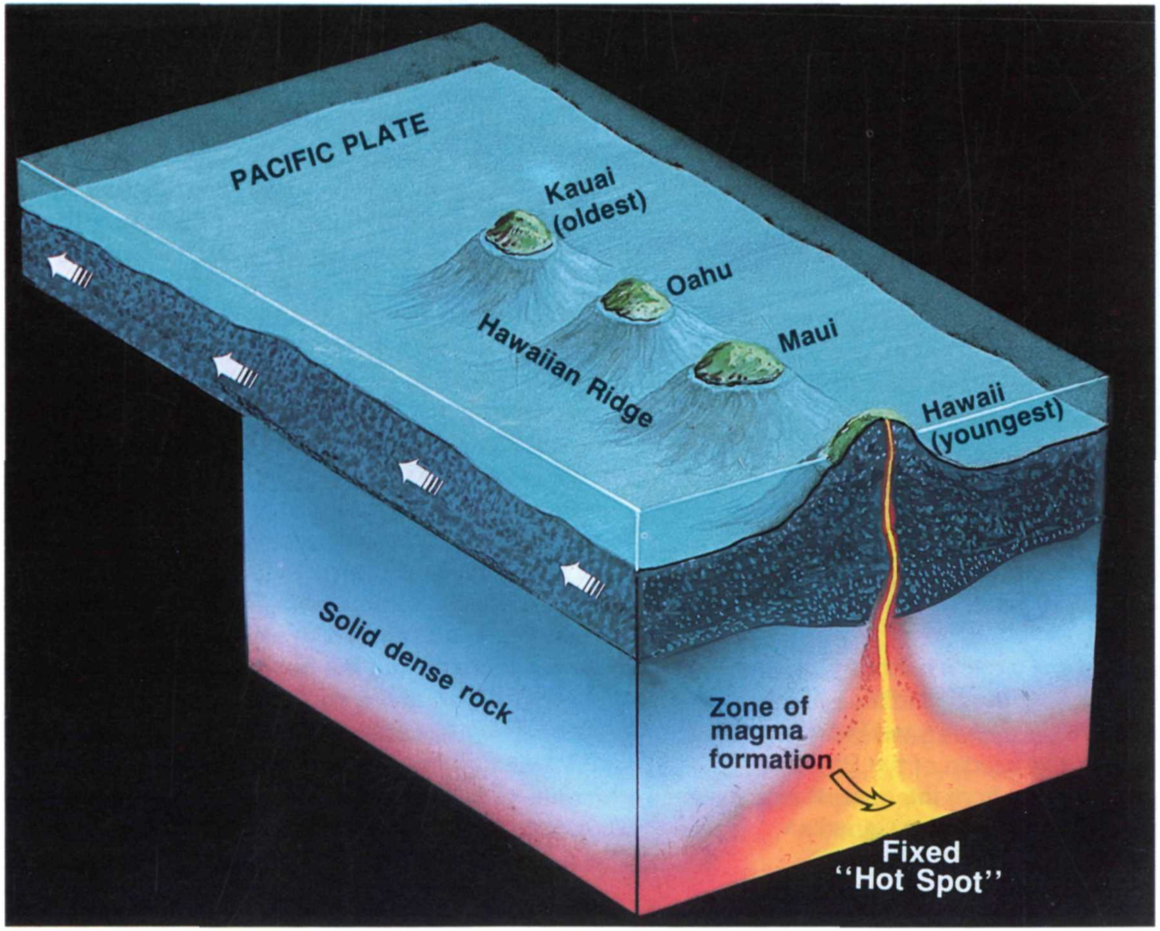
(3) *Transform fault*—one plate slides horizontally past another. The best known example is the earthquake-prone San Andreas fault zone of California, which marks the boundary between the Pacific and North American Plates.

The great majority of the world's earthquakes and active volcanoes occur near the boundaries of the Earth's shifting plates. Why then are the Hawaiian volcanoes located near the middle of the Pacific Plate, more than 2,000 miles from the nearest plate boundary? 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 the Pacific Ocean in general, and the Hawaiian Islands in particular.

According to Wilson, the distinctive linear shape of the Hawaiian-Emperor Chain reflects the progressive movement of the Pacific Plate over a deep immobile hot spot. This hot spot partly melts the region just below the overriding Pacific Plate, producing small, isolated blobs of magma. Less dense than the surrounding solid rock, the magma rises buoyantly through structurally weak zones and ultimately erupts as lava onto the ocean floor to form 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-Emperor Chain. Scientists interpret the sharp bend in the chain, about 2,200 miles northwest of the Big Island, as indicating a change in the direction of plate motion that occurred about 43 million years ago, as suggested by the ages of the volcanoes bracketing the bend.

Part of the Big Island, the southeasternmost and youngest island, presently overlies the hot spot and still taps the magma source to feed its two currently active volcanoes, Kilauea and Mauna Loa. The active submarine volcano Loihi, off the Big Island's south coast, may mark the beginning of the zone of magma formation at the southeastern edge of the hot spot. The other Hawaiian islands have moved northwestward beyond the hot spot, were successively cut off from the sustaining magma source, and are no longer volcanically active.



Artist's conception of the northwestward movement of the Pacific Plate over the fixed Hawaiian "Hot Spot" to illustrate the formation of the Hawaiian Ridge-Emperor Seamount Chain. *(Modified from a drawing provided by Maurice Krafft, Centre de Volcanologie, Cernay, France.)*

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

Even on the Big Island alone, the relative ages of its five volcanoes are compatible with the hot-spot theory. Kohala, at the northwestern corner of the island, is the oldest, having ceased eruptive activity about 60,000 years ago. The second oldest is Mauna Kea, which last erupted about 3,000 years ago; next is Hualalai, which has had only one historic eruption (1800-1801), and, lastly, both Mauna Loa and Kilauea have been vigorously and repeatedly active in historic times. Because it is growing on the southeastern flank of Mauna Loa, Kilauea is believed to be younger than its huge neighbor.

The size of the Hawaiian hot spot is not known precisely, but it presumably is large enough to encompass the currently active volcanoes of Mauna Loa, Kilauea, Loihi and, possibly, also Hualalai and Haleakala. Some scientists have estimated the Hawaiian hot spot to be about 200 miles across, with much narrower vertical passageways that feed magma to the individual volcanoes.

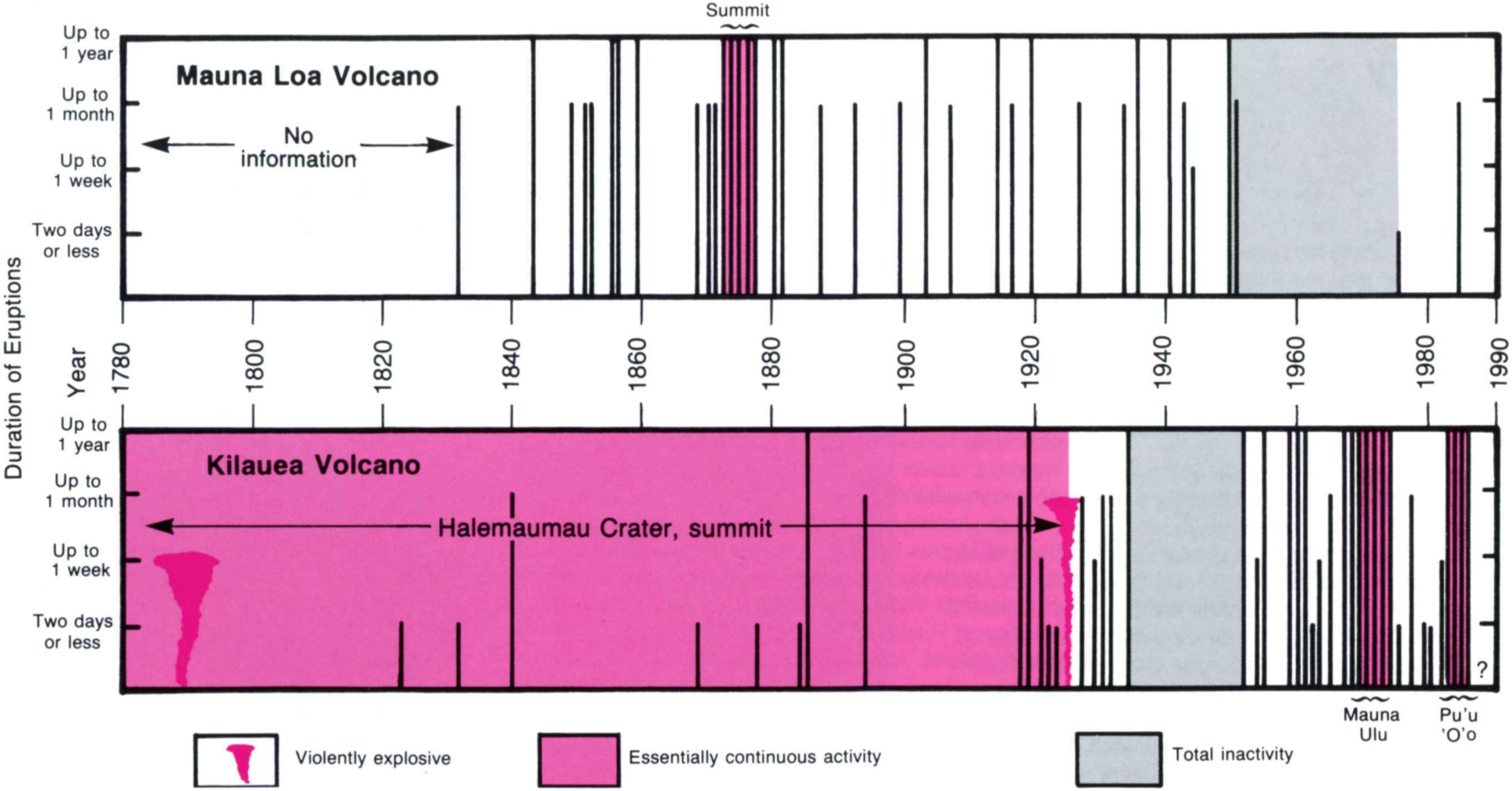
Hawaiian Eruptions in Recorded History

Hawaii has a brief written history, extending back only about 200 years, compared to such volcanic regions as Iceland, Indonesia, Italy, and Japan. Written accounts exist for most Hawaiian eruptions since 1820, when the first American missionaries settled in Hawaii. Descriptions of earlier eruptions are sketchier, because they are based only on interpretations of ancient Hawaiian chants and stories told by Hawaiian elders and early European residents to the American missionaries.

All the known historic Hawaiian eruptions have been at Mauna Loa and Kilauea Volcanoes except for the following: the 1790? (year uncertain) eruption of Haleakala Volcano on Maui, and the 1800-1801 eruption of Hualalai Volcano, on the west coast of the Big Island. Although an exception to the overall northwest-southeast shift of volcanic activity, a series of submarine eruptions also probably occurred in 1955-56 between the islands of Oahu and Kauai and near Necker Island, about 350 miles northwest of Kauai.

On March 30, 1984, both Kilauea and Mauna Loa were in simultaneous eruption, the first time since 1924. Kilauea's Pu'u 'O'o eruption began its 17th high-fountaining episode since January 1983 *(above photograph by Kepa Maly, National Park Service)* and a Mauna Loa eruption, which began on March 25, continued to feed a major lava flow that advanced toward the city of Hilo *(bottom photograph by Scott Lopez, National Park Service.)*

Hawaiian Eruptions in Recorded History



Graph summarizing the eruptions of Mauna Loa and Kilauea Volcanoes in recorded history. Information is sketchy for historic eruptions before 1820, when the first American missionaries arrived in Hawaii. The total duration of eruptive activity in a given year, shown by the vertical bar, may be for a single eruption or combined for several separate eruptions.

The active lava lake within Halemaumau Crater overflowing its levee, as painted by D. Howard Hitchcock in 1894. *(Photograph by J.D. Griggs with permission of the Volcano House Hotel, owner of the original painting.)*

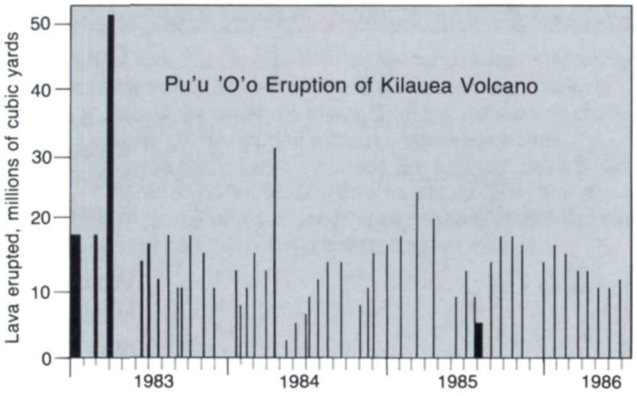
For the past 200 years, Mauna Loa and Kilauea have tended to erupt on average every two or three years, placing them among the most frequently active volcanoes of the world. Some intervals of repose between eruptions at a given volcano have been much longer than its long-term average. The individual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

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

Since July 1950, Hawaiian eruptive activity has been dominated by frequent and sometimes prolonged eruptions at Kilauea, while only two short-lived eruptions have occurred at Mauna Loa (July 1975 and March-April 1984). As of September 1986, Kilauea's eruption at Pu'u 'O'o, which began in January 1983, shows no signs of decline. Except for the nearly continuous eruptive activity at Halemaumau for a century before 1924, and at Mauna Loa summit between 1872 and 1877, the Pu'u 'O'o eruption has now become the longest lasting single Hawaiian eruption in recorded history.

A pattern of alternating dominant activity between Mauna Loa and Kilauea could imply that both volcanoes may alternately tap the same *deep* magma source. Whether this is so is a topic of scientific debate, because abundant chemical and physical evidence indicates that each volcano has its own *shallow* magma reservoir that operates independently of the other.

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



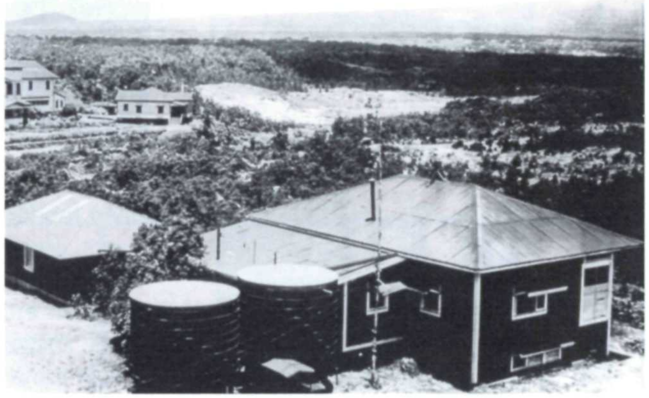
Brief high-fountaining episodes (shown by bars) alternated with longer intervals of low-level activity during the Pu'u 'O'o eruption. Width of bar indicates duration of high fountaining.

Volcano Monitoring and Research

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

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

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

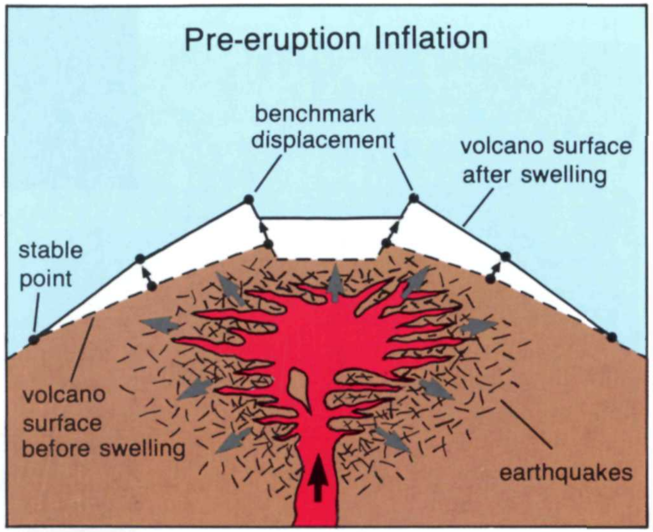


Above: The first Hawaiian Volcano Observatory (HVO), located near the site of the present Volcano House Hotel, as it appeared around 1922. *(Photographer unknown; courtesy of the Bishop Museum, Honolulu, Hawaii.)* *Below:* HVO at its present site, after the addition of a new wing (with observation tower) and renovation in 1986. *(Photograph by J.D. Griggs.)*

Since 1948, it has been been operated by the USGS. During the past 75 years of research, HVO scientists have developed and refined most of the surveillance techniques now commonly employed by volcano observatories worldwide.

Volcano monitoring

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



Hypothetical cross section of Kilauea Volcano. Magma entering the shallow reservoir exerts pressure on the volcano, causing earthquakes and distorting its shape from the dotted-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. The changes in the volcano's shape and the occurrence of the earthquakes can be tracked precisely by *volcano-monitoring* techniques.

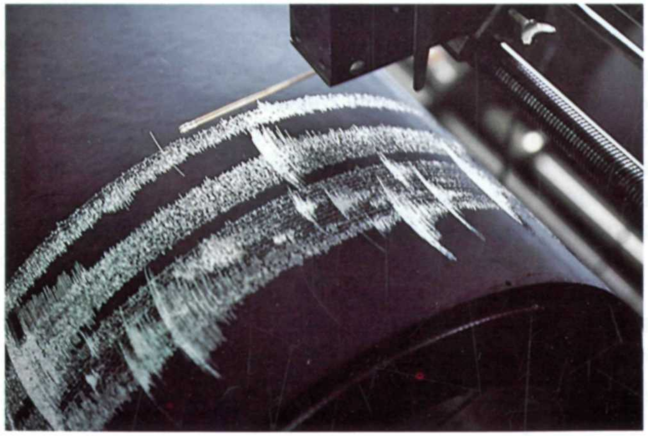
Hawaiian Volcano Observatory (HVO) scientist using laser-ranging instrument (left) to make electronic-distance measurement (EDM). *(Photograph by Christina Heliker.)* The laser beam is reflected back to the EDM instrument by a cluster of retro-reflectors (right), and a precise determination of the horizontal measurement is made by a small computer within the instrument. *(Photograph by Robin T. Holcomb.)*

HVO scientists using an optical-level instrument to determine ground tilt, calculated from readings to three or more stadia rods (one seen at right). Use of umbrella improves readings by eliminating disruptive air-temperature fluctuations caused by passage of clouds. *(Photograph by J.D. Griggs).*

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

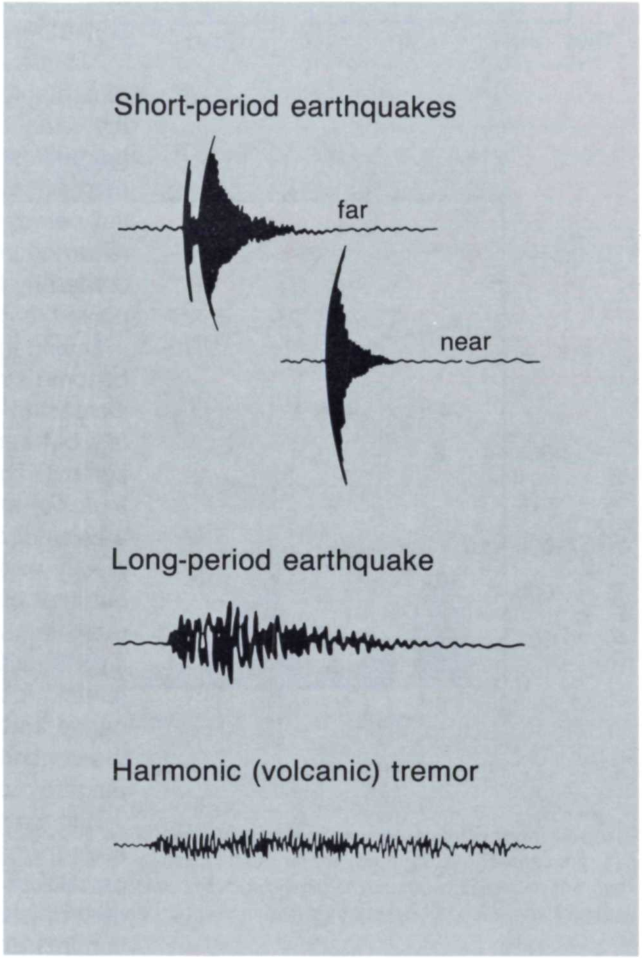
Tilt changes and associated relative vertical displacements also can be detected by periodic remeasurement of arrays of benchmarks by *leveling*, a high-precision field surveying method. Changes in horizontal distances between benchmarks can be monitored in the field by using portable *electronic distance measurement* (EDM) instruments that utilize laser or infra-red beams. Collectively, these commonly used ground-deformation monitoring techniques have a measurement precision of a few parts per million or less. The notion of one part per million can be visualized in terms of a very dry martini—1 drop of vermouth in 16 gallons of gin!

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 the seismometer are converted into electronic signals, which are transmitted by radio and are recorded on *seismographs* located at the volcano observatory. The seismic data are analyzed to determine the time, location, depth, and magnitude of the earthquakes. Mapping the earthquake activity allows HVO scientists to track the subsurface movement of magma.



Above: A *smoke-drum* seismograph. A sharp-needle pen "writes" the seismic signature by scratching recording paper coated with carbon black (soot). *(Photograph by Robert W. Decker.)* For more precise monitoring, however, HVO records and analyzes seismic activity by use of photographic-film and computerized magnetic-tape recording systems. *Right:* Examples of common seismic signatures typically recorded before and during eruptions.

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



Anatomy of an eruption: The inflation-deflation cycle

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

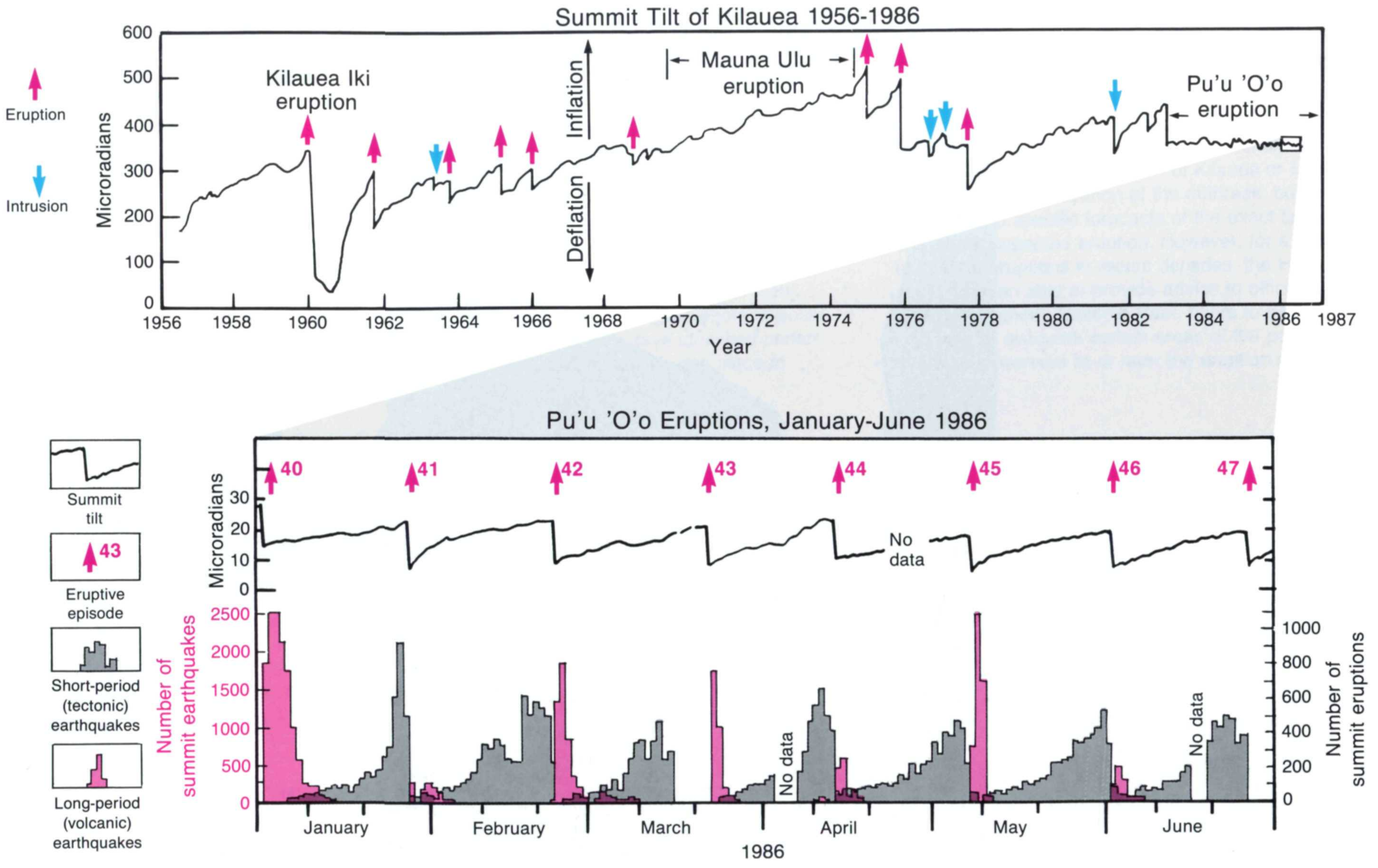
During inflation the rocks surrounding the reservoir become stressed, and this stress is partly relieved by *increasing numbers of earthquakes, too small to be* felt, but easily recorded by seismometers at Kilauea summit. These earthquakes (called *short-period* or *tectonic*) are recorded as high-frequency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

Kilauea's distinctive inflation-deflation pattern is seen for nearly every eruption, regardless of the amount of tilt change observed. For example, the pattern is dramatically shown for the Kilauea Iki eruption in 1959, which involved the largest tilt change observed to date (nearly 300 microradians); the same pattern is also well shown for activity involving tilt changes of only 20 microradians or less, such as the continuing eruption at Pu'u 'O'o.

Forecasting eruptions

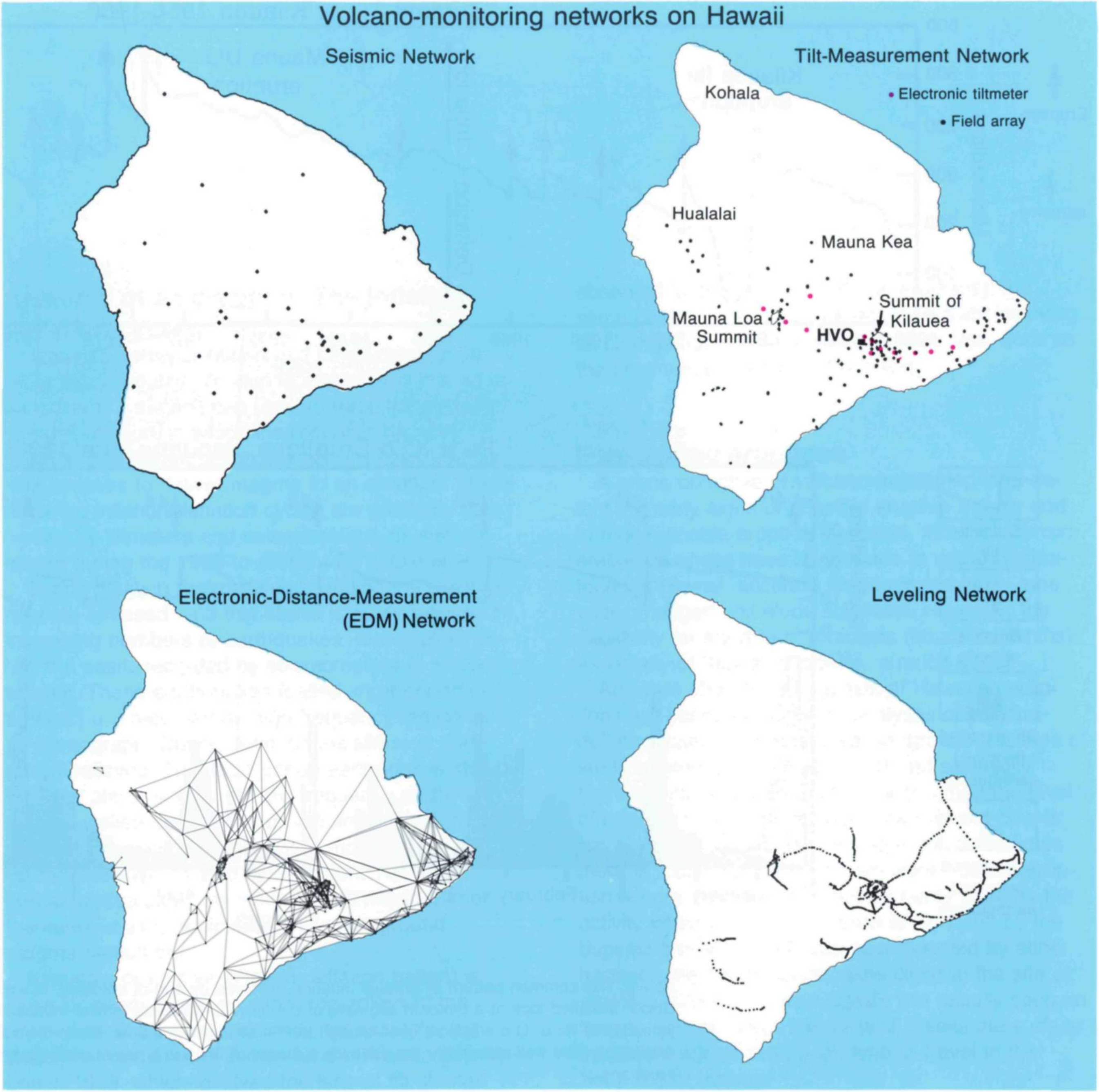
A prime objective of volcano monitoring is to detect the early signs of possible eruptive activity and to make reliable eruption forecasts. Although considerable advances have been made in volcano monitoring in Hawaii, accurate long-term forecasts (one year or longer) still elude scientists. However,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

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



Above: The common pattern of gradual inflation, followed by abrupt deflation, is well demonstrated by major eruptions and intrusions. *Below*: Detailed look at a 6-month segment of the tilt record reveals similar inflation-deflation patterns for the high-lava fountaining episodes of Pu'u 'O'o eruption, even though the tilt changes and time intervals involved are much smaller (compare scales of the two drawings). Also well shown are the variation patterns of the two types of earthquakes that commonly precede and accompany Kilauea eruptions.

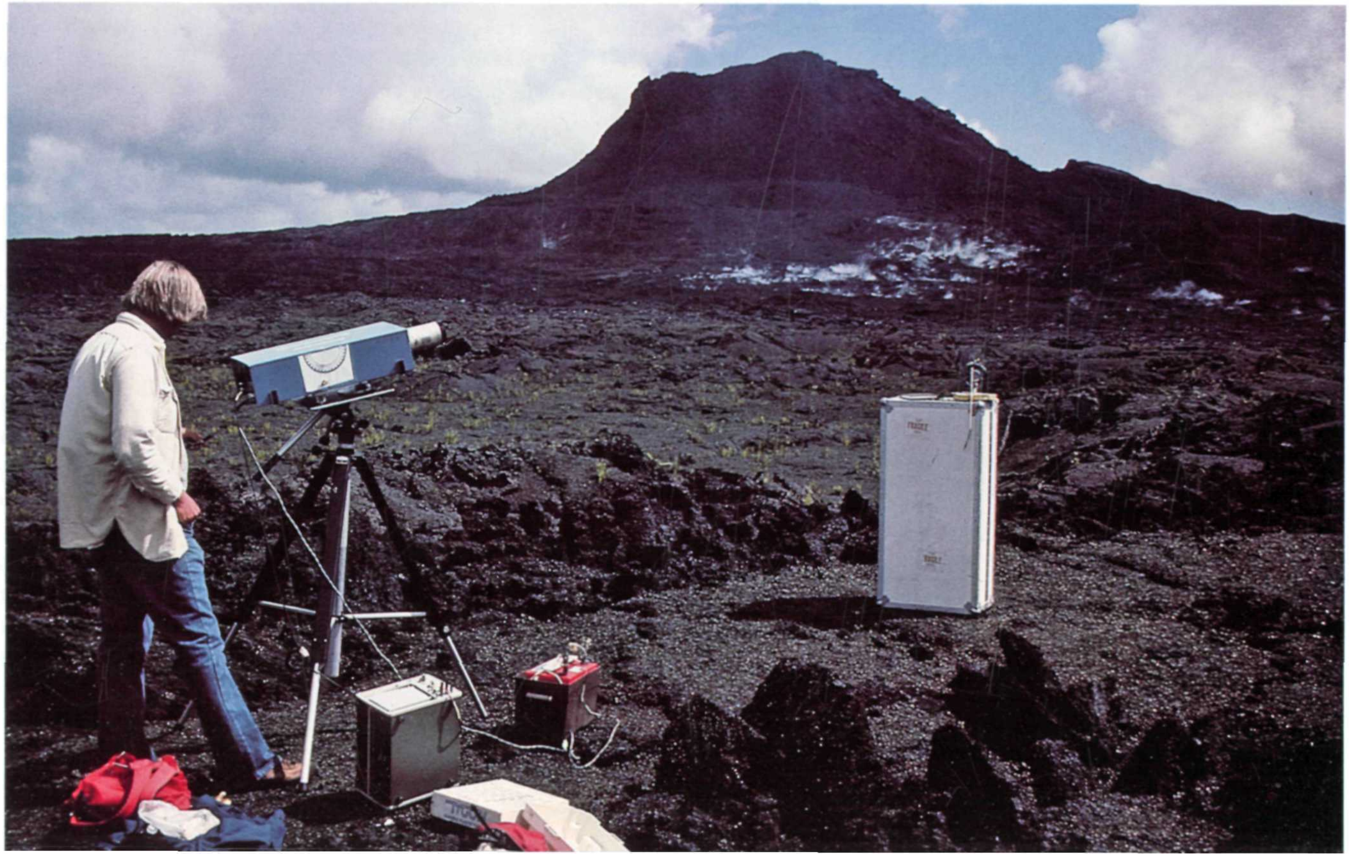
The principal volcano-monitoring networks operated by the Hawaiian Volcano Observatory. For more information about these networks and other monitoring networks, see article by Heliker and others (*Selected Readings*).



The combination of seismic and ground-deformation monitoring has proved to be the most useful and reliable technique in the short-term forecasting of eruptions at Kilauea. Some experimental techniques being developed or tested show promise and should increase forecasting capabilities in the future. These new methods include monitoring the changes in: the composition and amount of volcanic gases discharged (such as sulfur dioxide, carbon dioxide, hydrogen, helium, and radon); the magnetic and gravitational fields of the volcano; and the various geoelectrical properties of the volcano.

So far, the data from these experimental techniques have not given definitive precursors to possible eruptions. However, they have identified underground movement of magma from one place to another, sometimes unaccompanied by measurable ground deformation or earthquakes. Experience on well-studied active volcanoes in Hawaii and elsewhere has shown that the best monitoring is achieved by using a combination of approaches rather than relying on any single method.

At present, scientists generally can identify the increased potential for eruption of Kilauea or Mauna Loa and the likely location of the outbreak, but they cannot make specific forecasts of the exact timing or size of the expected eruption. However, for a number of Kilauea eruptions in recent decades, the HVO staff has been able to provide advice to officials of Hawaii Volcanoes National Park, hours to days in advance, to evacuate certain areas of the park and to station observers at or near the eruption site.



Scientist using a correlation spectrometer (COSPEC) to measure the emission of sulfur dioxide gas from the Pu'u 'O'o vent. This instrument was originally developed to measure the discharge of sulfur dioxide from industrial smokestacks in monitoring atmospheric pollution. *(Photograph by J.D. Griggs.)*

Kilauea's Volcanic "Plumbing System"

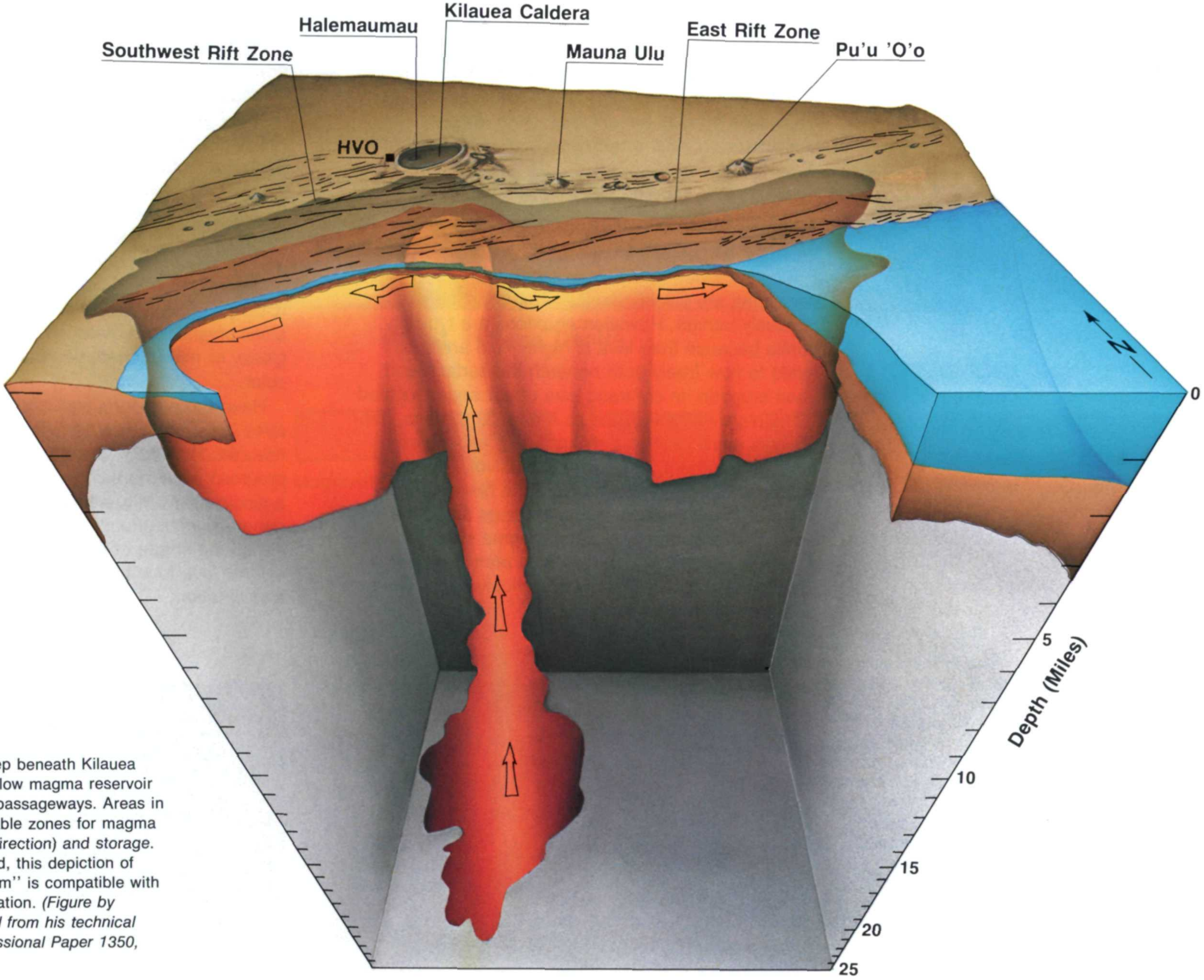
From years of monitoring and research at HVO, Kilauea's volcanic "plumbing system" is now relatively well understood. This system links the processes involved in the formation, transport, storage, and, ultimately, eruption of magma to build and feed Hawaii's active volcanoes.

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

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

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

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



Cut-away view looking deep beneath Kilauea Volcano, showing the shallow magma reservoir and the principal magma passageways. Areas in yellow are the most favorable zones for magma movement (arrows show direction) and storage. Though greatly generalized, this depiction of Kilauea's "plumbing system" is compatible with all known scientific information. *(Figure by Michael P. Ryan, simplified from his technical illustrations in USGS Professional Paper 1350, Volume 2, Chapter 52.)*

Eruptive Style: Powerful But Usually Benign

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

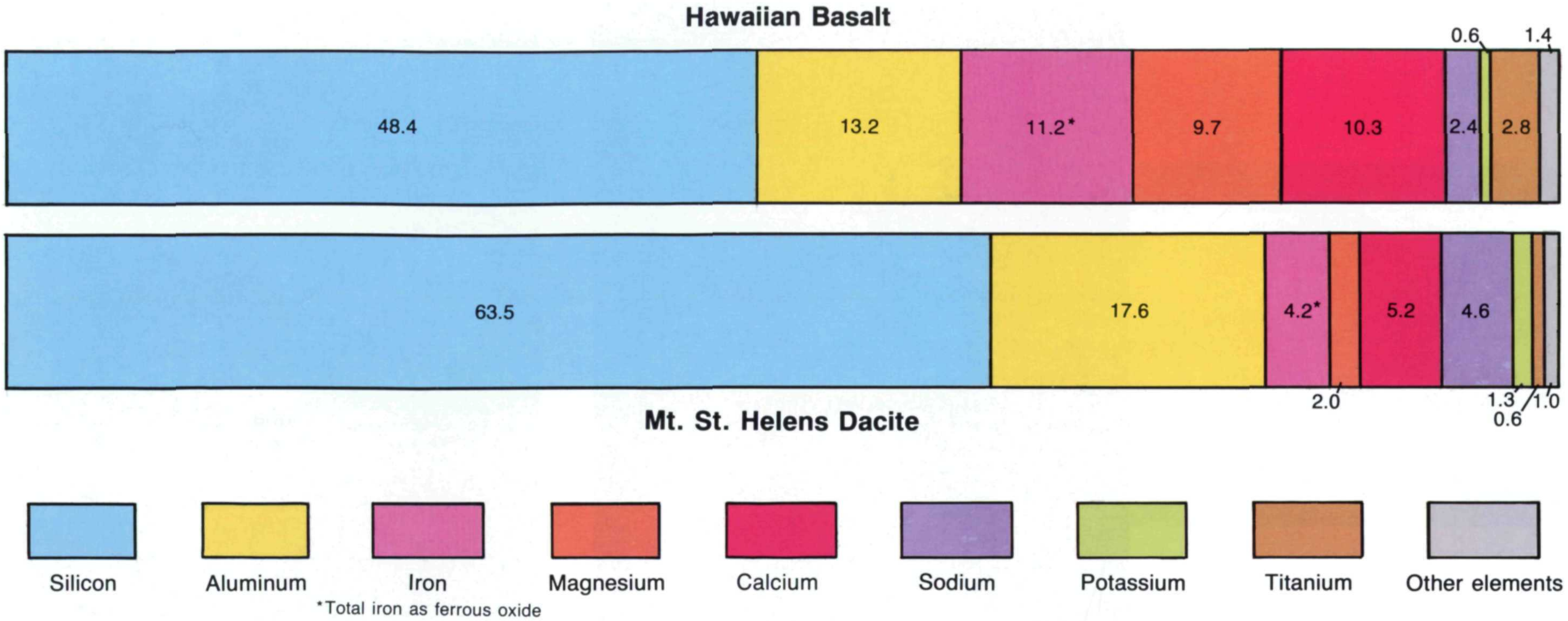
Typical activity: "nonexplosive" or weakly explosive

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

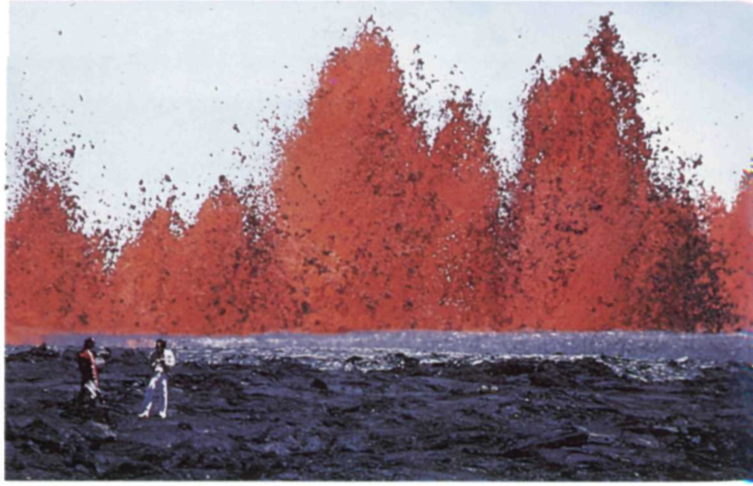
Lava *viscosity* ("stiffness" or "resistance to flow") is largely determined by the chemical composition and temperature of the magma, the amount of crystals in the magma, and the gas content. The high fluidity (low viscosity) of Hawaiian lavas derives mainly from its *basaltic* composition, characterized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

Hawaiian eruptions typically start with *lava fountains* spouting from a series of nearly continuous fissures, "curtain(s) of fire." As most eruptions progress, lava-fountain activity becomes localized at a single *vent* (an opening from which lava issues), generally within hours of the initial outbreak. Depending on the shape of the vent and other eruptive conditions, lava fountains can vary widely in form, size, and duration.

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



Above: Graph illustrating the difference in average chemical composition between lava erupted by Hawaiian volcanoes and by Mount St. Helens in 1980. The number given for each chemical element gives the amount (in weight percent) of that element (expressed as oxide) contained in the lava. *Left:* Note the contrast in color and texture between Hawaiian basalt (dark) and Mount St. Helens dacite (light). *(Photograph by J.D. Griggs.)*



Lava fountains can vary widely in size and form. *Center:* 1,900-foot high fountain during Kilauea Iki eruption in 1959, the highest ever observed anywhere in the world. *(Photograph courtesy of the National Park Service.) Right above:* A discontinuous row of lava fountains ("curtains of fire") 50-100 feet high during the 1971 Kilauea summit eruption as viewed from the air. *(Photograph courtesy of the National Park Service.) Right below:* "Curtain of fire" viewed from the ground during the 1984 Mauna Loa eruption. *(Photograph by Richard B. Moore.)*

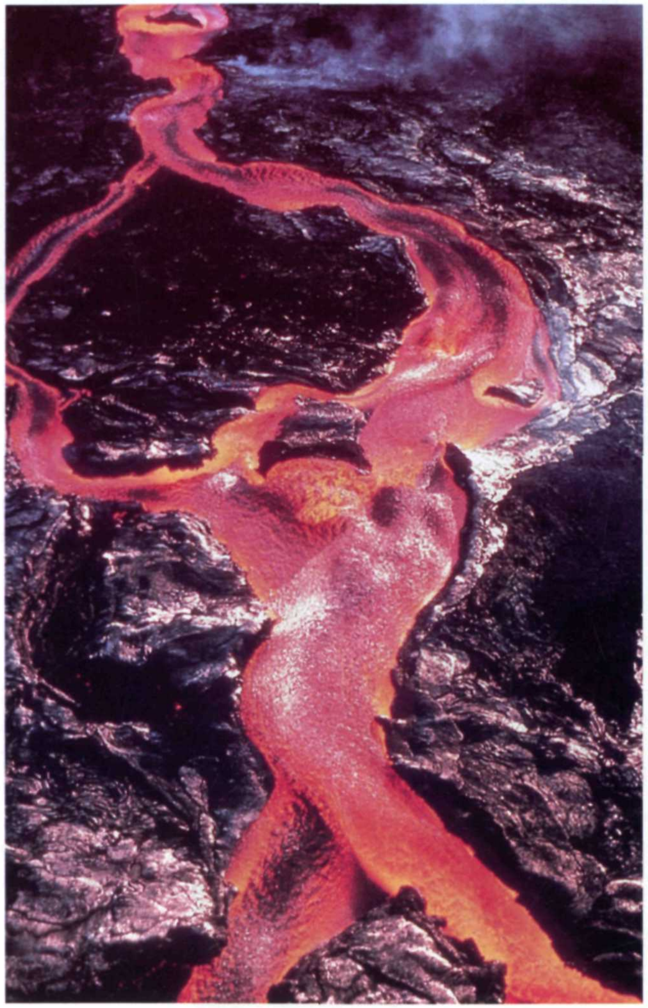
Left: Night view (time-exposure) of a "spray" lava fountain, 50-70 feet high, during the 1972-74 Mauna Ulu eruption of Kilauea. *(Photograph by Robin T. Holcolmb.) Top:* A 40-foot arching "hose" fountain spurts from Pu'u 'O'o vent in 1983. *(Photograph by J.D. Griggs.) Bottom:* A "dome" fountain, about 45 feet high, plays continuously for hours during the 1969-71 Mauna Ulu eruption. *(Photograph by Jeffrey B. Judd.)*

During the 1959 Kilauea Iki eruption, lava fountains shot 1,900 feet, the record height for historic Hawaiian eruptions and likely the highest lava fountain yet observed on Earth. More recently, some of the vigorous eruptive episodes of the 1983-to-present Pu'u 'O'o activity have produced lava fountains about 1,500 feet high. Though impressive, even these spectacularly high lava fountains are products of relatively weak explosive activity. By comparison, the May 1980 explosive eruption of Mount St. Helens sent ash more than 12 miles into the atmosphere. When the rate of gas release is too low to cause fountaining, lava merely wells up, flows quietly, or oozes from the vent.

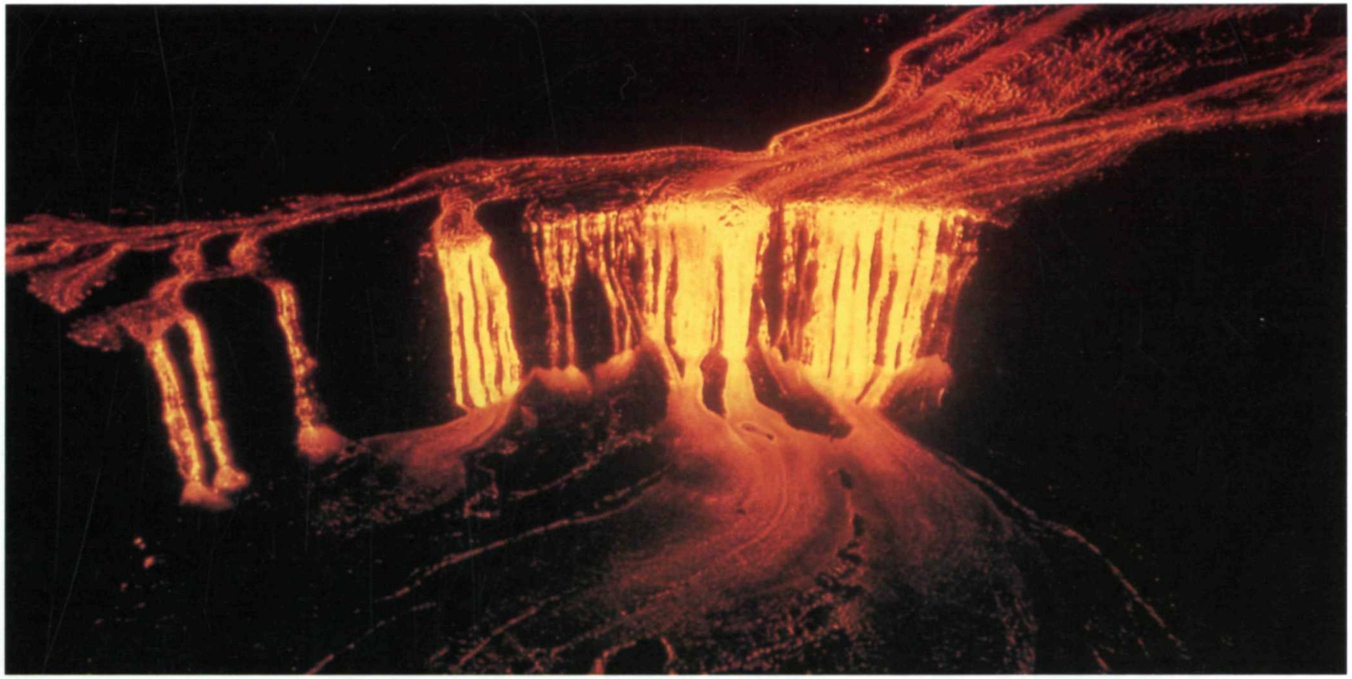
Lava falling from fountains and issuing quietly from vents often forms incandescent *lava streams* or *lava flows*, leading to the colorful term "rivers of fire," often used in popular accounts of Hawaiian eruptions. During some Mauna Loa eruptions, several lava flows rushed down the steep slopes at 35 miles per hour! During long-lived eruptions, lava flows tend to become "channeled" into a few main streams. Overflows of lava from these streams solidify quickly and plaster on to the channel walls, building natural *levees* or *ramparts* that allow the level of the lava to be raised. Lava streams that flow steadily in a confined channel for many hours to days may develop a solid crust or roof and thus change gradually into streams within *lava tubes*. Because the walls and roofs of such tubes are good thermal insulators, lava flowing through them can remain hot and fluid much longer than surface flows. Tube-fed lava can be transported for great distances from the eruption sites. For example, during the 1969-74 Mauna Ulu eruptions at Kilauea, lava flows traveled underground through a lava-tube system more than 7 miles long to enter the ocean on five occasions.

Red-hot blobs of liquid lava ejected during one of the high-fountaining episodes at Pu'u 'O'o are transformed to solid black fragments upon rapid cooling in flight. Helicopter (upper left) gives scale. *(Photograph by J.D. Griggs.)*

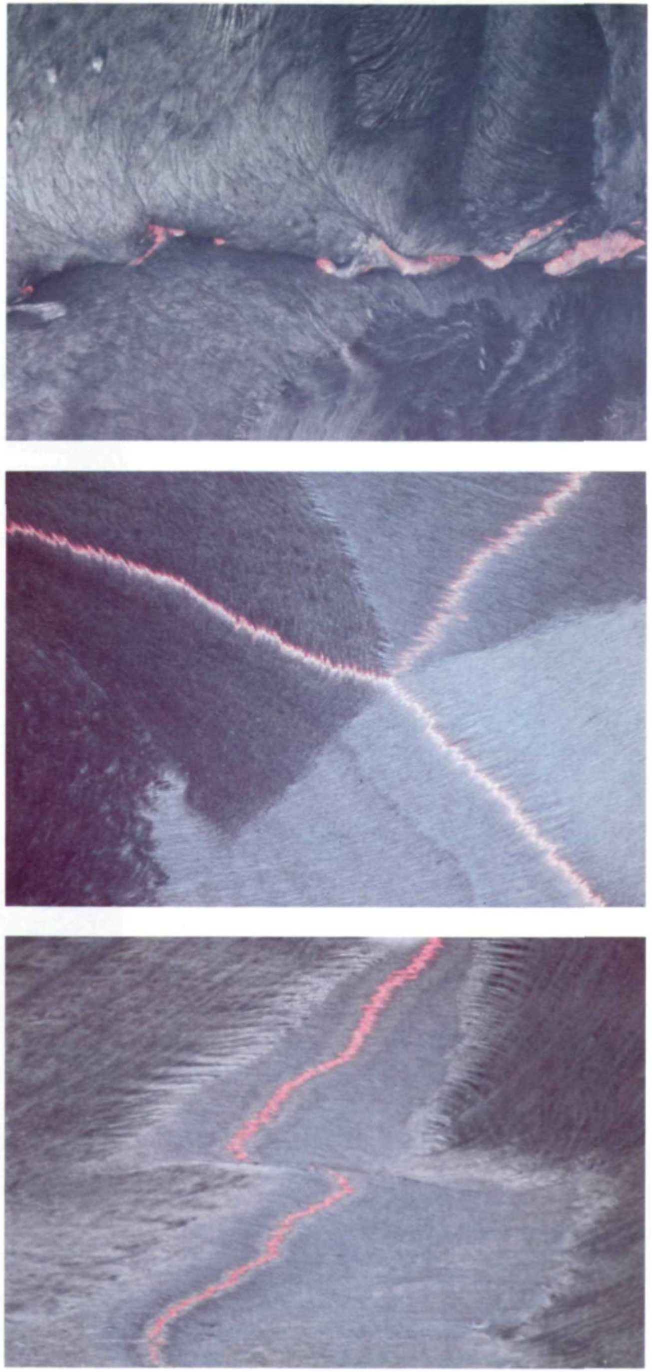
Center: Aerial view of braided lava flow of the 1984 Mauna Loa eruption. With imagination, some people see in this flow pattern the figure of Pele, Goddess of Volcanoes, with her arms raised. *(Photograph by Maurice Krafft, Centre de Volcanologie, Cernay, France.)* *Above right*: Inside the Thurston Lava Tube, Hawaii Volcanoes National Park. *(Photograph by Taeko Jane Takahashi.)* *Below right*: How Thurston Lava Tube might have looked when it was "active" a few hundred years ago can be appreciated from this view through the collapsed roof ("skylight") of a lava tube active during the 1969-71 Mauna Ulu eruption. *(Photograph by Jeffrey B. Judd.)*



Right: Lava cascades plunge 160 feet into Lua Hou Crater, upper part of Mauna Loa's southwest rift zone, during July 1975 eruption. *(Photograph by Robin T. Holcomb.) Below:* A clockwise-circulating lava lake (nearly 500 feet across) in Pauahi's west pit formed during the same eruption. Bright small spots seen on the lake surface are caused by trees bursting into flame. *(Photograph by Robert I. Tilling.)*



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



The century-long lava-lake activity at Halemaumau ceased after the explosive 1924 eruption; however, a lava lake was active there for about 8 months during the 1967-68 eruption. Not until the 1969-1974 Mauna Ulu eruptions, on Kilauea's upper east rift zone, however, did scientists have an opportunity to observe the development and behavior of a long-lived active lava lake outside the summit region of a Hawaiian volcano. The lava-lake behavior at Mauna Ulu, including movement and collision of thin plates of surface crust floating on circulating molten lava, provided a small-scale version of the Earth's global plate tectonics.

Surface movements of the active lava lake within Mauna Ulu crater in 1971 provide an instructive, but very small-scale, analogy to movements of the Earth's tectonic plates. *Left*: View looking east and down (about 200 feet) at the lava-lake surface. *Center*: Closer view of moving slabs of solidified crust, ranging in size from a few feet to several tens of feet across but only a few inches thick, rafted by circulating lava beneath. *Right*: Even closer views of lake surface to show small-scale analogs to the three common types of boundaries between tectonic plates: *Convergent* boundary between two slabs of crust (upper); *Divergent or spreading* boundaries between three slabs (middle); and *Transform fault* (lower) offsetting the spreading boundary between two slabs. *(Photographs by Wendell A. Duffield.)*

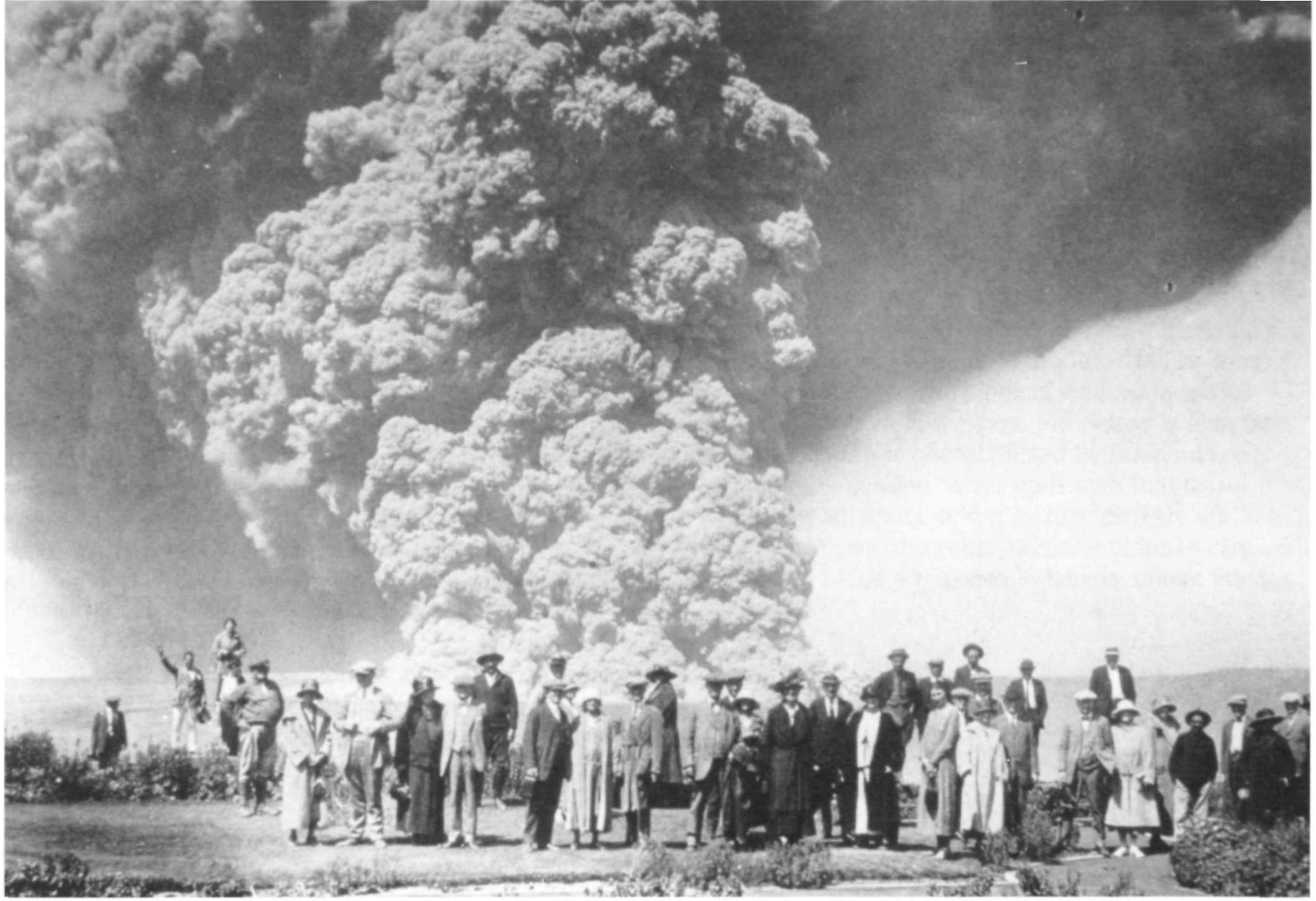
Infrequent explosive activity

Explosive eruptions that deposit large volumes of *pyroclastic debris* over large areas—like the May 1980 eruption of Mount St. Helens—are rare at Hawaiian volcanoes. The term "pyroclastic"—derived from Greek *pyro* (fire) and *klastos* (broken)—is a general term to describe all types of fragmented new magma or old solid rock ejected during explosive eruptions. Less than 1 percent of Hawaiian eruptions have been violently explosive, based on the scarcity of pyroclastic deposits. In contrast, some volcanic chains formed along the convergent boundaries of the Earth's tectonic plates contain 90 percent or more pyroclastic material.

This footprint and others preserved in the muddy ash deposits of Kilauea's explosive eruption in 1790 are believed to be those of Hawaiians who survived the hot explosion cloud. *(Photograph by James F. Martin, National Park Service).*

In 1790, a series of major explosive eruptions, which probably lasted a few days to a few weeks, deposited a blanket of pyroclastic debris up to 30 feet thick in and around Kilauea summit. At the time of these eruptions, a band of about 250 Hawaiian warriors, led by Keoua, chief of the Puna district in eastern Hawaii, was marching across the summit region of Kilauea to battle the army of a rival chief, Kamehameha. Some of Keoua's warriors were caught in a hot, high-velocity explosion cloud, composed mainly of volcanic steam and gases but little ash. The hot gases seared the warriors' lungs, killing about 80 of them by suffocation. Footprints preserved in the muddy ash deposits of the 1790 eruption are thought to be those of the surviving warriors; these still can be seen by hiking the Mauna Iki (Footprints) Trail in Hawaii Volcanoes National Park. Had the Hawaiian Volcano Observatory been at its present location on the summit of Kilauea in 1790, it almost certainly would have been destroyed.

A much less energetic explosive eruption took place at Halemaumau Crater in May 1924. Three months before the eruption, the long-lived lava lake in Halemaumau played actively about 150 feet below the crater rim. Beginning in February, the lake surface began to drop rapidly, and soon the lake drained entirely to expose the crater floor. Throughout March and April, the crater floor further subsided, apparently in response to magma moving from the summit reservoir into the east rift zone. By May 6, Halemaumau's floor was more than 600 feet below the rim.



Tourists posing in May 1924 (at a safe distance!) at Kilauea Volcano as a large explosion cloud rises thousands of feet into the air. *(Photograph courtesy of the Bishop Museum.)*

A series of steam explosions began on May 10 at Halemaumau and continued vigorously for two and a half weeks. Each explosion lasted from a few minutes to 7 hours; the most powerful ones sent ash plumes more than a mile high and hurled large blocks, some weighing several tons, more than a half mile from Halemaumau. Many of these blocks were red hot. A photographer, who ventured too close to the crater, was struck by a falling block and died the next day from his injuries. When the explosions ended, Halemaumau was about twice as wide, and eight times as deep, as before the eruption.

The 1790 and 1924 eruptions were explosive because they involved the violent mixing of ground water and magma or hot rocks. During both eruptions, as the the magma column subsided in the vent, ground water came into sudden contact with hot material and flashed explosively to steam. The 1924 eruption ejected only chunks of solid, hot older rocks; none was newly formed from magma. The 1790 eruption expelled fragments of solid, older rocks and new magmatic material, suggesting that ground water mixed with both. Though impressive, the 1924 explosions produced only about one-tenth of 1 percent of the volume of the 1790 explosions.

The pyroclastic deposits exposed at Kilauea indicate that about two dozen major explosive eruptions have occurred during the past 70,000 years. Mauna Loa apparently has had less frequent explosive eruptions during the same time interval. Judging by their distribution and thickness, Kilauea's prehistoric pyroclastic deposits had to be produced by explosive eruptions at least as powerful as the 1790 eruption and, in some cases, several times stronger.

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

Because of their seashore locations, most small deposits from littoral explosions are quickly removed by erosive action of the ocean surf. Larger deposits, however, are more permanent and form *littoral cones*, such as the 100-foot-high Pu'u o Mahana, near the south tip of the Big Island, formed during a prehistoric Mauna Loa eruption.

Pu'u o Mahana is the site of Hawaii's famous "green sand beach," composed of the shiny green mineral *olivine* (a magnesium-iron-silicate) eroded from the littoral cone and concentrated by wave action. The conspicuous occurrence of olivine, sometimes also called "Hawaiian diamond," in the pyroclastic deposits that form the prominent cone that is Honolulu's landmark reportedly prompted early visitors to name it "Diamond Head." *Peridot*, a gem-quality variety of olivine, is the birthstone for the month of August.

Center: Molten lava being shredded by *littoral* explosions upon entry into the ocean during the 1969-71 Mauna Ulu eruption. *(Photograph by Donald W. Peterson.)* *Right above*: Pu'u o Mahana, a prehistoric littoral cone of Mauna Loa, is the site of the Big Island's green-sand beach. *(Photograph by J.D. Griggs.)* *Right below*: Close-up of the green sand, which obtains its color from wave-concentrated grains of the green mineral *olivine*. *(Photograph by Robert I. Tilling.)*

Hawaiian Volcanic Products, Landforms, and Structures

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

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

Lava flows

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

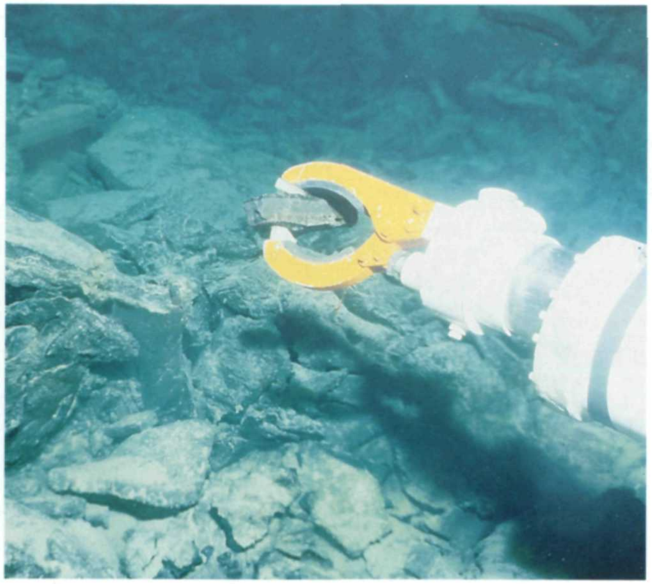
Center: An active clinkery *aa* lava flow advances over the smooth surface of earlier erupted *pahoehoe* lava during the 1972-74 Mauna Ulu eruption. *(Photograph by Robert I. Tilling.) Right:* Closer views of the surface of an aa flow (above) and a pahoehoe flow (below). *(Photographs by J.D. Griggs and Taeko Jane Takahashi, respectively,)* The contrast between the surfaces of pahoehoe and aa flows is immediately obvious to anyone hiking Hawaiian lava fields. Walking on dense pahoehoe can almost be as easy as strolling on a paved sidewalk. But walking across aa is like scrambling over a building-demolition site or battle zone, strewn with loose, unstable debris of all shapes and sizes. The jagged rubble of aa 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 pahoehoe throughout their extent, and a few flows solidify completely as aa. Most flows, however, consist of both pahoehoe and aa in widely varying proportions. In a given flow, pahoehoe upstream commonly changes to aa downstream, but aa lava flows do not change into pahoehoe flows. The explanation for this one-way change lies in the delicate balance between the initial gas content of the lava, the changes in lava viscosity, and the rate of deformation ("shear strain") of the lava during flow and cooling. Once this critical balance is upset, pahoehoe can change to aa.

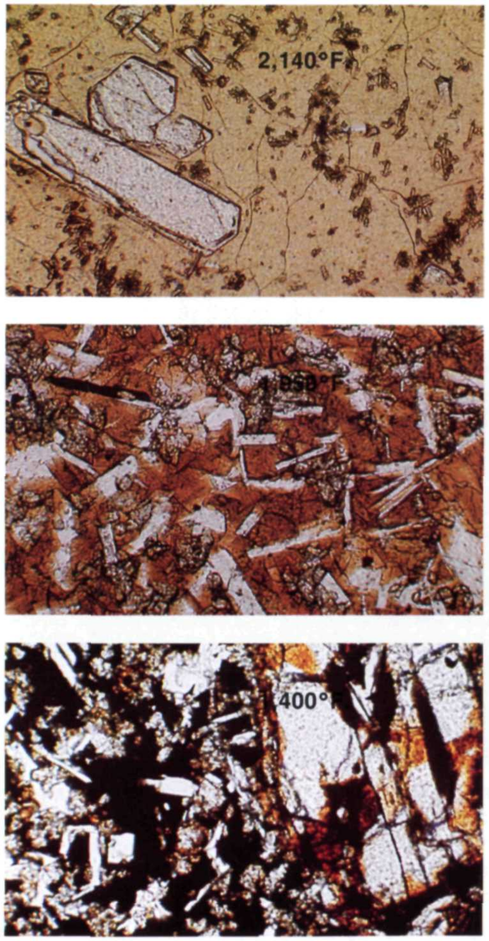
Hawaiian lava is fluid enough to travel great distances, especially if it is transported through lava tubes. Some historic flows are longer than 30 miles; in general, pahoehoe flows tend to be longer than aa. Lava tubes may be preserved when the eruption ends and the lava drains away to leave open tunnels. They may be as much as several tens of feet in diameter, and some have been followed by *spelunkers* (cave explorers) for nearly 10 miles. Ancient Hawaiians used lava tubes as places of shelter and as burial caves. Visitors to Hawaii Volcanoes National Park can walk through Thurston Lava Tube, which formed in a pahoehoe flow a few hundred years ago.

Fluid lava erupted or flowing under water may form a special structure called *pillow lava*. Such structures form when molten lava breaks through the thin walls of underwater tubes, squeezes out like toothpaste, and quickly solidifies as irregular, tongue-like protrusions. This process is repeated countless times, and the resulting protrusions stack one upon another as the lava flow advances underwater. The term *pillow* comes from the observation that these stacked protrusions are sack- or pillow-shaped in cross section. Typically ranging from less than a foot to several feet in diameter, each pillow has a glassy outer skin formed by the rapid cooling of the lava by water. Much pillow lava is erupted under relatively high pressure created by the weight of the overlying water; there is little or no explosive interaction between hot lava and cold water. The bulk of the submarine part of a Hawaiian volcano is composed of pillow lavas.

Below: SCUBA-diving scientist's view of incandescent lava breaking through the solidified shell of a *pillow-lava* lobe to form another tongue as underwater flow advances during the 1969-71 Mauna Ulu eruption. *(Photograph by Richard Grigg, University of Hawaii.)*



Left: Pillow lava on the submerged western slope of Mauna Loa at a water depth of about 2,500 feet. The research submarine's mechanical arm (right) can be manipulated by scientists on board to collect samples. *(Photograph by Daniel Fornari, Lamont-Doherty Geological Observatory of Columbia University.)*



Above: Specimens from the 1965 lava lake in Makaopuhi Crater (about 2 miles east of Mauna Ulu), sampled by drilling, as seen under the microscope (field of view about 0.05 inch). The amount and kinds of crystals increase with decreasing temperatures as the lava lake cools. *(Photomicrographs by Thomas L. Wright.)* *Right above:* Looking about 400 feet down from the rim of Kilauea Iki Crater to the surface of the lava lake formed in the 1959 eruption and a site of drilling studies (oval). *Right below:* Close-up of drilling operations. HVO scientists wear asbestos gloves in handling hot drilling steel. *(Photographs by Robin T. Holcomb.)*

Abundant studies in recent decades, by remotely *controlled deep-sea cameras* as well as by small, manned research submarines, 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 directly observed. Twice during the 1969-74 Mauna Ulu eruptions of Kilauea, teams of SCUBA-diving scientists watched and filmed pillow lavas being formed as lava flows entered the sea. Well-formed pillows also have been studied on the submarine parts of Kilauea and Mauna Loa, as well as the submerged parts of the 1800-1801 lava flows of Hualalai Volcano off the west coast of Hawaii.

Another common lava product is the *ponded flow* or *lava lake*, the formation of which has been described earlier in connection with eruptive style of Hawaiian volcanoes. The surface of lava that is ponded 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. Lava lakes were formed in Alae (1963 and 1968), Makaopuhi (1965), and Kilauea Iki (1959) Craters. The deep lava lake (350 feet) formed during the November-December 1959 eruption at Kilauea Iki is the only one of these still easily visible and accessible.

The lava lakes have been investigated in detail because they furnish natural crucibles for study of the cooling, crystallization, and chemical change of basaltic lava. These studies have included drilling holes through the solid crust of the lake to measure temperature and other properties and to sample the still-molten lava in the interior. In physical terms, the formation of the lava lake's solid crust by cooling can be compared to the formation of a sheet of ice on top of a body of water during a winter freeze. By 1987, all of the still-molten 1959 lava in the interior of the lake at Kilauea Iki will have solidified, although the internal temperature of the lake will remain hundreds of degrees hotter than the surface temperature for many more years.

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

Fragmental volcanic products

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

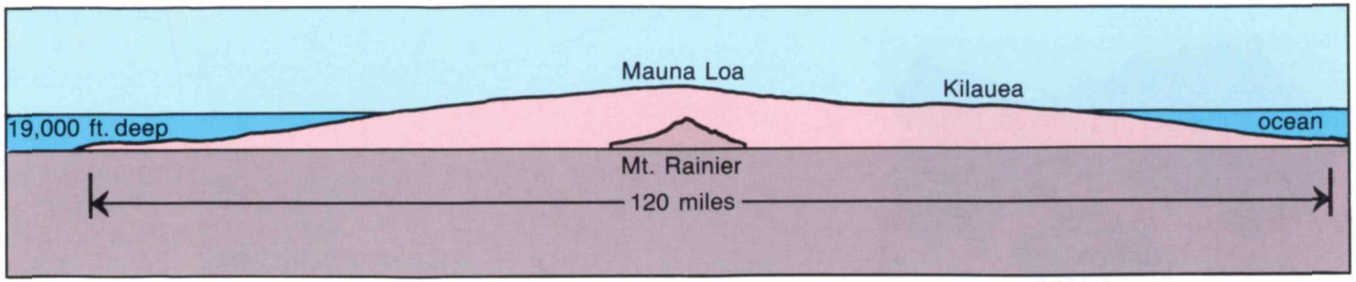
Shiny strands of volcanic glass, called *Pele's hair* (above) are commonly found downwind from active eruptive vents. Volcanic *spatter* commonly becomes tightly welded to form mounds around active vents (below). *(Photographs by Donald W. Peterson and Richard B. Moore, respectively.)*

Some common Hawaiian fragmental volcanic products (top to bottom): *reticulite; Pele's tears; volcanic bombs; and accretionary lapilli,* spherical accumulations of volcanic ash, generally formed during violently exposive eruptions. *(Top two photographs by J.D. Griggs, bottom two photographs by John P. Lockwood.)*

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

If the scoria or pumice clots are sufficiently soft to flatten or splash as they strike the ground, they are called *spatter*. The still-molten character of spatter fragments can cause them to stick together to form *welded spatter* or *agglutinate*. Drops of lava ejected in very fluid condition and solidified in flight can form air-streamlined spherical, dumbbell, and irregular shapes. Drop-shaped lapilli are called *Pele's tears*, after the Hawaiian Goddess of Volcanoes. In streaming through the air, Pele's tears usually have trailing behind them a thin thread of liquid lava, which is quickly chilled to form a filament of golden brown glass, called *Pele's hair*. Pele's hair can form thick mats downwind from high lava fountains near a vent; it also can be blown many miles from the vent.

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 scale.



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

Volcanic landforms and structures

Hawaiian volcanoes exemplify the common type of volcano called 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.

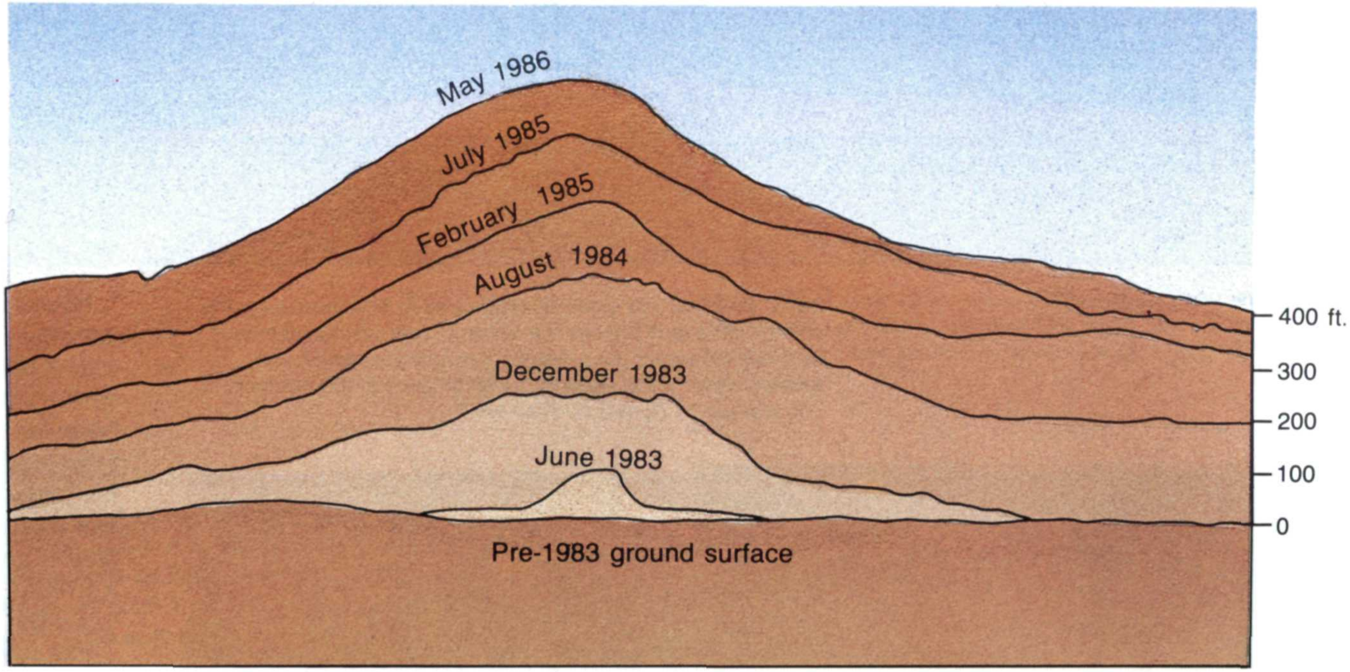
The Hawaiian shield volcanoes are the largest mountains on Earth. Mauna Kea Volcano rises 13,796 feet above sea level but extends about 19,700 feet below sea level to meet the deep ocean floor. Its total height is nearly 33,500 feet, considerably higher than the height of the tallest mountain on land, Mount Everest (Chomolungma) in the Himalaya (29,028 feet above sea level). Mauna Loa stands not quite as high as Mauna Kea but is much larger in volume. The profile of the Mauna Loa shield appears smooth, whereas the shield profile of Mauna Kea has a more uneven appearance, reflecting the growth of numerous small cinder cones on its upper slopes after shield formation. In size, composite volcanoes are dwarfed by the Hawaiian shield volcanoes.

Aerial view from the south of snow-covered Mokuaweoweo, the summit caldera of Mauna Loa Volcano, and several pit craters of its southwest rift zone, Mauna Kea Volcano, which last erupted about 3,000 years ago, can be seen in the distance. *(Photograph by Donald W. Peterson.)*

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. Kilauea's summit caldera is about 2.5 miles long and 2 miles wide. Mokuaweoweo, the summit caldera complex of Mauna Loa is more elongate, measuring about 3 by 1.5 miles. The terms *crater* or *pit crater* are applied to similar but smaller collapse features.

Rift zones radiate from the summit calderas of both Mauna Loa and Kilauea and extend down the volcanic flanks into the sea. They are elongate tapering ridges expressed by prominent open fissures, 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 pre-existing neighboring volcanoes. Most Hawaiian eruptions take place either within summit calderas or along rift zones.

Repeated forceful intrusions of magma into the rift zones of Kilauea have pushed that volcano's south flank southward toward the sea. This seaward movement is readily measurable at rates as high as a few inches per year. Eventually the accumulated seaward movement causes the south flank to become unstable, ultimately resulting in a large earthquake. Such earthquakes occur periodically and are accompanied by substantial and sudden movements along faults cutting the south flank (the Hilina Fault System). For example, in response to a magnitude-7.2 earthquake beneath the area on November 29, 1975, Growth profiles of Kilauea's newest volcanic cone, built during the Pu'u 'O'o eruption.

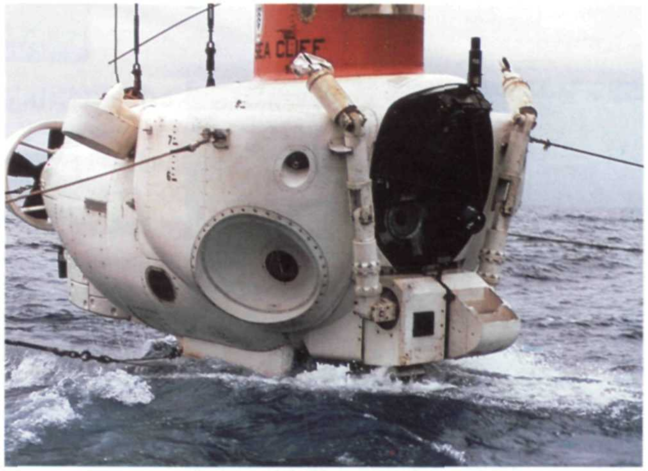


Aerial view of some *scarps* of the Hilina Fault System, expressed as sharp cliffs on the south flank of Kilauea Volcano. *(Photograph by Donald A. Swanson.)*

points on Kilauea's south flank dropped as much as 11 feet and shifted southward as much as 24 feet. The *scarps* (steep slopes) of the Hilina faults are well expressed as *palis* (Hawaiian for cliffs) on Kilauea's south flank.

Prolonged eruptions on Kilauea's east rift zone have given scientists unprecedented opportunities to observe the growth of Hawaiian volcanic landforms. The 1969-74 eruptions created two prominent volcanic shields: a symmetrical 397-foot-high mound at Mauna Ulu (Hawaiian for "growing mountain") and, abutting it, a more irregular shield, 328 feet high, over the site of buried Alae Crater. The highest volcanic landform of historic age in Hawaii is the cone being built by the 1983-to-present Pu'u 'O'o eruption. By September 1986, this cone had grown to a height of more than 830 feet.

Loihi: Hawaii's Newest Volcano



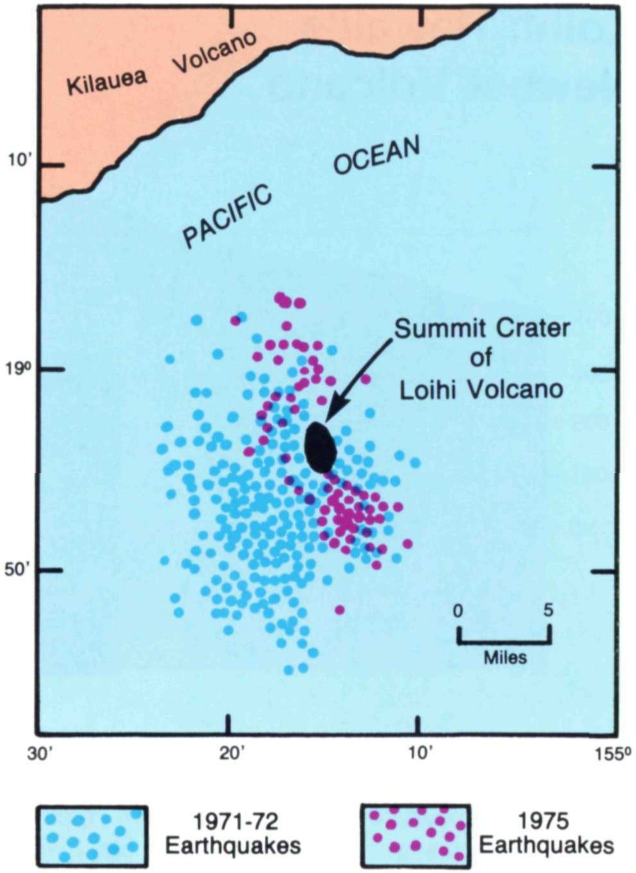
If the hot-spot theory is correct, the next volcano in the Hawaiian chain should form east or south of the Big Island. Abundant evidence indicates that such a new volcano exists at Loihi, a seamount (or submarine peak) located about 20 miles off the south coast of the Big Island. Loihi rises 10,100 feet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

Photographs taken by deep-sea camera show that Loihi's summit area has fresh-appearing, coherent pillow-lava flows and talus blocks. Examination of samples dredged from Loihi indicates that the pillow-lava fragments have fresh glassy crusts, indicative of their recent formation. The exact ages of the sampled Loihi flows are not yet known, but certainly some cannot be more than a few hundred years old. In fact, the occurrence of earthquake swarms at Loihi during 1971-1972, 1975, and 1984-85 suggests major submarine eruptions or magma intrusions into the upper part of Loihi. Thus, Loihi appears to be a historically active, but as yet submarine, volcano.

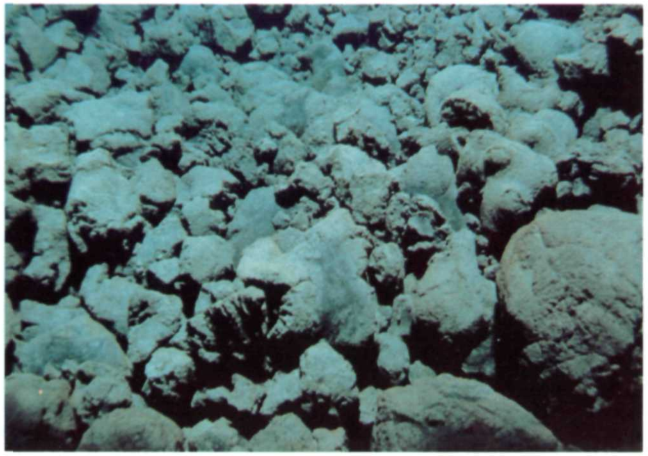
Above: A 3-man research submarine, the *DSV Sea Cliff*, is transported on the stern of its mother ship, the *Maxine D. Below:* The *Sea Cliff* being launched for a dive. *(Photographs by Daniel Fornari, Lamont-Doherty Geological Observatory of Columbia University.)*

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

Studies of Loihi provide a unique opportunity to decipher the youthful submarine stage in the formation and evolution of Hawaiian volcanoes. When might the still-growing Loihi emerge above the surface of the Pacific to become Hawaii's newest volcano island? It will almost certainly take several tens of thousands of years, if the growth rate for Loihi is comparable to that of other Hawaiian volcanoes. It is also possible that Loihi will never emerge above sea level and that the next link in the island chain has not yet begun to form.



Above: Map showing the locations of earthquakes that occurred during 1971-72 and 1975 in the vicinity of Loihi. These two earthquake swarms, plus a similar occurrence in 1984-85, provide seismic evidence that Loihi is an active submarine volcano.



Left: The flank of Loihi, showing broken pillow lava of a fresh flow, as seen from about 7 feet above the volcano's surface at a water depth of about 4,200 feet. *(Photograph by Alexander Malahoff, University of Hawaii.)*

Volcanic Hazards and Benefits

Left: House being consumed by advancing lava during the 1960 Kapoho eruption of Kilauea. *(Photographer unknown.) Below:* View of Kapoho village during the 1960 eruption before it was entirely destroyed *(photographer unknown)* and a post-eruption scene showing the remnants of corrugated iron roofs to mark the site of the lava-buried village *(photograph by Robert I. Tilling).*

In the short term—on a human time scale—some Hawaiian eruptions can be extremely destructive, causing major disruptions in the daily lives of the people affected by them. On a geologic time scale (thousands to millions of years), however, the eruptions have been beneficial.

Volcanic hazards

More than 270,000 people have been killed directly or indirectly by volcanic activity worldwide during the past 500 years. Nearly all of the deaths have been caused by explosive eruptions of composite volcanoes along the boundaries of the Earth's tectonic plates. The worst recent volcanic disaster was in November 1985, when mudflows triggered by a relatively small eruption of glacier-capped Nevado del Ruíz Volcano, Colombia, buried the town of Armero and killed more than 22,000 people. In contrast, fewer than a hundred people have been killed by eruptions in the recorded history of Hawaii and only one of them in this century.

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

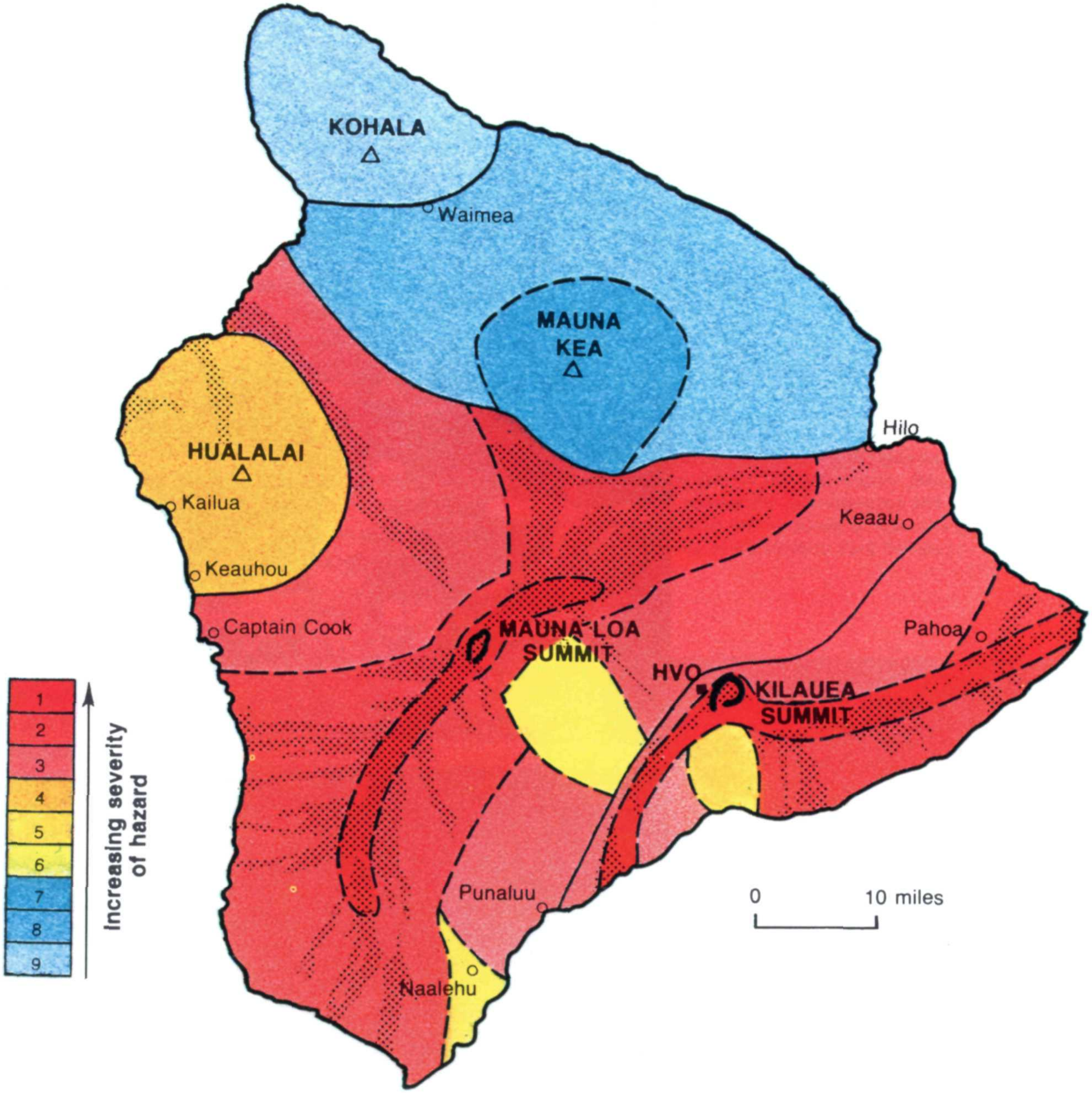
Although the typically gentle Hawaiian eruptions pose little danger to people, their lava flows can be highly destructive to populated and cultivated areas. For example, the village of Kapoho was entirely destroyed during the 1960 eruption in the lower east rift zone of Kilauea. More recently, flows from Kilauea's Pu'u 'O'o eruption have covered and destroyed dwellings and house lots in the Royal Gardens subdivision on the volcano's southeastern flank. The outskirts of Hilo, the largest city on the Big Island, with a population of about 40,000, are built in part on the pahoehoe lava flows of the 1881 Mauna Loa eruption. During the March-April 1984 eruption of Mauna Loa, Hilo was threatened. Lava flows advanced nearly 16 miles in about 5 days, and a bright red glow in the sky over the area of the incandescent flows could be seen on clear nights. The citizens and officials of Hilo became increasingly concerned as the eruption continued. Fortunately the flows stopped about 4 miles short of the nearest buildings on the city's outskirts.

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

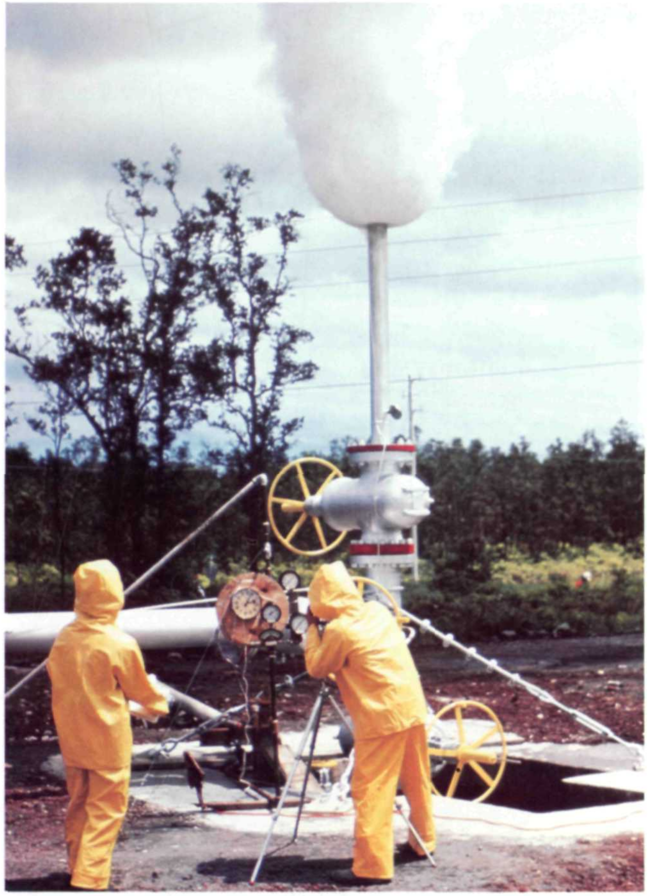
It is useful to distinguish between the terms *hazards* and *risks*. Evaluation of *hazards* is based on geologic information only and considers the likelihood of destructive volcanic phenomena and products in a given area; assessment of *risks* evaluates the likelihood of loss of life and property in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

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

Map of the Big Island showing the volcanic hazards from lava flows. Severity of the hazard increases from zone 9 to zone 1. Shaded areas show land covered by historic flows from three of Hawaii's five volcanoes (Hualalai, Mauna Loa, and Kilauea).



Pressure testing in 1976 of a geothermal well drilled into Kilauea's lower east rift zone. This well currently produces three megawatts of electricity. *(Photograph courtesy of the Hawaii Geothermal Project.)*



Sugar cane thrives in the fertile volcanic soils derived from products of past Hawaiian eruptions. Mauna Kea Volcano is seen in the distance. *(Photograph by Robert I. Tilling.)*

Volcanic benefits

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

Given enough rainfall, areas buried by new lava recover quickly; revegetation can begin less than 1 year after the eruption. Erosion and breakdown of the volcanic material can form fertile soils over periods of tens to thousands of years. These rich soils fostered the agricultural development of the Hawaiian Islands, as represented principally by the sugar, pineapple, coffee, and macadamia nut industries. Some of the volcanic products provide an abundant local source of raw materials for landscaping, housing and construction, and road building. In recent years, volcanic energy has been harnessed by a geothermal power plant on Kilauea's east rift zone; the three megawatts of electricity produced are fed into the grid of the local utility company. Much larger capacity geothermal development is under discussion.

Hawaii's majestic volcanic mountains, beautiful beaches, and pleasant climate combine to make the islands a popular tourist attraction, which includes two heavily visited national parks. Haleakala National Park on Maui, founded in 1961, features the spectacularly eroded summit crater of 10,023 foot-high Haleakala Volcano, active as recently as about 1790. Hawaii Volcanoes National Park, created by Congress in 1916, contains the two currently active Hawaiian volcanoes, Mauna Loa and Kilauea. This park is one of the few places in the world where the processes and products of active volcanism can be viewed safely and comfortably by the nonspecialist and volcanologist alike. Indeed, millions of park visitors have experienced "live" the sights, sounds, and smells of volcanic eruptions and gained a firsthand appreciation of the phenomena that created and shaped these beautiful islands.

Benefits of research at the Hawaiian Volcano Observatory

Hawaii is both a natural laboratory for the study of eruptive phenomena and a volcanic wonderland for visitors. The challenge facing scientists and government officials is clear: to reduce the adverse impact of eruptions in the short term, so that the residents and tourists in Hawaii can continue to enjoy the long-term benefits of volcanism. Toward this end, the Hawaiian Volcano Observatory (HVO) will continue to give timely warnings of anticipated volcanic activity, reliable and current progress reports on an eruption once it starts, and the best possible technical information on volcanic hazards posed by any eruption, present or future. In addition, the high eruption frequency of its volcanoes and the availability of state-of-the-art research facilities at HVO combine to make Hawaii an excellent training ground for volcanologists from around the world. HVO and other scientists are striving to improve volcano-monitoring and eruption-forecasting techniques, in order to reduce the risks associated with eruptions of active volcanoes in Hawaii and elsewhere.

Above: Visitors on the rim of Mauna Ulu crater, silhouetted against the dusky sky (upper right), observe an active lava lake sloshing a few tens of feet below them. *Below:* Park visitors safely watch spectacular lava cascades and "curtains of fire" during the August 1971 eruption at Kilauea's summit. *Photographs courtesy of the National Park Service.)*

Selected Readings

These works cited furnish additional information on topics not covered, or only briefly discussed, in the booklet.

Armstrong, R.W., 1983, editor, Atlas of Hawaii (Second Edition): University of Hawaii Press, Honolulu, 238 p. (A very handy reference volume compiled by the Department of Geography, University of Hawaii, describing the natural, cultural, and social environment of Hawaii, the 50th State.)

Brantley, Steven, and Topinka, Lyn, 1984, Volcanic studies at the U.S. Geological Survey's David A. Johnston Cascades Volcano Observatory, Vancouver, Washington: Earthquake Information Bulletin, v. 16, no. 2, p. 41-120. [A well-illustrated report of the activities and workings of the Observatory, which was established in 1981 as a sister volcano observatory to the Hawaiian Volcano Observatory (see Heliker and others, 1986).]

Dalrymple, G.B., Silver, E.I., and Jackson, E.D., 1973, Origin of the Hawaiian Islands: American Scientist, v. 61, no. 3, p. 294-308. (One of the best and most readable summaries of the "hotspot" hypothesis for the origin of the Hawaiian Ridge-Emperor Seamount Chain.)

Decker, Robert, and Decker, Barbara, 1981, Volcanoes: W.H. Freeman and Company, San Francisco, 244 p. (An information-packed introduction to the study of volcanoes written in an easy-to-read style.)

Decker, R.W., Wright, T.L., and Stauffer, P.H., 1987, editors, Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, 1,667 p. (This two-volume set represents the most comprehensive collection of multidisciplinary scientific articles on Hawaiian volcanism available to date, containing 65 reports.)

Duffield, W.A., 1972, A naturally occurring model of global plate tectonics: Journal of Geophysical Research, v. 77, no. 14, p. 2543-2555. (The first technical article to draw some interesting analogies between the movements of the crust of an active lava lake with much larger scale movements of the Earth's tectonic plates.)

Eaton, J.P, and Murata, K.J., 1960, How volcanoes grow: Science, v. 132, p. 925-938. (The classic scientific article that presented the first comprehensive model for the workings of Hawaiian volcanoes, incorporating the results of modern volcano monitoring by the Hawaiian Volcano Observatory.)

Editors, 1982, Volcano: in the series Planet Earth, Time-Life Books, Alexandria, Virginia, 176 p. (A well illustrated and readable general survey of volcanoes and their activity.)

Heliker, Christina, Griggs, J.D., Takahashi, T.J., and Wright, T.L., 1986, Volcano monitoring at the U.S. Geological Survey's Hawaiian Volcano Observatory: Earthquakes and Volcanoes (formerly Earthquake Information Bulletin), v. 18, no. 1, 72 p. (An informative and richly illustrated article on the monitoring and research activities of the Observatory that was founded in 1912.)

Lipman, P.W., and Mullineaux, D.R., editors, 1981, The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, 844 p. (The most comprehensive collection of scientific articles on Mount St. Helens available to date; it contains 62 reports on many aspects of the 1980 eruptions of this best-known U.S. explosive volcano. This volume provides an instructive comparison with U.S. Geological Survey Professional Paper 1350, edited by Decker and others, which summarizes present knowledge on Hawaiian volcanoes, the best-known U.S. non-explosive volcanoes.)

Macdonald, G.A., Abbott, A.T., and Peterson, F.L., 1983 (Second Edition), Volcanoes in the sea: The geology of Hawaii: University of Hawaii Press, Honolulu, 517 p. (A handsome book that provides the best overview of the eruptive and other geologic processes that have shaped the Hawaiian Islands.)

Peck, D.L., Wright, T.L., and Decker, R.W., 1979, The lava lakes of Kilauea: Scientific American, v. 241, no. 4, p.114-128. (An excellent summary of the methods and scientific results of drilling of Kilauea's molten lava lakes, which are natural laboratories for studying the cooling and crystallization of Hawaiian magma.)

Tilling, R.I., 1982, Volcanoes: U.S. Geological Survey series of general-interest publications, 46 p. (A general introduction for the nonspecialist to the study of volcanoes, with focus on the nature, types, workings, products, and hazards of volcanoes.)

Tilling, R.I., 1984, Monitoring active volcanoes: U.S. Geological Survey series of general-interest publications, 13 p. (A generalized introduction to the common techniques of volcano monitoring, with a brief commentary on some eruptions during the 1975-1982 period, including Mauna Loa, Kilauea, Mount St. Helens, and El Chichón [Mexico].)

Tilling, R.I., 1984, Eruptions of Mount St. Helens: Past, present, and future: U.S. Geological Survey series of general-interest publications, 46 p. (A nontechnical summary, illustrated by many color photographs and diagrams, of the abundant scientific data available for the volcano, with emphasis on the catastrophic eruption of May 18, 1980, which caused the worst volcanic disaster in U.S. history.)

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

Selected Viewings

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

Case History of a Volcano, National Educational Television, Film Service, Indiana University Audio-Visual Center, Bloomington, Indiana 47401. (A presentation of the methods used by scientists of the Hawaiian Volcano Observatory to study Hawaiian volcanoes.)

Eruption of Kilauea, 1959-60, Modern Talking Picture Service, Inc., 5000 Park Street North, St. Petersburg, Florida 33709. (This award-winning film contains spectacular footage of the highest lava fountains ever recorded and of the formation of Kilauea Iki lava lake.)

Fire Mountain, Encyclopedia Britannica Educational Corporation, 425 North Michigan Avenue, Chicago, Illinois 60611. (Short but excellent film on the 1969-71 Mauna Ulu eruption of Kilauea Volcano.)

Fire Under the Sea—The Origin of Pillow Lava, Moonlight Productions, 2650 California Street, Apt. B, Mountain View, California 94040. (This film features 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 Mauna Ulu eruptions of Kilauea.)

Heartbeat of a Volcano, Encyclopedia Britannica Education Corporation, 425 North Michigan Avenue, Chicago, Illinois 60611. (A case study of an eruption of Kilauea Volcano through the eyes of the scientists of the Hawaiian Volcano Observatory; it contains dramatic scenes of active lava tubes.)

River of Fire, Hawaii Natural History Association, Ltd., Hawaii Volcanoes National Park, Hawaii 96718. (A video cassette that documents the March-April 1984 eruption of Mauna Loa Volcano and contains some of the best footage of Hawaiian lava flows ever filmed.)

The 1955 Eruption of Kilauea Volcano, Hawaiian Islands, Modern Talking Picture Service, Inc., 5000 Park Street North, St. Petersburg, Florida 33709. (A brief film that includes good footage of lava fountains, formation of cinder cones, and advance of lava flows into the Pacific Ocean.)

Volcano—The Birth of a Mountain, Encyclopedia Britannica Educational Corporation, 425 North Michigan Avenue, Chicago, Illinois 60611. (The photographic record of the formation of the 397-foot-high volcanic shield at Mauna Ulu during the 1969-74 eruption of Kilauea; features excellent lava-fountaining and lava-flow scenes.)

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	To convert	to	Multiply by
Length	inch	centimeter	2.5
	foot	centimeter	30.0
	yard	meter	0.91
	mile (statute)	kilometer	1.61
Area	square inch	square centimeter	6.4
	square foot	square meter	0.09
	square mile	square kilometer	2.6
Volume	gallon (U.S.)	liter	3.8
	cubic foot	cubic meter	0.03
	cubic yard	cubic meter	0.76
	cubic mile	cubic kilometer	4.0
Temperature	degree Fahrenheit (^{0}F)	degree Centigrade (^{0}C)	1.8 then add 32

The Kona coast, western part of the Island of Hawaii, is well known for its spectacular tropical sunsets. *(Photograph by Taeko Jane Takahashi.)*

March 3, 1849

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our *fish and wildlife, 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 assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. administration.