Makaʻu Pele: A Learning Game for the Big Island

The stars are on fire, and the moon;
Cold winter is turned to hot summer;
The island is girdled with storm;
The land is scoured and swept barren;
The heavens sag low—high surf in the Pit—
There's toss of a stormy ocean,
Wild surging in Kilauea;
Fire-bellows cover the rocky plain,
For Pele erupts her very self.

Translation of native Hawaiian chant from
Pele and Hiiaka—A Myth from Hawai'i
by N. Emerson (1915)

Pele Rejoicing is a painting by Wallace Kong. Reproduced pending permission from Wallace Kong.

The Main Hawaiian Islands and Hawaiian Hotspot

The Hawaiian-Emperor Chain is the classic example of a hotspot chain formed by a mantle plume. It is the longest (~6000 km in length), and a tectonically simple (distant from any plate margin or continent for over 70 Myr), example of an oceanic island chain or hotspot track on Earth. The Hawaiian hotspot has produced more than 100 volcanoes over 82 million years. The active southeast portion of the chain (the Main Hawaiian Islands) is surrounded by a ~1000 km-wide bathymetric swell, which is thought to be associated with a hot buoyant mantle plume beneath the lithosphere. Hawaiian volcanoes grow from the seafloor to their full height above sea level in about 1 to 1.5 Myr. After their formation, each volcanic island moves off the hotspot with the movement of the Pacific plate, currently migrating at a rate of 9-10 cm/yr to the northwest.

The eight Main Hawaiian Islands extend from southeast to northwest, 625 km from the Island of Hawai'i (the Big Island) to Ni'ihau (Fig. 1). The Main Hawaiian Islands consist of 19 individual shield volcanoes, with 2 shield volcanoes making up the Islands of Oʻahu, Molokaʻi and Maui and 5 subaerial shield volcanoes on the Big Island. The Big Island has the largest land area above sea level, greater than all of the other Main Hawaiian Islands combined, and has the highest elevations (~13,800 ft or 4200 m above sea-level).

Of the entire volume of the Main Hawaiian Islands, from their base on the sea floor to their tops, 97% of the volume is below sea level and less than 3% is above sea level. The ages of the Main Hawaiian Islands are oldest in the northwest (4-6 Myr old) and youngest in the southeast (less than ~1 Myr old), demonstrating how the islands move to the northwest on top of the Pacific oceanic crust. The Hawaiian Islands formed on ~90-100 Myr old oceanic crust that formed at a mid-ocean ridge spreading center called the East Pacific Rise.

The Main Hawaiian Islands lie in the middle of a broad swell that is ~1-1.5 km higher than the surrounding seafloor and ~1000 km across, extending along the axis (trend) of the Main Hawaiian Islands. There is a moat (called the Hawaiian Moat), or broad depression, and a flexural arch (called the Hawaiian Arch) surrounding the Main Hawaiian Islands (Fig. 1). The broad swell creating the Hawaiian Arch is caused by thermal uplift of hotter-than-normal, buoyant mantle beneath the Pacific Plate (the Hawaiian mantle plume) that spreads out laterally around the hotspot and is deflected to the northwest by the migrating Pacific Plate.

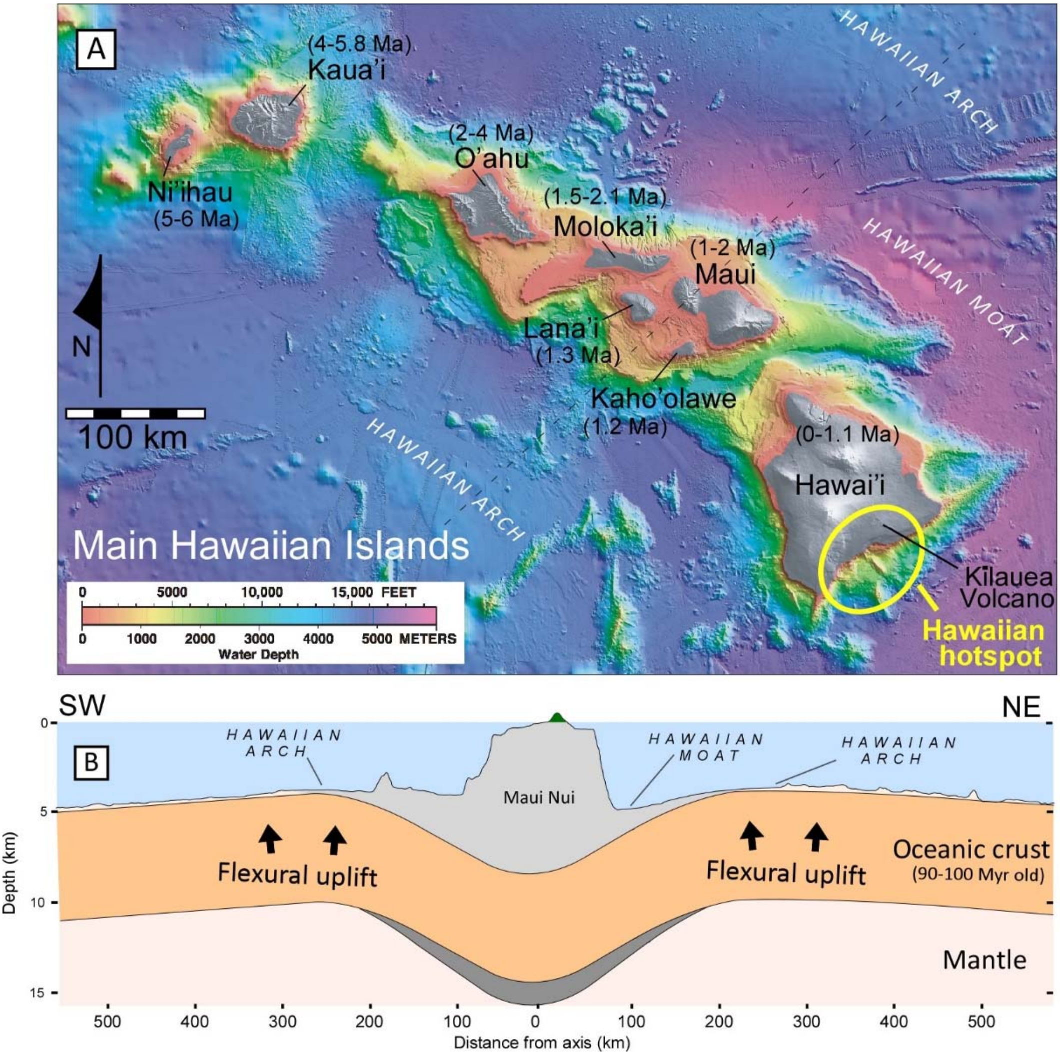
The Hawaiian Moat around the Hawaiian Islands is caused by flexural depression of the oceanic crust because of the heavy load of the Hawaiian Islands as they form above the Hawaiian hotspot. The growing mass of the Hawaiian Islands flexes the oceanic crust downward as they form on the hotspot and cause the oceanic crust to be flexed upward at a radial distance of ~300 km away from the hotspot (Fig. 1).

Hawaiian volcanoes subside (sink) during and after their formation. It is initially rapid (2.6 mm/yr for the Big Island) and thought to be caused by loading of the lithosphere from the accumulation of lavas above the Hawaiian hotspot. The total amount of subsidence varies with the age and size of the volcano. It is inferred from a sharp change in slope, or paleoshoreline, which marks the former shoreline at the end of shield building that represents the maximum extent of the volcano as an island.

As the Main Hawaiian Islands move northwest on the oceanic crust, they undergo a period of uplift (currently the islands of Oahu, Molokai and Lanai) as the Hawaiian Islands move over the flexural arch. After they pass the area of flexural uplift they subside once again, for the rest of their lifetime (Fig. 2). This later subsidence is slower and considered to be a consequence of the lithosphere beneath Hawaiʻi becoming colder and denser.

Hawaiian volcanism is thought to be the surface manifestation of melting occurring within a deep-seated mantle plume, or ‘hotspot’, beneath the Pacific Plate (Fig. 2). The hotspot theory was developed in part to explain Hawaiian volcanism.

Figure 1. Bathymetry of the Main Hawaiian Islands with ages, showing the Hawaiian Arch and Moat. Gray areas are above sea level. The central part of the Hawaiian hotspot at depth is shown with a yellow circle.



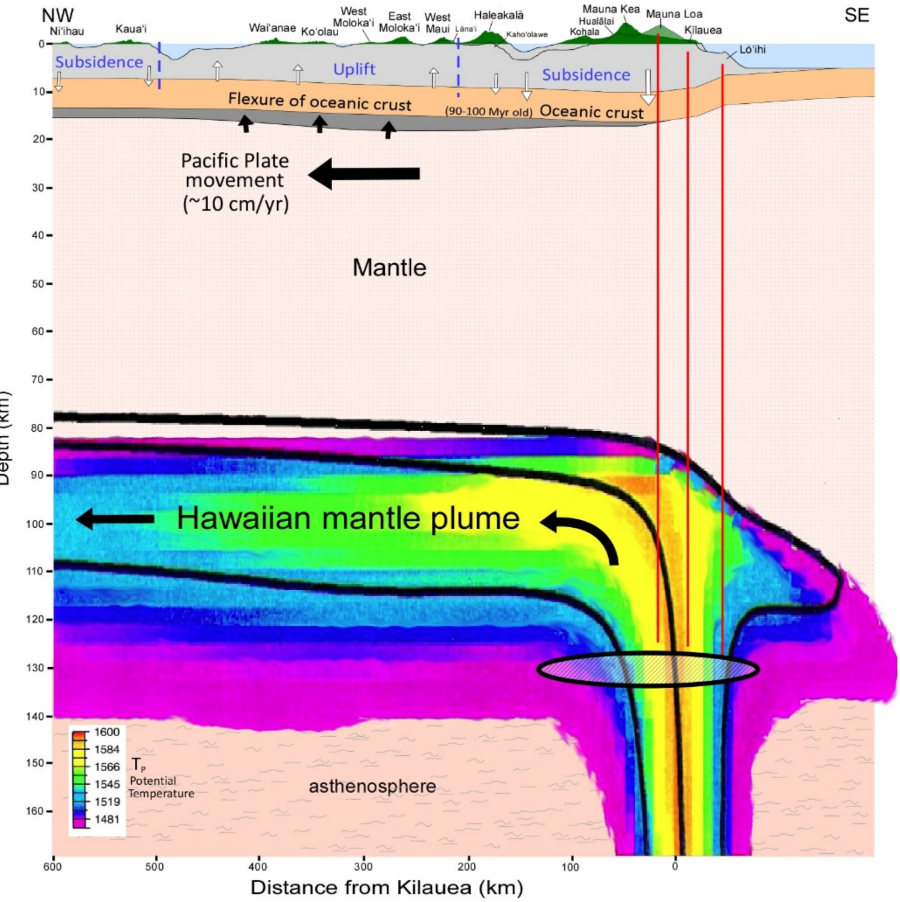


Figure 2. Hypothetical cross-section of the Hawaiian mantle plume and Main Hawaiian Islands, with depth (in km) and distance along the axis of the Hawaiian Islands. Colors indicate potential temperature of the mantle in the Hawaiian plume from a model by Ribe and Christensen (1999).

The origin of the hotspot is generally believed to be a plume of high-temperature material upwelling. The Hawaiian plume is thought to be a narrow column (~50 km wide) of thermally buoyant, hotter-than-normal rock (~250 °C hotter than surrounding mantle). The discovery of both a seismically defined deep conduit under the Big Island, and erupted lavas with distinctive geochemical compositions, have established support for the presence of a deep mantle plume. Recent studies indicate that the long-lived Hawaiian hotspot (>80 Myr) may ultimately originate near the boundary between Earth's outer liquid core and the lowest part of the mantle (~2900 km deep).

Kīlauea, Mauna Loa and Lōʻihi are the most active Hawaiian volcanoes. They are directly above the central part of the rising mantle plume stem of the Hawaiian hotspot (Fig. 3). The lavas that erupt on these Hawaiian volcanoes are thought to originate from partial melting within the upper Hawaiian plume probably at 80 to >100 km depth. These partial melts are extracted from the upwelling mantle within the melting region and pool together, and are transported through chemically-isolated channels towards the surface. The magma system for the Hawaiian volcanoes extends from the melting region, or source, to the uppermost parts of the volcanoes.

Models of mantle plumes indicate the plume likely has a radial structure with a hot central core and temperatures decreasing outward from the plume center. As plume material moves into the temperature range where melting takes place (allowing for decompression melting), the greatest amount of magma (or melt flux) is produced at the center of the plume because of the hotter temperatures (Fig. 3C).

Like a flame blowing in the wind, the vigorous Hawaiian mantle plume is strongly elongated in the direction of the plate motion to the northwest, extending far 'downstream' from the plume stem along the Hawaiian Ridge. The narrow stem of the Hawaiian plume also spreads out beneath the moving oceanic lithosphere (Pacific plate).

As a shield volcano moves on the oceanic crust above the melting zone at the top of the plume stem, the eruption rate (or melt flux) begins with a low rate and gradually becomes higher and peaks before trailing off (Fig. 3E). The youngest volcano on the Hawaiian Ridge, Lōʻihi, rising from the seafloor southeast of the Big Island, does not sample the plume center yet, but is sampling the front edge or 'upstream' side of the plume. Conversely, later-stage rejuvenated volcanism, like Diamond Head, is associated with melts formed from the 'downstream' part of the plume.

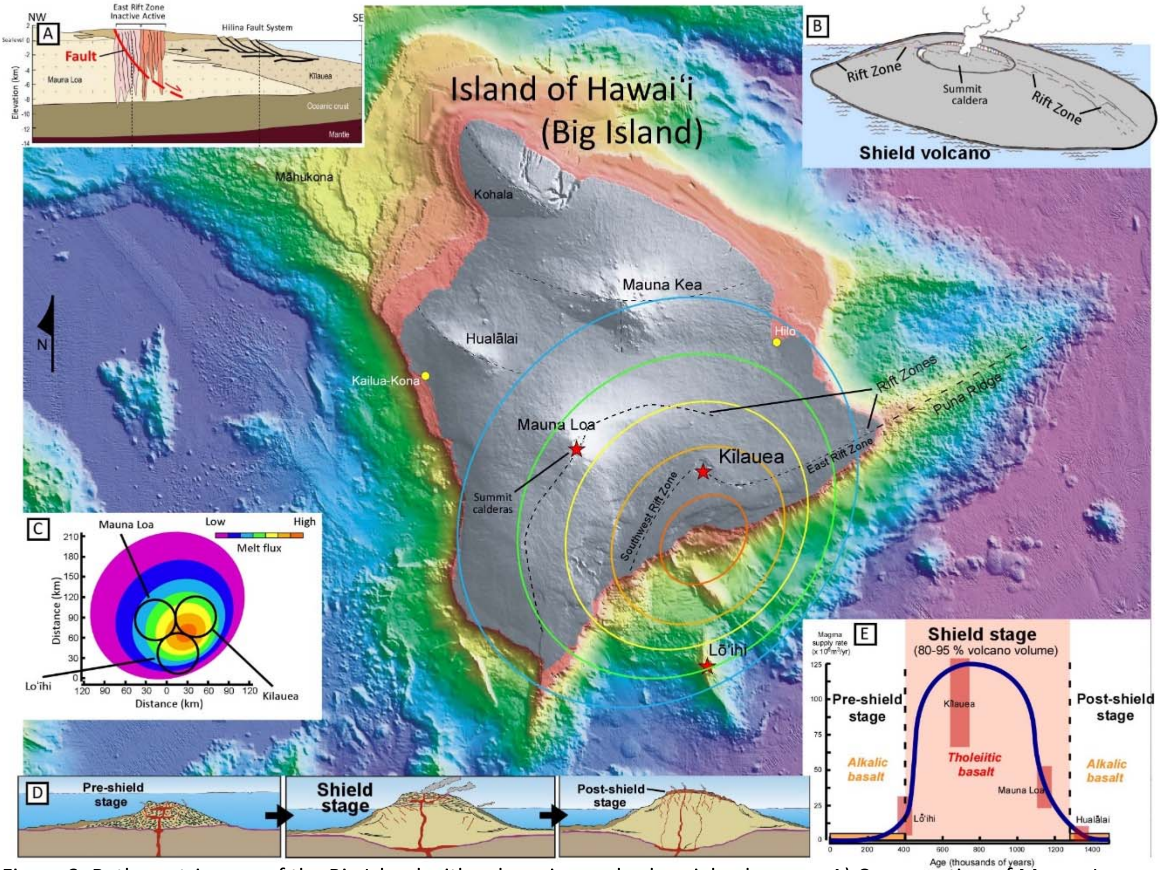


Figure 3. Bathymetric map of the Big Island with submarine and subaerial volcanoes. A) Cross-section of Mauna Loa and rift zone of Kilauea (after Swanson et al., 1976). B) Sketch of shield volcano with rift zones. C) Colored circles approximate the melt flux shown above the map of the Big Island. From Farnetani and Hoffman (2010). D) Sketches of the pre-shield, shield, and post-shield stages of growth of Hawaiian volcanoes. E) Growth history for a Hawaiian shield volcano, showing time periods for stages and primary type of erupted lava. From Garcia et al. (2005).

Growth of the Big Island and Hawaiian Shields

The Big Island is made up of the tops of 5 subaerial volcanoes, with 2 submarine volcanoes offshore on the surrounding flanks of the island (Lōʻihi to the south and Māhukona to the northwest; Fig. 4). There are two parallel lines of volcanoes that make up the Big Island: the western (or Loa) sequence of Māhukona, Hualālai, Mauna Loa and Lōʻihi and the eastern (or Kea) sequence of Kohala, Mauna Kea and Kīlauea.

The two highest volcanoes, Mauna Kea and Mauna Loa, rise as enormous broad shields to about 13,800 ft (4,200 m) above sea level. Mauna Loa is the largest active volcano on Earth — 4 km above sea level, 5 km below sea level to the surrounding ocean floor, and the center of Mauna Loa has depressed the sea floor another 8 km in the shape of an upside-down volcano — with a total thickness at its center of 17 km from the base of the volcano to the top. Like a floating iceberg, most of the volume of the Big Island (94%) is below sea level.

The growth of the Big Island began with Māhukona about 1.5 Myr ago. Kohala then grew on the east flank of Māhukona, and Mauna Kea grew on the south flank of Kohala and rose above sea level about 0.5 Myr ago. Then Hualālai grew on the west flank of Mauna Kea, and Mauna Loa grew on the south flanks of Hualālai and Mauna Kea. Kīlauea is currently growing on the southeast flank of Mauna Loa (Fig. 3A).

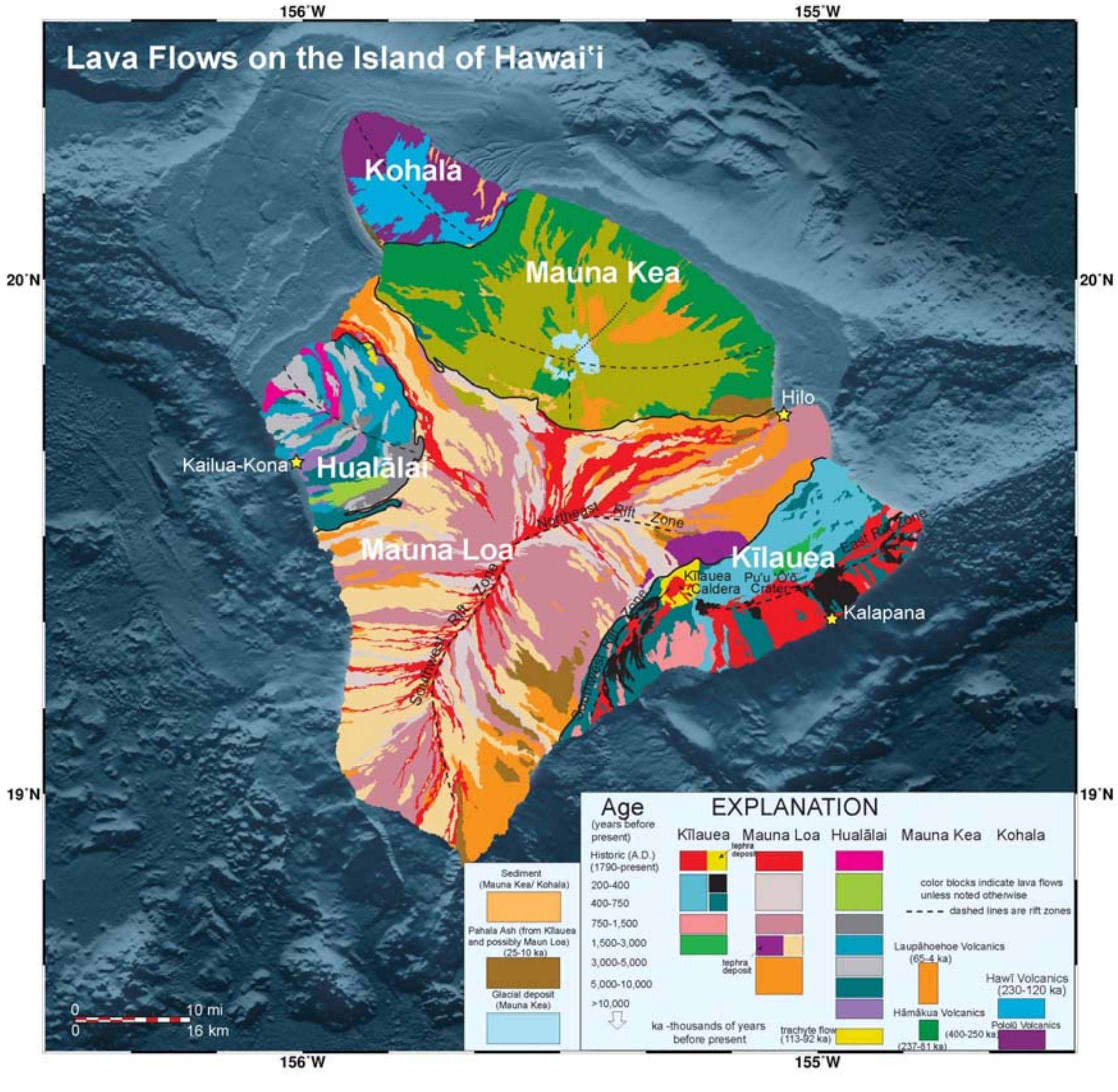
Hawaiian shield volcanoes grow in three main stages — *pre-shield, shield and post-shield* (Fig. 3D). The earliest lavas of each volcano form either on the deep (~5 km) Cretaceous oceanic crust or on the flanks of an adjacent volcano. The typical eruptive sequence for Hawaiian volcanoes starts with pre-shield **alkalic** basalt lavas (with lower silica, and higher sodium and potassium contents), followed by voluminous eruptions of **tholeiitic** basalt lavas (with higher silica, and higher iron and magnesium contents) of the shield stage (forming 95-99% of volcano) capped by weakly **alkalic** basalt lavas of the post-shield stage (Fig. 3E). Lavas formed during the pre-shield stage are deeply buried by subsequent volcanism (>3 km) and are unlikely to be sampled after shield-stage volcanism. Post-shield stage lavas usually form a thin cap of lava flows with tephra cones (e.g., <10 to ~1000 m on Mauna Kea Volcano) on the upper parts of the subaerial shield volcanoes extending to near sea level. The entire main eruptive sequence for Hawaiian shield volcanoes may take ~1.5 Myr to form.

Rift Zones and Magma Movement. As Hawaiian shield volcanoes grow in height, the flanks of the volcanoes extend by gravitational spreading in a direction where they are not buttressed by an adjacent shield volcano. The eruptions that build up Hawaiian shield volcanoes mostly occur at the summits and along the rift zones (Fig. 4B). Rift zones are concentrations (1-4 km wide) of near-vertical cracks, or fissures, that radiate out from the summit along a curved path to the tips of the volcano, and extend deep into the volcano (Fig. 4). Most Hawaiian volcanoes have two main rift zones, and sometimes one or more minor rift zones. The East Rift Zone of Kīlauea Volcano extends about 55 km subaerially, and an additional 60+ km underwater creating a formation known as Puna Ridge.

The intrusion of magma into the shield volcano occurs mostly below the summit and within the rift zones. Intrusions form *dikes* (wall-shaped bodies of rock when lava fills a crack) when lava cools and crystallizes within the rift zone, or lead to eruptions when lava reaches the surface. Rift zones spread apart from forceful injection of dikes as magma intrudes into the volcano, or lateral extension of the volcano may allow dikes to intrude. These intrusions and the lateral extension of the shield volcano may cause faulting or movements of large parts of the volcano that can result in giant landslides onto the ocean floor. As magma rises up into Kīlauea Volcano into a shallow summit reservoir, it pressurizes and swells the volcano, deforming and tilting the volcano's surface. This is called inflation of the volcano. After an eruption, as magma leaves the summit reservoir on Kīlauea, the pressure is relieved and contraction causes changes in tilt and displacement of the volcano's upper surface, called deflation. All the historical eruptions of Kīlauea and Mauna Loa have been preceded by the intrusion of a dike in the same part of the shallow magma system due to increasing pressure in the magma system, and inflation.

In historical times, since about 1750, four of the volcanoes of the Big Island have been volcanically active (Hualālai, Mauna Loa, Kīlauea and Lō‘ihi). The last eruption of Hualālai was in 1801, Mauna Loa in 1984 and Lō‘ihi in 1996. Kīlauea volcano has been erupting nearly continuously from 1983 to the present day, and is one of Earth’s most active volcanoes.

Figure 4. Map of lava flows on the surface of the Big Island, with explanation for age.



Styles of Eruptions and Volcanic Features in Hawai'i. Hawaiian volcanoes are well known for their fluid eruptions of molten lava streaming or oozing down the flank of the volcano. The term 'Hawaiian style' is used by volcanologists to describe highly-fluid, non-explosive lava activity worldwide. Although effusive (non-explosive) volcanic activity may be the dominant style of eruptive activity in the last few hundred years on Hawaiian volcanoes, there are a wide variety of eruptive processes and landforms from Hawaiian volcanism.

Hiking around the landscapes of Hawaiian shield volcanoes on the Big Island reveals — craters and calderas, lava shields and complex cones, lava tubes and perched lava ponds, lava deltas, lava channels, spatter ramparts and cones, lava lakes, pāhoehoe and ʻaʻā flows, tumuli (mounds), lava tree molds and more. These volcanic features form from a range of effusive to weakly explosive to highly explosive eruptions. Recent studies indicate more frequent explosive eruptions on Hawaiian volcanoes in the past than previously recognized, but of lesser volume and area of extent than Pacific Ring of Fire stratovolcanoes, such as Mt. St. Helens. The different types of Hawaiian eruptions each have their own set of hazardous and potentially destructive behavior.

The different eruptive behavior is due to a large number of factors, like the nature of the magma being erupted (lava chemistry and gas content), the magma supply rate (or amount of magma erupted over time), the environment into which they erupt (air, water, or even snow), interaction with groundwater, and stresses on the volcano. Some eruptions are short-lived, lasting days to weeks, whereas other eruptions are long-lived, lasting years to decades, like the current Puʻu ʻŌʻō eruption going on nearly continuously since 1983.

Figure 5. Clockwise from top left, lava flows from flank eruption of Puʻu ʻŌʻō in 1992. Explosive eruption from Halemaʻumaʻu Crater at summit in 1924. Lava lake in Overlook vent in Halemaʻumaʻu Crater in May, 2015. Aerial view of Halemaʻumaʻu Crater with steam plume from Overlook vent in 2014. Aerial view of Kīlauea summit caldera from the southwest. Photos from USGS Hawaiian Volcano Observatory and Bishop Museum.

Summit caldera and craters. Hawaiian shield volcanoes evolve as they grow. They develop broad depressions at their summit, as many volcanoes on Earth do, because of the presence of a large magma body directly beneath the summit. As the volcano continually erupts, large amounts of magma drain from the summit reservoir removing support for overlying rock and creating a void where a large area of the summit collapses along faults to form a broad caldera several kilometers across. A volcanic crater is a circular hole in the ground, smaller than a caldera, which forms from explosive eruptions or collapse, or both, commonly as a site of repeated volcanic activity.

Effusive and Weakly Explosive Volcanism and Their Features

Effusive eruptions are the non-explosive outpouring of molten lava on earth's surface. Effusive eruptions generate a wide array of forms depending on the physical properties of the lava, such as lava viscosity, effusion or flow rate (volume per unit time), and environment of eruption (air, water, local topography). Viscosity is a function of lava chemistry, temperature, gas content and crystallinity. Lava flows are the most common volcanic features in Hawaii, usually with lava travelling in surface flows, channels and tubes to the flow front. Lava flows form several types of crusts (ropy and shelly pāhoehoe, or blocky ʻaʻā) that create numerous flow or cooling features, including accretionary lava balls, tree molds, stalactites and stalagmites, and columnar jointing. Basaltic lava flows on Hawaiian volcanoes frequently, but not always, flow within the summit caldera, or from the summit or rift zone at high elevation down to lower elevation, often to where the lava enters the ocean.

Lava fountains, fissures and lakes. Volcanic centers are usually concentrated near the summit and along rift zones on Hawaiian shield volcanoes. The volcanic activity, near a central vent or opening, is frequently erupted at a high rate in the form of lava fountains (tens to hundreds of meters high), fissure eruptions from large cracks, and lava lakes. Volcanic cones form from the fountaining of lava and the eruption of lava flows over a vent for a prolonged period of time. In the dynamic setting of volcanic eruptions, volcanic cones and crater floors periodically collapse. Repeated overflows of lava lakes sometimes build broader lava shields. Lava lakes are covered with a thin silvery crust that deforms and breaks as the crust moves over a constantly convecting lake. Fissure eruptions produce spectacular, but usually short-lived, curtains of fire. The lava fountains, lava lake and fissure eruptions are products of variable magma supply and stresses within the rift zone or beneath the summit.

Figure 6. Clockwise from top left, Pu'u 'Ō'ō on the East Rift Zone in 2007. Ocean entry on southeast coast of Kīlauea in 2007. Fissure eruption on the East Rift Zone in 1983. High lava fountain from the young Pu'u 'Ō'ō cone in 1983. Lava lake within Pu'u 'Ō'ō cone in 1992. Photos from USGS Hawaiian Volcano Observatory.

Magma transport and storage within the volcano. Kīlauea Volcano has a complex internal plumbing system that brings magma to the summit and out to the flanks of the volcano through the rift zones (Fig. 7). Recent studies suggest most magma entering Kīlauea may be stored in reservoirs that are 1 to 5 km beneath the summit, or where it passes through the summit reservoir system to erupt within the caldera or be transported laterally into the rift zones that may feed eruptions >50 kilometers from the summit.

The summit of Kīlauea has an oval-shaped caldera (~5 x 3 km), or shallow collapse basin, created by faulting of the upper volcano surface after emptying of magma reservoirs after major eruptions, most recently around about 1500 and 1790 AD. Studies of deformation, gravity and seismicity around the summit suggest there may be two distinct long-lived connected magma reservoirs, a deeper one at ~3-5 km depth, and a smaller, shallower one at ~1-2 km depth. The repeated pressurization and swelling of Kīlauea's surface as magma enters the shallow summit reservoir, and contraction as pressure is relieved after eruptions, occur in what are called cycles of inflation and deflation. Swarms of earthquakes, and the inflation and deflation of the upper volcano surface, are used to track the movements of magma and formation of dikes at different levels within Kīlauea Volcano to help predict and understand these volcanic eruptions.

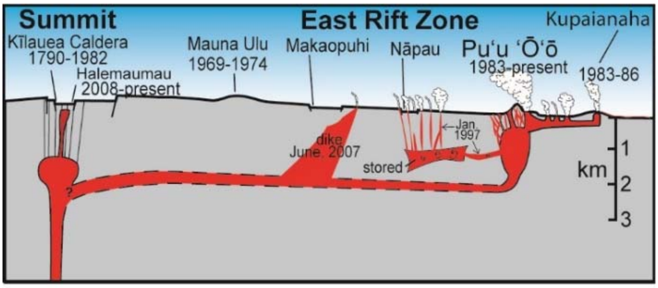


Figure 7. Hypothetical cross-section of the magma plumbing system through the summit and rift zones of Kīlauea. The magma pathways and storage areas are exaggerated in size.

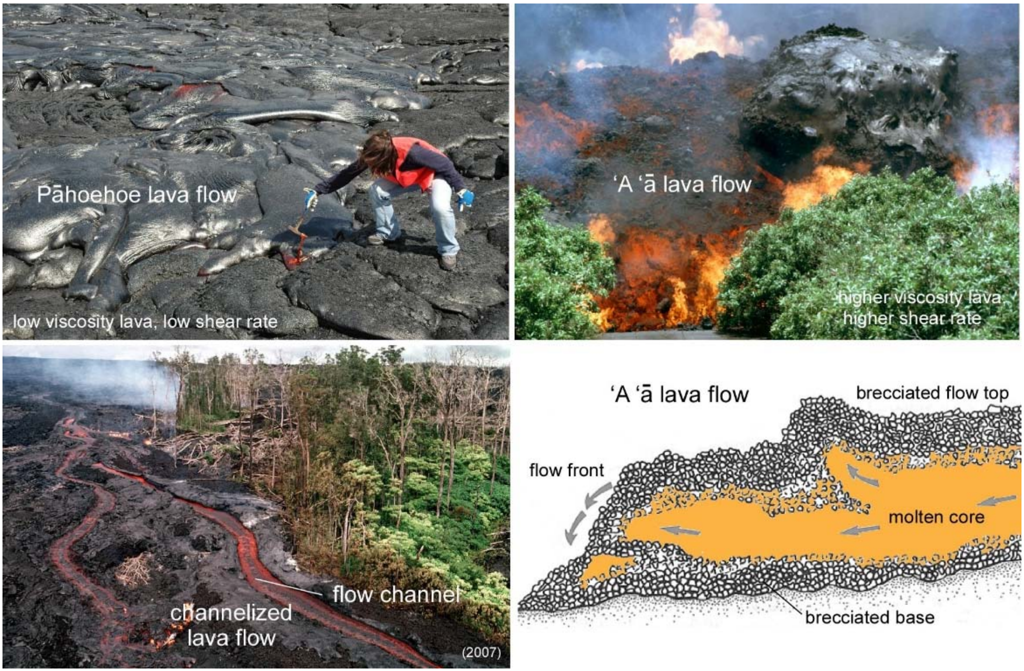


Figure 8. Clockwise from top left, pāhoehoe lava flow on the coastal plain of Kīlauea in 2009. ‘A‘ā flow near Kalapana in 1990 (from USGS HVO). Drawing of a cross-section of an ‘a‘ā flow. Channelized flow on Kīlauea in 2007 (from USGS HVO).

Lava flows, channels and tubes. As basaltic lava travels away from the vent area it takes on different forms due to the varying conditions of flow emplacement. Subaerial basaltic lava comes in two primary forms on Hawaiian volcanoes, named after the Hawaiian terms pāhoehoe and ‘a‘ā. Submarine basaltic flows typically form pillow basalt, sheet flows or fragmental deposits. Most low- to moderate -volume basaltic pāhoehoe flows are fed by lava channels or tubes (crusted over channels). Pāhoehoe lava flows are a network of interconnected inflated lobes. The solidified surface of pāhoehoe flows form many textures (ropy, entrail, slabby, shelly) due to the dragging and deformation of the thin hot plastically-deforming crust as the underlying lava continues to flow. Fresh lobes often breakout from underlying lobes. Pāhoehoe lava flows tend to form rapidly-advancing primary flows and smaller, slower moving breakouts.

‘A‘ā flows are basaltic lavas that have higher viscosity and undergo greater stirring or shear stress, where a jagged, uneven crust forms. Near source fountains and channels often solidify into ‘a‘ā crusts. Over prolonged eruptions lava flows typically develop thermally-insulated lava tube systems that transport the lava long distances, typically from near the source to the ocean entry. The roofs of lava tubes frequently collapse forming holes in the lava tube called skylights. In lava flows with moderate to high effusion rates, lava may travel over long distances in open-channel flows like a river. Overflows or blocking of the channel occur frequently in these relatively short-lived events.

Figure 9. Left, large firehose flow where lava tube intersects cliff on the southeast coast of Kīlauea. Right, Nāhuku (Thurston) lava tube near the summit of Kīlauea.

Figure 10. Clockwise from top left, diagram of lava delta collapse, after Mattox and Mangan (1997). Photo of ocean entry in 2007, from USGS HVO. Photos of lava delta collapse in 2009.

Lava-water interaction. Most years since 1990, lava has been flowing into the ocean on the southeast coast of Kīlauea Volcano in lava tubes or flows. The rapid mixing of lava and water causes the seawater to transform to steam, increasing in volume by 1000 times, generating sudden fragmentation or explosion of the lava. In this coastal setting, lava flows and fragmental debris build out from the coast as a delta. Lava-water interaction occurs in the confined space of lava tubes, causing a buildup of pressure and violent explosions of the lava tube system and collapse of the lava delta. Explosive lava-seawater interaction occurs in the forms of jets, blasts, bubble burst and fountains where tube-fed pāhoehoe enters the ocean and commonly forms a littoral cone.

Highly Explosive Eruptions Recent studies of Kīlauea's long-term volcanic behavior over the last 2,500 years by HVO scientist Don Swanson have revealed centuries of explosive eruptions alternating with centuries of mostly effusive eruptions. Ash layers from explosive eruptions have been found below the surface all over the Big Island, and oral histories by Hawaiians indicate Kīlauea has erupted explosively since human settlement. The cause of some explosive eruptions is believed to be from the interaction of groundwater with Kīlauea's shallow magma reservoir. The explosions are driven by the rapid volumetric expansion of water as it turns to steam on contact with magma. Hydrovolcanic eruptions can greatly vary, depending on the ratio of water to magma and the confining pressure. An explosive eruption in 1924 was caused by groundwater entering the conduit weeks after the draining of a lava lake in the summit crater. Kīlauea's explosive behavior will return again in the future.

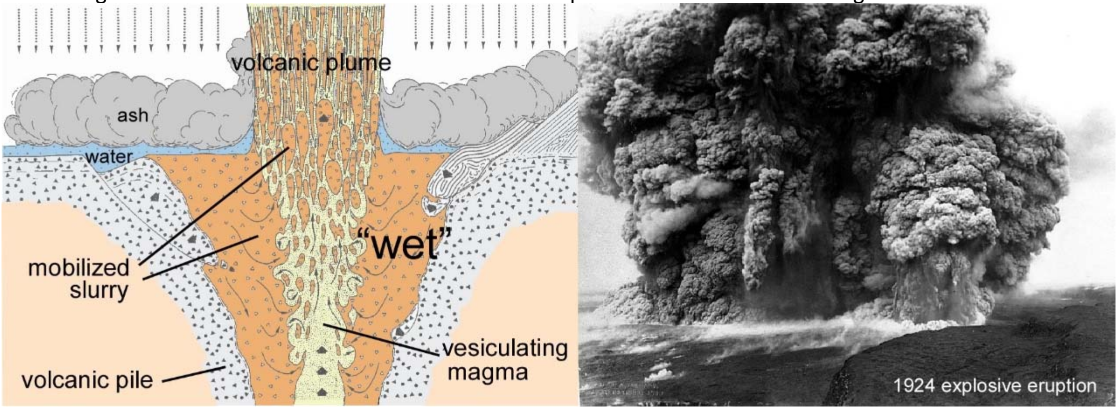
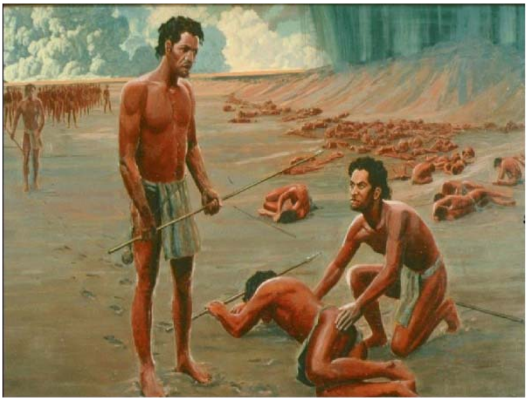


Figure 11. Above left, diagram of a powerful phreatomagmatic eruption. Above right, photo of 1924 explosive eruption from Kīlauea's summit. A powerful phreatomagmatic eruption from Keanakāko'i Crater on Kīlauea in 1790 CE generated base surges that have been estimated decades after the eruption resulted in the death of between 80 to 400 Hawaiians. The explosive eruptions in 1790 from Keanakāko'i Crater destroyed part of Keōua's army from a surge of searing-hot gas and ash, and played a critical role in Hawaiian history. To the right is an artist's reconstruction of the 1790 eruption and deaths of part of Keōua's army, from HVNP. Besides the history of Kīlauea's summit told by Hawaiians, the older explosive eruptions of Kīlauea can be recognized and studied by deposits of volcanic ash, footprints, and other archaeological evidence.



History of Kīlauea Summit Caldera and Rift Zones

Kīlauea Volcano is the youngest subaerial volcano in the Hawaiian Islands and is actively growing through its midlife (for ≤0.6 Ma). Kīlauea rises 1240 m above sea level on the southern flank of its larger neighbor, Mauna Loa (4168 m). Over the last three and a half decades Kīlauea has been erupting lava at the highest rate of any volcano on Earth. Lavas have destroyed >200 homes and a National Park visitor center, and polluted the air for many Hawai`i residents for decades. The subaerial surface of Kīlauea is almost completely resurfaced with new lava flows about every 1000 years, as it grows on the shoulder of its larger neighbor. Gravitational spreading of the southern flank of Kīlauea Volcano is occurring along a detachment fault system that is rooted near the base of the volcano, making the south part of the volcano susceptible to collapse, or catastrophic landsliding.

Kīlauea Volcano periodically shifts its' eruptive behavior between different styles of activity. The history of the summit of Kīlauea has revealed periods of caldera formation and phases of refilling of the caldera with lava flows. Collapse of the summit caldera is thought to occur when there has been rapid draining of the magma in Kīlauea's summit reservoir, when the overlying area of the summit collapses into this void. The shield-stage eruptions of Kīlauea also shift back and forth between explosive and effusive (lava flow) eruptions over periods of hundreds of years — explosive for over ~1000 years, effusive for ~500 years, explosive for ~300 years and effusive for the last 230 years (Fig. 12). Explosive activity (~60% of the time) appears to occur during times of very low magma supply rate to the shallow magma reservoirs in Kīlauea, and may happen at times when the summit caldera intersects the water table, where fractures and pore spaces are filled with groundwater.

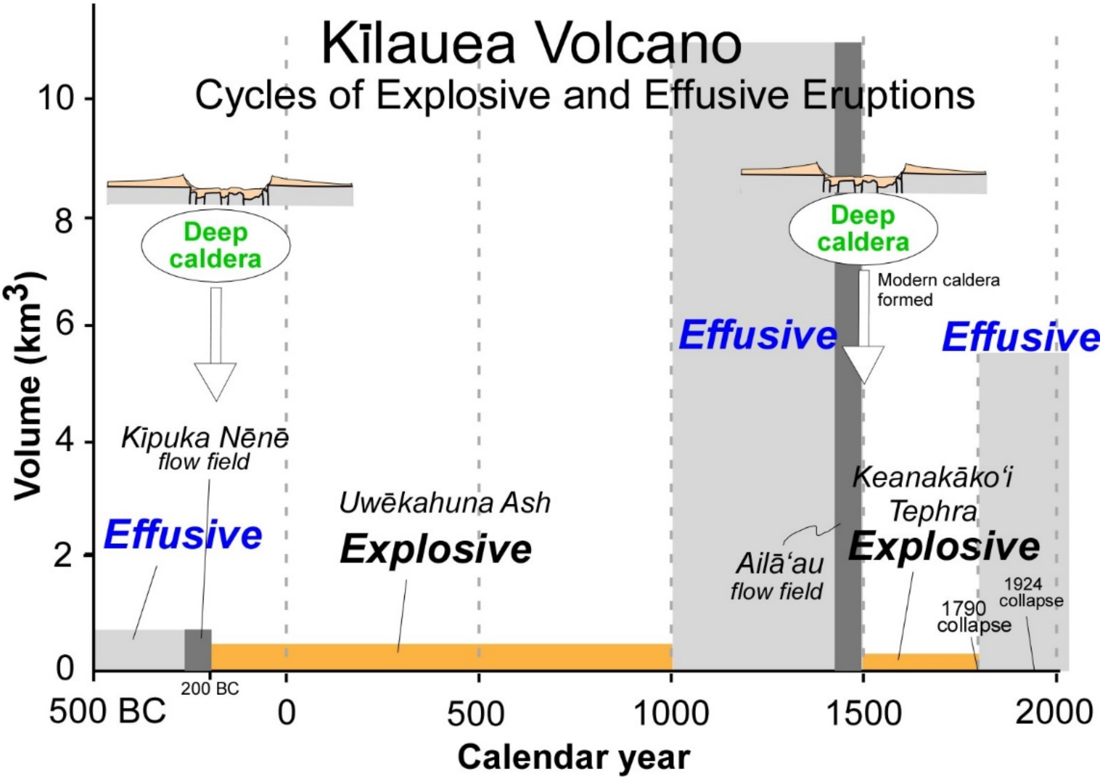


Figure 12. History of explosive and effusive eruption cycles on Kīlauea Volcano, based on Swanson et al. (2014).

Kīlauea eruptions occur in and around its summit caldera and on the East and Southwest Rift zones (Fig. 13). Prior to 1955, historical (post-1820) eruptions on Kīlauea occurred at or near the summit. Since 1955, eruptions on the rift zone have become more common, especially along the East Rift Zone. Most eruptions on Kīlauea Volcano since 1800 have been effusive or weakly explosive eruptions, except for an eruption in 1924.

Inflation of the surface of Kīlauea is often accompanied by a concentration of earthquakes, as magma moves in Kīlauea's shallow magma plumbing system. These concentrations of earthquakes are commonly referred to as earthquake swarms. When new eruptions first start on the East Rift Zone of Kīlauea, the ground surface opens up by forming large cracks, or fissures, where magma erupts in curtains of fire. Many eruptions on the East Rift Zone begin with a period of lava fountaining followed by lava flows. Kīlauea Iki on the upper East Rift Zone was the site of a spectacular eruption in 1959 with lava fountaining reaching 580 m high and a lava lake that filled and drained repeatedly for four weeks.

Figure 13. Left, lava lake inside Overlook vent in Halemaʻumaʻu Crater in 2014. Right, small lava lake within Pu'u 'Ō'ō Crater active at the same time in 2014. Photos from USGS HVO.

Kīlauea currently has two active eruptions: Puʻu ʻŌʻō (1983-present) on the East Rift Zone, and a crater in the summit caldera called Halemaʻumaʻu (2008-present). There are no other historical examples of any Hawaiian volcano erupting concurrently from two sites for multiple years. Puʻu ʻŌʻō has been Kīlauea's longest-lived and largest-volume historical eruption. Prior to the Pu'u 'Ō'ō eruption of Kīlauea, the previous multi-year eruption was uprift (toward the summit) from Pu'u 'Ō'ō at Mauna Ulu from 1969-1974.

The Puʻu ʻŌʻō eruption began on January 2, 1983 with the intrusion of a dike within Kīlauea's East Rift Zone. It was followed 24 hours later by eruptive activity along a discontinuous 7 km long fissure, which localized to a central vent, Puʻu ʻŌʻō. The eruption can be categorized into three broad phases based on eruptive style and location: (1) ***1983-1986***: brief (mostly less than 24 hours), episodic eruptions (24 day average repose between eruptions) with fountaining up to 400 m, mainly from the Puʻu ʻŌʻō vent (2) ***1986-1992***: nearly continuous effusion from the Kupaianaha vent, 3 km uprift, which was considered to have a shallow (<100 m deep) conduit connection with Puʻu ʻŌʻō; and (3) ***1992-Present***: nearly continuous effusion mostly from vents within, and on the southwest and east flanks of Puʻu ʻŌʻō, and from rootless shields ~2 km east of Puʻu ʻŌʻō. This pattern was interrupted in 1997 by the ~150 m collapse of the crater floor inside the Puʻu ʻŌʻō cone, and propagation of eruptive fissures 4 km uprift of Puʻu ʻŌʻō, and again in 2011. Afterwards, and until June 2007, lava erupted nearly continuously from flank vents on Puʻu ʻŌʻō (episode 55). The other notable Kīlauea eruptive activity during the Puʻu ʻŌʻō eruption is an ongoing summit eruption with mild, infrequent explosivity that began in March 2008.

The wide variety of volcanic activity on the Big Island presents a range of hazardous processes, and attractions, for residents and visitors.

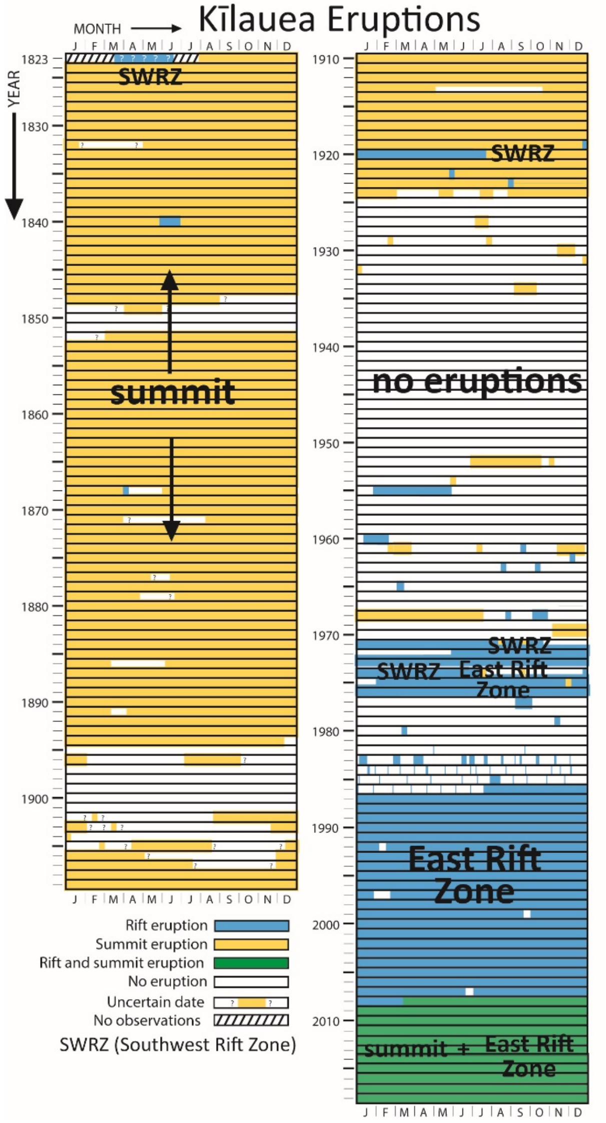


Figure 15. Summary of historical eruptive activity at Kīlauea Volcano from the first written observations in August 1823 to 2017. Activity is subdivided by location of eruptive activity. Modified after Garcia (2015), based on references therein.

The Nature of Volcanic Hazard Risk Reduction in Hawai'i

In 1912, Thomas Jaggar, a Harvard and MIT geologist, came to Hawai'i to establish the Hawaiian Volcano Observatory (HVO) on the summit of Kīlauea Volcano. Jaggar had been deeply influenced by visiting the ruined city of St. Pierre on the island of Martinique in the Caribbean after a devastating eruption of Mont Pelée in 1902 killed 28,000 people. This experience, and other earthquake and tsunami disasters around the world, inspired Jaggar to establish HVO for humanitarian purposes, with the main objective of using scientific research to reduce the risk from natural hazards. Over the century since 1912, HVO scientists, as well as many university scientists and government officials, have developed techniques for monitoring volcanic eruptions, earthquakes and other hazards — to understand, educate and help protect citizens living with the active threat of natural hazards in Hawai'i.

Hawai'i is recognized worldwide as one of the most volcanically active areas of the world. The dynamic ocean island setting of the Big Island has a long history of frequent eruptions with spectacular lava fountains and rivers of lava, destructive earthquakes and landslides, and impacts from Pacific-wide and local tsunami. Living on such large, active volcanoes for residents of the Big Island comes with accepting and appreciating the risks. As former HVO scientist-in-charge Jim Kauahikaua states, "Those of us who live here deal with the consequences of volcanic activity every day — both good and bad. So, if we choose to live on the Island of Hawai'i, we must learn to live in harmony with the dynamics of its ever-changing environment."

Scientists have approach researching Hawaiian volcanic hazards of mostly effusive eruptions in the last century by studying lava flow emplacement and hazards, creating hazard zone maps, estimating probabilities of lava inundation, forecasting flow paths, and providing advice on lava diversion, emergency management and land-use planning. The techniques for monitoring active volcanoes, which have evolved and been practiced at HVO, include:
Seismic monitoring of earthquakes using a network of instruments on the volcano as one of the primary techniques for tracking the movement of magma within the volcano.
Deformation monitoring of slight movements of the volcano's surface using ground and satellite-based instruments track movements of large amounts of magma in the volcano as it inflates and deflates.
Volcanic-gas monitoring by collecting gas samples near the vent and using instruments to help scientists estimate the depths and volumes of magma.
Geologic monitoring using fieldwork to make geologic maps, observe flows and obtain lava samples for tracking an ongoing eruption and developing an understanding of the magma plumbing system and transportation of magma within and on the surface of the volcano.
All of the monitoring results are communicated with the scientific community, government and emergency management officials, and the media and residents, to help forecast, educate and protect the public.

During the 2014-2015 Pāhoa lava flow crisis on Kīlauea Volcano (Fig. 16), when a 20-km long lava flow encroached upon the town of Pāhoa before coming to a halt, flows were observed and tracked by HVO using flights by helicopters, ground-based mapping, and satellite imagery. The public were kept informed about progress and forecasts for the lava flows and educated about hazards. Preparations for possible lava flow inundation by Hawai'i County crisis included building emergency access road to prevent residents from being cut off from the rest of the Big Island and physical barriers to protect utility poles.

Figure 16. 2014-2015 Pāhoa lava flow crisis.

The primary way to reduce the risk from active lava flows is through diversion. Three ways of diverting, or delaying, lava flows that have been attempted in Hawai'i, are by using explosives, water, or physical barriers. Army aviators bombed the upper channels of lava flows for the first time in 1935 to attempt to divert a lava flow from Mauna Loa from threatening the water supply above Hilo. A stone wall was built during the 1880-1881 eruption of Mauna Loa that threatened Hilo. Physical barriers were built to protect structures and properties during the 1955 and 1960 Kīlauea eruptions in the Puna area. The use of water to delay or stop flows has not been very successful in Hawai'i, but was successful in Iceland in 1973 on a much larger scale. Hawaiian cultural influences and beliefs, as well as legal considerations, have traditionally been reasons why diverting or bombing lava flows to protect properties have not been used. Any interference of the natural flow of lava by people may result in other properties being damaged or destroyed, which may not have been had the diversion not been used. In 1990 when lava flows threatened properties in Kalapana, some homeowners decided to move or relocate structures, to try to save their homes, but most of the properties were destroyed. In 1960, lava flows destroyed much of the village of Kapoho on Kīlauea's East Rift Zone. Interviews of residents from the village of Kapoho, after their town was destroyed by the eruption, found that Hawaiians favored the construction of barriers to divert lava flows, but did not support bombing to divert lava flows.

The two most populous areas of the Big Island, Hilo and Kailua-Kona, are at the greatest risk from lava flows emanating from Mauna Loa. After 1800, Mauna Loa erupted about once every six years, and since 1900, there have been 12 eruptions. The most recent eruption of Mauna Loa was in 1984 when lava flows stopped within 7 km (4.5 miles) of Hilo. South Kona has the highest risk form lava flow inundation from eruptions on the Southwest rift zone of Mauna Loa, whereas Hilo has the greatest risk from eruptions of the Northwest rift zone of Mauna Loa. Lava flows from Mauna Loa would likely travel faster from the summit to Kailua-Kona due to geography. Hazard assessment for lava flows involves estimating where and how far lava flows are likely to travel, and how quickly they will travel.

Other natural hazards on the Big Island include explosive eruptions, gas emissions, earthquakes, tsunami and volcano flank collapse, as well as severe storms and flooding. Thomas Jaggar suggested that the key to minimizing damage from earthquakes was to improve construction of buildings. Persistent release of volcanic gases (SO_2, and small amounts of hydrogen sulfide, carbon monoxide, and HCL and HF) are emitted in large volumes from Kīlauea. The sulfur dioxide reacts with moisture, oxygen, and sunlight to form volcanic smog, called vog in Hawai'i, which is an irritant to lungs and eyes, and creates acid rain that damages crops and plants. Ashfall, pyroclastic flows or surges, volcanic gases, and volcanic bombs, are all direct volcanic hazards from explosive eruptions of Hawaiian shield volcanoes. Large rapid flank displacements of Mauna Loa and Kīlauea may present significant hazards for residents of the Big Island by generating an earthquake, giant landslide, or associated tsunami. A tsunami that killed 46 people on the southeast coast of the Big Island near Punalu'u was generated by the earthquake and flank movement in 1868. During an earthquake in November 1975, the 7.2 magnitude event was accompanied by 8 meters of vertical displacement, which generated a tsunami on the coast where two campers were killed at Halapē on the south coast of Kīlauea.

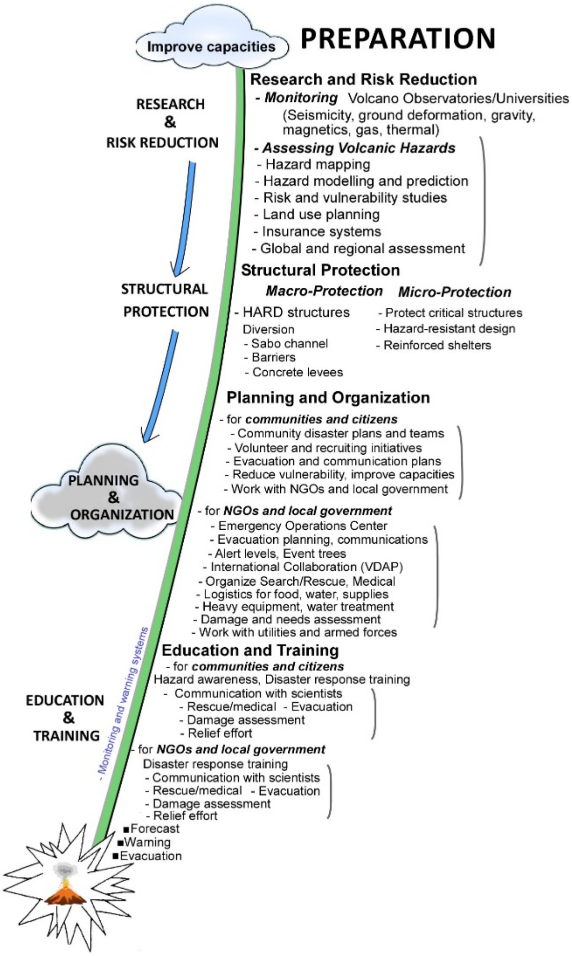


Figure 17. One view of planning and preparation for natural hazards, in anticipation of volcanic hazards.

A catastrophic volcano collapse would generate very large tsunami that would dramatically impact the neighboring Hawaiian Islands. Geologic evidence indicates ancient landslides (>120, 000 years) from the west side of Mauna Loa likely generated tsunami 155 m high that impacted neighboring islands. The southeast side of Kīlauea Volcano is currently undergoing gravitational slumping. The instability of the southern flank of Kīlauea Volcano, which periodically results in the seaward displacement of the volcano, will likely lead to earthquakes, tsunami, and landslides. Living with the hazards of active volcanoes is a way of life for residents of Hawai'i, and the Big Island is a natural laboratory to monitor, forecast, educate and protect the public in this dynamic geologic environment.