Putting Kilauea in Perspective

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On March 26, 2019, the Hawai'i Volcano Observatory (HVO) lowered the alert level for Kilauea to NORMAL, which means the volcano is in a non-eruptive state.

Introduction

Last summer, as Kilauea erupted on Hawai'i's Big Island (fig. 1) and the people of Guatemala recovered from the tragic events that followed Volcán de Fuego's violent outburst, volcanoes were very much in the news. We are fascinated by them, and as we view the devastating effects of their terrible power, many are wondering if similar eruptions could happen closer to home? In the United States the principal concerns are Mount St. Helens and other volcanoes in the Cascade Range of the Pacific Northwest (fig.2), in which case the answer is both yes, but not any time soon, and no.

Figure 1. Lava erupts from a fissure in Kilauea's lower East Rift Zone on May 15, 2018. Kilauea began to erupt twelve days earlier on May 3 (USGS, 2018). Photo courtesy of the U.S. Geological Survey.

Figure 2. The Cascade Range of the Pacific Northwest has several volcanoes that have erupted within historical times. Shown here are Mount St. Helens (foreground) and Mount Rainier in Washington State. Photo by John Pallister, U.S. Geological Survey Cascades Volcano Observatory.

Cascade volcanoes

More than 99% of Earth's volcanism is associated with plate boundaries (Burke and Wilson, 1976), either along spreading centers like the Mid-Atlantic Ridge where the formation of new ocean crust is slowly widening the gap between Eurasia and Africa on one side and North and South America on the other; or above subduction zones at convergent plate boundaries where one of the colliding plates (invariably oceanic because oceanic crust is denser than continental crust) is overridden by the other and sinks into the mantle. The 450 or so volcanoes that circle the Pacific Ocean in the so-called Ring of Fire (fig. 3) are all products of subduction.

The Cascade volcanoes are part of the Ring of Fire. About 50 miles offshore of Vancouver Island in British Columbia is one end of a deep trench that extends southwards along the Pacific coast in a 620-mile subparallel arc to Cape Mendocino in northern California. This is the Cascadia subduction zone, where three small slabs of ocean crust, the Explorer, Juan de Fuca, and Gorda plates are colliding with and diving east and northeastwards beneath the North American plate.

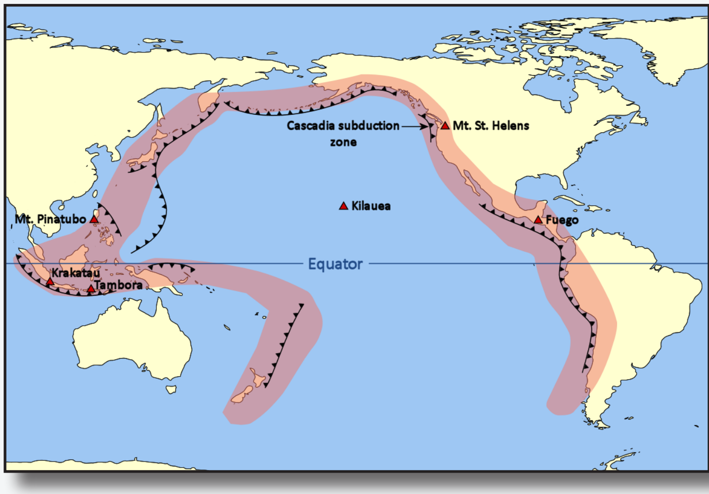
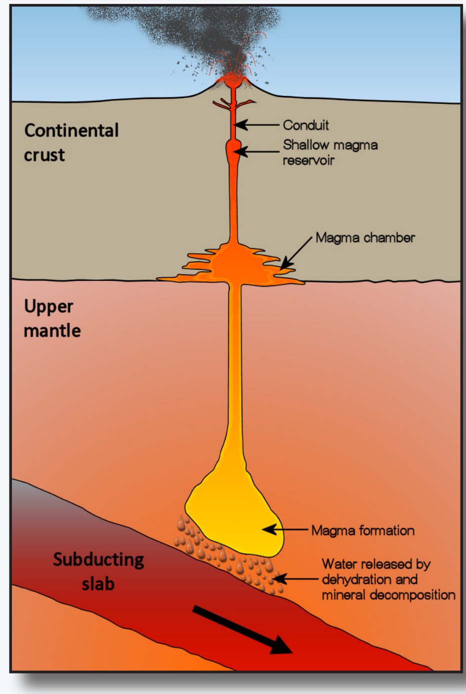


Figure 3. Hundreds of volcanoes circle the Pacific Ocean in the so-called Ring of Fire (shaded pink). Major convergent plate boundaries (subduction zones) are depicted as black lines with sawteeth pointing in the direction of movement of the subducting plate. Red triangles represent some of the ring's more well-known volcanoes. The location of Kilauea is also shown.

Figure 5. Formation and ascent of magma beneath Mount St. Helens. Magma forms as water is released from the subducting slab into the overlying mantle. Because it is more buoyant than the surrounding rock, the magma rises towards Earth's surface. Most remains in a large chamber at the base of Earth's crust, but some will continue upwards and eventually erupt from the volcano. Based on an image by Daniel Dzurisin, U.S. Geological Survey.



The essential features of a subduction zone at a convergent ocean-continent plate boundary are shown in figure 4. Subducting oceanic plates are typically rich in hydrous (water-bearing) minerals and free water that has become trapped in voids in the descending plate. A few dozen miles below the surface, all this water is released as the plate begins to dehydrate and the minerals decompose under the intense heat (fig. 5). Enormous volumes of water vapor and some carbon dioxide (CO_2) escape into the overlying rock of the continental lithosphere, chemically altering the rock (a process called metasomatism), which causes a significant reduction in its melting temperature. The resultant magma, being less dense than the surrounding unaltered and still-solid rock, rises into Earth's crust where most of it remains, slowly cooling and solidifying, in large chambers several miles below the surface. Some, however, continues upwards and erupts, often explosively, to form a volcanic arc – a chain of volcanoes inland of, and parallel to, the subduction zone (fig. 6).

There are two main reasons why volcanic activity associated with oceanic-continental plate convergence tends to be so violent. The first has to do with the chemical composition of the magma, in particular its silica content*, because this, along with temperature, are what control the magma's viscosity – its ability to flow. As a general rule, silica-rich magmas are more viscous than silica-poor magmas. Continental crust is composed mostly of light-colored felsic (sodium-, potassium-, and silicon-rich) igneous and metamorphic rocks of primarily granitic composition. Rhyolitic and dacitic (high-silica, volcanic) magmas derived from these rocks are consequently highly viscous and do not flow well. Temperature has an inverse effect on magma viscosity: provided nothing else changes, a magma's viscosity decreases with increasing temperature.

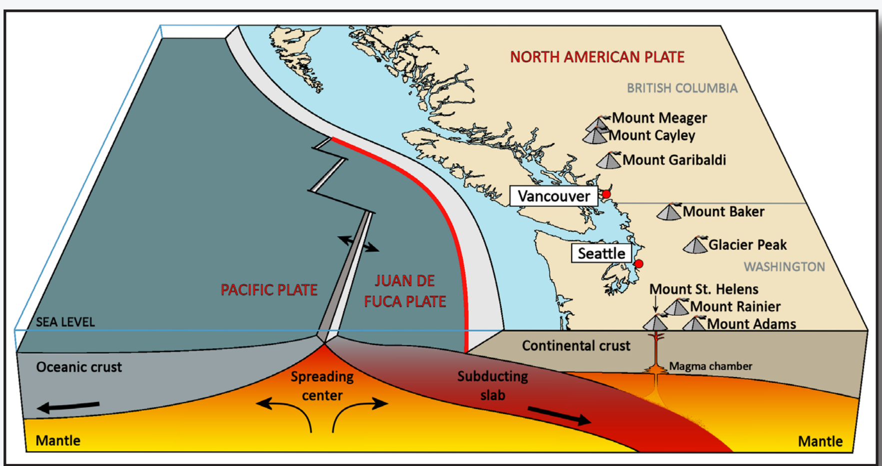


Figure 4. Simplified cross-section of the Cascadia subduction zone, where three small slabs of ocean crust, the Explorer, Juan de Fuca, and Gorda plates are colliding with, and diving east and northeastwards beneath the North American plate. The Explorer and Gorda plates are not shown. A deep trench forms where the ocean plate begins to move downwards into the mantle and drags the leading edge of the overlying continental plate with it. Based on an image courtesy of the U.S. Geological Survey.

The second reason is all that water. Between about 1 and 5 percent of a magma's weight is dissolved gas, most of which is water. Although some of it may be incorporated into new minerals formed during metasomatism, most of the water released into the lithosphere by a sub-

**The chemical composition of igneous rocks is usually reported as the relative abundance (in wt %) of each element in the form of its simple oxide. For example, silicon is reported as SiO_2 (silica), aluminum as Al_2O_3 (alumina), and iron as its monoxide FeO.*

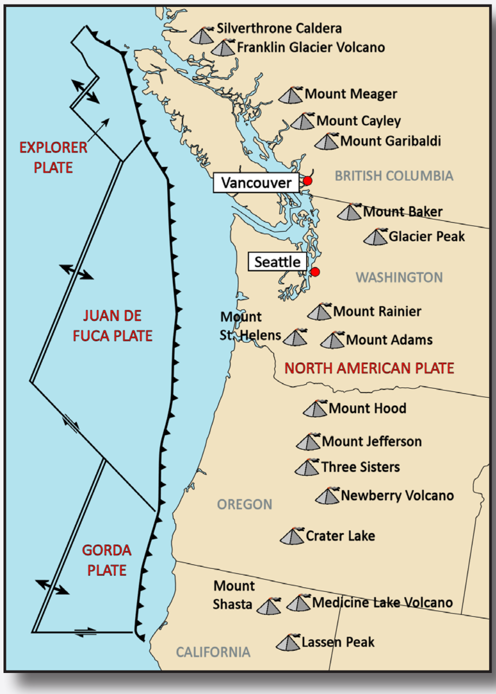


Figure 6. The Cascades volcanic arc. The saw-toothed line has the same meaning as in figure 3. Drawing based on images courtesy of the U.S. Geological Survey and NASA WorldWind.

ducting plate remains dissolved in the rising magma along with other volatiles like CO_2 and sulfur dioxide (SO_2). As it moves upwards through the crust, the corresponding decrease in geostatic pressure eventually reaches a point at which the magma begins to degas. Gas bubbles, small and few in numbers at first, expand and multiply as the magma approaches the surface but, constricted by the magma's high viscosity, cannot escape and their internal pressure builds up even as the geostatic pressure continues to fall. If this pressure difference becomes too great, by sudden exposure to atmospheric pressure during an eruption or the accumulation of too much gas in the magma reservoir beneath the volcano, for example, the bubbles react by exploding. The effect is much the same as when the top is removed from a can of well-shaken soda. This is what happened at Fuego on June 3, 2018 and on Mount St. Helens in May 1980 when the biggest landslide in Earth's recorded history triggered a violent eruption that blasted the top of the mountain to smithereens and sent a massive cloud of ash and shattered rock hurtling towards the stratosphere (fig. 7). Explosive eruptions like these are incredibly destructive and capable of wreaking havoc on a very large scale through potentially far-reaching hazards like pyroclastic flows, lahars (volcanic mud flows), and ash falls.

Volcanoes have been erupting in the Cascades for more than half a million years and will continue to erupt for as long as the Cascadia subduction zone feeds them. Mount St. Helens is one of eleven Cascade volcanoes that have erupted in the last 4,000 years and one of seven that have erupted since the beginning of the eighteenth century, some multiple times. Those of us who remember the 1980 eruption of Mount St. Helens may well live to see it erupt again but it will be a while yet before that happens. For now, the volcanoes in the Pacific Northwest are quiet and pose no imminent threat to the people who live there.

Figure 7. Eruption column from Mount St. Helens, May 18, 1980. View is from the southwest. Photo by Robert Krimmel, U.S. Geological Survey.

Volcanic "hot spots"

There are no plate boundaries within 2,000 miles of the Hawai'ian Islands.

Hawai'i's volcanoes are, instead, the surface expression of what is known as a "hot spot": generally attributed to a persistent upwelling of a column or plume of hot material from a point source deep in Earth's mantle. (Not everyone agrees with this hypothesis. The origin of hot spots has been the subject of a fierce geologic debate for more than forty years. [See, for example, Foulger, 2011, 2018; Pratt, 2016.]) Estimates of the number of hot spots around the globe vary wildly from around 20 to several thousand, depending on how they are defined, but the general consensus is that there probably aren't more than a few dozen. Most are located under oceanic plate interiors or at mid-ocean ridges and besides the Hawai'ian hot spot include the island groups of Galapagos, Pitcairn, and Samoa in the Pacific, Réunion in the Indian Ocean, and Iceland in the north Atlantic. A handful of continental hot spots are also known to exist, most notably the one below Yellowstone National Park in Wyoming.

Almost all oceanic crust, whether generated at mid-ocean ridges or by island volcanism, is composed of basalt. Derived from magmas produced within Earth's mantle, basalts are characteristically dark in color, low in silica and rich in heavier elements like calcium, magnesium, and iron relative to their felsic counterparts. The comparatively low viscosities of silica-poor basaltic magmas means they are more inclined to flow and less likely to erupt explosively because of the ease with which any dissolved gases are able to escape. Lava flows are commonly associated with effusive (non-explosive) volcanic activity.

Effusive eruptions are generally not as violent as explosive eruptions and their effects are more localized. They are dangerous nonetheless. Kilauea's current activity is restricted to the summit caldera and a roughly 50 square mile area on the east side of the Island of Hawai'i (Big Island) (fig. 8). It is the latest episode in an eruptive phase that began along the East Rift Zone on the volcano's southeast slope in 1983 and has since continued without a break. In 2008, following a hiatus of 25 years, the summit also began to show signs of renewed activity that in May 2018 forced the closure of the entire Kilauea section of Hawai'i Volcanoes National Park after the summit caldera started to subside (fig. 9). The accompanying increase in seismicity, still-molten flying debris from collapse explosions, and the emission of hazardous levels of ash and SO_2 kept the park closed for months. In the lower East Rift Zone, lava flows destroyed 716 homes and about 30 miles of roads along with everything else over an area of 13.7 square miles, and an estimated 2,500 people had to be evacuated (USGS, 2019). Yet casualties were mercifully few, mainly because Hawai'ian lava flows don't move very fast – a few miles an hour at most – so they are easily outrun.

Figure 9. Ash billows from a crater at the summit of Kilauea Volcano following a collapse explosion caused by a rock fall from the crater walls on May 9, 2018. Photo courtesy of the U.S. Geological Survey.

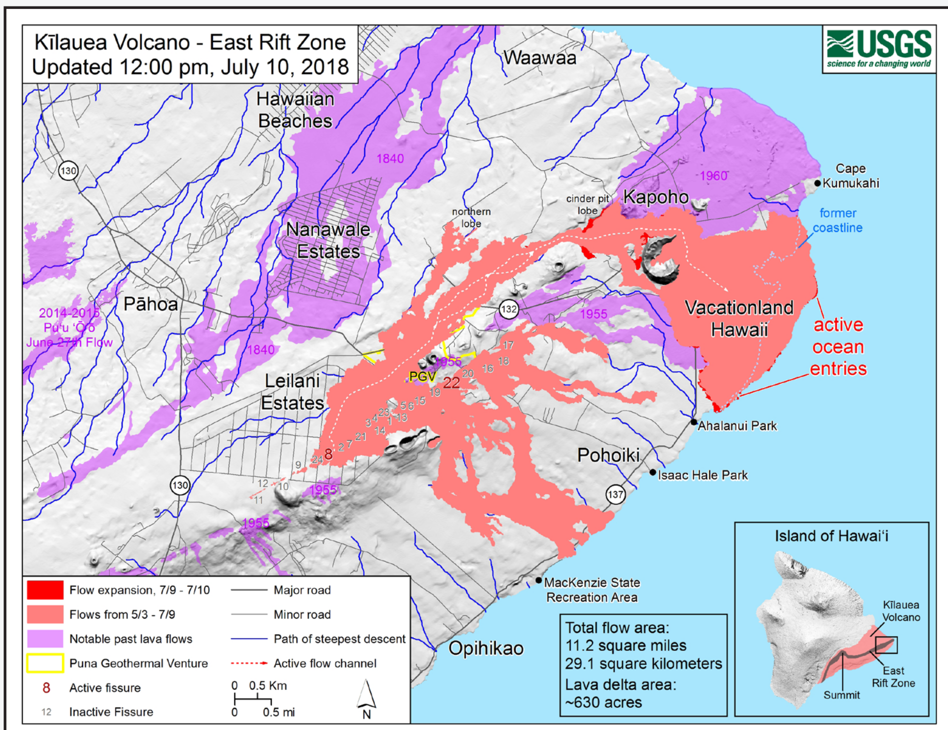


Figure 8. Map of Kilauea's lower East Rift Zone. Orange and red areas indicate the extent of lava flows erupted between May 3 and July 10, 2018. Light purple areas represent older flows, erupted in 1840, 1955, 1960, and 2014-2015. Source: U.S. Geological Survey Hawai'ian Volcano Observatory.

Some media headlines portrayed the entire Island of Hawai'i as a scene out of Dante's Peak. Local businesses blamed those "doomsday scenarios" for a marked decrease in the number of tourists visiting the island last summer (Raymond, 2018). The truth is, Kilauea occupies about 550 square miles (13.7%) of the above-sea level area of Hawai'i Island (figs. 8, 10). The volcano's relatively remote position left the rest of the island largely unaffected by its activity and even within its confines only a fraction of the area was seriously impacted (fig. 11). In other words, around 90% of Hawai'i Island and virtually all the rest of the state were safe. Nor is there cause for concern that a Kilauea-style eruption could happen in the continental U.S. because the tectonic setting is all wrong. Effusive basaltic eruptions in continental settings are rare in the geologic record and are generally considered to be the result of a hot spot underlying a region of crustal extension (pulling apart) associated with rifting and the breakup of large landmasses.

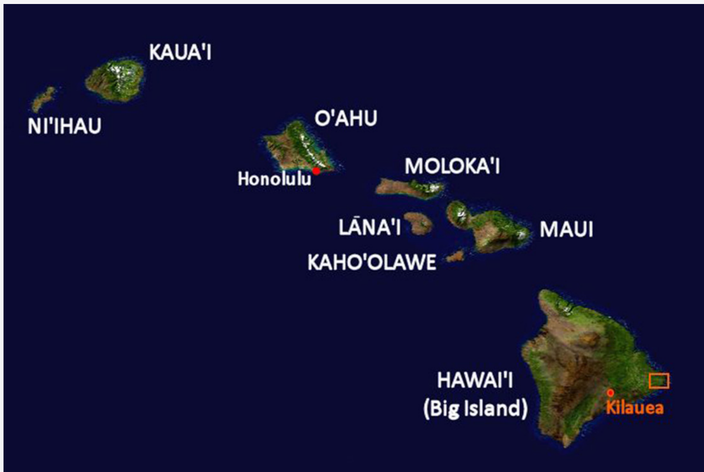


Figure 10. Satellite image of the Hawai'ian Islands showing the location of Kilauea. Image courtesy of NASA/Goddard Space Flight Center.

Monitoring volcanoes

Volcanic activity in the United States and the Commonwealth of the Northern Mariana Islands in the western Pacific is monitored by the U.S. Geological Survey (USGS) through its Volcano Hazards Program (VHP). The USGS has volcanic observatories in Alaska, California, Hawai'i, Washington State, and Yellowstone whose prime responsibility is to keep authorities and the public informed of volcanic hazards within their designated geographic area. Updates are issued by each observatory at monthly, weekly, or daily intervals, depending on the level of activity. For the latest on Mount St. Helens, Kilauea, or any of the other 160-plus volcanoes currently deemed active in the U.S. visit the USGS Volcano Hazards Program website at https://volcanoes.usgs.gov/index.html. Here, in addition to current activity alerts, you will find a wealth of information on U.S. volcanoes including geology and eruption histories; volcanoes

Figure 11. As awe-inspiring as it is, Kilauea's latest eruption only impacted a small part of the Hawai'i Island. These images are a sampling of the Hawaiian Volcano Observatory's impressive photo and video chronology of the volcano's activity since May 3, 2018. For more, go to https://volcanoes.usgs.gov/volcanoes/kilauea/multimedia_chronology.html.

A. Lava from a fissure in Kilauea's lower East Rift Zone slowly engulfs a road in the Leilani Estates subdivision.

B. On July 12, 2018, Fissure 8 became the only one of 24 that opened along the lower East Rift Zone since May 3, 2018 to remain active. Lava fountains from the fissure reached heights of up to 260 feet (the Capitol tower in Bismarck is about 242 feet high).

C. Lava from fissure 8 flows along an approximately 8-mile-long open channel before it enters the ocean. The clouds are a corrosive vapor known as "laze" (lava + haze), a potentially deadly mixture of steam, hydrochloric acid (HCl) and volcanic glass fragments formed by chemical reactions between the molten lava and seawater.

in general, volcanic hazards, monitoring procedures, field guides, education resources, and a lot of spectacular imagery and other multimedia. Another good resource, especially for volcanoes outside the U.S. is the Smithsonian Institute's Volcanoes of the World database (http://volcano.si.edu/), which contains detailed information on more than 2,600 volcanoes worldwide that have or are believed to have erupted during the last 2.5 million years.

An account of the 2018 Kilauea events by the scientists who witnessed and monitored them was published in Science earlier this year (Neal and others, 2019). Today, North Dakota is a long way from active volcanoes, but a number of volcanic ashes are recorded in rocks in the state (fig. 12).

Figure 12. Although volcanoes do not appear to have been part of the North Dakota landscape for at least the last 500 million years, layers of volcanic ash are present in the state. An ash layer is exposed in the Sentinel Butte Formation in an outcrop in McKenzie County. Unaltered volcanic ash (the white layer) is sandwiched between two layers of swelling clay (blue layers).

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