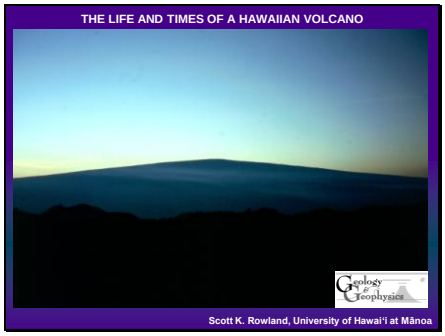
Kahua A‘o Geology Lesson #2: The Evolution of a Hawaiian Volcano – Handouts

The Life and Times of a Hawaiian Volcano

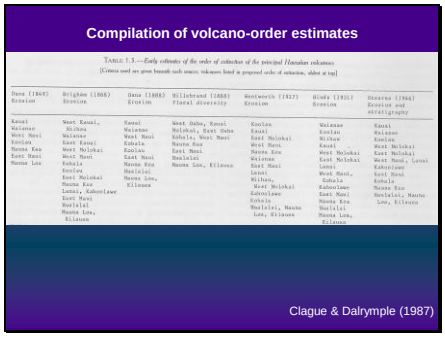


Hawaiian volcanoes are probably some of the best-studied in the world. One of their aspects that has long been recognized, but which is still not fully understood, is how they evolve from young volcanoes to old seamounts. Geologists noticed that the volcanoes were obviously younger at the SE end of the chain, and older at the NW end. They also noticed that the morphology of the volcanoes differed, even accounting for erosion. And finally, when examining an individual volcano it was clear that older flows and younger flows were not the same. How these changes work, however, was elusive until the early 1980s. Remember also that the early attempts to explain Hawaiian volcano evolution occurred without the benefit of Plate Tectonic theory.

Satellite image of the Hawaiian Islands

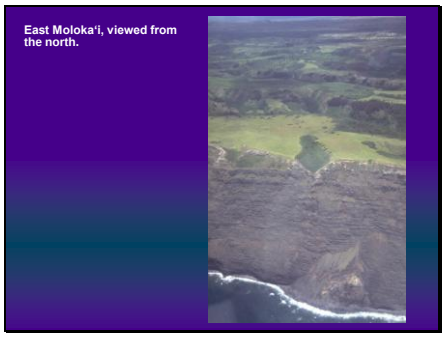
The earliest western geologists noticed that there were obvious age differences in the islands as one moved from southeast to northwest. They didn’t have satellite images, of course, but they could notice the differences from the surface.

Compilation of volcano-order estimates



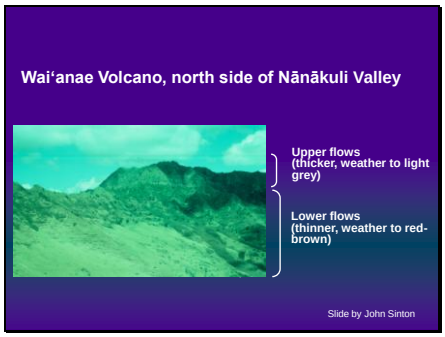
Lots of folks made estimates of the order in which the Hawaiian volcanoes had gone extinct, mostly based on the degree to which they were eroded.

East Moloka‘i



Also, from early on, geologists noticed that the lower parts of Hawaiian volcanoes consist of many, relatively thin lava flows that tend to weather to a red-brown color. The upper parts, on the other hand, consist of fewer, but thicker, lava flows that typically weather to a light grey or white color. This cliff on the north coast of Moloka‘i illustrates this relationship very well.

Waiʻanae Volcano

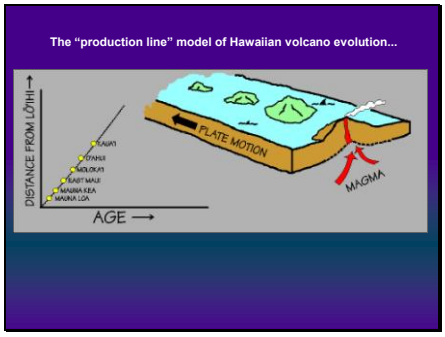


Another example is Waiʻanae volcano, on Oʻahu.

Lower- & Upper-style layers

Additionally, on some of these volcanoes, there is an indication that some time passed between the last lower-style layer and the first upper-style later. For example, in the photo at left, on Kohala, a soil layer that has developed on the uppermost of the thin, lower flows, and it was buried by the lowermost of the thick, upper flows. In the photo on the right, from W. Maui, there is a soil layer at the top of the red flows (it is slightly redder), and it underlies the lowest grey flow. The interpretation is that the volcano erupts one type of lava throughout most of its life, pauses (during which time the soil develops), and then erupts again, but this time producing a different type of lava. The early observations didn't offer an explanation of why there might be these differences or even of what the differences are, only that they exist.

The "production line" model of Hawaiian volcano evolution

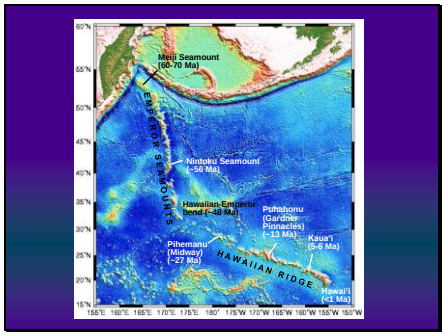


Meanwhile, however, what are we talking about here? Why would we expect a Hawaiian volcano to change its behavior at all? The answer lies with the relationship between the ideas of plate tectonics and so-called hot spots. This is an idea that dates from the early 1960s, and it was seen as a test of plate tectonics. Namely, if there was a stationary (and therefore deeper than the plate) source of magma with a plate moving over it, one should find a line of volcanoes that is young at one end and old at the other. Sure enough, that's exactly what we see in Hawaiʻi. In fact, if you plot volcano age vs. distance from Lōʻihi, the data produce a relatively good line. Here is a good place to stop and talk to your students about graphs. Namely, what is the slope of a graph good for? How do you calculate the slope? X-axis over Y-axis. Do the units on the axes matter? Of course. If you calculate x-axis over y-axis, you also have to calculate x-axis units over y-axis units. When you do so for the units shown here, you get distance/time, which is velocity. This is the velocity of the plate moving over the hot spot.

Hot spots on Earth

It is a little bit hard to tell if the idea of hot spots was used to test plate tectonics (the official story) or if plate tectonics were used to confirm the idea of hot spots. Either way, the concept of deep-seated magma sources that are unaffected by the whims of moving plates, has become pretty strongly accepted among earth scientists today. This map shows one set of authors' list of known hot spots. Some or most of these are probably familiar to you, but others may not be. Other authors have produced slightly different maps because they have slightly different criteria for defining a hot spot. One thing that jumps out at you is the paucity of hotspots within continents. Does this mean that for some reason hot spots can't burn their way through the thicker continental crust? Or do continents avoid hot spots?

The Hawaiian-Emperor Chain

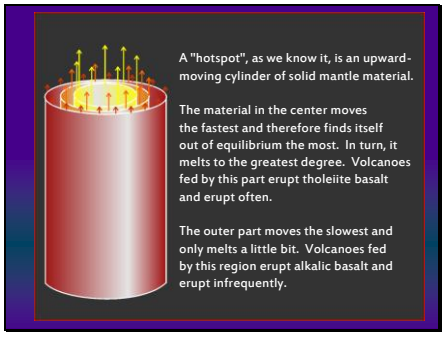


The Hawaiian hot spot is by far the best studied, and it also happens to be one of the most productive. This rather impressive chain of almost 200 volcanoes has been produced by the Hawaiian hot spot. It includes the well-known major Hawaiian volcanoes (on the islands of Hawai'i to Ni'ihau), volcanic remnants and the bases of atolls in the NW Hawaiian islands (Papahanaumokuakea), and the emperor seamounts. 60-70 million years ago, Meiji seamount, was where Lō'ihi is, and maybe plesiosaurs swam in its offshore waters!

Relative size of the Hawaiian-Emperor Chain

This map shows the same set of data superimposed on North America to perhaps give a better idea for how impressive the Hawaiian-Emperor chain is.

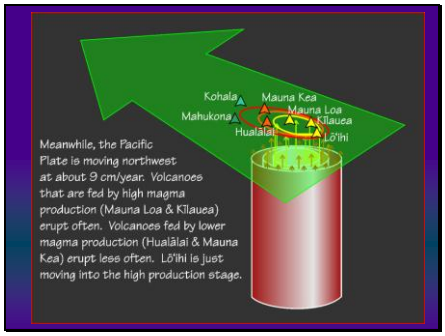
The hot "spot" as a hot "column"



This diagram, based on discussions with Ken Rubin, provide an explanation for how a Hawaiian volcano evolves throughout most of its life. First, you need to imagine the hot "spot" as a hot "column" instead. It is a hot column of mantle rock that is rising through the adjacent mantle because it is hotter and therefore buoyant. Recall that the mantle is almost entirely solid, so this rising is taking place in the solid state. Again, the idea of solids "flowing" is a difficult one for many students to grasp, but it does indeed occur. The entire column does not rise at the same rate. Instead, the central, hotter, more buoyant portion rises faster than the outer, cooler, less buoyant portion. Additionally, the outer portion is dragging against the surrounding mantle. Recall that one way to induce melting is to decompress a hot solid, and this is exactly what occurs at the uppermost part of the hot column. Importantly, the faster that rocks decompress, the

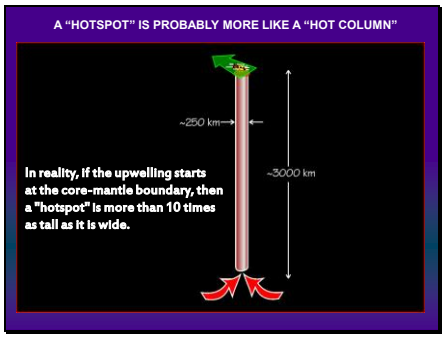
more it melts. Additionally, the more melt that is produced, the more diluted certain incompatible elements will be in that melt. The result is that when you compare the outer and inner portions of the melt region, there will be differences both in the composition of the melt and in its volume. Specifically, the center will produce large volumes of tholeiitic basalt whereas the outer portion will produce smaller volumes of alkalic basalt.

Tectonic plate movement over the hot "column"



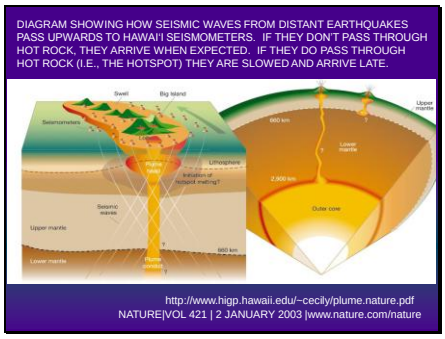
Next imagine a portion of the Pacific plate moving over the top of this hot column. The inner and outer melting portions will be stretched downstream a bit, but there will still be a somewhat bulls-eye pattern. If you were to follow an individual location on the over-riding plate, it would initially not know there was a hot column at all. Next, it would move over the outer portion of the column, and small volumes of alkalic basalt would start to work their way through to feed a small, young, undersea volcano. After a while, the point that we are following will move over the interior portion of the column, and larger volumes of tholeiitic magma will erupt through, building by far the greatest proportion of the volcano. Eventually, the point will move off the central portion and again over a region of low-supply alkalic magma-production, which, when it erupts, produces a small cap of alkalic basalt on top of the massive tholeiitic shield. Finally, the location will move off the hot column all together, and the volcano will die.

The "hotspot" as a "hot column"



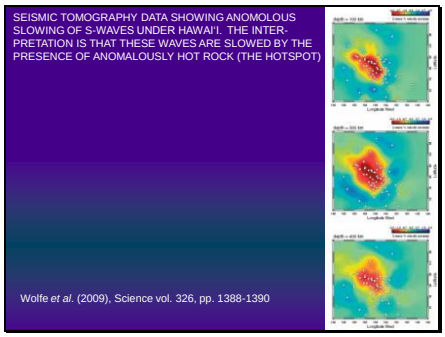
The size of the column is quite speculative, but based on the area of uplifted lithosphere around Hawai'i, it is probably around 250 km across. If, as some have suggested, the entire mantle convects, then the height is about 3000 km. It is a pretty long, skinny column.

Seismic Tomography



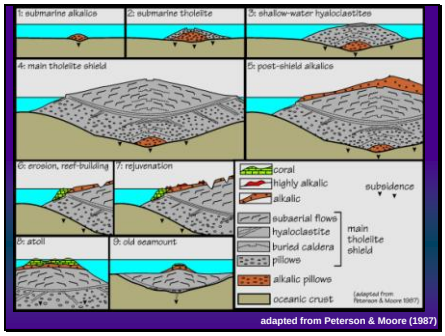
Recent work by Cecily Wolfe, at UHM, used a technique called seismic tomography to detect the column (which she calls the plume conduit). She and her co-workers set out a huge array of seismometers, and compared the arrival times of the same earthquake at different locations. Waves that travel through hotter rock are slowed down relative to those that pass only through cooler rock. By mapping all the different paths, Cecily came up with a map of where the mantle is hotter.

Seismic Tomography



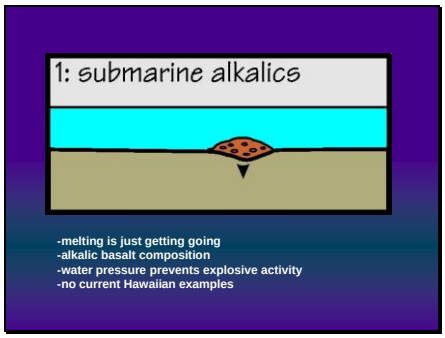
These are some of her data, shown as slices at different depths. The colors indicate what is called the s-wave anomaly, which means the difference between measured s-wave velocity and expected s-wave velocity (s-waves are one of two types of earthquake waves that pass through the body of the earth, and they are particularly susceptible to variations in the rigidity of rock, making them ideal for this technique). The data show that at least as far as 400 km below the surface, there is an obvious region of negative velocity anomaly (almost certainly due to the rock being hotter).

Life Stages of a Hawaiian Volcano



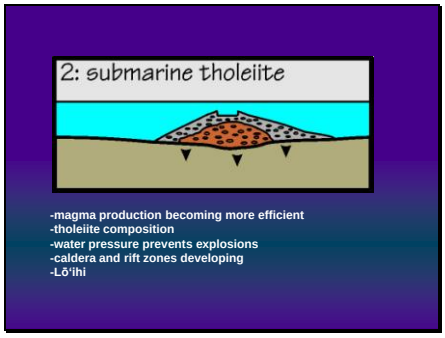
With or without the plate-tectonic/hot spot understanding, the typical order of events on a Hawaiian volcano has been derived. It is important to remember that these are human-defined steps – the volcanoes couldn't care less about them. Some volcanoes skip certain steps, some stay in a particular step for a long time whereas others only briefly. In fact, it is the variability that makes studying this process so interesting. As is diagrammed here, a typical Hawaiian volcano starts its life as a small seamount, and ends its life as a small seamount. Along the way it grows, becomes very active, then slowly dies off. A few briefly rejuvenate, but all eventually stop erupting, and erode and subside below sea level.

Stage 1: Submarine Alkalics



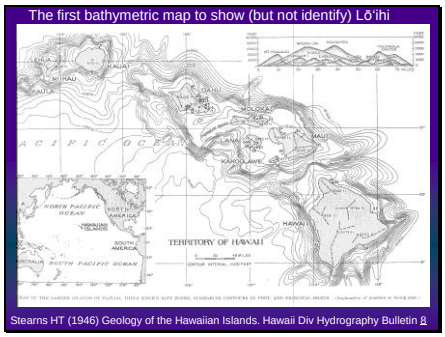
The very first stage in a Hawaiian volcano's life is somewhat conjectural. We know from the hot-column model that the first melts that a point on the lithosphere encounters will be alkalic, and we also know that the magma-production rate will be small.

Stage 2: Submarine Tholeiite



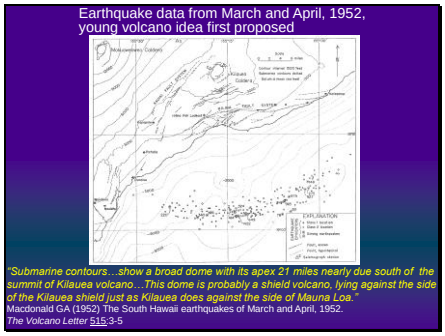
As the now-established volcano moves closer to the center of the hot column, both the magma composition and magma supply rate increase. Tholeiite lavas are erupted, and they bury the early alkalic lavas. On Lō'ihi, the only Hawaiian example currently in this stage lavas sampled from the summit and upper flanks are tholeiite whereas those sampled from the lower flanks are alkalic. Lō'ihi, therefore, hasn't yet completely buried its early alkalic base.

First Bathymetric Map of Lōʻihi



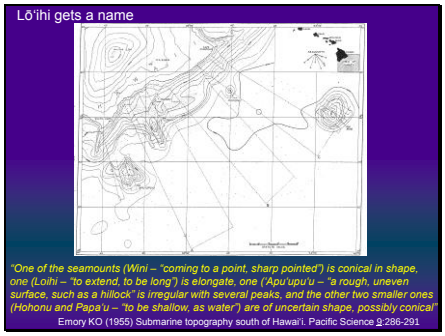
The human history of Lōʻihi is an interesting story. The first bathymetric map to show Lōʻihi was published in 1946.

Earthquake Data



In 1952, Gordon Macdonald proposed that perhaps it was the youngest Hawaiian volcano. His idea was based on Lōʻihi's location (next in line SE of Kīlauea) as well as the fact that there were commonly earthquakes in its vicinity, although the sparse seismometer network at the time could not pinpoint those earthquakes very well.

Lōʻihi gets a name

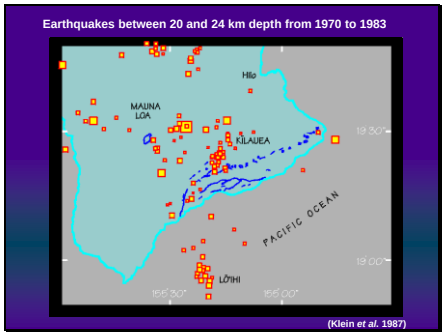


In 1955, Kenneth Emory named Lōʻihi based solely on its form (elongate) in map view. He named a bunch of other seamounts using the same system.

Lōʻihi gets a name

Not everyone likes the name Lōʻihi, nor the fact that it was named without consultation with the people who live closest nearby. They instead call it Kama ʻehu, the red child.

Earthquakes between 1970 – 1983



As the seismic network on Hawaiʻi got better, the ability to pinpoint earthquakes also improved, and it was clear that whatever Lōʻihi was, it was often seismically active. Additionally, an oceanographic cruise in the late 1970s happened to dredge a sample from Lōʻihi's summit, and it turned out to be very young-looking basalt. After a particularly noticeable seismic swarm in late 1987, NSF funded a joint UH/Woods Hole rapid-response cruise using the submersible ALVIN.

Pillow Lava

pillow lavas on Lō'ihi, viewed from the ALVIN submersible

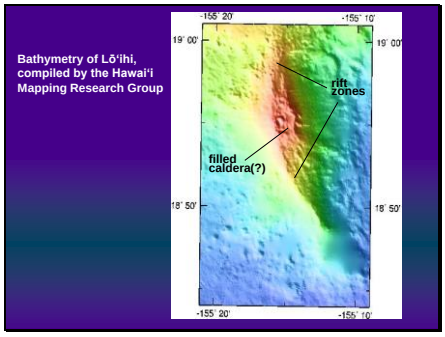
At Lō'ihi, we found young pillow lavas, warm water, and very high CO2 concentrations in the water. The young-volcano interpretation was proved correct. In April 1996 Lō'ihi erupted, and in July of the same year, it produced the largest seismic swarm ever recorded on a Hawaiian volcano. Apparently what happened was the eruption emptied the shallow magma chamber. The volcano managed to hang on for about 3 months until July, when the summit collapsed to produce a deep pit. The seismic swarm recorded this collapse. Pillow lavas are essentially under-water pahoehoe. You might think that under-water eruptions should be really explosive (hot lava + water 'n all), but they are not. The reason for this is that at these depths, water pressure prevents water vapor from forming, and therefore there are no explosions.

Talus on the flanks of Lō'ihi

talus on the upper flanks of Lō'ihi, viewed from ALVIN

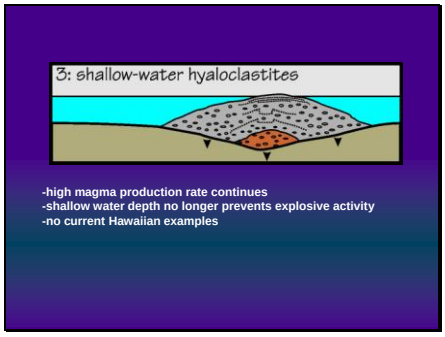
The flanks are quite steep, and covered with talus.

Bathymetry of Lō'ihi



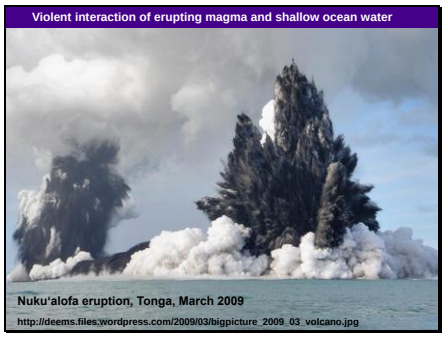
Bathymetrically, Lō'ihi is obviously elongate, has a relatively flat summit, and very steep flanks. It appears to have two rift zones, and the summit has the appearance of a very shallow caldera, which is basically filled to the brim. A caldera so early in life means that it also has a magma chamber early in life (there has to be something to collapse into).

Stage 3: Shallow-water hyaloclastites



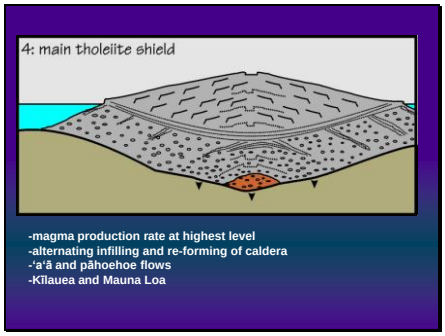
When the summit of the volcano reaches to about 200 m below the surface, the water pressure is no longer sufficient to prevent explosive lava-water interactions, and the eruptions change from passive effusion of pillow lavas to strong steam explosions. These explosions occur every time the volcano erupts as it builds itself from ~200 m below sea level to above sea level. After that it erupts lavas again. There is therefore a ~200 m-thick layer of hyaloclastite (black sand and rubble) sandwiched between pillow lavas below and subaerial lavas above.

Nuku'alofa eruption, Tonga, March 2009



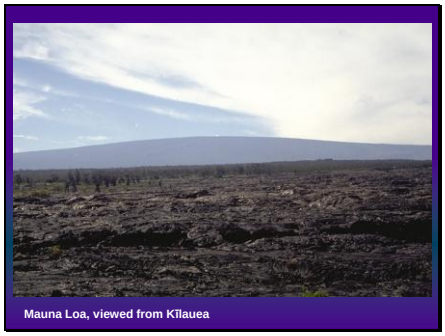
The eruptions during this stage of a Hawaiian volcano's life probably look something like this. Vigorous mixing between rapidly expanding magma and water occurs, leading to violent steam explosions. The particles rain back down to produce a blanket of unconsolidated fragmented material. The geologic term is hyaloclastite, but normal people call it black sand.

Stage 4: Main Tholeiite Shield



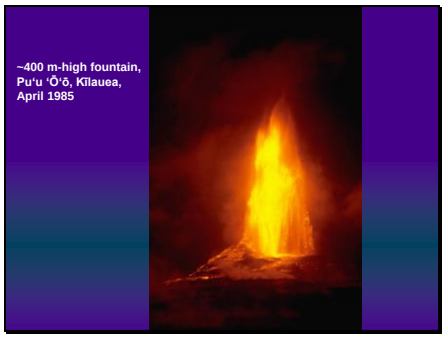
Eventually the volcano gets past sea level, moves over the center of the hot column, and thereby starts producing large volumes of tholeiite basalt. This is the stage during which the great majority of the volcano's volume is produced. This is also the eruptive stage that we understand the best because both Mauna Loa and Kīlauea are in this stage, and they have each erupted many times.

Mauna Loa, viewed from Kīlauea



The volcano during this stage achieves the classic "shield" shape, with frequent, high-volume eruptions of fluid lava. The fact that it is fluid means that it cannot pile up steeply, but instead, runs easily down the slope. The fact that the eruptions produce large volumes means that even if the vent is near the summit, material will also be added to the flanks, also helping to keep the slopes gradual. Finally, because there is a shallow magma chamber in this stage, as we'll see in a moment, the magmas that erupt have had a chance to stall for a while and lose some of their dissolved gas. This means that lava fountains are somewhat reduced and thereby don't produce huge cinder cones – the shield profile is preserved.

Pu'u 'Ō'ō, Kīlauea, April 1985

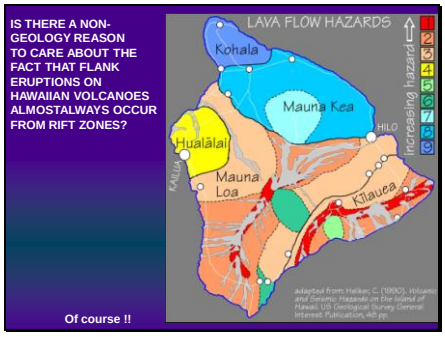


Despite the "reduced" gas, however, eruptions during this stage can be spectacular.

Topography of Mauna Loa's SW rift zone

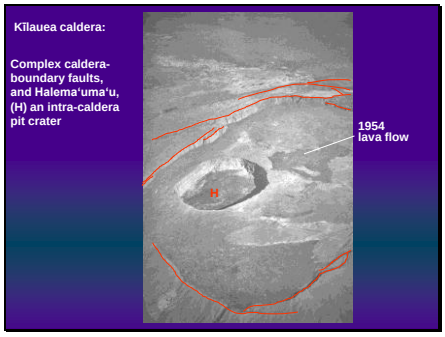
One of the major volcanic structures on a typical Hawaiian volcano is rift zones. It is rift zones that make Lōʻihi elongate, and therefore gave it its name, however, as with many things, it is the subaerial examples that are understood to a much greater degree. This is a computer rendition of Mauna Loa's southwest rift zone, with post 1778 flows shown in black. Note that if you trace them up to their sources, all those sources lie along the axis of a ridge that runs from upper right (near the summit) to lower left. This ridge is the axis of the rift zone. This image has been vertically exaggerated, and the slopes are actually much more gradual. Hawaiian volcanoes either erupt at their summit or along one of their rift zones, and rarely anywhere else.

Lava Flow Hazards



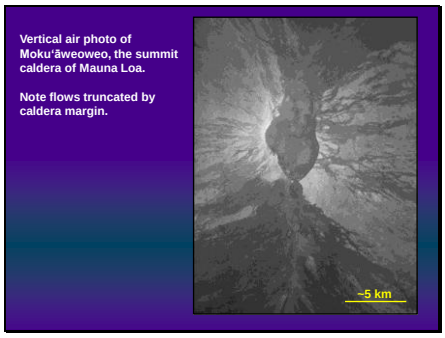
This lava-flow hazard map shows that the highest hazards occur along the active rift zones of Kīlauea and Mauna Loa, with lesser hazards downslope from these.

Kīlauea Caldera



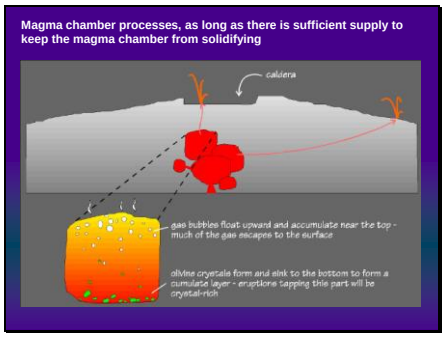
The other major volcanic structure that has been studied considerably at Mauna Loa and Kīlauea is summit calderas. In some older evolution schemes for Hawaiian volcanoes, there was a specific "caldera" stage, coinciding with the main shield stage. We now know, however, that each Hawaiian volcano has had many calderas during its life time. At a caldera there is a constant struggle between collapsing, which enlarges the caldera, and infilling, which shrinks it. It just so happens that both Kīlauea and Mauna Loa are in stages where calderas are obvious.

The summit caldera of Mauna Loa



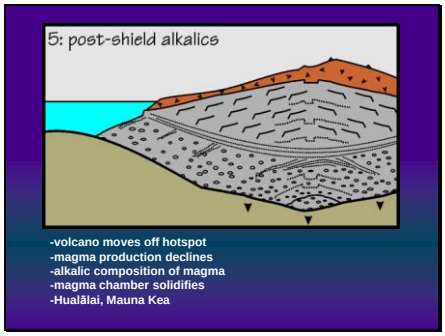
Note that if we were to have visited Mauna Loa some 700 or so years ago, we would have found no summit caldera at all. At that time, it had infilled completely, and lava flows were spilling out in all directions. Some of these flows can be seen in this vertical air photo, and note that as you trace them uphill, you end up at the caldera rim before you ever get to their source vents. This means that those vents were once above what is now the caldera floor, and have since collapsed in and been buried by later lavas.

Magma Chamber Processes



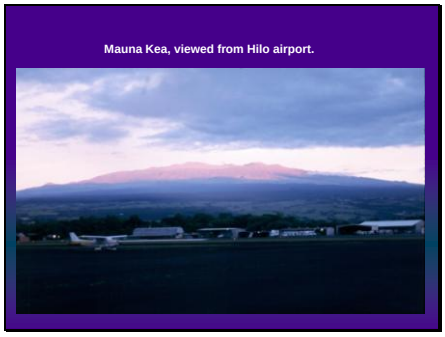
A caldera, even one that periodically comes and goes, is an indication of an active magma chamber. Most of the time Hawaiian magma chambers are drawn as simple balloons, but almost certainly they are complex inter-connected voids rather than one single void. Two important processes occur within a magma chamber. The first is that olivines crystallize out of the magma and sink to the bottom. The magmas thereby "evolve" because the olivines preferentially take away Mg and Fe relative to Si. The second important process, mentioned earlier, is that as magma sits in the magma chamber, gases exsolve and escape. This reduces the explosivity of Hawaiian eruptions somewhat compared to what they would be like if the magma came all the way from where it is generated and didn't lose any gas along the way.

Stage 5: Post-shield Alkalics



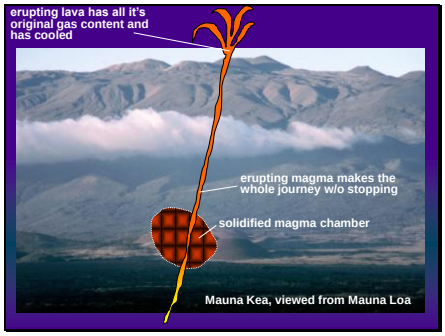
Eventually the volcano moves off the central part of the hot column, into the down-stream portion where low volumes of alkalic magmas are produced. The total volume of these lavas is small compared to the volcano as a whole, and it is often likened to a "cap" of alkalics. In older texts, it was often referred to as the alkalic "cap". Now days, we refer to it as post-shield alkalics.

Mauna Kea, viewed from Hilo airport



Mauna Kea is a good example of a Hawaiian volcano in the post-shield alkalic stage. Viewed from Hilo, its profile is very different from that of the classic, smooth, gentle Mauna Loa. There are two reasons why the volcano becomes bumpier and steeper.

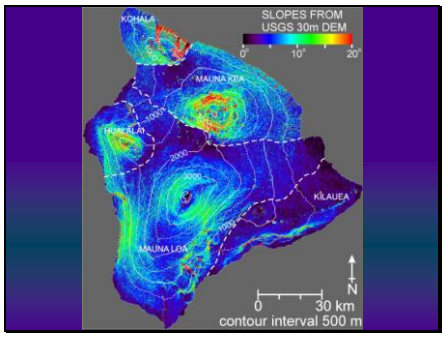
Mauna Kea, viewed from Mauna Loa: magma chamber processes



The bumpiness is due to the presence of very large cinder cones. These large cones are the product of very high lava fountains, indicating higher amounts of gas as compared to the volcano in its tholeiite stage. This higher amount of gas can be tied directly to the lack of a shallow magma chamber. As the volcano moves off the hot spot the supply rate drops and the magma chamber is not replenished often enough to prevent solidifying all together. This means that there is no shallow place within the volcano for rising magmas to stop for a while and de-gas. If they are going to erupt, they will pass from the source region (or a deeper magma chamber) to the surface all in one trip. With no chance to lose gas, the lava fountains are especially high, and this produces large cinder cones. Additionally, the lack of supply means that there are no conduits within the volcano for the magma to utilize. It needs to cut its own pathways through the volcano, and in so doing it cools and becomes viscous.

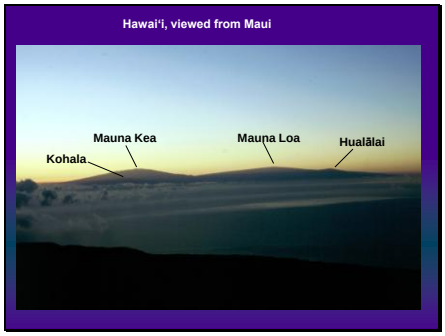
Viscous lavas can hold a much steeper slope, so this contributes to the overall steepening of the volcano.

Map of the ground slope



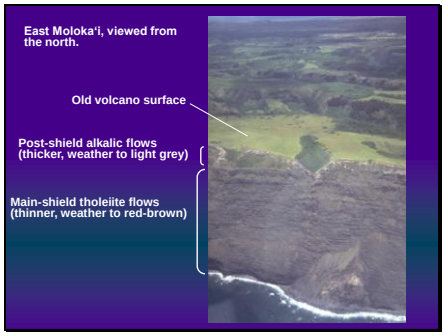
In this map of the ground slope, it is obvious that Mauna Loa and Kīlauea, the two volcanoes in the main tholeiite shield stage, have much lower average slopes than do Hualalai and Mauna Kea, the two volcanoes that are in their post-shield alkalic stage.

Hawai‘i, viewed from Maui



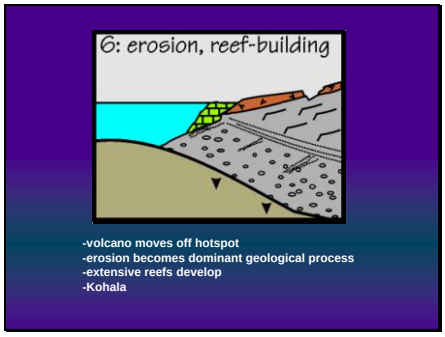
From Maui, the different profiles are easy to compare.

East Moloka‘i



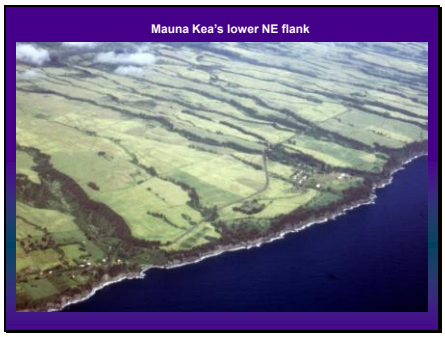
The result, as again seen here on Moloka‘i, is a stack of very many think tholeiite flows below, “capped” by a few alkalic flows above. The most common mineral in the tholeiite flows is olivine, and when it weathers, the iron in it oxidizes, giving the familiar red-brown color. In most of the alkalic basalts, the most common mineral is plagioclase feldspar, and when it weathers, it turns from clear to white.

Stage 6: Erosion, reef-building



At some point the volcano moves far enough off the hot spot so that it is not supplied by magma at all. Erosion becomes the dominant geologic process, and extensive reefs are able to develop because they are no longer being buried by lava entering the ocean.

Mauna Kea's lower NE flank

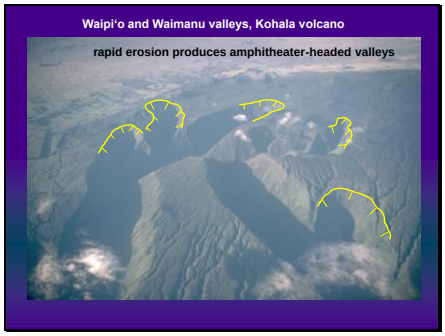


It is important to notice, however, that the volcano doesn't just shut off completely one day. Instead, there is a slow decline in eruption rate accompanied by a slow increase in erosion rate, with both processes operating simultaneously.

Laupāhoehoe Mauna Kea

An excellent place that represents this interplay is Laupāhoehoe, on the flanks of Mauna Kea. Here, the eruption rate has dropped so that large gullies have been cut by flowing water. Eruptions at Mauna Kea haven't died off completely, however, and a few 10s of thousands of years ago, a lava flow happened to flow into the upper reaches of a water-cut valley. Like any fluid would, the lava utilized the stream valley and flowed to the coastline and into the ocean.

Waipi'o and Waimanu valleys, Kohala volcano

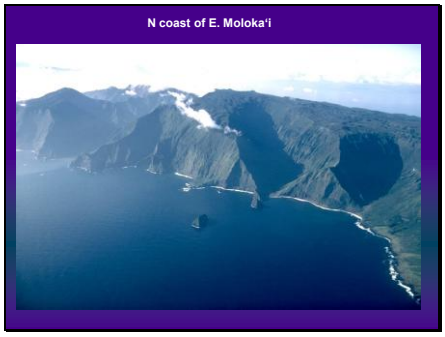


Erosion, particularly by streams, dissects the otherwise relatively smooth profiles of Hawaiian volcanoes. A process called stream piracy leads to the situation where there are a few very large valleys and lots of small ones.

Reef development

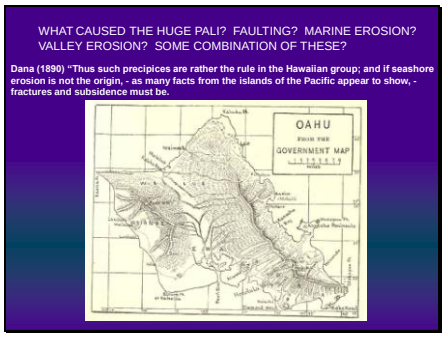
Once lava flows stop entering the ocean all the time, extensive reefs are able to develop along the fringes of a volcano.

Erosional processes



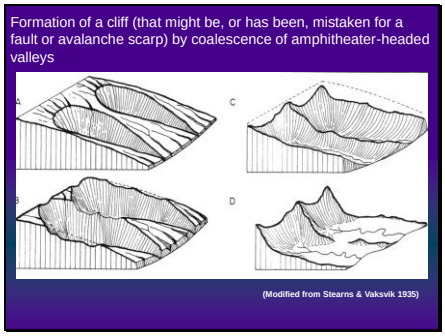
In addition to slow erosional processes, there are also catastrophic events. The north coastline of Moloka'i has figured prominently in the recognition and understanding of these catastrophic events.

What caused the huge pali?



High pali are pretty hard to miss, and back in the late 1800s, JD Dana, an American geologist, speculated about how they might have formed. He considered that they might be fault scarps or that they might have been formed from erosion.

Formation of a cliff

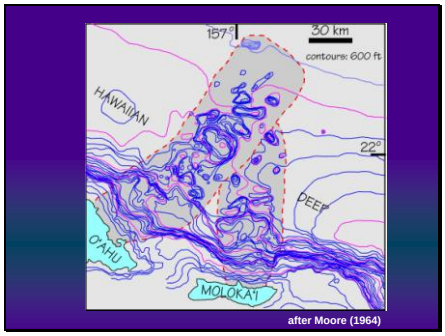


This series of diagrams shows how a line of cliffs can develop when the headwalls of several large amphitheater-headed valleys merge.

Nu'uanu pali

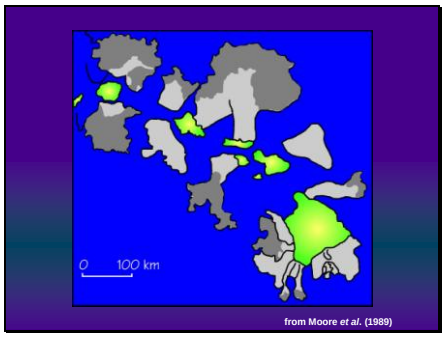
An obvious example of this is the Nu'uanu pali. Remnant ridges, such as the two that drop down from Konahuanui, indicate that valley coalescence is what produced this "linear" pali.

Giant underwater avalanches



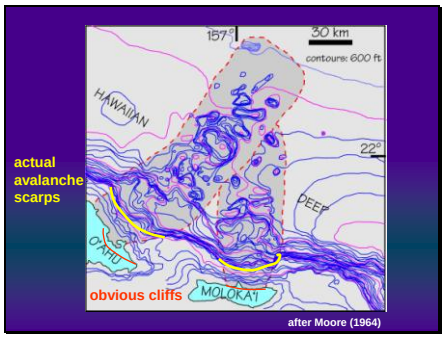
Based on newly-released bathymetric charts, a USGS geologist named Jim Moore proposed that giant underwater avalanches had occurred off the NE and N coasts of O'ahu and Moloka'i, respectively. Landslides have a classic shape, namely a steep, usually arcuate headwall, and a run-out region of disorganized lumps, known as hummocky topography. These Hawaiian avalanches share these morphological characteristics, but they are huge. Moreover, Jim Moore observed that the debris portion extends down the flanks of the two islands, across what is called the Hawaiian Deep (formed by down-bowing of the oceanic crust by the weight of the islands), and up the other side. The avalanche material therefore moved uphill by 700-800 meters, under water! The only way for this to have happened would be for them to be moving quickly. These were therefore not slow, creeping landslides, but instead, catastrophic avalanches. Geologists are trained from birth that it is not fair to explain things with catastrophes, and Moore's idea was not readily accepted.

Giant underwater avalanches



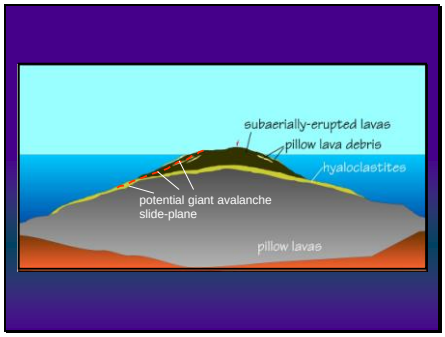
In the early 1980s, due to demands from Ronald Reagan that the US know what is within its 200-mile territorial waters, all the offshore was mapped using sonar. They found a lot more giant underwater avalanches, and it soon became apparent that these are relatively common, and must be part of the life cycle of most Hawaiian volcanoes. Most of these were true avalanches, with the material moving catastrophically downward and outward, and breaking up as it moved. Off two volcanoes, however, the motion is much more subdued. Specifically, Waiʻanae and Kīlauea seem to have instead moved by coherent slumping of huge blocks.

Giant underwater avalanches



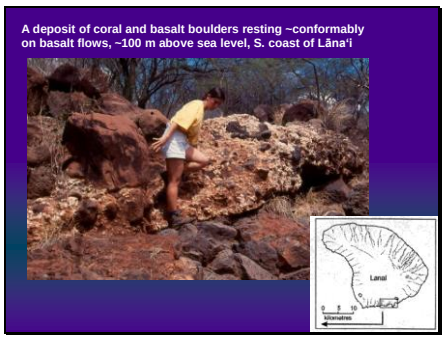
Moore proposed that the Nuʻuanu pali and N. cliffs of Molokaʻi are the headwall scarps of the giant avalanches. However, there are some geological reasons why this cannot be the case. Specifically, Olomana, the Keolu hills, and Mokulua islands are all parts of the pre-avalanche Koʻolau volcano, and they are in place. If the pali (that is landward of all of these) were the landslide scarp, there is no way that they could still be there. We now consider that the scarps of the landslides are offshore, where there are obvious "bites" in the edge of a wide under water shelf. The edge of this shelf is at a depth of ~200 m, and at the time of the Nuʻuanu avalanche, was probably just offshore. The avalanches therefore may have taken place wholly under water. What then, of the obvious Nuʻuanu pali and N. Molokaʻi cliffs. Probably the removal of the submarine volcano flanks destabilized the remainder of the volcano, accelerating smaller-scale erosion, and producing pali via the headwall-merging scenario mentioned earlier.

Weaknesses within the volcano



Why would a volcano fail in the first place? This is an unanswered question. One potential weakness within the volcano is that layer of hyaloclastite, which, as you'll recall, is left over from the time during which the volcano was transitioning from submarine to subaerial. The products during that time are poorly consolidated, and although they end up being sandwiched between coherent pillow lavas below and coherent 'a'a and pahoehoe lavas above, it is still a weak layer.

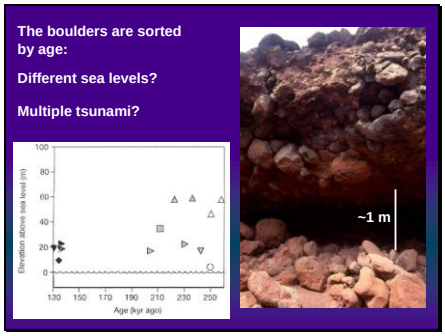
Tsunamis produced as a result of giant avalanches



An obvious next question is if these avalanches are catastrophic, what kind of tsunami will they generate? This is an unanswered question, which unfortunately has taken on a life of its own in the pseudo-science Discover TV world. Jim Moore and his brother George mapped a strange unit of large coral and basalt boulders along the south coast of Lanaʻi. They followed the deposit inland to about 100 m elevation, and interpreted it to be the deposit of a giant tsunami caused by a giant avalanche off the W. flank of Mauna Loa. They considered that the tsunami waves would radiate outward in all directions from the W.

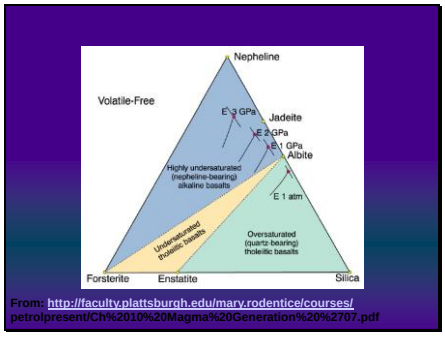
Mauna Loa source, and would therefore approach Lana‘i from the south.

Tsunamis produced as a result of giant avalanches



Ken Rubin, in our department, led a study that collected age information on clasts within this so-called Hulopoe gravel. They found that the boulders are sorted by age. Specifically, boulders that are around 130,000 years old are only found from the coast up to about 20 m above sea level. Boulders ranging in age from 200,000 – 250,000 years in age are found from the coast all the way up to 60 m above sea level. They could think of no mechanism by which a tsunami could sort boulders by age, and instead suggested that the deposit is instead the result of multiple episodes of higher sea level.

Geochemstry of Hawaiian rocks



Pretty soon geochemists analyzed a number of Hawaiian rocks, and realized that there were chemical differences between the lower, thinner flows and the upper, thicker flows. In particular, the lower flows are what is called tholeiite basalt (or tholeiitic basalt) and the upper, thicker flows are what is called alkalic basalt. Fresh samples of tholeiitic and alkalic basalt look pretty much identical to normal people, but their subtle geochemical differences turn out to be the key to unraveling the evolution of Hawaiian volcanoes. The differences between the two types of basalt were defined based on theoretical pressure-temperature calculations as well as laboratory experiments. These didn’t contribute a lot toward our understanding of what might be going on within a Hawaiian volcano, however. Experiments in the 1960s showed that the composition of the first melt that comes out of a heated rock will be different depending on the pressure. The little red dots show the initial melt composition on what is called a ternary plot. At a pressure of 1 atmosphere, the composition will be tholeiitic basalt. If the melting occurs at higher temperatures, the first melt has a composition of alkalic basalt. This led to the reasonable conclusion that as a Hawaiian volcano ages, the depth at which melting occurs decreases. Shallow melting early on produces the lower sequence of thin-bedded tholeiitic basalts, and deeper melting as the volcano dies off produces the upper sequence of thicker-bedded alkalic basalts. There was one other way to produce different types of basalt, however, and understanding of this other mechanism didn’t occur until the 1980s.