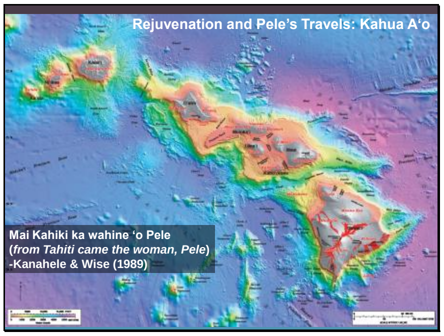
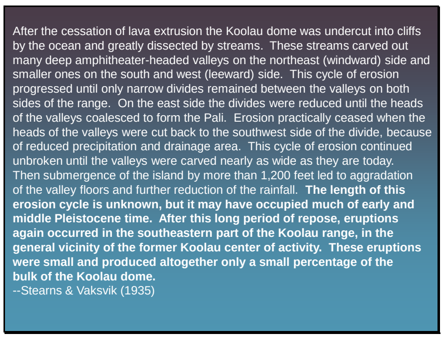
Kahua A‘o Geology Lesson #2: The Evolution of a Hawaiian Volcano: Rejuvenation – Handouts

Rejuvenation and Pele's Travels: Kahua A‘o



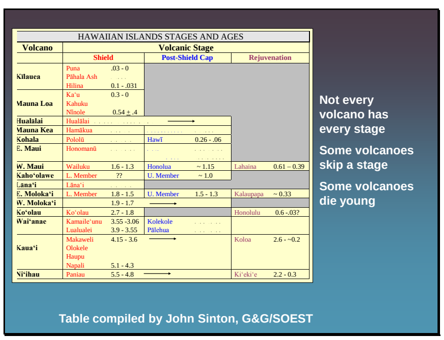
Our previous discussion of Hawaiian volcano evolution got us as far as the volcano moving off the hot spot and starting to erode, both slowly and catastrophically. All that can pretty reasonably be put into the context of the Pacific plate moving over a ~concentrically zoned hot spot, and once the volcano moves off the hot spot, it does off. The one aspect of the evolution that does not fit the scenario is the fact that some Hawaiian volcanoes come back to life long after they have moved off the hotspot, sometimes after a million years of not erupting. This is called the Rejuvenation stage, or rejuvenated volcanism stage.

Relative age difference: older volcanoes



Many early geologists noted the obvious relative age difference between parts of some older volcanoes, for example Ko‘olau, as described here. The key aspects of what we know about rejuvenated volcanism are stated in this classic 1935 book. After Ko‘olau stopped erupting, it underwent a long period of erosion then came to life. The volume of this rejuvenated volcanism is very small.

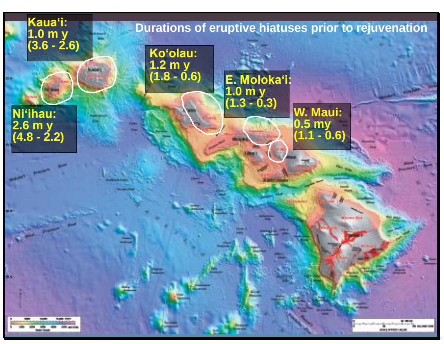
Hawaiian Islands Ages & Stages


HAWAIIAN ISLANDS STAGES AND AGES

Volcano	Volcanic Stage: Shield		Post-Shield Cap		Rejuvenation	
Kīlauea	Puna	.03 - 0				
	Pāhala Ash	. . . . .				
	Hilina	0.1 - .031				
Mauna Loa	Ka‘u	0.3 - 0				
	Kahuku					
	Nīnole	0.54 ± .4				
Hualālai	Hualālai	. . . .	→			
Mauna Kea	Hamākua	. . . . . .	. . . .	. . . . . .		
Kohala	Pololū	. . . . . .	Hawī	0.26 - .06		
E. Maui	Honomanū	. . . .	. . . .	. . . .		
W. Maui	Wailuku	1.6 - 1.3	Honolua	~ 1.15	Lahaina	0.61 – 0.39
Kaho‘olawe	L. Member	??	U. Member	~ 1.0		
Lāna‘i	Lāna‘i	. . . . . .				
E. Moloka‘i	L. Member	1.8 - 1.5	U. Member	1.5 - 1.3	Kalaupapa	~ 0.33
W. Moloka‘i		1.9 - 1.7	→			
Ko‘olau	Ko‘olau	2.7 - 1.8			Honolulu	0.6 -.03?
Wai‘anae	Kamaile‘unu	3.55 -3.06	Kolekole	. . . .		
	Lualualei	3.9 - 3.55	Pālehua	. . . .		
Kaua‘i	Makaweli	4.15 - 3.6	→		Koloa	2.6 - ~0.2
	Olokele					
	Haupu					
	Napali	5.1 - 4.3				
Ni‘ihau	Paniau	5.5 - 4.8	→		Ki‘eki‘e	2.2 - 0.3

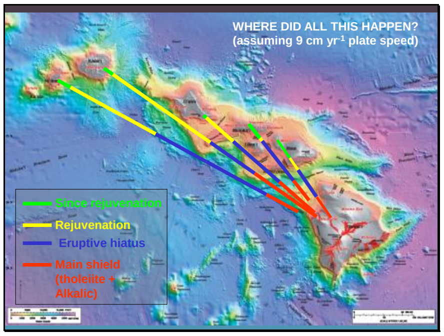
This table shows the various stages of all the volcanoes making up the 8 main Hawaiian islands. Note that not all the volcanoes have experienced a rejuvenation stage. You might say this is because some haven't reached that age yet, but that isn't the only story. Wai‘anae and W. Moloka‘i are both older than W. Maui, the youngest volcano to have undergone rejuvenation, yet neither of them has.

Durations of eruptive hiatuses prior to rejuvenation



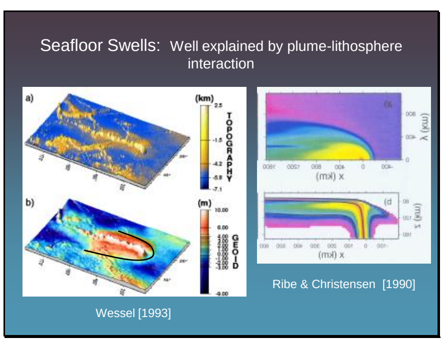
Here are some of the same data overlain on a map. Each of the volcanoes that have undergone rejuvenation are circled in white. The numbers indicate the length of time that the volcano was inactive between the end of its post-shield alkalic cap (or tholeiite shield if it didn't have an alkalic cap) and the start of its rejuvenation stage. Note that the duration of this eruptive hiatus varies from half a million years (W. Maui) to 2.6 million years (Ni‘ihau).

Where did all this happen?

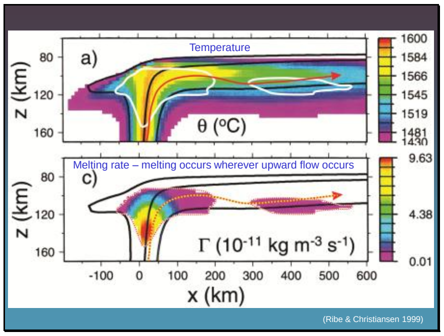


If you combine a plate velocity of 9 cm per year and the volcanic stage data from John Sinton's table, you can backtrack to see where each volcano was while it went through those stages. In this diagram, red indicates the main shield (tholeiite plus alkalic). Blue indicates the eruptive hiatus. Yellow indicates rejuvenation volcanism, and green indicates the time since the last rejuvenation stage eruption. The boundary between blue and yellow indicates where each volcano was when it came out of the eruptive hiatus and rejuvenated, and the location for where this happened is not particularly constant. Niʻihau started to rejuvenate after it had moved ~400 km from the hotspot, and approximately where Waiʻanae is today. Kauaʻi, and Koʻolau started to rejuvenate about 300 km from the hot spot, when they got to where Penguin Bank is today. E. Molokaʻi started to rejuvenate when it was ~250 km from the hotspot, not very far from where it is today. W. Maui started to rejuvenate when it had moved ~200 km from the hotspot, at about where E. Maui is today. Why would we care where this rejuvenation started? Because knowing this is useful for trying to figure out why rejuvenation occurs in the first place (spoiler alert: we don't really know). Something else you can notice from this is the different durations of rejuvenation. Niʻihau and Kauaʻi, in particular, spent 1.9 and 2.4 million years in this stage, respectively. This is far longer than the time since the last rejuvenation eruption of either, suggesting that perhaps it isn't pau. Koʻolau spent 800,000 years in its rejuvenation stage, and the last eruptions (the Koko rift) were only 40,000 – 50,000 years ago.

Seafloor Swells

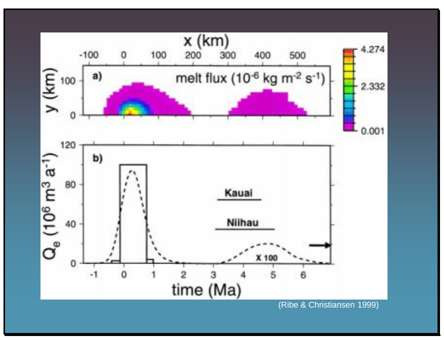


Mantle plume modeling



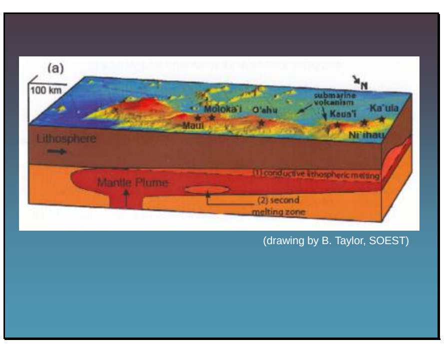
One attempt to explain rejuvenation depends on a complicated computer model of the motion, temperature, density, and other physical characteristics of the hot spot plume. Basically, by modeling all the processes that should be going on, they figured out the direction that plume-mantle would be flowing. Anywhere that motion is upward, decompression melting will take place. In the main plume stem, the upward motion is obviously driven by buoyancy, and this is where the majority of melting occurs. After partially melting, the material then sinks back a little bit, and the pressure will increase, countering melting. About 300 km past the main plume axis, however, the material starts to spread laterally as well as downstream. In order to conserve mass, lateral spreading is accompanied by thinning against the base of the lithosphere. Thinning means the lower part of the plume material is moving upward, and because upward motion induces melting, a second zone of melting is created. Recalling from the map that showed where rejuvenation occurred, a distance of 300-400 km from the hotspot fits where Niʻihau, Kauaʻi, and Koʻolau started rejuvenating. E. Molokaʻi (~250 km) and W. Maui (~200 km) both started rejuvenating closer to the hotspot than the model predicts.

Volume flux & Time



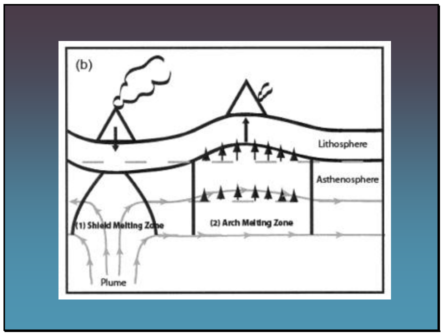
This is a map view of volume flux on the top, and a graph of flux vs. time on the bottom. Note that the times of rejuvenation of Niʻihau and Kauaʻi (the black bars) correlate to the time and position of the secondary melt zone.

Melting away from the hot spot



Brian Taylor, the Dean of SOEST produced this diagram to illustrate a second scenario for melting away from the hotspot. The idea is that the mantle plume transmits heat to the overlying lithosphere, and eventually at some point downstream, enough heat has been transferred so that the lithosphere starts to melt a little bit. That little bit would be the rejuvenation-stage volcanism.

Melting away from the hot spot



The most recent model was proposed by Todd Bianco and Garrett Ito. They note that when the lithosphere is loaded by the weight of a growing volcano (or volcanoes), that downward motion is partially accommodated by upward motion at a location away from the load. Depending on the thickness and strength parameters that you feed into the model, plus the viscosity of the mantle (and lots of other things), it is possible to have the lithosphere bow upward at a distance appropriate to where we find rejuvenation volcanism. If the asthenosphere and lithosphere both move upward, there is no pressure loss from less rock above. There is pressure loss from less water above, however, and whether that is sufficient to allow melting, I'm not sure.

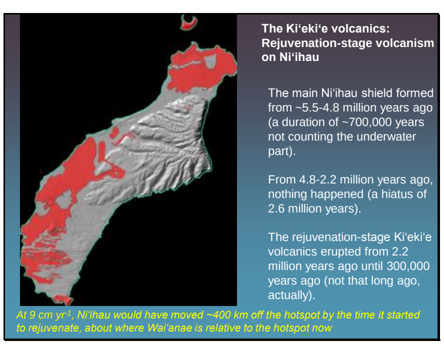
Ni'ihau and Lehua viewed from the north

Now let's start our tour of rejuvenation volcanism, from northwest to southeast, starting with the Ki'eki'e volcanics of Ni'ihau.

Ni'ihau volcano

Ni'ihau volcano is old, and most of it has eroded and/or slumped away. All that remains of the main shield is a patch of rugged valleys and ridges making up the east/central part of the island. A high cliff on the E coast is probably a remnant of an avalanche scar. The old center of the volcano is offshore to the east. The rest of the island is relatively low-lying, and consists of rejuvenation stage volcanics and sedimentary rocks left over form high stands of sea level.

Ki'eki'e volcanics

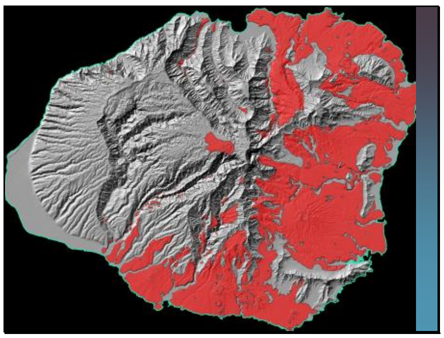


On this map, the Ki'eki'e volcanics are shown in red. Note that although the duration of rejuvenation was long (2.2 million to 300,000 years ago), only a few eruptions took place, so the average interval between eruptions was very long.

Lehua Islet, viewed from the east

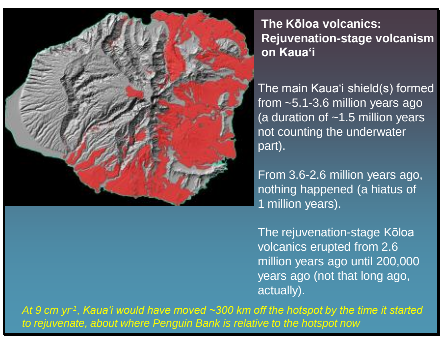
Lehua, off the N. end of Niʻihau has the classic form of a tuff ring, indicating that the eruption that formed it involved violent lava-water explosions.

Kauai



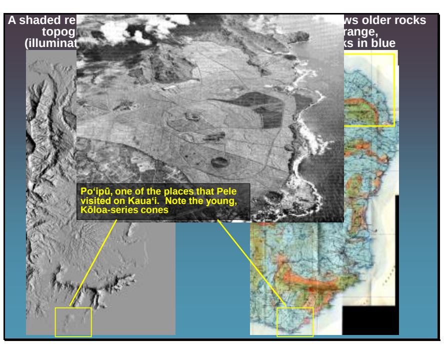
The most extensive rejuvenation stage of any Hawaiian volcano occurs on Kauaʻi. Essentially the entire E half of the island is veneered by one or more flows of the Koloa volcanic series.

Koloa volcanics



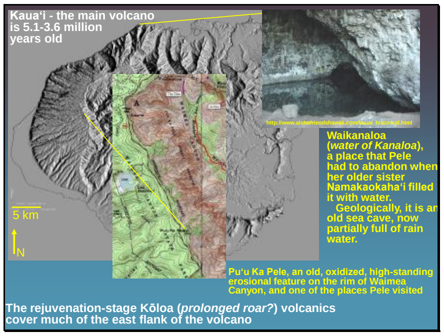
In some places the Koloa volcanics are only 1 flow thick, whereas in others they are 3-4 flows thick.

Koloa volcanics



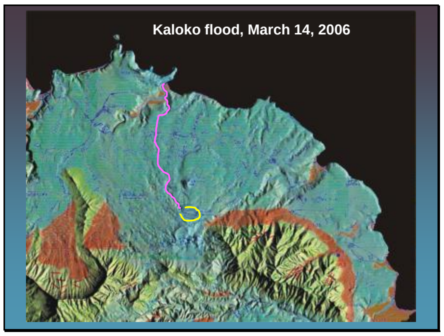
The Koloa volcanics are named for 3 or four young vents near the town of Koloa, on the south shore of Kauaʻi. In this old air photo, they stand out clearly within the sugar cane fields. This is near Poʻipu, one of the places that Pele visited on her journey southeastward, trying to find a home.

Kaua'i – the main volcano



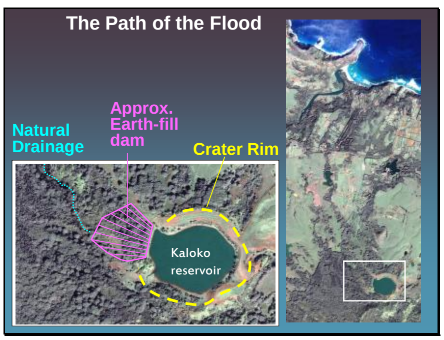
A couple of the other places Pele visited are not volcanic vents.

Kaloko flood, March 14, 2006



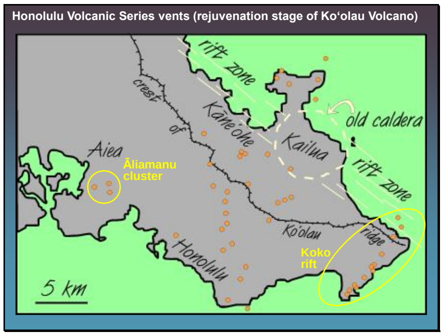
A Koloa volcanic series vent near the north shore featured prominently in a recent tragedy on Kaua'i. In 2006, during the 42 days and 42 nights of rain, a reservoir within Kaloko crater failed catastrophically, killing 7 people. In this figure, older Kaua'i rocks show up as highly eroded islands, surrounded by much less-eroded Koloa rejuvenation vents and lavas in blue.

The Path of the Flood



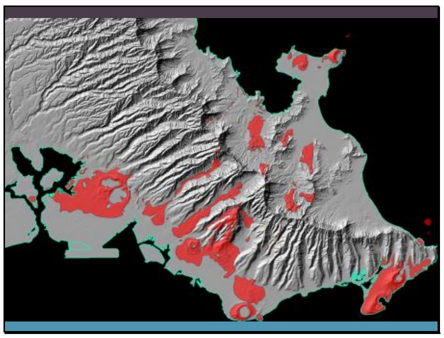
Kaloko reservoir is a reservoir because it is an old crater – it was already a depression surrounded on almost all sides by a berm. All they had to do (back in the 1920s) was block the one outlet, which was on the east side, with an earthen dam. As long as the dam held, the reservoir could fill with water. Earthen dams, however, will always fail if water ever overtops them, so they always have a spillway that is armored with concrete. That way the lowest point on the dam is not going to suffer from catastrophic erosion if the water level ever gets so high that it starts to spill out. Unfortunately, it appears that the landowner buried the spillway, meaning that some location on the earthen dam was the lowest spot. Once water started flowing over it, it eroded a channel, which allowed the water to flow faster, which eroded more, which eroded the channel deeper, which allowed the water to flow even faster, and so on. Catastrophic collapse was inevitable.

Honolulu Volcanic Series vents



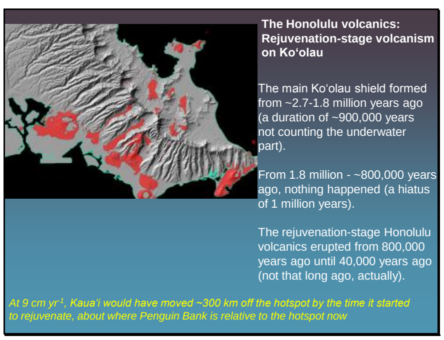
Probably the best-studied series of rejuvenation-stage vents and flows is the Honolulu volcanic series, the rejuvenation stage of Ko‘olau volcano. 40-something vents are scattered about the SE end of Ko‘olau, some in obvious lines, others more or less just scattered.

Honolulu Volcanic Series: vents & flows



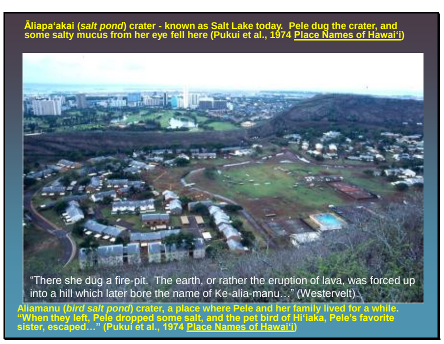
The red color indicates the Honolulu volcanic series vents and flows. People have looked hard for patterns related to the structure of the old volcano, but nothing obvious has ever jumped out. In some cases the vents are in the backs of valleys (Nu‘uanu, Pālolo), in others they are on the ridges between valleys (Kalihi, Tantalus), and in others they are down on the coastal plain (Le‘ahi, Pūowaina, Mokapu). They clearly post-date the carving of the valleys, however.

The Honolulu volcanics: Rejuvenation-stage volcanism on Ko‘olau



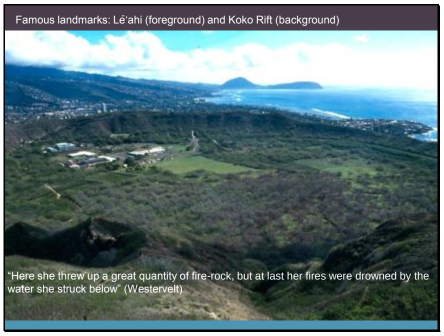
Like Kaua‘i, Ko‘olau had moved to about where Penguin Bank is now when it started rejuvenating. This is consistent with that secondary zone of melting that was modeled by Ribe & Christiansen. Note that the most recent rejuvenation volcanism on Ko‘olau, the Koko rift, is only 40-50 thousand years old, which is quite young. It is definitely statistically possible that another Honolulu volcanic series eruption could occur, although nobody is predicting it.

Aliapa‘akai & Aliamanu



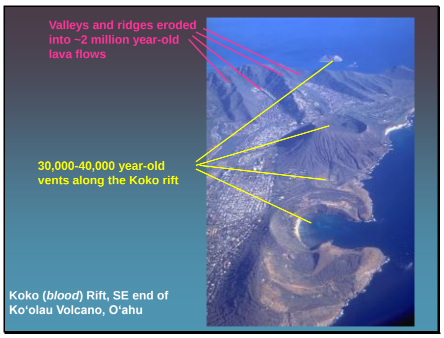
Aliapa‘akai and Aliamanu are two Honolulu series vents that Pele visited on her way southeastward.

Le‘ahi



Le‘ahi is also a place that Pele visited during her southeastward travels.

Koko rift

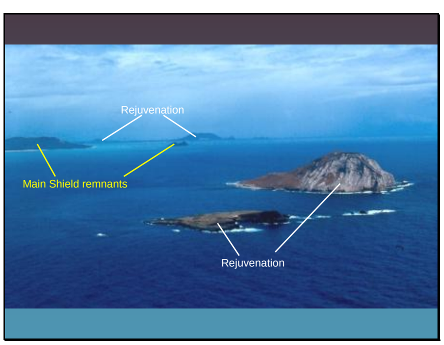


This is the Koko rift, which extends from Manana to the north, past Hanauma Bay, and continues offshore, where there are 2-3 additional vents. Almost all these eruptions took place offshore of what the island looked like at the time, so there were violent interactions between the erupting magma and shallow ocean water.

Shallow oceanic eruptions

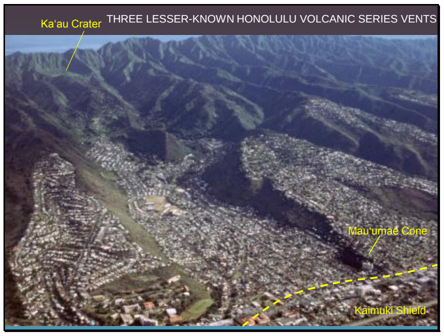
Most of the Koko rift eruptions (and many other Honolulu series eruptions) would have looked something like this.

Northernmost vents of the Koko rift



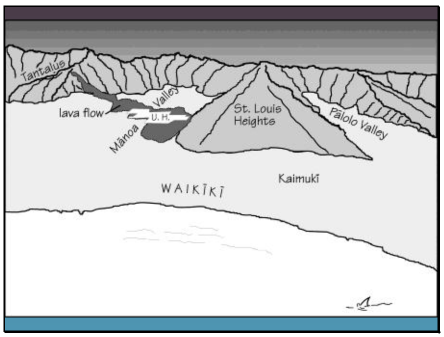
Manana and Moku Hope are the northernmost vents of the Koko rift. The hills on Mokapu peninsula are also rejuvenation stage vents, but not all the offshore islands in this area are. The Mokulua islands and the hills behind Ka‘ohao are both fragments of the original main Ko‘olau shield, and provide excellent evidence that the giant avalanche scar could not have been the Nu‘uanu pali.

Honolulu series vents



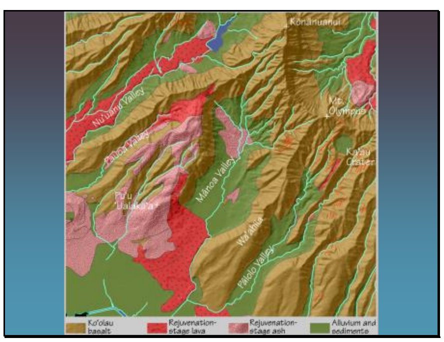
One of the better defined trends of Honolulu series vents is made up of Leʻahi, Kaimukī, Mauʻumae, and Kaʻau. Some people also lump in Kupikipikiʻo (also known as Black Point), although not much is known about it. Leʻahi was hydromagmatic because it interacted with shallow ocean water. Kaimukī was a “dry” eruption without much gas, and produced a lava shield with little or no fountaining – the lava just welled up in a crater and flowed away in all directions. Mauʻumae was a typical “Hawaiian style” eruption with high fountaining. And Kaʻau was also hydromagmatic, but the water involved was groundwater trapped behind dikes high in the Koʻolau Mtns. Just because these vents lie along a line doesn’t necessarily mean that they were genetically related, however.

Mānoa: UH Campus



UH Campus sits on the second-youngest rejuvenation stage lava flow (after all the Koko rift stuff), the ~70,000 year-old Tantalus flow. The vents for this eruption opened up on the ridge between Makiki valley and Mānoa valley, and the lava flowed down into the (already existing) Mānoa valley. The lava flowed across the valley and bumped up against the base of Waʻahila ridge, diverting Mānoa stream away from its previous central location in the valley.

Mānoa: Tantalus rejuvenation-stage

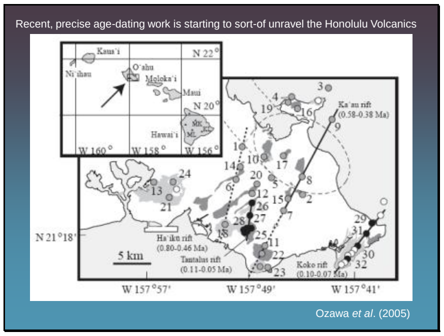


This geologic map shows the effect of the Tantalus rejuvenation-stage lava on the course of Mānoa stream. It is likely that for at least a little while, Mānoa stream was dammed by the flow and a lake developed. I don’t know if anyone has ever gone looking for it. Note also that Pālolo stream was diverted westward by the lavas of the Kaimukī shield.

Mānoa: Tantalus rejuvenation-stage

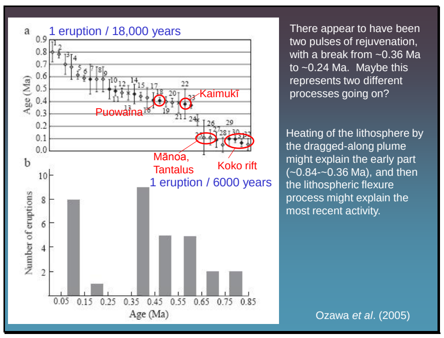
From UH campus, you can see some of the Tantalus cinder cones, which appear as bumps up on the ridge.

Recent, precise age-dating work: Honolulu volcanics



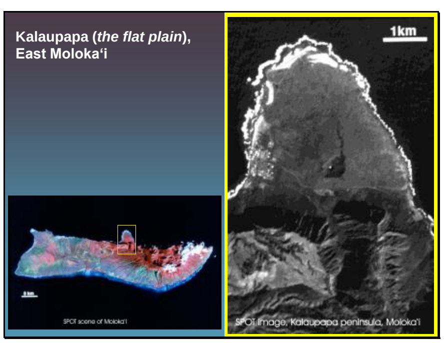
The most comprehensive age-dating work on any set of rejuvenation stage eruptions was undertaken a few years ago. These authors collected lavas and spatter from as many Honolulu volcanic series vents as they could. Some vents offer only fine-grained ash, which alters very quickly, making it difficult to attain accurate age information.

Pulses of rejuvenation



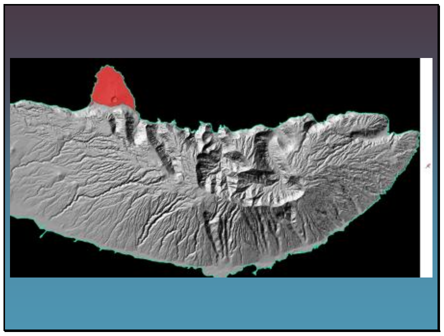
When they produced a rank-order plot (oldest to youngest plotted by number), they noticed that there seem to have been two pulses of eruptions. One pulse lasted from about 800,000 years ago to about 380,000 years ago. Then there was a pause, with only one eruption (ʻAliamanu) between 380,000 years ago and 100,000 years ago. Then about 100,000 years ago, the eruptions started up again, continuing until the Koko rift eruptions. The average recurrence intervals during these two pulses were 1 eruption every 18,000 years and 1 eruption every ~6000 years. The fact that there were two pulses and that the eruptive behavior was different during them (at least with respect to frequency) suggests that perhaps two different mechanisms were at work. Perhaps the early part occurred due to the conductive heating of the lithosphere mechanism, and the later pulse occurred due to the lithospheric flexing or the modeled Ribe & Christiansen model. Obviously there is still much to learn.

Kalaupapa, East Molokaʻi



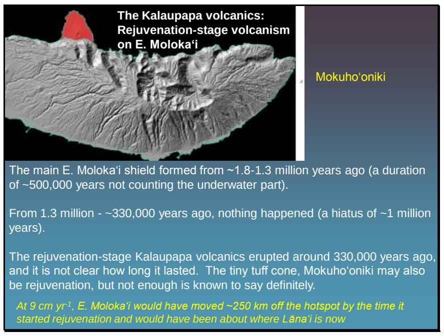
Next down the chain is E. Molokaʻi volcano. It boasts the largest single rejuvenation stage feature, Kalaupapa peninsula.

Kalaupapa, East Moloka'i



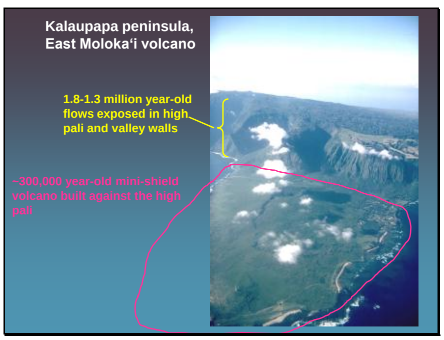
Kalaupapa is banked against a set of very high ocean cliffs, and clearly post-dates the cliffs. As you will recall, the cliffs got their head start from the giant avalanche, but aren't the scar itself. Two tiny islands near the east end of the island, Mokuhoʻoniki, are remnants of what is probably also a rejuvenation-stage vent, but nobody has studied it well enough to know.

The Kalaupapa volcanics



Note that the duration of Kalaupapa's eruption is 500,000 years, which is pretty long, even considering the huge volume. Whether that included some breaks or whether it is just uncertainty in the samples is unknown.

Kalaupapa peninsula, East Molokaʻi volcano

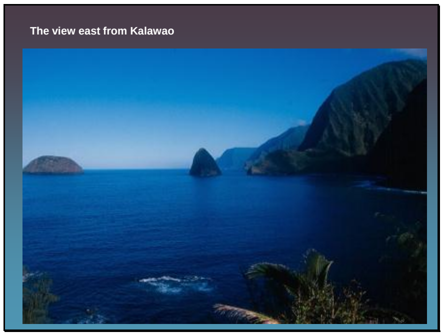


This oblique air photo shows how Kalaupapa juts out from the base of the pali. It also shows the contrast between the highly eroded main E. Molokaʻi shield and the much younger Kalaupapa peninsula. You can also see Kauhako crater and a sinuous trench that runs downhill away from it. This trench is probably a collapsed lava tube.

Kalaupapa from the start of the trail down the cliff

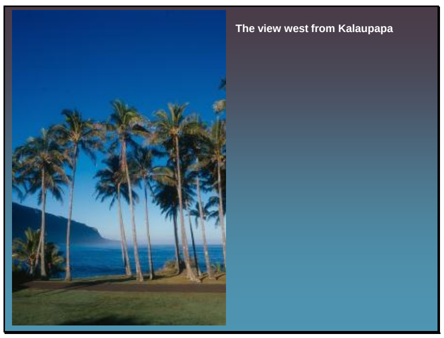
This is the view from "topside" down to the peninsula. Note that the beach in the left foreground, which is close to the base of the pali, is dominated by material eroded from the lava flows (it is a black sand beach). The beaches farther out toward the point, however, are dominated by calcareous sand.

The view east from Kalawao



From Kalawao, on the east side of the peninsula, you can look along the towering pali that make up the N coast of E. Molokaʻi. The two little islands, Mokapu and Okala, are remnants of the main shield.

The view west from Kalaupapa

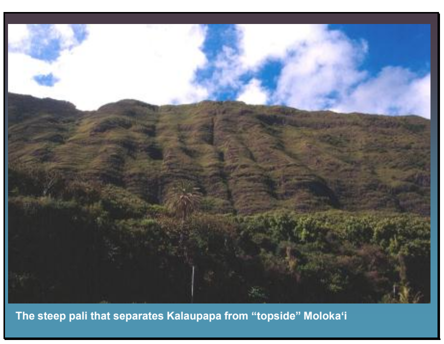


The view west is similar, although the pali are not as high because the main shield slopes away in that direction.

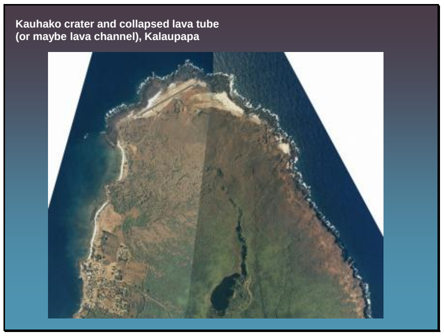
From Kalaupapa, looking south

From Kalaupapa looking south, you can see the imposing pali behind.

The steep pali that separates Kalaupapa from "topside" Molokaʻi

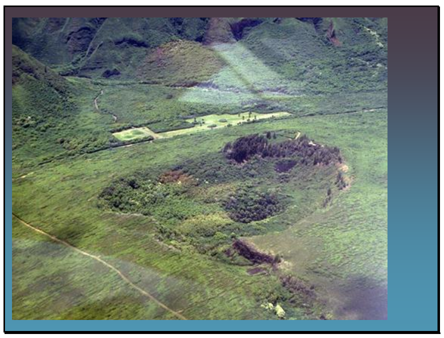


Kauhako crater and collapsed lava tube (or maybe lava channel), Kalaupapa



Kalaupapa is interesting from a volcanological point of view as well as from a volcano evolution point of view. This satellite image shows Kauhako crater, an inner crater within Kauhako crater, and the collapsed lava tube heading off to the north.

Main rim of Kauhako crater

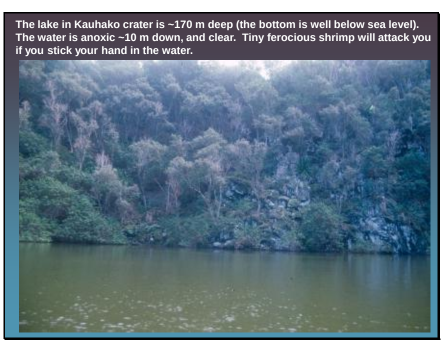


This view shows the main rim of Kauhako crater. The inner crater is hard to see in this view.

Kauhako crater

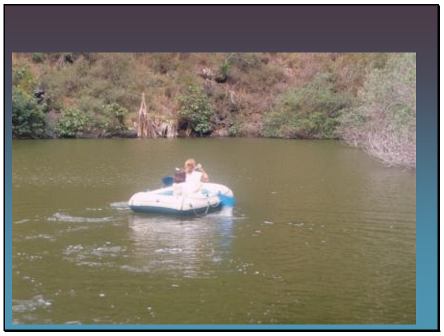
This view shows the morphology of Kauhako crater. There are lots of interesting geological features on the inner platform (plus at least one burial deep in a hole), but it is so overgrown, that it is really difficult to study anything.

The lake in Kauhako crater

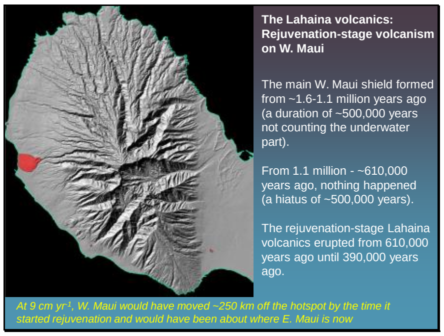


I got to go down to the lake in 2001 with a USGS scientist who was studying the water column in the lake, taking samples ever few tens of meters from bottles tethered to a weighted line. We had to lug a rubber boat down a very steep trail every time we went down to sample.

The lake in Kauhako crater

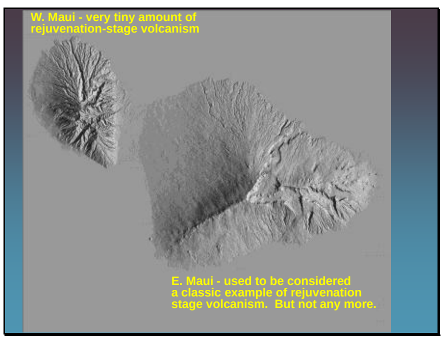


The Lahaina volcanics



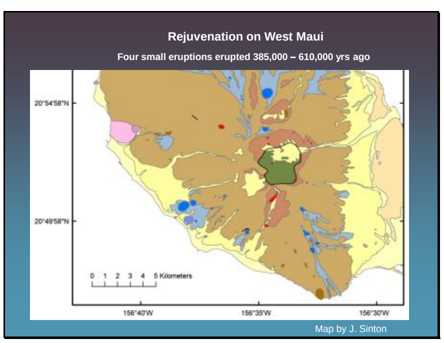
Unlike Kalaupapa, which is an impressively voluminous rejuvenation feature, the Lahaina volcanics are pretty pathetic. Four tiny eruptions out on the south and western rim of the volcano are all that have ever been identified.

Rejuvenation-stage volcanism on Maui



The two Maui volcanoes are different in a number of ways. W. Maui is much smaller than E. Maui, and has a somewhat small post-shield alkalic cap. E. Maui is way bigger, and its post-shield alkalic cap is huge, covering almost the entire volcano. Moreover, the youngest eruptions on E. Maui (e.g., in Haleakalā crater) used to be considered rejuvenation-stage volcanism, but as we'll see in a bit, that is no longer considered correct.

Rejuvenation on West Maui



W. Maui's rejuvenation stage eruptions are shown in purple, and are almost impossible to see because they are so small.

Pu‘u Kīlea

One of the best to visit is Pu‘u Kīlea, which erupted through an alluvial fan which had formed from material washed out of Olowalu valley. There is not much to direct you to the right place, but once you are there it is worth it. In addition to the interesting geology, there are petroglyphs. But they are not the same as those that you typically see carved into vesicular pahoehoe flows. In this case, they were created by hammering the oxidized coating off of flat, vesicle-free lava, which must have been much more laboroius.

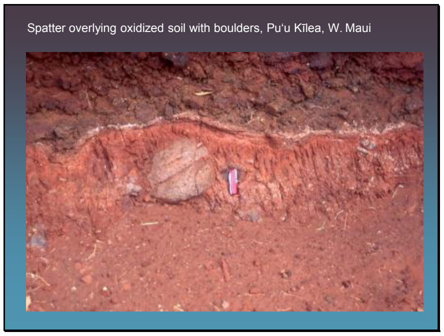
Lava flow overlying soil with boulders, Pu‘u Kīlea, W. Maui

This outcrop shows the base of the Pu‘u Kīlea flow resting on an alluvial soil that contains rounded residual boulders.

Rejuvenation-stage spatter lying on old soil, Pu‘u Kīlea, W. Maui

Nearby, spatter from the Pu‘u Kīlea vent is also sitting directly on an old, oxidized soil.

Spatter overlying oxidized soil with boulders, Pu‘u Kīlea, W. Maui

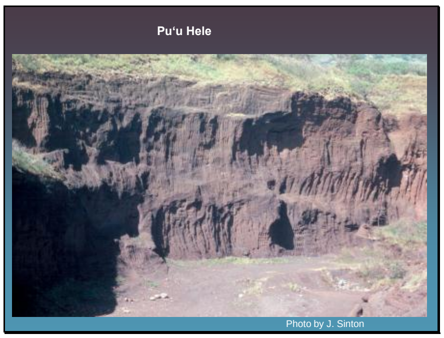


The reaction between the overlying hot spatter and lava has produced some interesting structures within the upper few 10s of cm in the old soil, but I don’t know of anyone who has studied this.

Pu‘u Hele

The largest rejuvenation stage feature on W. Maui is Pu‘u Hele, consisting of a large cinder cone and flow. Much of the cone, however, has been quarried away.

Pu‘u Hele

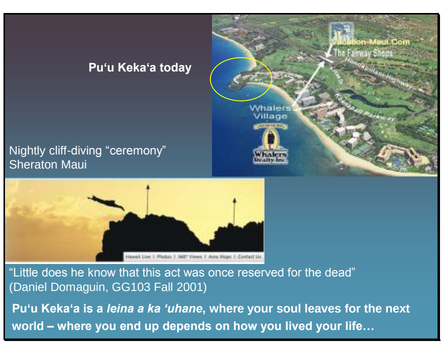


Geologists like cinder quarries because they give us access to the internal structure of a cinder cone. It is kind of destructive, though.

Keka‘a Point – a Lahaina Volcanics spatter cone

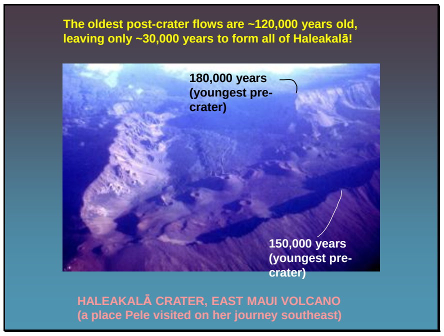
Finally, we get to Keka‘a point, the northernmost rejuvenation feature on W. Maui. Although it is right on the coast, it is a cinder and spatter cone, produced by a “dry” eruption. This probably means that sea level was a good deal lower when the eruption occurred.

Pu‘u Keka‘a today



Now, of course, Pu‘u Keka‘a is barely visible under a fancy Ka‘anapali hotel. This quote about jumping off into the ocean comes from one of my students, who produced a poster about Pu‘u Keka‘a for a final project a few years ago.

The oldest post-crater flows



Pele, the sacred land hewer