A Silent Intrusion:
New Insights into Volcano Dynamics

by

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The Dangers of Volcanoes

"It was hard to distinguish where the streets had been. Everything was buried under fallen walls of cobblestone and pink plaster and tiles, including 20,000 bodies....As I look back on the Martinique experience I know what a crucial point in my life it was....I realized that the killing of thousands of persons by subterranean machinery totally unknown to geologists...was worthy of a life work." – Thomas A. Jaggar, *My Experiments With Volcanoes*

In the first months of 2018, the Lower Puna district on the island of Hawai'i was postcard-perfect: lush-rainforests, blue-seas lapping against sandy beaches, and a sweet tropical breeze. It was truly paradisal, but Madame Pele, the Hawaiian goddess of fire and volcanoes, had other ideas. Lower Puna is home to a flank of Kīlauea volcano known as the East Rift Zone, and by mid-May 2018, it would be scarred by the opening of dozens of new chasms, all spitting molten rock and debris hundreds of feet into the air. By mid-July a ten-story tall spatter cone – a mini-volcano of sorts – had formed over what had once been the subdivision of Leilani Estates (*HVO*, 2018a). This lava-spitting cone and the rivers of lava flowing from it to the sea was a truly frightful and awe-inspiring sight to behold. Luckily, there was no loss of life. However, by the time Madame Pele decided she had done enough and returned to quiescence in August, the eruption had claimed 716 homes, and had added 875 acres of land to the island (*HVO*, 2018b).

Volcanoes are one of the most primal and destructive forces on Earth, and have made a notable impression upon the human consciousness; mention of the word brings to mind images of fiery destruction and names like Pompeii, Krakatoa, and Mount St. Helens. Unfortunately, for a natural hazard with such significant impact on humanity, there remains much to learn about the inner workings of volcanoes and how to predict their activity. This knowledge is crucial to saving lives by mitigating the hazard imposed upon us by volcanic eruption. However, up to present day, despite a strong impetus to grow our understanding of this natural phenomenon, as much, if not more, has been learned about the vast expanse of outer space than about the destructive force that lies beneath our feet, threatening our very existence.

The disparity in our comprehension of volcanoes relative to other parts of the natural world is largely the result of two factors: long periods of rest between eruptions relative to a human lifespan; and the fact that we cannot dig on the massive scale that would be required to excavate and physically explore a volcano and its plumbing. In other words, our understanding is limited by both the infrequency of eruptions and the indirect observations that can be made from the surface. This is not to say that trying to understand volcanoes is a lost cause, but rather that new techniques for examining underground processes are of great interest to both the scientific community and humanity. One of the best ways to discover these new techniques is by exploring all possible avenues for observation. Although we are bound to the surface, many different sources of data exist for volcano monitoring, and the development of many of these is in no small part thanks to one of the pioneers of modern volcanology, Thomas Jaggar.

After witnessing the havoc wreaked by eruptions on Martinique in 1902, Thomas Jaggar (Ph.D. in Geology, Harvard, 1897) dedicated his life's work to better understanding volcanoes. He was the first to install seismometers at the summit of Kīlauea in 1912, creating the first volcano observatory in the United States. As a testament to his life's work, the Hawaiian Volcano Observatory has stood watch over Kīlauea and the swinging moods of Madame Pele for over a century (*Decker et al.*, 1987). Today, the Hawaiian Volcano Observatory operates one of the world's most extensive volcano monitoring networks. It keeps measurements of ground deformation, shaking, and volcanic gas chemistry along with many other quantities (*Decker et al.*, 1987; *Babb et al.*, 2011). I took advantage of the data from this substantial network during the summer 2018 Kīlauea eruption (*USGS*, 1956) to interpret and link them to physical volcanic processes. In particular, I examined how the ground shaking may be leveraged to gain new insight into subsurface volcanic processes.

Dynamic Volcanic Processes

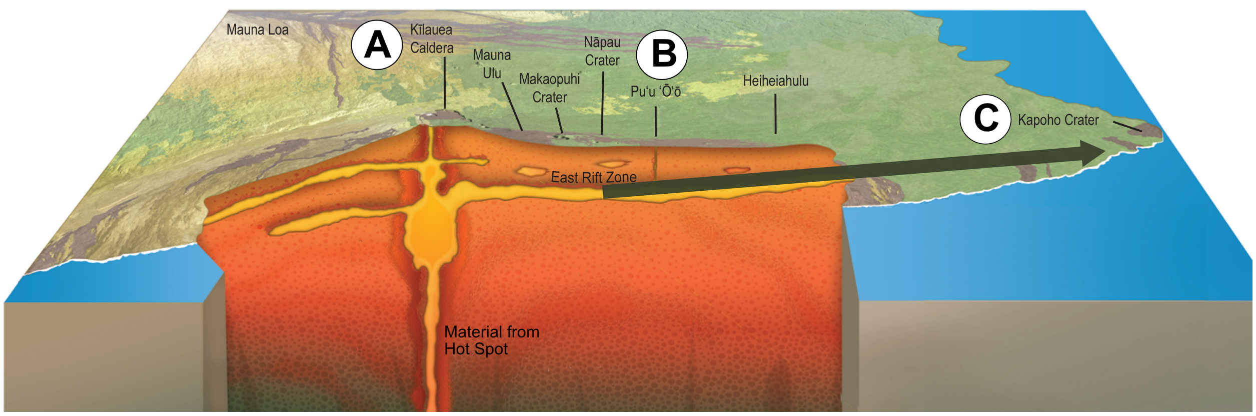

Figure 1: A cutaway diagram depicting a simplified model of Kīlauea and its subsurface plumbing system fed from a deeper source. Note the location of: (A) Halema'uma'u crater at the summit; (B) Pu'u O'o vent further downrift; and (C) the area of active eruption on the East Rift Zone. Modified from *Poland et al.* (2014).

Before it emerges on the surface as lava, molten rock is called magma (*Grotzinger et al.*, 2010). Volcanoes typically have a shallow area for magma storage fed by a deeper source. In the case of Hawai'i's Kīlauea volcano, magma chambers are thought to exist below the summit at a depth of a few kilometers (Figure 1; *Wright and Klein*, 2011; *Poland et al.*, 2014). The locations and sizes of these chambers vary with time as the volcanic system evolves and cycles between periods of eruption and repose. The system is drained during eruptions, and is refilled otherwise (*Anderson et al.*, 2015). Outside of this basic dichotomy, there remain many gaps in our understanding of these dynamic cycles of deflation and inflation in the magma chambers and the related processes of eruption and recharge.

Even within a single eruption, the progression of observed events across the volcanic system hint at the complex and deeply interconnected systems hidden beneath the ground. The 2018 Kīlauea eruption included activity at Halemaʻumaʻu crater (at the summit of the volcano; Ⓐ in Figure 1), the East Rift Zone (located about thirty kilometers away on the flank of the volcano; Ⓒ in Figure 1), and the active Puʻu Oʻo vent (between the East Rift Zone and the summit; Ⓑ in Figure 1).

As a precursor to the presence of lava on the surface, Puʻu Oʻo crater experienced significant draining on April 30th, and a sequence of small earthquakes moved east from Puʻu Oʻo crater towards the East Rift Zone between April 30th and May 2nd (*HVO*, 2018a; *Neal et al.*, 2019). Past precedence suggests such an earthquake sequence can be attributed to fresh magma moving through the ground and occupying new space, much like a subway train shaking the ground as it passes (*Rubin et al.*, 1998; *Klein et al.*, 1987). Following these events, the eruption formally began with lava-spewing chasms opening in the East Rift Zone on May 3rd (Figure 2; *HVO*, 2018a).This seqeunce suggests a link between Puʻu Oʻo and the East Rift Zone at the beginning of the eruption. Following the start of the eruption, a large Magnitude 6.9 earthquake occurred on May 4th (*Masse and Needham*, 1989; *HVO*, 2018a).

Figure 2: (a, b) Explosive events that occured as Halemaʻumaʻu crater at the summit of Kīlauea collapsed over the course of the eruption. (c) A river of lava flows down to the sea from (d) active vents in the Lower East Rift Zone of Kīlauea. Photo Credit: *HVO, United States Geological Survey.*

As the eruption evolved, Halemaʻumaʻu at the summit became integrated into the system lower down the flank. Since 2008, a lava lake has been present on the floor of Halemaʻumaʻu (*Patrick et al.*, 2013). The level of this lake began to drop significantly beginning on May 6th, indicating movement of the subsurface magma away from the summit system. The draining of the lava lake was followed by significant explosive collapses of Halemaʻumaʻu's crater wall (Figure 2). The first of these occurred on May 15th, and created an ash cloud more than 3000 meters in height (*HVO*, 2018a). These events are triggered as draining lava exposes the wall of the crater, steepening the cliff face and creating a rockslide that falls into the lava lake and results in an explosion and ash cloud (*Neal et al.*, 2019). The explosive collapse events represent an increase in the speed and magnitude of the draining at the Halemaʻumaʻu lava lake, a change that was mirrored by an increase in output from active vents in the East Rift Zone (*Patrick et al.*, 2019). This draining continued until the end of the eruption in early August, at which point, 885 million cubic meters of material had been lost from the summit (Figure 3; *Neal et al.*, 2019). Notably, the volume of material lost from the summit is remarkably consistent with the volume of lava that erupted from active vents on the East Rift Zone (*Patrick et al.*, 2019).

The nature and timing of these events strongly suggest a connection between Puʻu Oʻo and the Lower East Rift Zone at the beginning of the eruption, followed by a connection of the Puʻu Oʻo - Lower East Rift Zone system to other parts of the volcano including the Halemaʻumaʻu system at the summit. However, a large piece of the story, one that is potentially crucial to better understanding the behavior of volcanic systems, is missing. Unlike the connection between Puʻu Oʻo and the Lower East Rift Zone that was accompanied by migrating seismicity, there were no corresponding earthquakes taking place around the time when the summit and Puʻu Oʻo were connected. How was a connection between these two systems forged? Without being able to view the subsurface movements of magma, this is a hard question to answer; however, addressing it could save both lives and infrastructure from undetected magmatic intrusions that could result in unwarned-of-eruption. This thesis seeks to answer this question through systematic analysis of ambient seismic noise data.

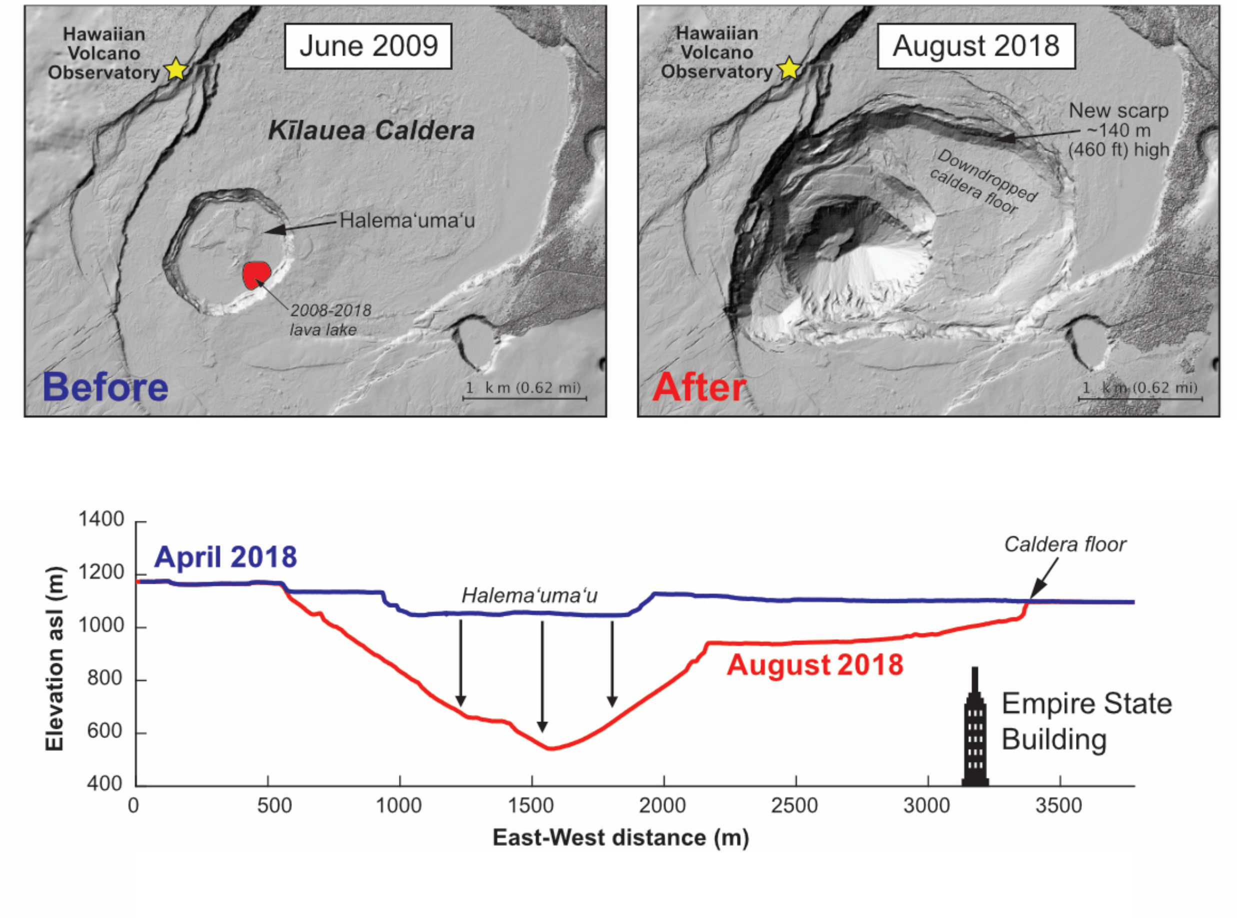

Figure 3: A comparison of the shape and depth of Halemaʻumaʻu crater at the summit of Kīlauea (top left) before the 2018 activity and (top right) after the collapse events. (bottom) An east-west cross-section comparison showing the degree to which the crater was enlarged. Modified from *HVO* (2018b).

Imaging the Subsurface with Noise

Much like how x-rays passing through the body can reveal the bones within, seismic waves passing through the ground can reveal the locations and sizes of large bodies of magma or the volcanic conduits that feed them. Information about these waves are collected by

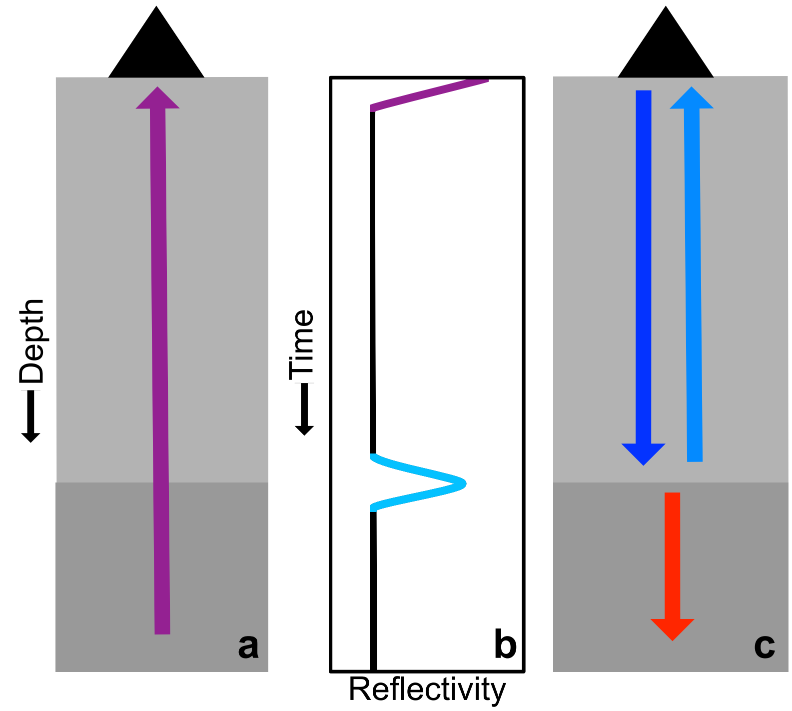

Figure 4: (a) A cartoon in depth cross section depicting initial arrival of seismic energy (magenta arrow) at a station (black triangle). (b) This energy is recorded as the initial peak (magenta) in the reflectivity function whose y-axis is time increasing down, and whose x-axis is reflectivity. (c) The energy reflected from the surface (blue arrow) reaches a boundary and is reflected (cyan arrow) and refracted (red arrow). This reflected energy coming back up is recorded at the station, and results in another peak in the reflectivity function later in time (b).

observing how the ground shook in certain locations, at certain times. From these observations, signals of interest can be extracted, and meaningful physical conclusions can be drawn.

The ground beneath us is built up of layers of different materials, one upon another. When seismic energy encounters the boundary between two layers, there are two options. The energy can be either refracted, passing through the boundary on a possibly different trajectory, else it is reflected, bouncing back from whence it came to be recorded at the surface (Figure 4; *Shearer*, 2009). For my purposes, I am concerned with the latter of these two outcomes, reflection. The instances of these reflections can be obtained by correlating a seismogram with itself to look for similar peaks separated in time (Figure 4b).

The time function with the reflection peak is generated by taking a time series (e.g., movement of the ground with time) and comparing it with itself at different time offsets to find similar waveforms (*Bracewell*, 1986). Applied to seismology, it is used to identify the return of a previously recorded seismic wave that has bounced off a reflecting boundary, and is referred to as a reflectivity function (Figure 4b; *Claerbout*, 1985). By determining how long it takes for the reflected energy to return, the depth of the reflecting boundary and subsurface wave speed may be inferred, and strength of reflection is determined by amplitude of the peaks (*Thompson and Cooper*, 1972; *Yokoi and Margaryan*, 2008). This method has been used for the imaging of various subsurface layers such as the boundary between the crust and the mantle (e.g., *Kennett et al.*, 2015). In volcano monitoring, it is often used to detect the boundary between solid rock and magma, and to examine how this boundary changes over time (e.g., *McKee*, 2012; *De Plaen et al.*, 2016).

In order for the reflectivity function to exist, a source of energy is needed to generate the reflected waves. For example, in oil exploration, anthropogenic energy sources such as controlled explosions are used (*Dobrin and Savit*, 1960). However, such sources provide only a snapshot of the subsurface in the moments directly following the energy release. For a dynamic environment such as an erupting volcano, it is infeasible to set off controlled blasts often enough to monitor the evolution of the system. Consequently, it is necessary to find another source of seismic energy for continuous imaging of volcanic systems.

A source of energy for this type of study needs to occur almost all of the time in order to allow detection of rapid changes. One natural source of seismic energy fitting this criterion is ocean waves impacting the shoreline and being converted to seismic energy. This seismic energy travels underground for hundreds of miles, and when recorded by seismometers, are referred to as microseisms, a type of seismic noise. Noise is typically defined as anything not related to earthquake signals, which are the focus of classical seismology. While it may seem odd to use “noise”, the main benefit of using oceanic microseisms is that it is continuous and occurs naturally 24 hours a day, seven days a week without human involvement (*Stutzmann et al.*, 2009; *Ardhuin et al.*, 2011). These oceanic microseisms can be leveraged as the energy source for calculation of reflectivity functions that allow for easy monitoring of changes in the subsurface with a high temporal resolution (e.g., *Draganov et al.*, 2009),and consequently make Hawaiʻi an ideal location for this type of study.

Seismic energy is recorded by seismometers, of which the Hawaiian Volcano Observatory has a substantial network (*Decker et al.*, 1987). The seismometers used in this study belong to four stations strung along the flank of Kīlauea between the activity on the East Rift Zone and Halemaʻumaʻu at the summit (*USGS*, 1956) (Figure 5). These stations can be used to get an idea of the structure directly beneath them. In this case, the areas beneath the seven stations are of particular interest because they likely host the subsurface structure that evolved during the eruption.

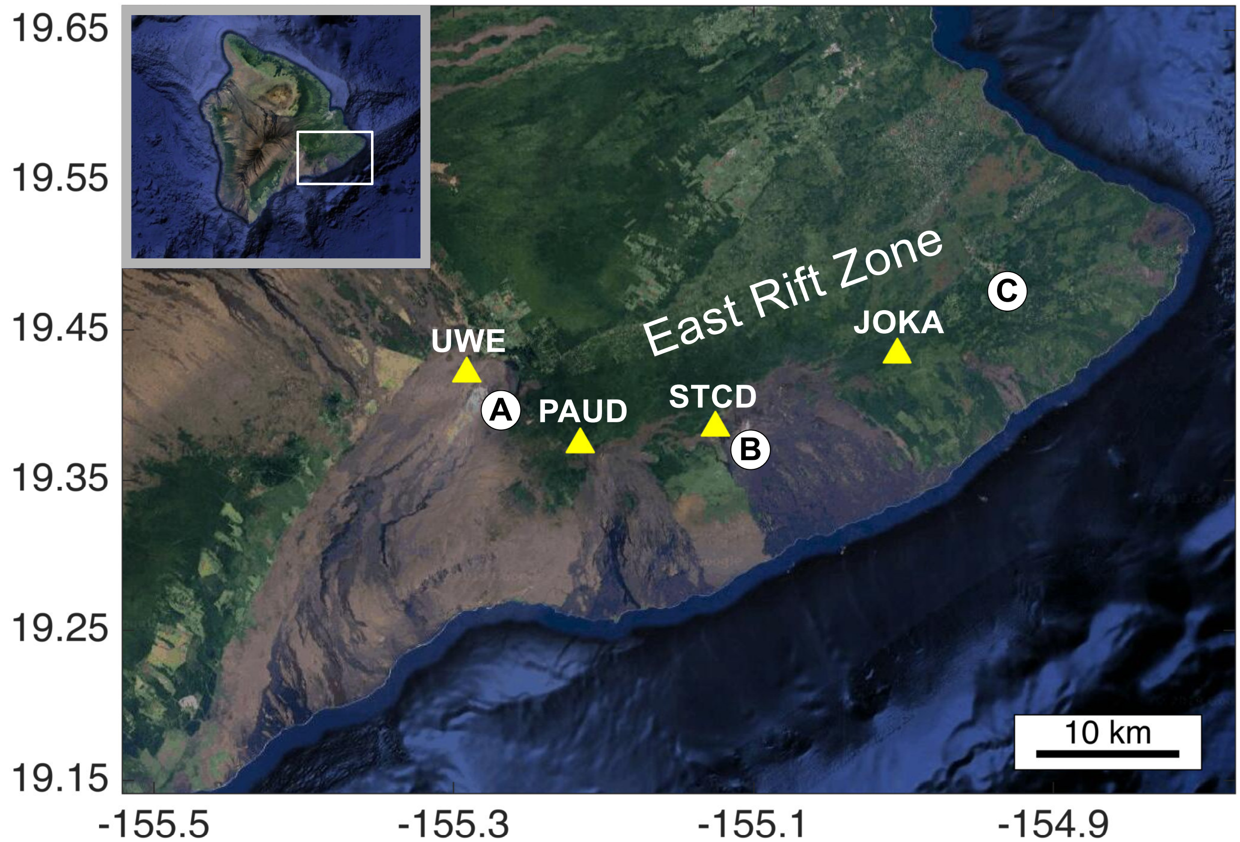

Figure 5: A map of the four stations from the HVO seismic network that are considered in this study (yellow triangles) on the island of Hawai'i (area shown as white rectangle in inset map of Hawai'i). The circles mark: (A) Halem'uma'u at the summit, (B) Pu'u O'o vent midway down the flank, and the (C) Lower East Rift Zone where active fissures and flows were located in the 2018 eruption. Imagery Credit: *Google Earth,* 2018.

An Unexpected Disappearance

At the onset of this project, my intent was to use ambient seismic noise to monitor the evolution of the reflectivity function in the subsurface between the East Rift Zone and Halemaʻumaʻu at the summit of Kīlauea over the course of the summer 2018 eruptive activity. That is to say, I wanted to seismically map the subsurface plumbing system. To this end, I retrieved data from seven Hawaiian Volcano Observatory seismic network (*USGS*, 1956) (Figure 5), and wrote computer programs to compute the reflectivity functions on an hourly basis for each of the seven stations from the beginning of January 2018 to the end of the eruption in August 2018. The computations took about two weeks to perform using Harvard's Odyssey super computer. From there, I began my analysis of the reflecting boundaries between subsurface layers and their evolution.

Through the beginning of 2018, the data showed little to no variation in the subsurface system, meaning that the layout and structure of the subsurface layers were stable and unchanging (Figure 6). This is to be expected, as the precursory signs of the impending eruption did not appear until mid-April 2018, and no surface expression was observed until May 3rd (*HVO*, 2018a). Though some shifting in the subsurface structure was observed immediately preceding the eruption and continuing for a few days, a much more significant and puzzling change began on May 5th.

In my analysis, all signs of reflecting boundaries at Halemaʻumaʻu and the summit disappeared on May 5th. Over the next eight days, the reflecting boundaries from the summit down the flank of Kīlauea towards the East Rift Zone also began to disappear one-by-one. By

May 13th, the reflecting boundaries disappeared at all of the stations (Figure 6). Certainly something odd was happening. More curiously, the reflecting boundaries returned to all stations by the end of May. While the original goal of the study was to analyze the evolution of the subsurface system through examination of the movement of reflecting boundaries, the disappearance of reflectors offered a much more interesting problem.

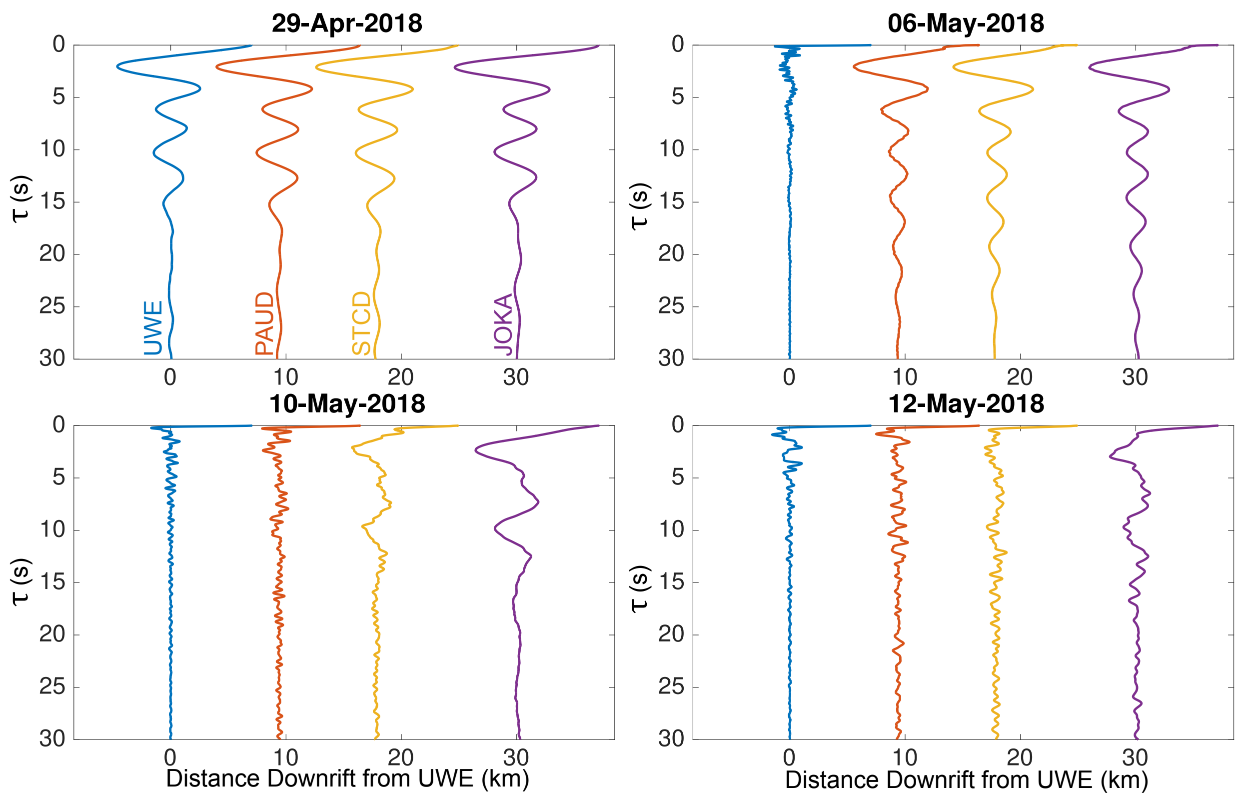

Figure 6: The reflectivity functions at all four stations, UWE (blue), PAUD (red), STCD (yellow), and JOKA (purple). Peaks in the reflectivity functions show reflecting boundaries in the subsurface. Note the disappearance of these peaks and the resultant flattening of the reflectivity functions at one station after another over time.

Shaking Out A Physical Interpretation

Disappearance of reflective boundaries in the ambient seismic noise reflectivity functions is usually a result of two possible scenarios. Either the seismic waves are not detected due to an instrumental problem, or they are not actually reflected due to some physical change in the subsurface. The movement of the decorrelation signal downrift to encompass all sevens stations was a pattern unlikely to have resulted from instrumental problems. Moreover, comparison of the timing of the decorrelation to the ground observations of the eruption, shows that progression of the decorrelation, which started on May 5th, was preceded by a Magnitude 6.9 earthquake on May 4th (*Masse and Needham*, 1989; *HVO*, 2018a). The decorrelation at all stations by May 13th was also followed by the first of the collapse events at the summit on May 15th (*HVO*, 2018a). This remarkable series of events provides a very strong case for a physical interpretation of the signal involving volcanic-processes, and all but rules out instrumental error.

If not due to instrumental error, the disappearance of reflectors must come from decorrelation (Figure 7). Decorrelation occurs when seismic energy is scattered such that a reflection cannot be detected, and therefore the reflecting boundaries effectively disappear from the reflectivity function. This is analogous to how light scattered by fog obscures objects you would otherwise be able to see. On a clear night with no fog, you can see an object such as a car some distance away using a flashlight. This is a result of light bouncing off of the car and then traveling to your eyes with relatively little loss in energy. However, in foggy conditions, the light from the flashlight interacts with water droplets and is reflected in all directions. Only some of these weak reflections return to your eye, and these perceived as “blurry” fog. While some of the light may travel to the car and bounce off of it, by the time it reaches your eyes, it will be so weak that the car can barely be seen, if at all.

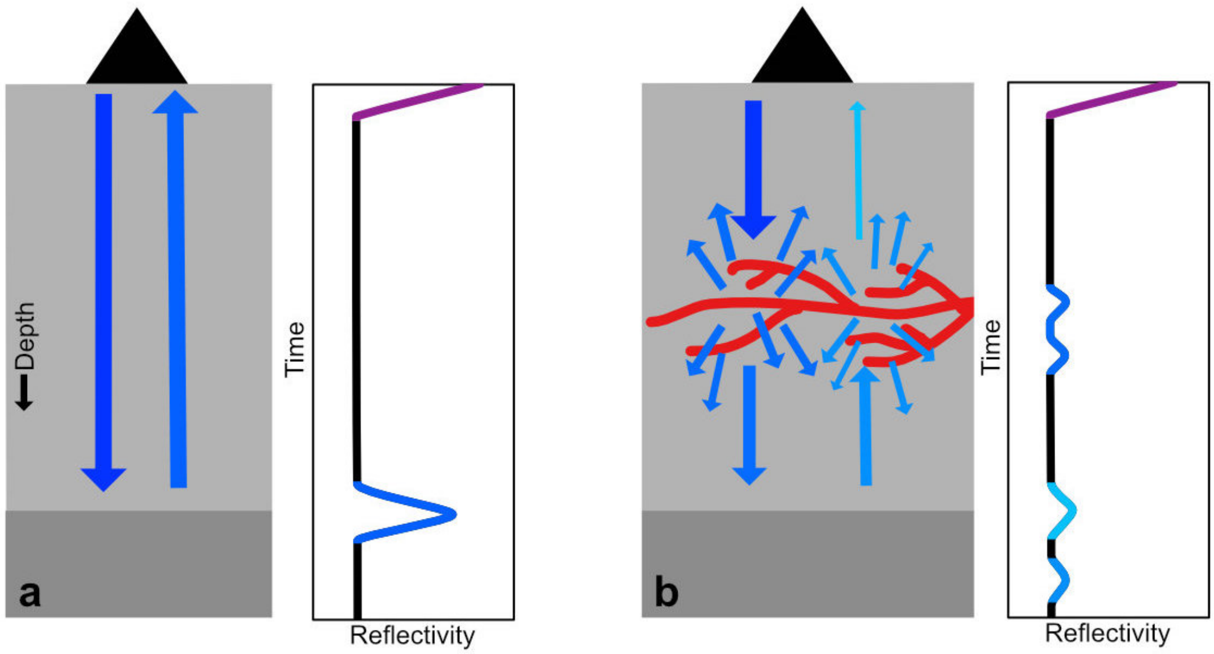

Figure 7: (a) A cartoon depiction of a situation where seismic energy is reflecting back to a station (left) allowing for imaging of a subsurface reflector using the reflectivity function (right), and (b) a decorrelation situation where an intrusion of magma (red segments) scatters the seismic energy (left) such that energy is reflected back to the station nearly continuously at lower amplitudes, and the reflector is not clearly visible (right). The reflectivity functions show the initial instance of energy (purple; Figure 4) and the reflected energies (peaks with various shades of blue).

The presence of a large earthquake before the appearance of the decorrelation signal, and the beginning of the explosive collapses at Halemaʻumaʻu after the migration of the decorrelation from the summit into the East Rift Zone is significant. The earthquake may have had a large effect on the subsurface, potentially triggering a change in the plumbing system. The collapses mark the beginning of summit involvement in the eruption. Together, these suggest that this decorrelation signal which moved downrift was related to the creation of a stronger connection from the summit to the active system erupting further downrift along the flank of the volcano. Interpreting this decorrelation signal as the creation of a new connection from Halemaʻumaʻu and the summit to Puʻu Oʻo and the East Rift Zone makes sense for several reasons. First, any new connection would involve injection of liquid magma into otherwise solid ground. This type of influx has been shown to scatter seismic waves so that they are not reflected back properly, which in turn causes decorrelation similar to that observed in our study (e.g., *Obermann et al.*, 2015) (Figure 7). Moreover, several previous studies of the Kīlauea summit system have come to the concluded that such an intrusion of magma into the region directly east of the summit could be triggered by a large earthquake such as the one that occurred on May 4th (e.g., *Judson et al.*, 2018). There also exists compelling evidence from ground observations for a shift in the eruption from a Puʻu Oʻo and East Rift Zone connection to a Halemaʻumaʻu, Puʻu Oʻo, and East Rift Zone connection. Together, the data forms a convincing argument that the decorrelation signal was the result of an intrusion of magma into the area east of the summit, between Halemaʻumaʻu and Puʻu Oʻo.

Normally, such an intrusion of magma is accompanied by earthquakes generated by the rock fracturing under increased pressure (e.g., *Lockwood et al.*, 1999; *Hurst et al.*, 2018). Indeed, this is the case for the intrusion which occurred at the beginning of the 2018 activity between Puʻu Oʻo and the East Rift Zone from April 30th to May 1st. This preceded the opening of the first active vents (*HVO*, 2018a; *Masse and Needham*, 1989). However, there is no increase or migration of earthquakes corresponding to the migration of the decorrelation, or any possible intrusion from May 5th to May 13th between Halemaʻumaʻu at the summit and the East Rift Zone (*Masse and Needham*, 1989; *USGS*, 1956).

Despite inconsistency with what is expected from an intrusion of this sort, the lack of earthquakes could be reconciled with the magmatic intrusion inferred from the decorrelation. Rather than rupturing through completely solid rock, the intrusion may have entered an area already fractured by a previous intrusion. In that case, the magma would have only needed to re-open existing fractures, thus releasing less energy than fracturing solid rock would. Such a situation would create fewer and smaller earthquakes. If these earthquakes were too few and too small to be detected, the intrusion would effectively be silent.

Proposed Model

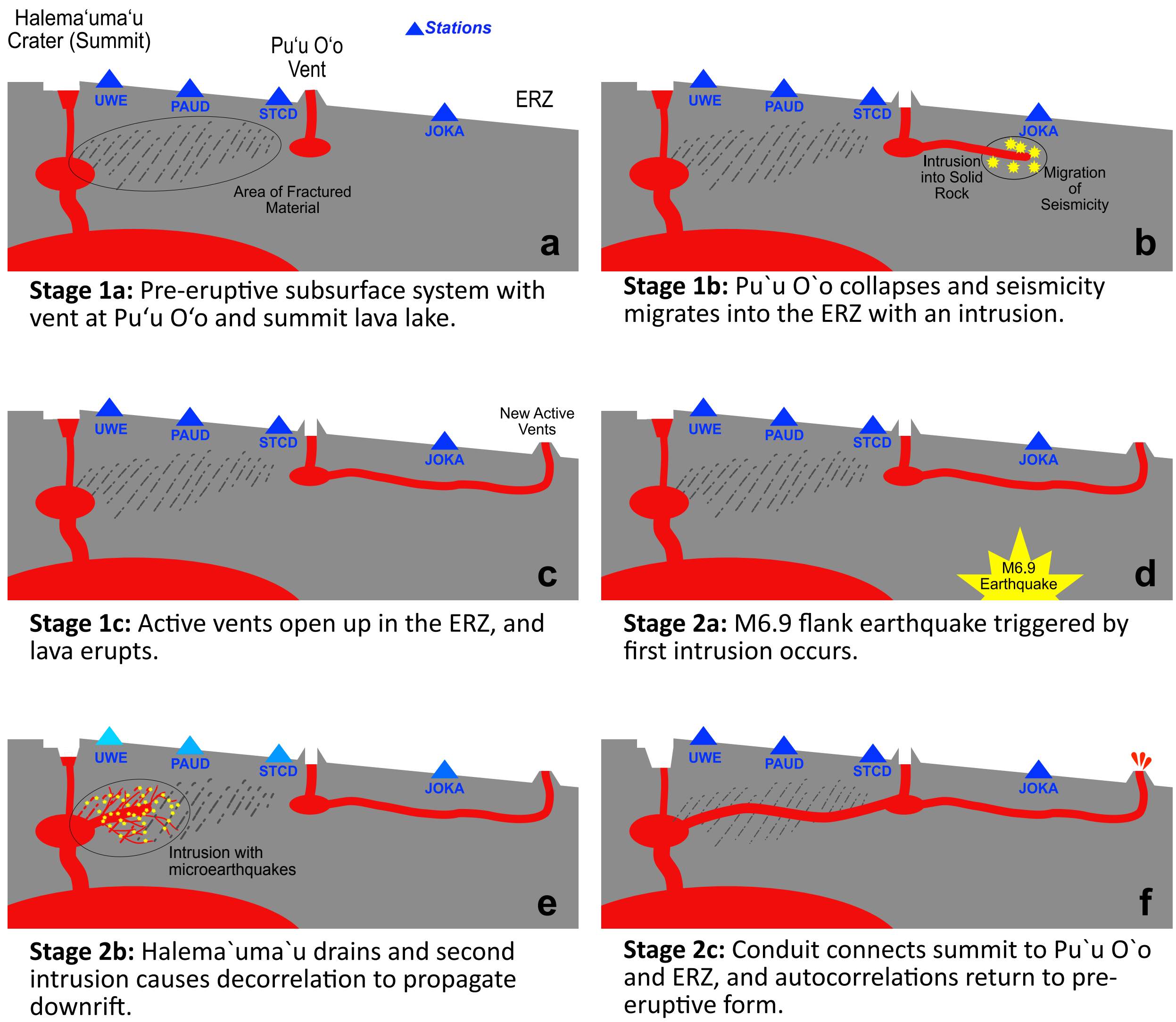

Figure 8: A two-stage eruption model where the steps for each stage are presented as cartoon depth cross sections. The color of the stations indicate how similar the reflectivity functions are with the pre-eruptive form, with light colors indicating a greater degree of decorrelation.

Embracing this possibility, I propose a model for the evolution of the subsurface magma transport system (Figure 8; *Lee et al.*, 2018). The model divides the development into two stages. The first stage leads up to the May 4th magnitude 6.9 earthquake and involves the area spanning Puʻu Oʻo to the Lower East Rift Zone. The second stage takes place after the May 4th magnitude 6.9 event and incorporates the Halemaʻumaʻu summit system into the Puʻu Oʻo and Lower East Rift Zone system.

The model starts with a pre-eruptive confirguration of Kīlauea (Figure 8a). The Puʻu Oʻo vent is active (continuous since 1983, *Poland et al.,* 2014), and a lava lake connected to a deep magma reservoir exists at Halemaʻumaʻu (active since 2008, Figure 1; *Patrick et al.,* 2013). The second step brings an interruption to this state when Puʻu Oʻo collapses, and an intrusion occurs into the area between Puʻu Oʻo and the Lower East Rift Zone. The intrusion is accompanied by migration of seismicity between April 30th and May 1st (Figure 8b). The third step begins when magma reaches the Lower East Rift Zone, new vents open up, and eruption of lava onto the surface starts. This marks a connected and active Puʻu Oʻo and Lower East Rift Zone system (Figure 8c).

The second stage begins with a magnitude 6.9 flank earthquake occuring on the interface between the oceanic crust and the island itself (Figure 8d). This earthquake was likely triggered by the rift-opening motion of the first intrusion between Puʻu Oʻo and the Lower East Rift Zone (*Chen et al.*, 2019; *Neal et al.*, 2019). The shaking from the earthquake then triggers an intrusion of deep-seated magma beneath Halemaʻumaʻu at the summit into the previously fractured region to the east (Figure 8e). Due to the fractured nature of the rock in the area, only microearthquakes occur and magma intrusion into fractures begins to scatter seismic energy. This scattering and microseismicity cause the reflectivity functions to decorrelate, with timing of the decorrelation tracking the magma front. Finally, the intrusion reaches the Puʻu Oʻo and Lower East Rift Zone system established in the first stage, resulting in increased lava output in the Lower East Rift Zone and increased rate of collapse at the summit. This creates a fully connected Halemaʻumaʻu, Puʻu Oʻo, and Lower East Rift Zone system (Figure 8f).

With full connection across the flank, material would be transported relatively smoothly in the established conduit, and there would be less magma pushing into the surrounding rocks. Magma will stop re-opening and filling cracks, and those already open will either drain and close or solidify. Consequently, without the numerous magma-filled cracks, the scattering stops, and the reflectivity functions return to the pre-eruptive form. The timing of this return to pre-eruptive form retreating back up the flank makes it more likely that the decorrelation is due to scattering, as microearthquakes would likely cease across the flank as soon as the conduit is established.

Implications for Monitoring

Outside the scope of the 2018 eruptive activity at Kīlauea, the results of this study still have wide-reaching implications. Whether the lack of earthquakes accompanying the inferred intrusion is due to an actual dearth of seismic activity, or an inability to detect said activity is not the point. The fact is that the typical earthquake-based methods for detecting such significant events did not suggest the notable intrusion of magma which is otherwise in evidence (*HVO*, 2018a). That a significant subsurface change could be essentially silent poses an interesting problem to volcanology. Perhaps more concerning though, is what this silence means in the realms of monitoring and hazard.

The detection of magmatic movement, especially that preceding eruption, is necessary for the effective management of volcano hazard and issuance of warnings to the public. For example, during the 1995 eruption of the Soufrière Hills Volcano on the island of Montserrat, clear signs of escalation of seismicity, including swarms of earthquakes, led to the city of Plymouth being successfully evacuated before it was almost completely covered by pyroclastic flows, saving many lives (*Robertson et al.*, 2000). Around the world, millions of people live in the shadow of volcanoes, including Kīlauea in Hawaiʻi, Mount St. Helens in the Pacific Northwest, or Campi Flegrei in Naples, just to name a few (*Small and Naumann*, 2001). Failure to detect significant subsurface changes in any volcano could put lives at risk, making the implications of a silent intrusion dire. If this type of silent intrusion were to occur as an undetected precursor, a major eruption could quietly materialize with potentially catastrophic results.

Fortunately, while my results suggest the possibility of a silent magmatic intrusion, the techniques I utilized also provide a methodology with which to recognize such an event, decorrelation in reflectivity functions computed from ambient seismic noise. Other studies have already shown that analysis of ambient seismic noise can be used to monitor the inflation of and pressure within magma chambers (e.g., *Bennington et al.*, 2015; *Brenguier et al.*, 2008; *Sánchez-Pastor et al.*, 2018). The suggestion from my work that these data sources can also detect otherwise silent intrusions further contributes to the body of work supporting use of seismic noise data analysis as a volcanic monitoring tool. The computations required for this type of analysis can be performed quickly enough to be done in near real time and with as few as one station. Therefore, incorporating such a technique would require little addition to existing monitoring infrastructure. This low-cost coupled with the the potential benefits for detection and risk reduction will hopefully serve to grow the momentum behind this methodology, which if added to the suite tools already used for volcano monitoring, could help keep populations living on and near volcanoes further from harm's way. On a larger scale, the favorable results stemming from leveraging ambient seismic noise will hopefully serve to encourage the continued exploration of novel data sources in pursuit of deeper understanding.

One might argue that this continued growth of the array of tools and body of scientific work are the greatest testament to Thomas Jaggar and his founding of the Hawaiian Volcano Observatory. However, I am compelled to argue that his true legacy lies not with the science itself, but rather with the millions of people whose lives are safer as a result. A silent intrusion that leads to unwarned-of-eruption is most certainly "subterranean machinery totally unknown," and it is easy for me to agree with Dr. Jaggar's sentiment that this subterranean machinery is truly worthy of a life's work. While this study presents interesting results, it is but a first step, and continued study of this phenomenon and refinement of the model presented here would help paint a clearer picture of the eruptive processes for not only the 2018 Kīlauea eruption, but also other events in both the past and future.

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