Insights Into the Collapse of Kīlauea Caldera Using Seismicity and Infrasound

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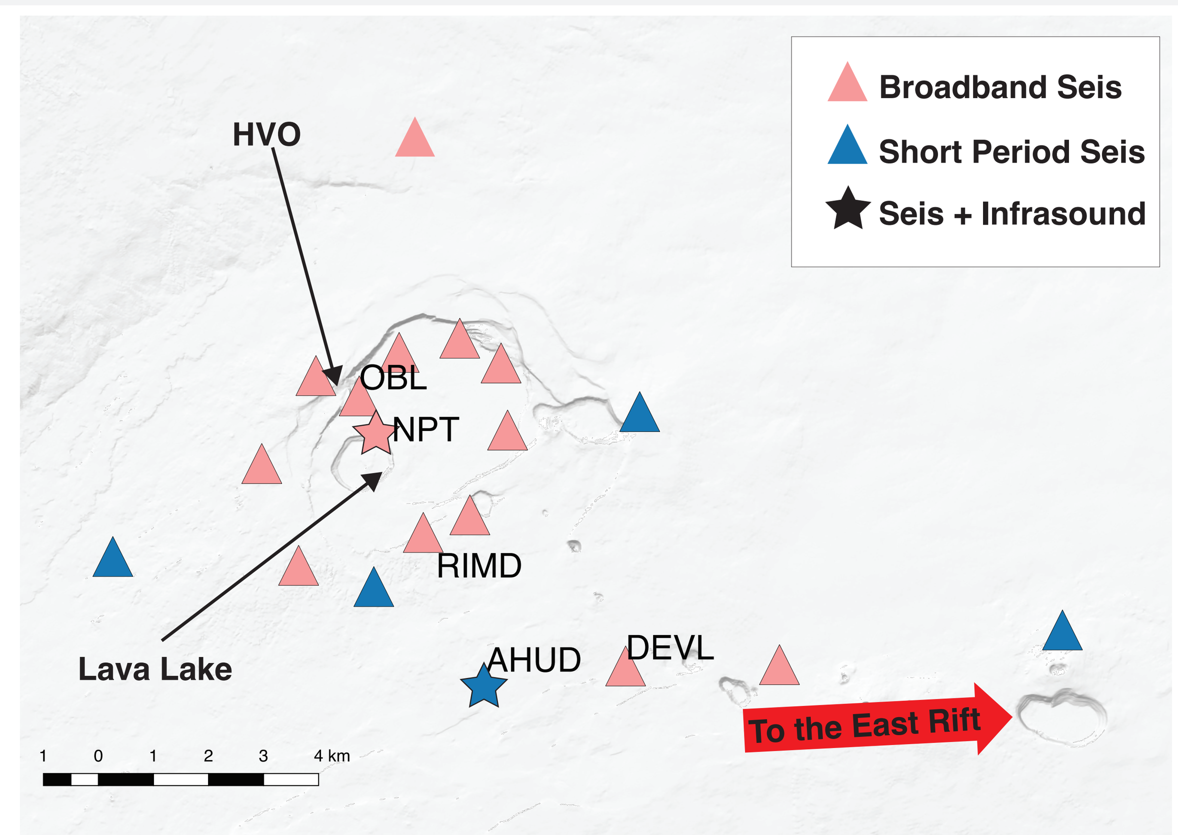
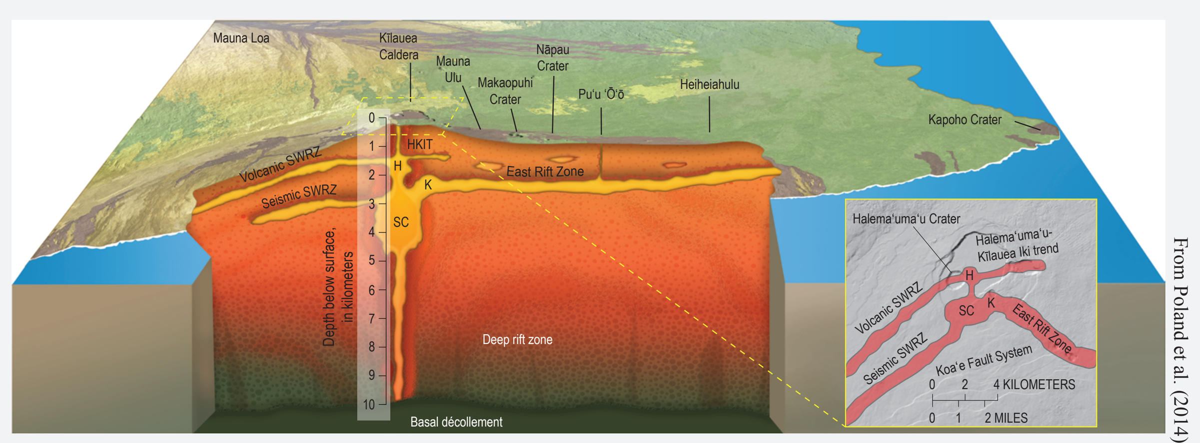
Introduction

- The summit of Kīlauea possesses a very high quality seismic network for many decades, currently composed mostly of broadband seismometers
- Infrasound arrays installed at AHUD since 2012 and NPT since 2017
- Long history of geologic and geophysical observations allows for a detailed understanding of the magma plumbing system



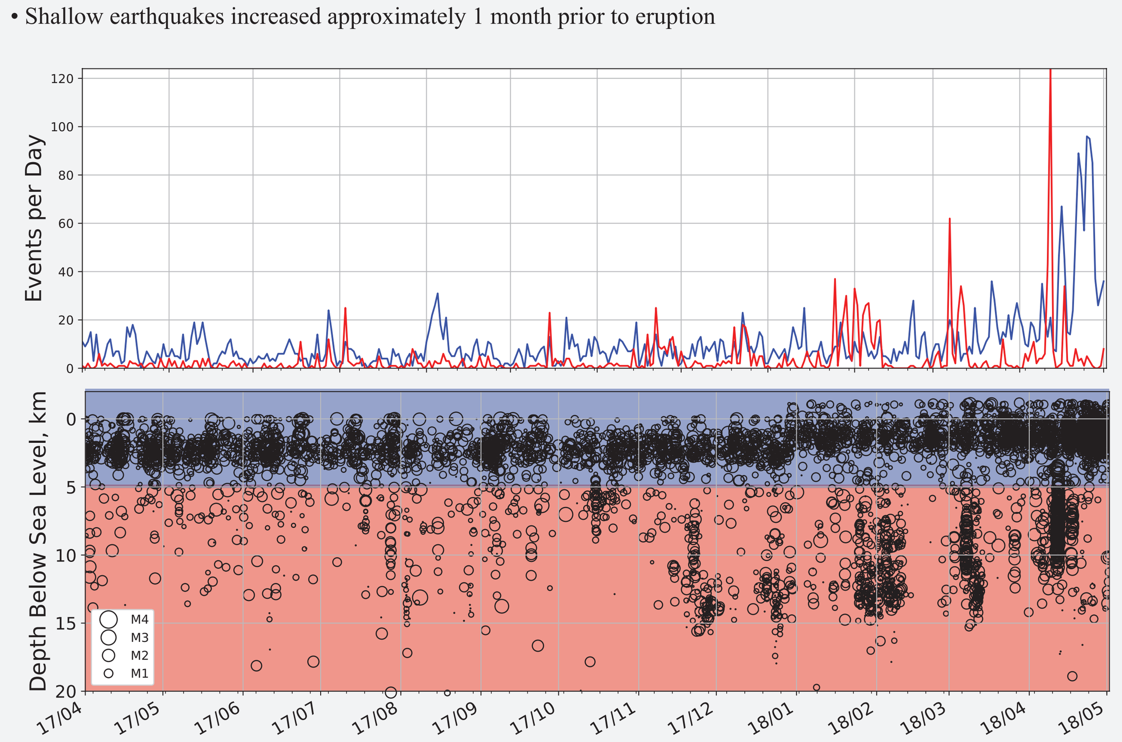
Station map showing seismic and infrasound array prior to the 2018 eruption of Kīlauea Volcano. Triangles represent seismic stations, and stars represent seismic stations with infrasound. Labeled stations are used in this poster. NPT lost communications on May 25, 2018. By early-June, the high frequency component of the collapse-explosion events clipped the proximal stations and the stations further from the source must be used.



Schematic diagram of the plumbing system under Kīlauea Volcano from Poland et al. (2014). The shallowest magma chamber under the caldera, denoted by "H" lies approximately 1-2 km below the surface and is offset to the northeast of the lava lake. Magma that is erupted in the East Rift Zone, including at Lelani Estates, transits through the summit before being laterally transported at shallow depths to the eruption site.

Summit Precursors

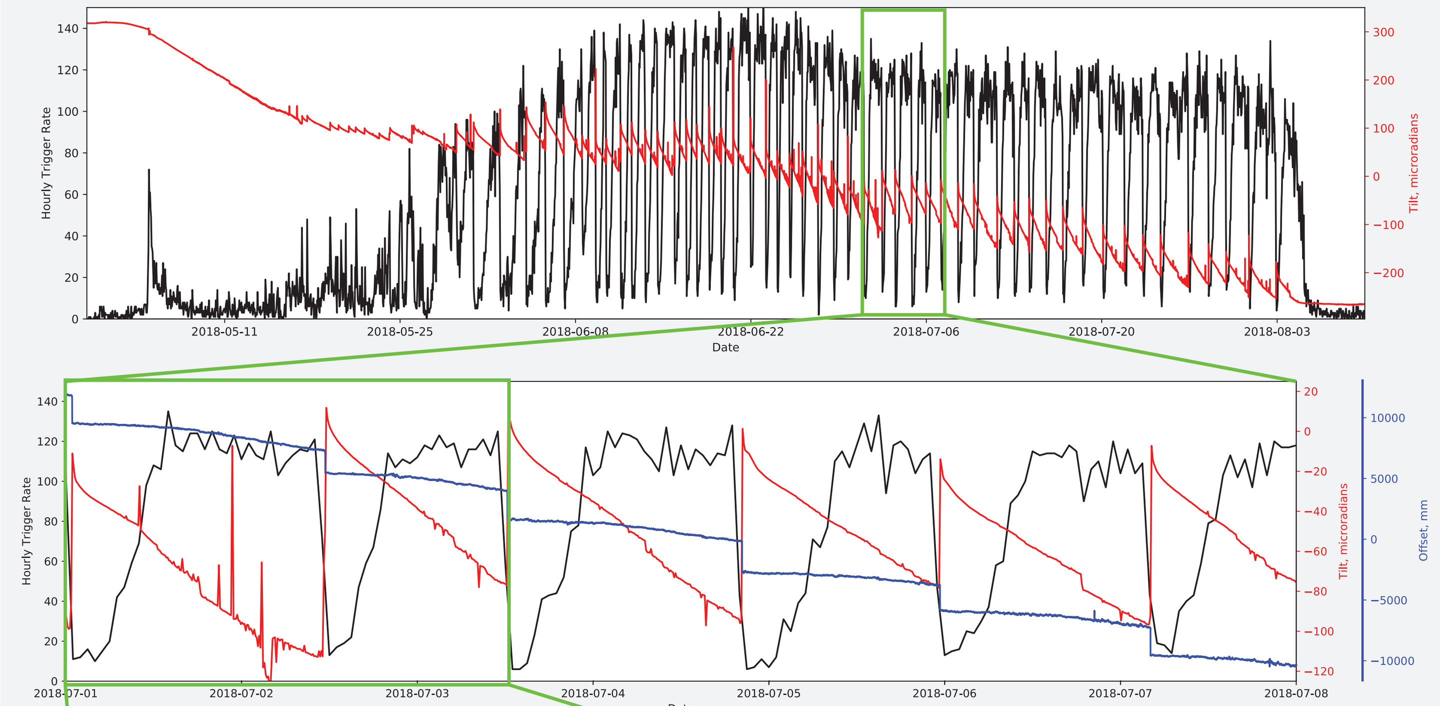
- Earthquakes at the summit of Kīlauea were elevated in the months to weeks prior to the 2018 eruption.
- Mid-crustal long period earthquakes began to increase about 6 months prior to eruption
- Shallow earthquakes increased approximately 1 month prior to eruption

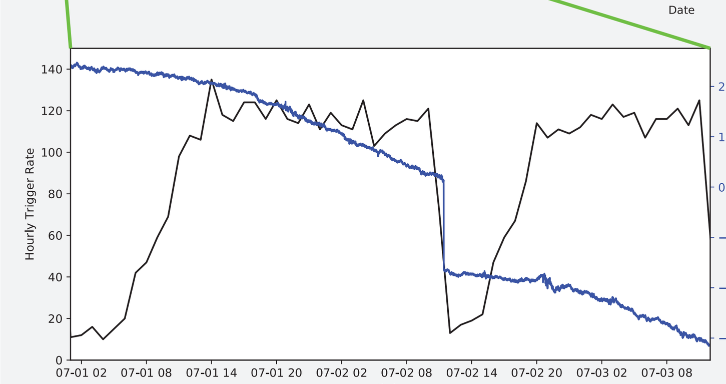


Top: Earthquake rate of located earthquakes beneath the Kīlauea Caldera during the year prior to the 2018 eruption. Blue line are earthquake rates of earthquakes less then 5 km depth and the red line is the earthquake rates between 5 and 20 km depth. Most earthquakes between 5 and 20 km are long period in nature. Bottom: Time depth plot of earthquakes (circles) under Kīlauea Caldera. Earthquakes are sized based on their magnitude. An apparent shift in depths in January 2018 reflects an artifact in the seismic catalog because of a datum change.

Cycles of Collapse

- After 2 weeks of unrest, Kīlauea began accomdating deflation associated with magma withdrawl with collapse cycles
  - Cycle consists of increasing seismic RSAM and earthquake rates, and deflation measured in both tilt and GPS
  - The cycle ends with a large collapse event with a large seismic and infrasound transient (see other sections), a step in GPS and an inflationary tilt step. Earthquake rates dropped to low levels after each collapse event.
  - Cycles became well established and highly regular by late May.
- Seismically, each cycle started with linearly increasing earthquake rates that built to a plateau
  - GPS velocities increased in rate when earthquake rates plateau
  - Plateau in earthquake rates lasts several hours, but its length was not useful for forecasting
  - Magnitudes of earthquakes (up to M4.4) also increased with increasing earthquake rates

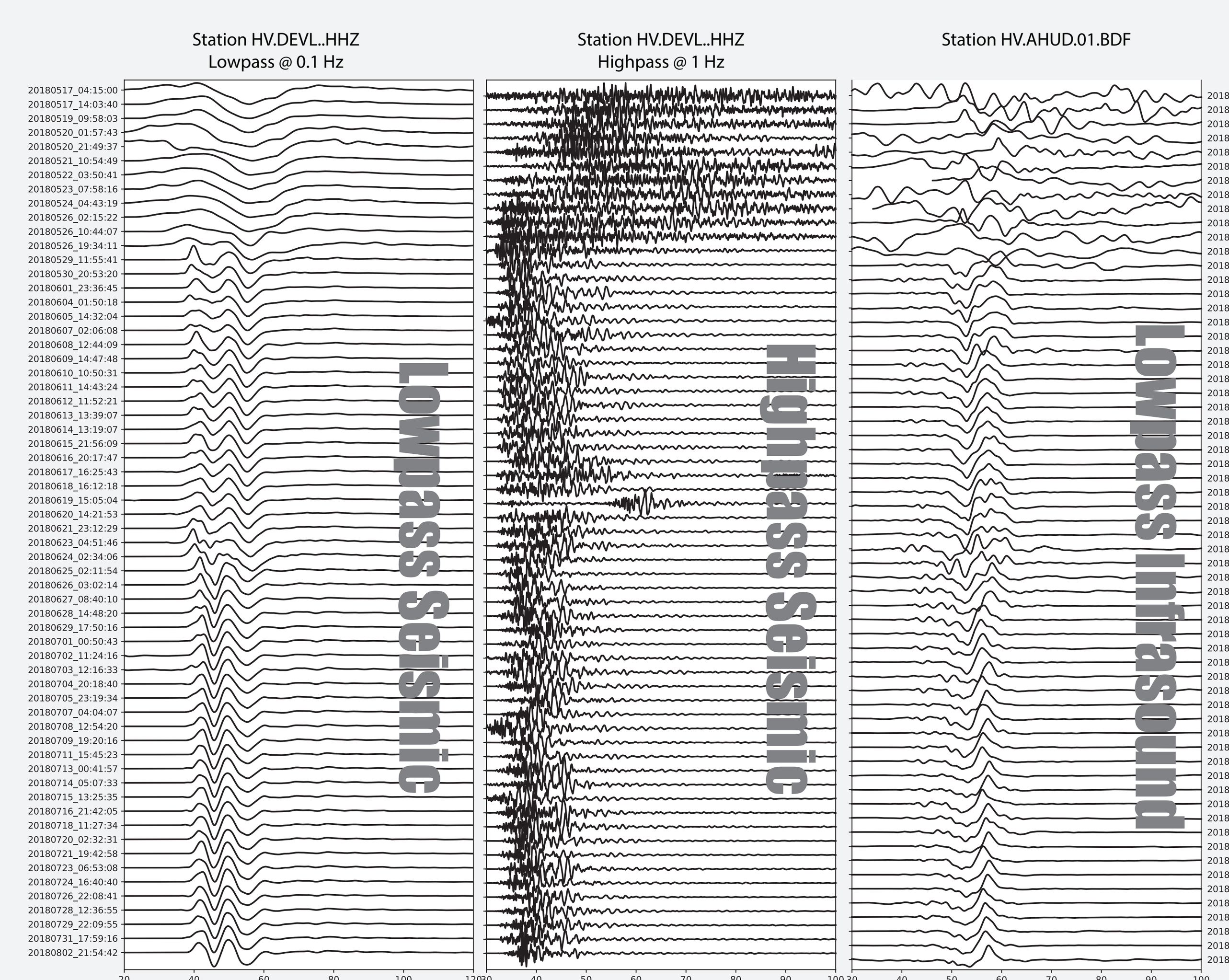




Time series of seismic triggers detected on station RSAM (black, ~1 km radius), radial tilt from station UWE (red) and vertical GPS offset from station CALS (blue), located inside the strongly deforming caldera block. Green boxes indicate insets in subsequent plots. Top: Overview of the entire 2018 eruption. Middle: Several collapse cycles in early July. Bottom: Two collapse cycles from early July. Only one large collapse event is shown to accentuate the vertical GPS offset.

Collapse Events...the King of the Collapses

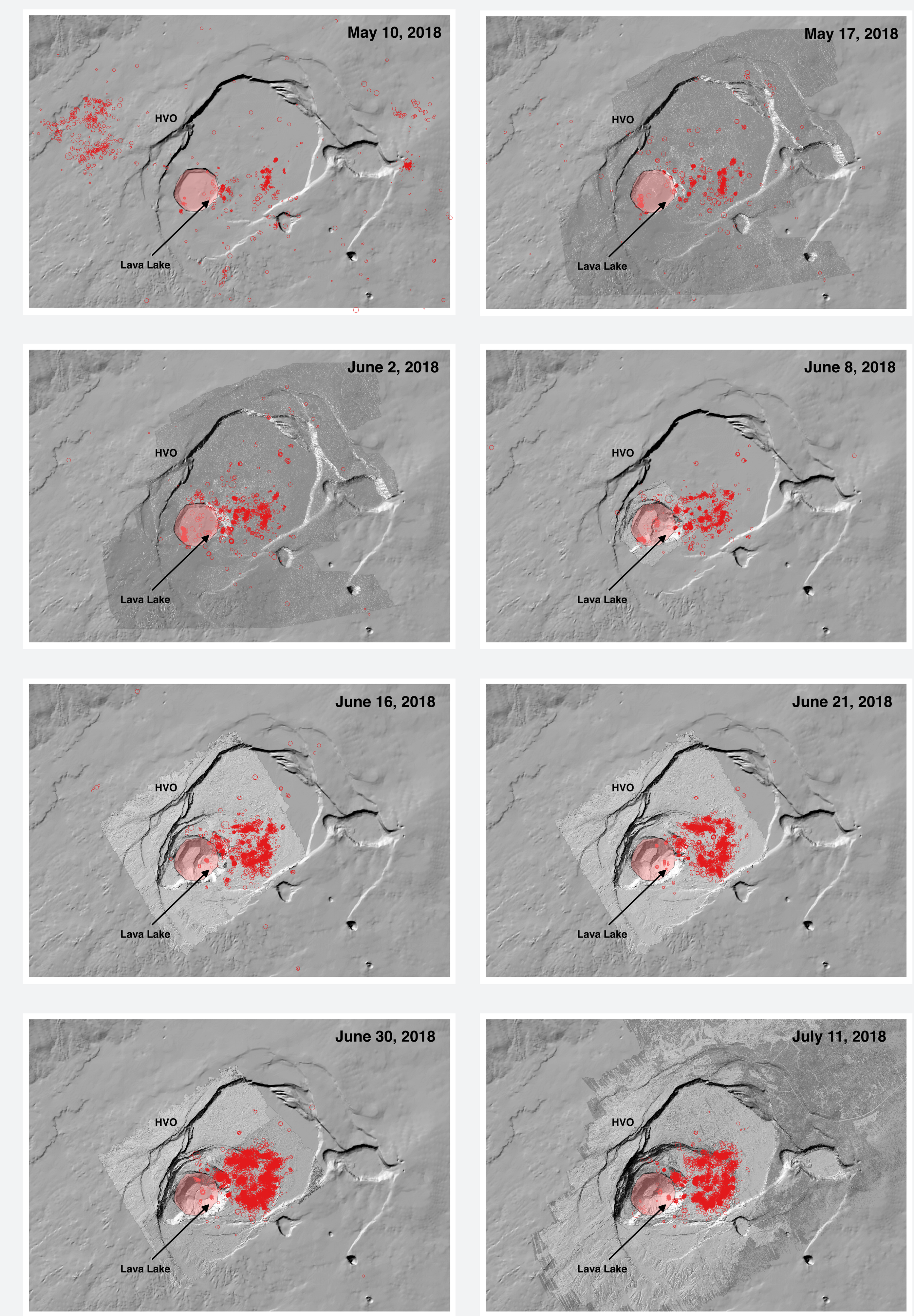
- In the VLP band, the seismic events decreased in dominant period and became larger
- In the low frequency infrasound band, the amplitudes became larger and signals simpler to interpret as pure collapse
- Events were highly repeatable at low frequencies in seismic and infrasound data, but are not repeatable at high frequencies.
  - High-frequency source must change location in each event, or utilize a new fault plane. Alternatively, the path at short wavelengths could have changed enough to alter the high frequency waveform.
  - Repeatability at long periods and non-similar waveforms at short periods argues for a composite source where the VLP and high frequency sources are separate, but triggered by the same mechanism

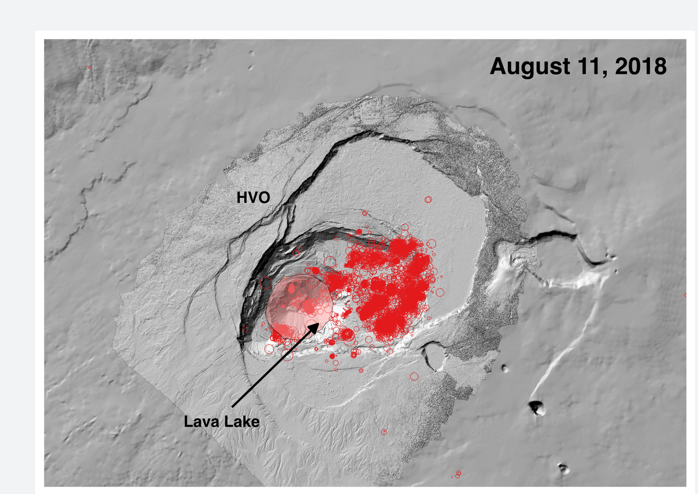


Record sections of collapse-explosion events during the 2018 Kīlauea eruption. Left: Lowpass (<0.1 Hz) filtered seismic data from station DEVL (~ 5 km radius). Middle: Highpass (>1 Hz) filtered seismic data from station DEVL (~ 5 km radius). Right: Lowpass (<0.1 Hz) infrasound from station AHUD (~ 5 km radius).

Relative Relocations

- Tens of thousands of earthquakes occured during the 2018 eruption. The scatter in automatic and reviewed locations obscures the migration patterns that occurred during the eruption.
  - Using reviewed and automatically locations to initiate a matched filter, we can detect many more earthquakes than a typical picker
  - Utilizing cross-correlation, the resulting locations have precision that is an order of magnitude less than reviewed event locations
- In general, earthquake locations migrated to the northeast, following strong deformation in that part of the caldera.
  - Some source areas to the north of Keanakāko'i Crater were active in early-May despite no surface deformation until mid-June
  - Sources initially under the southwest side of Halema'uma'u crater were inactive in June and July, only to reappear in August

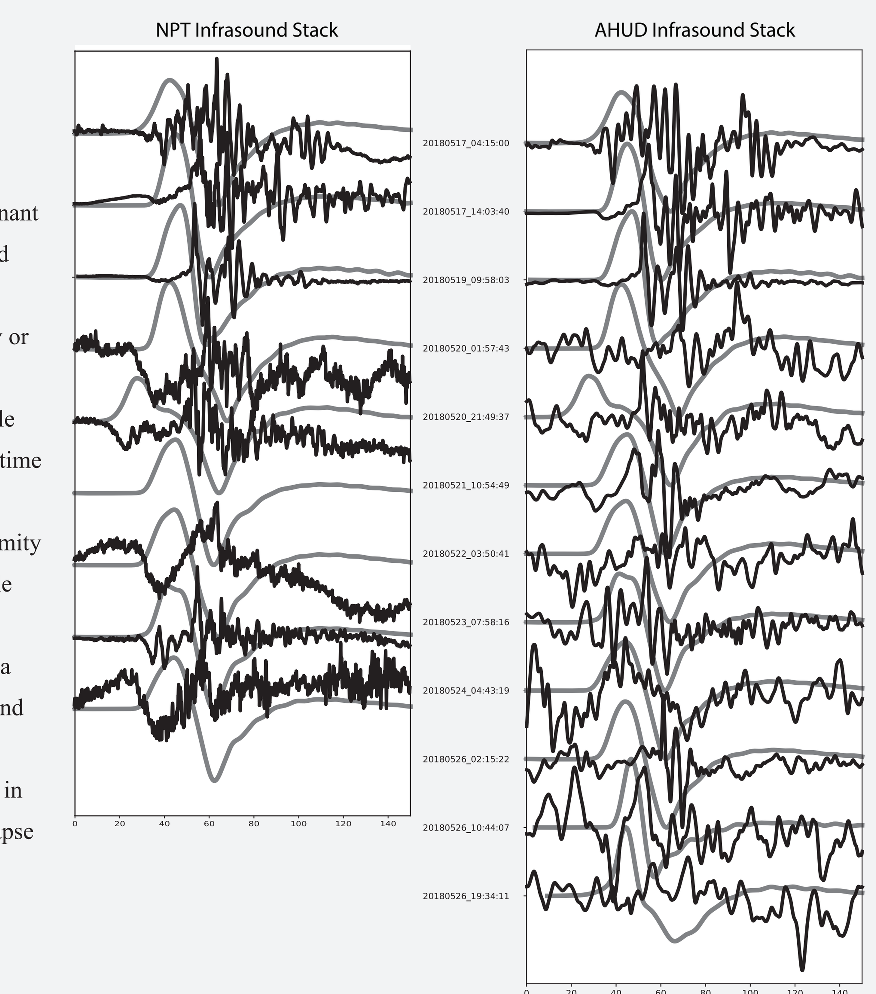




Relative relocation of earthquakes during the 2018 Kīlauea Caldera eruption. Earthquakes are plotted as red circles sized according to their magnitude. Earthquakes are shown in the interval between the date of the previous image and the date plotted on the upper right of the map. Automatically determined earthquakes were used to seed a matched filter to find additional evnets, which were cross-correlated and relocated here. Digital elevation maps are a combination of radar amplitude images (May 17, June 2), drone-derived elevations (June 8, June 16, June 21, June 30, August 11) and helicopter-based lidar (July 11). The initial outline of Halema'uma'u crater and location of the lava lake are shown in each image.

Did the Early Events Also Have a Collapse Component?

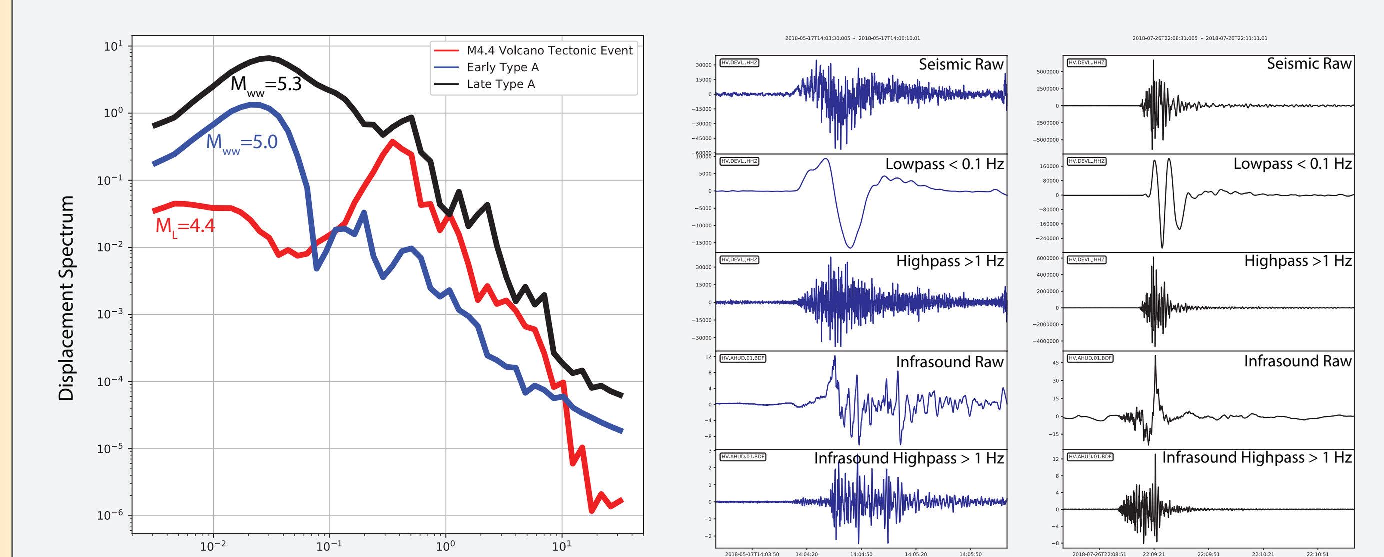
- The first dozen or so events had longer VLP dominant periods, explosions and relatively weak infrasound signals.
  - The amount of surface deformation was also low or non-existant.
- Record sections of infrasound stacks reveal a subtle down in most events that occurs around the same time as the initiation of the VLP earthquake.
  - More obvious on NPT because of its proximity
  - The down first motion is present in multiple directions
- Our interpretation is that these reflect collapse of a small volume at the surface, potentially right around the conduit, that likely initiated the VLP.
  - Much smaller amplitude compared to later in the sequence and thus surface area of collapse required is likely much smaller as well



Record section of first 12 events (as data permits) recorded with infrasound (black line) and seismic (gray line). The seismic data, is from HV.OBL..HHZ and has been lowpass filtered at 0.1 Hz. Infrasound for each event represents a stack of all components in the array projected back to the best fitting source. All infrasound data has been shifted with respect to the maximum correlation of the VLP waveform to aid in alignment. Infrasound data from AHUD (right) was further time corrected to the source (12 s) to aid in alignment with the VLP.

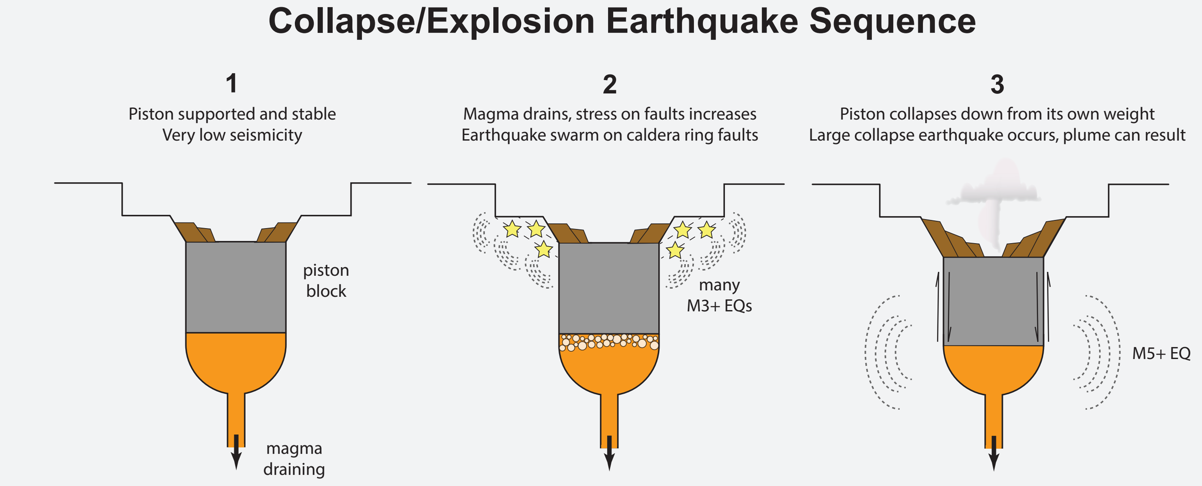
Where did the High Frequencies Go?

- Despite increases in high frequencies through the eruption, overall the collapse events were deficient in high frequencies compared to typical volcano-tectonic events.
  - Collapse events with moment magnitude of 5.3 only had high frequencies equivalent to a local magnitude 4.4 volcano tectonic event.
  - Early events were enriched in seismic VLP energy (<0.1 Hz) compared to higher frequencies (>1 Hz)
  - Later events had stronger seismic VLP energy then earlier events, but the higher frequencies were much more pronounced
    - High frequency band of later events often had impulsive arrivals, other characterisitics of a typical tectonic earthquakes



Comparison of early vs. late collapse explosion events to a volcano-tectonic event. Left: Smoothed displacement spectra of an early collapse-explosion event (blue), a later collapse-explosion event (black) and a volcano-tectonic event (red). Recordings are from station DEVL (~5 km radius). Collapse-explosion events and the volcano tectonic event are essentially co-located. Middle: Seismic and infrasound recording of the collapse-explosion event on May 17 at 14:03 UTC at different filter passbands. This is the same event shown in the blue line to the left. Infrasound data has been time shifted 12s to the source to align better with the seismic data. Right: Seismic and infrasound recording of the collapse-explosion event on July 26 at 22:08 UTC at different filter passbands. This is the same event shown in black to the left. Infrasound data has been shifted 12 s to the source to align better with the seismic data.

Collapse/Explosion Earthquake Sequence



Above is a schematic diagram showing the progression through a collapse cycle. Left: Immediately after a collapse event, earthquakes rates are low, yet magma continues to drain from the system. Middle: As the magma column continues to fall, it removes support from the plug above and faults around the plug within the caldera start to activate. Right: After some amount of time, the entire plug slips coherently generating the signals described here. Early in the sequence this phase was accompanied with minor explosions.