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Infrasound from the 2007 fissure eruptions of Kīlauea Volcano, Hawai'i

David Fee,[1] Milton Garces,[2] Tim Orr,[3] and Mike Poland[3]

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[1] Varied acoustic signals were recorded at Kīlauea Volcano in mid-2007, coincident with dramatic changes in the volcano's activity. Prior to this time period, Pu'u 'Ō'ō crater produced near-continuous infrasonic tremor and was the primary source of degassing and lava effusion at Kīlauea. Collapse and draining of Pu'u 'Ō'ō crater in mid-June produced impulsive infrasonic signals and fluctuations in infrasonic tremor. Fissure eruptions on 19 June and 21 July were clearly located spatially and temporally using infrasound arrays. The 19 June eruption from a fissure approximately mid-way between Kīlauea's summit and Pu'u 'Ō'ō produced infrasound for ~30 minutes—the only observed geophysical signal associated with the fissure opening. The infrasound signal from the 21 July eruption just east of Pu'u 'Ō'ō shows a clear azimuthal progression over time, indicative of fissure propagation over 12.9 hours. The total fissure propagation rate is relatively slow at 164 m/hr, although the fissure system ruptured discontinuously. Individual fissure rupture times are estimated using the acoustic data combined with visual observations. **Citation:** Fee, D., M. Garces, T. Orr, and M. Poland (2011), Infrasound from the 2007 fissure eruptions of Kīlauea Volcano, Hawai'i, *Geophys. Res. Lett.*, *38*, L06309, doi:10.1029/2010GL046422.

1. Introduction

[2] During the first half of 2007, the Pu'u 'Ō'ō crater complex (Figure 1) was the primary source of degassing and lava effusion at Kīlauea Volcano, Hawai'i. In mid-2007, dramatic changes occurred at Kīlauea, with an intrusion of magma along the volcano's upper east rift zone (ERZ) during 17–19 June causing deflation at the summit and draining and collapse of the Pu'u 'Ō'ō magma system. A minor fissure eruption between the summit and Pu'u 'Ō'ō accompanied the intrusion. Activity returned to Pu'u 'Ō'ō on 1 July as lava began to refill the crater. Lava lake growth terminated on 21 July when an eruptive fissure opened on the east rim of Pu'u 'Ō'ō crater and extended east for ~2 km. The fissure eruption accompanied renewed collapse of Pu'u 'Ō'ō crater and resulted in the formation of a long-lived eruptive vent on the ERZ [*Poland et al.*, 2008]. Table S1 of the auxiliary material gives a chronology of the mid-2007 activity as inferred from infrasound and other observations.[1]

[3] Previous infrasound studies of Kīlauea Volcano have detected a wide variety of eruptive activity. *Garcés et al.* [2003] were the first to record infrasound from Kīlauea and detected signals from Pu'u 'Ō'ō and the active lava tube system. *Fee and Garces* [2007] detected diurnal variations in infrasonic tremor amplitude and attributed this to propagation effects related to diurnal atmospheric variability. Recent work by *Matoza et al.* [2010] verified the diurnal variations of *Fee and Garces* [2007]. They postulated that oscillations of bubble clouds within the conduit produce the broadband component of infrasonic tremor at Pu'u 'Ō'ō, while the sharply peaked infrasonic tremor spectra may result from low velocity gas jets interacting with solid boundaries. *Fee et al.* [2010b] detailed infrasonic tremor and transient degassing bursts associated with summit eruptive activity at Kīlauea during 2008–2009. They showed how both signal types are explained by degassing exciting the steam-filled cavity into Helmholtz and acoustic resonance. The mid-2007 activity discussed in this manuscript adds fissure eruptions and collapse-related signals to the varied infrasound from Kīlauea. The collapse events presented here show similarities to some of the degassing bursts of *Fee et al.* [2010b]. Further, this study documents, for the first time anywhere, infrasonic signals associated with fissure formation and eruptions.

[4] The 19 June fissure eruption was located spatially and temporally using infrasound, but was not detected by any other geophysical monitoring. Detailed constraints on the 21 July fissure eruption, such as timing, location, and propagation rates, were also obtained from infrasound. The wealth of data from Kīlauea during mid-2007 allows us to speculate on the potential source of infrasound from fissure eruptions.

2. Data and Methods

[5] Data from a four-element infrasound array (MENE), located 12.6 km northwest of Pu'u 'Ō'ō crater, is used for this study (Figure 1). The array is the same as that used to study the 2008–2009 eruption at Halema'uma'u Crater [*Fee et al.*, 2010b] and the April 2007 Pu'u 'Ō'ō crater activity [*Matoza et al.*, 2010]. The Chaparral model 2.2 sensors used here have a flat frequency response between ~0.1 and 50 Hz and the array aperture is ~70 m. All times listed in the manuscript are in UTC.

[6] Array processing was performed using the Progressive Multi-Channel Correlation (PMCC) technique [*Cansi*, 1995]. Data were processed between 1–7 Hz in 10 frequency bands

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[1] Wilson Infrasound Observatories, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska, USA.

[2] Infrasound Laboratory, University of Hawaii at Manoa, Kailua-Kona, Hawaii, USA.

[3] Hawaiian Volcano Observatory, U.S. Geological Survey, Hawaii National Park, Hawaii, USA.

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL046422.

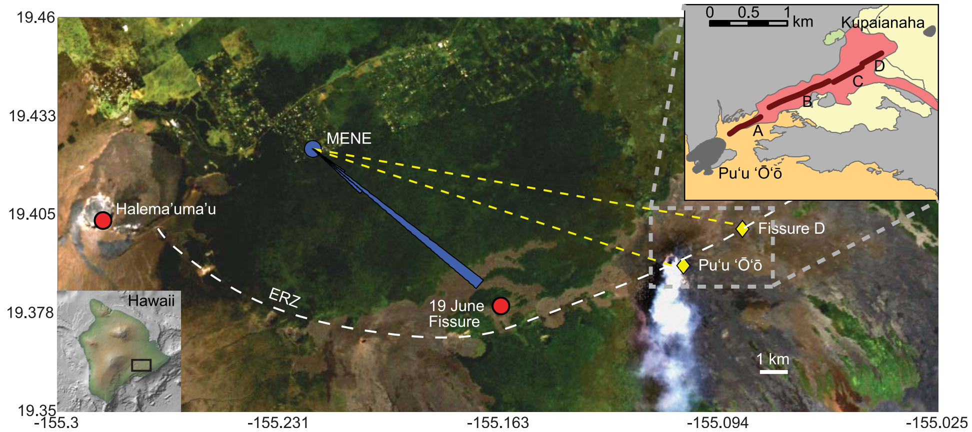

Figure 1. Map of the MENE infrasound array, mid-2007 fissure eruptions locations, and 19 June 2007 fissure detections. The blue circle represents the MENE infrasound array, and the blue beams are the detection azimuths between 19 June 10:15–10:45. The majority of the detections point to 132°, consistent with the 19 June fissure location (red circle). Pu'u 'Ō'ō and Fissure D are indicated by gold diamonds, and the starting and ending azimuths of the 21 July fissures are indicated by dashed gold lines (~102° and 108°). The inset image shows the locations of the 21 July 2007 fissure system (Fissures A-D).

with 10-second windows and 80% overlap. The 1–7 Hz band was selected due to the predominance of fissure eruption infrasonic signals in this band. In this manuscript, we use the term "detection" to define coherent acoustic energy recorded by PMCC in a single time window and frequency band. Acoustic travel times from the respective source to the station were removed assuming a 0.34 km/s sound speed, typical for the atmospheric conditions present during the study period. Data were beamformed using a time-delay beamforming method to increase the signal-to-noise ratio (S/N). Waveform filtering was performed using a 4-pole, zero-phase (acausal) Butterworth filter.

[7] Numerous phenomena may affect the accuracy of the infrasound detection azimuth. First, the component of wind perpendicular to the propagation path will deflect the signal (advection) and bias the azimuth estimate. During the 21 July eruption, a weather station near Pu'u 'Ō'ō (Mesowest station PALI2, 19.3175°N, –155.2922°W) recorded a maximum wind speed of 6.3 m/s, which corresponds to a maximum theoretical deflection from MENE to Fissure A of 1.1° from wind advection. The wind speed was much less during the main eruption sequence (<4 m/s between 10:00–20:00) so the average deflection is below 0.67° and can be ignored since it is lower than the azimuthal uncertainty. Spatial aliasing, uncertainties in the relative locations of the sensors, and low S/N could also contribute error.

[8] The agreement between the actual and observed azimuths of the 19 June and 21 July fissure eruptions (<2°) provides confidence in the azimuth estimates presented here. Similarly, the mean detection azimuth from MENE-Pu'u 'Ō'ō in the three days prior to 17 June is 110.1°, consistent with the expected detection azimuth during winds from the northeast (the typical wind pattern). A fissure eruption is also likely to be a distributed source, since numerous fissure segments could produce infrasound at the same time, so the spread in azimuths may represent multiple sources instead of errors in the azimuth estimation.

3. The 17–19 June 2007 Intrusion and Eruption

[9] An earthquake swarm on Kīlauea's upper ERZ and rapid deflation at Kīlauea's summit began on 17 June at 14:16 (Figure 1), indicating withdrawal of magma from the summit to feed an ERZ intrusion [*Poland et al.*, 2008]. Deflation at Pu'u 'Ō'ō began soon after, accompanied by a series of collapses over the next several days. The first collapse noticeable in a U.S.G.S. Hawaiian Volcano Observatory (HVO) Webcam [*Hoblitt et al.*, 2008] on the north rim of Pu'u 'Ō'ō crater occurred on 17 June 19:35 and was accompanied by a minor high-frequency (>1 Hz) infrasound signal.

[10] The earthquake swarm continued over the next 57 hours, and the Pu'u 'Ō'ō crater floor dropped ~80 m. Infrasound signals accompanied collapse events at Pu'u 'Ō'ō crater, including two significant events on 18 June. The first event occurred at 09:12:14, lasted for ~18 s, and had an amplitude of 0.094 Pa (Figures 2a and 2b). The second event began with a low-amplitude high frequency signal at 09:16:19 (part 1), followed by increased infrasonic tremor and then a higher amplitude signal at 09:16:32 (part 2), peaking at 0.194 Pa (Figures 2c and 2d). This was followed by a clear rarefactional (decompressional) onset in the 0.1–1 Hz band; we confirmed the polarity by applying both causal and acausal filters to the data. Infrasonic tremor followed both of these events, with the tremor lasting for >15 minutes after the 09:16 event. Both events were recorded by the Webcam as bright flashes from a vent within crater, indicating the lava surface was disrupted.

[11] On 19 June, the intrusion breached the surface in two short fissures with a total span of 165 m, located 6 km west of Pu'u 'Ō'ō along the northeast flank of the Kane Nui o Hamo shield (Figure 1), at an azimuth of ~132° from MENE. A clear infrasonic signal, focused between 2–10 Hz, was recorded between 10:15–10:45 from 132–133° (Figure 1), the same azimuth as the fissures. No other significant infrasound was detected during the presumed fissure opening time period. No visual, seismic, geodetic, or other geophysical evidence of the eruption onset was recorded. HVO field crews visiting the eruption site at ~17:00 estimated that lava had breached the surface at the fissure a few hours before, consistent with the acoustically derived onset. After the fissure opening, no infrasound from Kīlauea was detected by the MENE array until 1 July, when lava returned

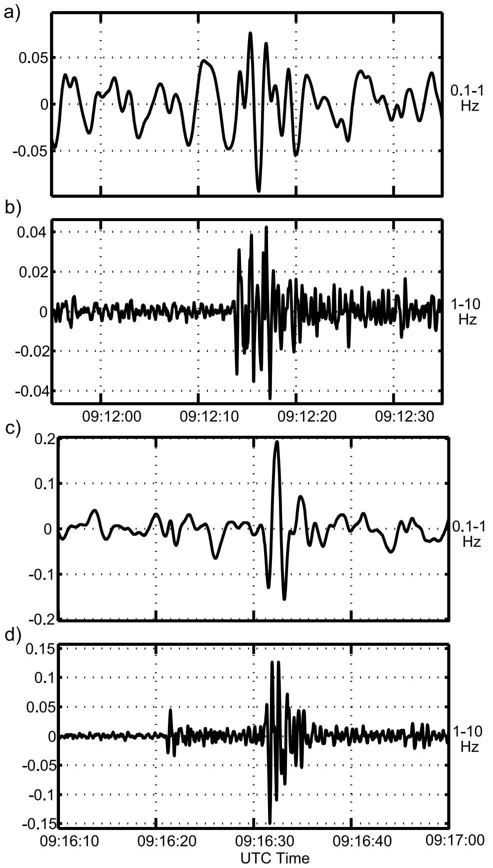

Figure 2. Beamed waveforms for the 18 June 2007 Pu'u 'Ō'ō collapse events. The first event occurred at ~09:12, which we divide into two frequency bands (a) 0.1–1 Hz and (b) 1–10 Hz. This event began with a sharp onset at 09:12:14 and lasted for ~18 s. The larger second event at 09:16 is similarly split into the (c) 0.1–1 Hz and (d) 1–10 Hz bands. It began with a small 1–10 Hz onset at 09:16:19, followed by elevated infrasonic tremor and a large rarefactional onset in the 0.1–1 Hz band at 09:16:32. The rarefactional onset in Figure 2d has been confirmed using causal and acausal filters. Both events were followed by increased infrasonic tremor. The acoustic travel time from source to receiver has been removed.

to Pu'u 'Ō'ō, indicating a direct connection between magma and the atmosphere had been reestablished.

4. The 21 July 2007 Fissure Eruption

[12] Pu'u 'Ō'ō crater slowly filled with lava during 1–21 July, accompanied by minor infrasonic tremor. At about 09:00 on 21 July, tilt measurements from an instrument on the north flank of Pu'u 'Ō'ō indicated rapid tilt to the east. HVO Webcam imagery revealed crater floor subsidence and rapid draining of the lava lake starting at approximately 09:55. The Webcam recorded glow to the east at 10:39, indicating an eruption, out of sight of the Webcam, was in progress. Field observations starting at about 17:40 documented lava erupting along a series of four fissure segments (designated A–D) extending from just below the east rim of Pu'u 'Ō'ō crater for ~2 km to the east (Figure 1) [*Poland et al.*, 2008].

[13] Although no unusual seismicity was noted during the formation of the 21 July fissure [*Poland et al.*, 2008], strong infrasound signals were recorded. Figure 3 shows the a) 1–7 Hz beamed waveforms, b) spectrogram, and c) number of detections per 5 minutes between 95–115°. The up-rift end of the 21 July fissure system (westernmost point of Fissure A) is 107.7° and 12.7 km from MENE, while the down-rift end (Fissure D) is 102.0° and 14.1 km (Figure 1). The acoustic onset of the eruption consists of a minor detection at 10:06 from ~108°. An emergent and higher-amplitude signal follows at 10:13 and continues for more than 6 hours (Figures 3a and 3b). The majority of the PMCC detections occur between 10:06–11:30, coincident with peak infrasonic amplitudes between 1–7 Hz (Figures 3b and 3c).

[14] The infrasonic signal shows a clear change in azimuth as the fissure propagated downrift (Figure 3c). The detection azimuths begin at ~108° at 10:06, and the majority of detections lie between 106–108° until 13:15 (Figure 3c). These azimuths correlate well with the azimuths to Fissure A (Figure 1, 106.3°–107.7°); thus, the higher amplitude infrasound and higher number of detections during this period suggest that the most vigorous degassing from the 21 July 2007 eruption occurred from Fissure A between ~10:06 and 13:15 (Figure 3). The detection azimuths begin to migrate at about 13:15, suggesting that new fissure segments were opening. During 13:15–16:00, the detections indicate a steady azimuthal progression to ~102° (Figure 3c), possibly corresponding to the rupture of Fissures B (104.1°–105.6°) and C (102.3°–103.4°) (Figure 1). The gradual nature of the azimuth progression and the limited azimuthal resolution do not allow for differentiation between the rupture of Fissures B and C. Detection azimuths stabilize after 16:00, suggesting that the majority of fissure propagation had ceased (Figures 2 and 3c). A helicopter overflight around 17:40 confirmed that Fissures A-C had all ruptured and that Fissure C hosted a 6–8 m lava fountain. Field crews arrived at the site by 20:00 and observed Fissure D opening in sections between 20:00 and 23:00. The recorded infrasound data cannot distinguish this activity, since the total length of Fissure D is small and not resolvable in azimuth (101.8–102.0°). Further, the azimuth to Fissure D is difficult to differentiate from Fissure C.

[15] Infrasound related to fissure activity gradually died out around 22 July 00:00 (Figure 3), indicating the end of vigorous degassing and fountaining, consistent with visual observations. The decrease in acoustic signals is not due to diurnal propagation effects, like those documented by *Fee and Garces* [2007]. The detections die out around 00:00 (14:00 local time), well after the nocturnal tropospheric ducting would have ended. The vigorous portion of the 21 July 2007 fissure eruption is therefore assumed to have lasted for 13.9 hours (10:06–00:00).

[16] We estimate fissure propagation characteristics using the acoustic and visual observations. The entire fissure system took 12.9 hours (10:06–23:00) to rupture a distance of 2.12 km, for an average propagation rate of 164 m/hr. The observed starting and ending infrasound azimuths (Figure 3c, 108° and 102°) are consistent with the azimuths of the entire fissure system (Figure 1, 107.7°–101.8°); however, the system appears to have ruptured discontinuously.

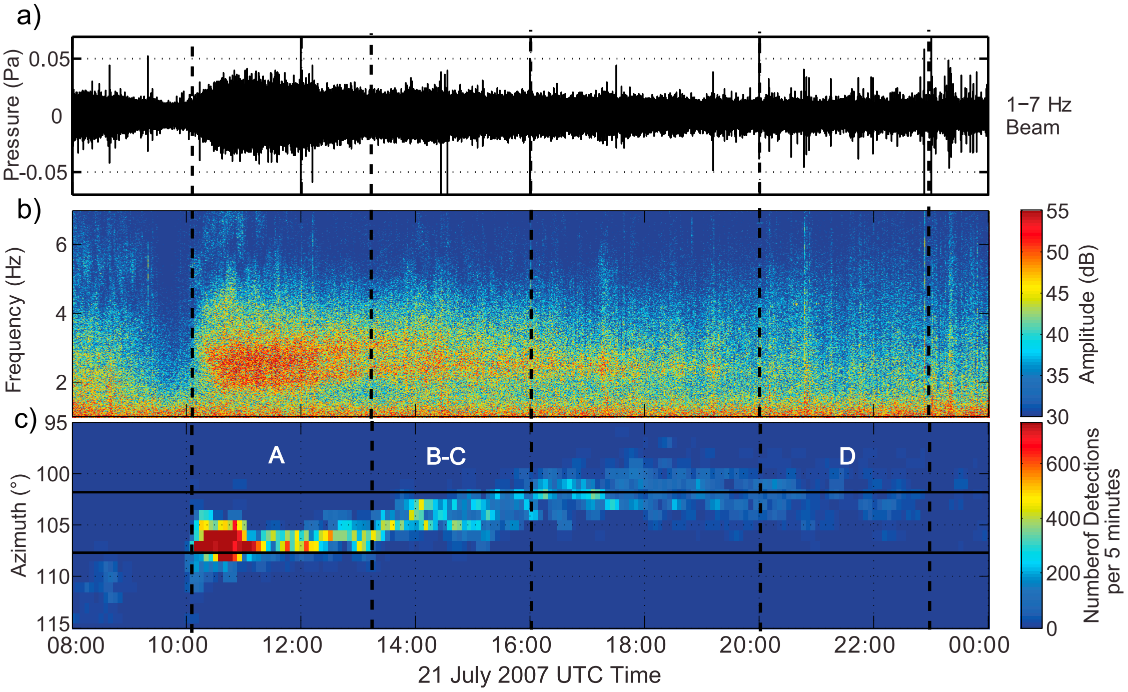

Figure 3. The 21 July 2007 fissure eruption. (a) 1–7 Hz beamed waveforms, (b) spectrogram, and (c) PMCC detections between 08:00–24:00 UTC. Solid lines in Figure 3c represent the approximate azimuth from the array to Fissures A and D, the start and end points of the fissure eruption. The dashed vertical black line at 10:06 represents the acoustic onset of the fissure eruption. A clear progression in the signal azimuth in Figure 3c represents the rupture of new fissure segments and the subsequent dotted black lines indicate approximate fissure rupture intervals inferred from the azimuthal progression and visual observations (see text for more details). Solid black horizontal lines represent the start and end of the fissure (108° and 102°, respectively). The maximum number of detections between 10:15–11:00 correlates well with the peak acoustic (Figure 3a) and spectral amplitudes (Figure 3b) and Fissure A (Figure 1), suggesting that this is where and when the most vigorous degassing occurred. Spectrogram units are in dB relative to $(20 \times 10^{-6}\ \mathrm{Pa})^2/\mathrm{Hz}$, and the beamforming was performed for a single azimuth.

Fissures A-C took ~5.9 hours (10:06–16:00) to rupture 1.81 km, giving a propagation rate of 307 m/hr. Fissure A erupted first at 10:06 and continued as the primary source of degassing until ~13:15 UTC. Fissures B-C then ruptured 1.24 km over 3.75 hrs for a rate of 331 m/hr. The rupture then paused for up to 4 hours, upon which Fissure D ruptured at a much slower rate of ~69 m/hr (based on visual observations).

[17] The 21 July fissure propagation rates are slower than those reported for other eruptive fissures. At Kīlauea, *Duffield et al.* [1982] estimated the propagation of the September 1971 fissure at 600 m/hr based on migration of lava fountains. *Okamura et al.* [1988] used both tilt and seismic data to determine a dike propagation rate of 550–700 m/hr during the onset of the 1983 Pu'u 'Ō'ō eruption. The 1984 Mauna Loa eruption had a large fissure system that ruptured at a rate of 1200 m/hr [*Lockwood et al.*, 1987]. A fissure eruption on Kīlauea's ERZ in 1991, in nearly the same location as the 21 July fissure, ruptured at ~1000 m/hr [*Mangan et al.*, 1995]. The relatively low fissure propagation rate and weak eruptive vigor of the 21 July eruption may be indicative of a relatively low-energy eruption, perhaps because the erupting lava had already degassed. Much of the erupted lava was probably derived from the pre-21 July Pu'u 'Ō'ō lava lake, as suggested by lava lake draining associated with fissure opening and low gas emissions measured prior to the 21 July eruption [*Poland et al.*, 2008].

[18] Within three weeks of the 21 July fissure opening, effusion focused on a single portion of Fissure D, which developed into a new long-term eruptive vent (still active as of February 2011). The Pu'u 'Ō'ō crater continued to act as the primary source of degassing, despite the lack of eruptive activity. Infrasonic tremor from Pu'u 'Ō'ō resumed on 25 July, and the crater remained the dominant acoustic source in this region, although occasional tremor bursts were detected from Fissure D over the remainder of 2007.

5. Acoustic Source

[19] The 18 June collapse signals from Pu'u 'Ō'ō represent the first two impulsive, transient infrasound events recorded at Kīlauea. Previous studies have reported only emergent, long duration tremor signals from Pu'u 'Ō'ō and its associated lava tube system [*Fee and Garces*, 2007; *Garcés et al.*, 2003; *Matoza et al.*, 2010]. The 18 June events are probably related to gas release that resulted from disruption of the ponded lava surface that existed within a vent inside Pu'u 'Ō'ō crater prior to its collapse. Bright flashes observed in HVO Webcam imagery, coincident with the infrasound signals, support this hypothesis, and the process is similar to that associated with some degassing bursts during 2008–2009 summit eruptive activity at Kīlauea [*Orr et al.*, 2009]. The rarefactional onset of part 2 of the 18 June 09:16 event (Figures 2c and 2d) may be explained by

downward motion of collapsing material. The infrasonic tremor following that event was likely related to degassing of the disturbed lava surface.

[20] We also detail the first infrasound data clearly associated with a fissure eruption at Kilauea (*Liszka and Garces* [2002] recorded long-range infrasound from the 2000 fissure eruption of Hekla Volcano, Iceland). Although the 19 June fissure is clearly detected in the infrasound, the S/N is too low to determine a source process. The 21 July 2007 fissure eruption, in contrast, had a much clearer signal and visual observations confirmed small-scale lava fountains (<8 m in height) that extended over numerous fissure segments. Low-level gas jetting from these fountains may be producing a form of jet noise. Recent studies have focused on jet noise from large, high velocity jets associated with Vulcanian-to-Plinian eruptions [*Fee et al.*, 2010a; *Matoza et al.*, 2009]. The infrasonic source of the Vulcanian-to-Plinian eruptions has been postulated to be related to large-scale turbulent eddies along the edge of the flow, primarily on the basis of their characteristic frequency spectrum. The 21 July fissure eruption produced relatively low-velocity, small-scale jetting. The acoustic spectrum here is relatively broadband and detections continued for ~14 hours (Figure 3b), but at much lower amplitude, higher frequency, and with a sharper roll-off than Vulcanian-Plinian jet noise. Thus the acoustic source here may be a form of jet noise, but because this is a basaltic system the jetting is characterized by fountains with large pyroclasts [*Sparks et al.*, 1997] and may produce different acoustics. The interactions of turbulent structures with the large pyroclasts [*Woulff and McGetchin*, 1976] may play a dominant role in producing sound during fissure eruptions and fountaining. The effect of a distributed source on the frequency spectra may be important as well.

6. Conclusions

[21] A series of dramatic changes at Kīlauea in mid-2007 produced infrasonic signals associated with the collapse of Pu'u 'Ō'ō crater and two fissure eruptions. The collapse and subsidence of Pu'u 'Ō'ō crater on 17–19 June produced multiple infrasonic signals. Two events had impulsive onsets—the first such signals recorded at Kīlauea. An event on 18 June 09:16 had a rarefactional onset between 0.1–1 Hz, indicative of a rare decompressional source. The collapse of the crater floor may have created this rarefaction and then disrupted the lava surface and released a large amount of accumulated gas, similar to some of the 2008–2009 activity at Halema'uma'u Crater. For the 19 June fissure eruption, infrasound constrains the timing when no other evidence of the onset of fissure opening exists. Infrasound recordings from the 21 July eruption resulted in insight into the timing, fissure propagation rate, and time period of principal degassing. Future research employing infrasound will lead to better understanding of eruptive processes, while also providing an additional tool for monitoring volcanic activity.

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D. Fee, Wilson Infrasound Observatories, Geophysical Institute, University of Alaska Fairbanks, 903 Koyukuk Dr., Fairbanks, AK 99775-7320, USA. (dfee@gi.alaska.edu)

M. Garces, Infrasound Laboratory, University of Hawaii at Manoa, 73-4460 Queen Kaahumanu Hwy., Kailua-Kona, HI 96740-2638, USA.

T. Orr and M. Poland, Hawaiian Volcano Observatory, U.S. Geological Survey, Crater Rim Drive, Hawaii National Park, HI 96718-0051, USA.