Interevent Seismicity Statistics Associated With the 2018 Quasiperiodic Collapse Events at Kilauea, HI, USA

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Abstract

Following the Mw 6.9 Hawaiian earthquake on 4 May 2018, a remarkable quasiperiodic sequence of collapse events began at Halema‘uma‘u Crater at the summit of Kilauea Volcano. The collapse events were associated with the drainage of magma from beneath the summit to the Lower East Rift Zone where fissure eruptions occurred. From 4 June 2018 to 2 August 2018 forty-seven collapse events Mw 5.3 ± 0.1 occurred with the same temporal pattern of seismicity occurring between sequential pairs of collapse events. This paper focuses on this interevent seismicity pattern. Following a collapse event, there was a relatively quiescent period. This was followed by a sudden increase in seismicity, occurring at a nearly linear rate of 397 ± 96 earthquakes per day. These seismically active periods lasted until the next collapse event occurred. The pattern then repeated itself beginning again with postcollapse quiescence. We provide a statistical summary of this seismicity behavior by isolating the quiescent and active times to look at immediate precollapse and postcollapse activity. In mid-June there were significant changes in the quiescent time lengths (decreased), the number of earthquakes during the interevent times (increased), and the rates of seismicity during the active times (increased). This type of interevent study could be conducted with other seismically well recorded, sequential caldera collapse events and also with other data types to look for potential physical explanations and an improved understanding of precollapse and postcollapse activity.

1. Introduction

The 2018 seismic and volcanic activity associated with Kilauea Volcano provides a unique opportunity to study a very well recorded, staged caldera collapse sequence associated with extensive magma drainage and lava eruptions. The 2018 events included magma draining from the summit, 24 fissure eruptions in the Lower East Rift Zone (LERZ) covering 35.5 km², and a quasiperiodic sequence of 62 distinct caldera collapse events at the summit associated with extensive seismicity (Neal et al., 2019). This unique set of caldera collapse events was associated with inflation and deflation cycles of the volcano’s summit as well as swarms of seismicity (Neal et al., 2019).

In addition to the frequent collapse events occurring with relatively consistent large moment magnitudes, there was a high level of smaller seismicity occurring around the summit (Neal et al., 2019). In early June, the collapse events had become more periodic and a regular pattern of this smaller magnitude seismicity was observable between sequential collapses. In contrast to a typical tectonic Mw 5 earthquake, which would produce an aftershock sequence with an exponential decay rate, these large seismic volcanic events were preceded by very high rates of seismicity and followed by relative seismic quiescence. A previous study of three basaltic caldera collapses (Piton de la Fournaise, Fernandina, and Miyakejima) focused on the temporal trend of total interevent time between stages of collapse and concluded that understanding interevent times is important to better understand the overall collapse dynamics (Michon et al., 2011).

Therefore, as a consistent feature of the interevent times, we chose to break down and study these smaller magnitude earthquake patterns to look for any significant changes throughout the sequence that may be associated with other physical changes in the system. This is a different approach to breaking down the interevent seismicity that has not been utilized in past large, episodic caldera collapse event studies analyzing Bárdarbunga Volcano, Miyakejima Volcano, Piton de la Fournaise, and Fernandina. Studies such as Kobayashi et al. (2003) (Miyakejima), Filson et al. (1973) (Fernandina), and Francis (1974) (Fernandina) have focused on caldera collapse related seismicity, but the sequence of events during the Kilauea caldera collapse differed in both levels of activity and density of monitoring equipment recording the events. The
quality and quantity of seismic data collected throughout the 2018 Kilauea sequence of events offers the unique opportunity to apply this approach to breaking down the interevent seismicity, but it could also be applied to other seismically well recorded collapse events in the future.

The purposes of this paper are (1) to introduce this approach to characterizing the precollapse and postcollapse event earthquakes so that it might be utilized in future studies and (2) present the statistical results for Kilauea to make them available to researchers examining the collapse process through other data or physical models of the volcanic system and collapse process.

2. Observations and Geologic Setting
2.1. The 2018 Kilauea Eruption

Neal et al. (2019) provided a thorough timeline of the volcanic and seismic events, which occurred during the 2018 period of heightened activity. They describe summit subsidence and the draining of the summit lava lake in Halemaʻumaʻu Crater beginning on 1 May 2018 at the start of the eruptive sequence. They reported that a Mw 6.9 tectonic earthquake occurred on 4 May on a thrust fault dipping at 20° to the northwest beneath the southeastern flank of Kilauea Volcano. Displacement on this fault resulted in the subsidence of the southeastern flank of the volcano. They also report that this earthquake further opened the rift zone and aided in magma transport away from the summit. According to Neal et al. (2019), after the Mw 6.9 event, the drainage of the summit lava lake increased and by 10 May the lava lake was out of view from the rim of the crater. Also, at this time they detail that ash explosions and eruptions were occurring at the summit as well as an increasing number of mid-magnitude earthquakes (M 3–4). At the end of May, subsidence of the caldera floor around Halemaʻumaʻu Crater began.

From 16 May to 2 August there were 62 total collapse events within the summit caldera, which were described by Neal et al. (2019) as very long period (VLP) events with the sources of these events associated with changes in volume. Initially, large emissions of ash and volcanic gases were reportedly associated with these events. From middle-late May, the first 12 of these collapse events at the summit occurred at irregular intervals with associated explosions. They also reported that they were preceded by a small inflationary period and produced seismic signals assigned moment magnitudes of 4.9 ± 0.2. Subsequently, these explosive irregular events became more periodic collapse events within Halemaʻumaʻu Crater, though with a double-couple component as reported in the United States Geological Survey (USGS) (2018a). From late May to early August, these latter 50 large collapse events occurred almost daily at the summit with Mw 5.3 ± 0.1. According to Neal et al. (2019), each collapse event resulted in the floor of the caldera dropping several meters. The summit magma chamber was continually drained sending magma down rift to the LERZ, and this episodic sequence of collapse events continued. They state that 2 August is when the final collapse event occurred at the summit and by 4 August the summit subsidence, the small seismicity, and the LERZ effusion had slowed or stopped. The walls of the deepened caldera extend to heights up to 100 m (Neal et al., 2019). A highly detailed account of the entire sequence broken up into daily reports has been given by the Hawaii Volcano Observatory (HVO) of the United States Geological Survey (USGS) (2018b).

2.2. Kilauea Volcano

Kilauea, a basaltic shield volcano, is the southeastern most of the five volcanic systems that make up the island of Hawai‘i, located in Hawaii, USA. A shaded relief map illustrating the surface structure of the summit caldera and Halemaʻumaʻu Crater prior to the 2018 events as well as their geographic location is given in Figure 1. A major feature within the large summit caldera at Kilauea is Halemaʻumaʻu Crater, which is nearly circular and had a diameter of about 1 km prior to the most recent sequence of collapse events. Kilauea has two active rift zones on the southern and eastern flanks of the volcano extending from the summit to below sea level. The LERZ has been particularly active in recent history in comparison to the less active southwest rift zone (e.g., Epp et al., 1983; Wolfe et al., 1987).

Kilauea Volcano is the result of hot spot volcanism and produces basaltic magmas with low viscosities (Turcotte & Schubert, 2014). Shield volcanoes such as Kilauea contain near-surface magma chambers that play an important role in activity. Input of magma from depth results in the growth and inflation of the magma chamber. Surface eruptions reduce the size of the magma chamber resulting in deflation (Lacey et al., 1981). Episodic inflation-deflation events at Kilauea have been extensively studied to gain insight
Eaton and Murata (1960) looked at swelling activity of the summit caldera using tiltmeter data from the 1959–1960 eruptions. Other examples include the 1969–1971 Mauna Ulu eruption (Swanson et al., 1979) and the 1983–1985 East Rift Zone eruption (Wolfe et al., 1987). Heliker and Mattox (2003) reported summit inflation-deflation events associated with fountaining eruptions of the LERZ. Mechanisms responsible for these events may include a temporary blockage in magma supply (Cervelli & Miklius, 2003) and/or convective overturns of the summit magma reservoir (Poland et al., 2009). Tilling et al. (2010) have also given an excellent overview of the volcanism at Kīlauea emphasizing the role of inflation-deflation cycles. Anderson et al. (2015) associate prior episodic summit inflation-deflation events to pressure variations in a shallow magma chamber located beneath the east margin of the Halema‘uma‘u Crater. Colella and Dieterich (2015) considered in detail a sequence of 47 inflation-deflation cycles at Kīlauea from 1983 to 1985 associated with fountaining eruptions. This eruption cycle had a number of similarities to the eruption cycle considered in this paper. The inflations and deflations occurred at the summit caldera, and the eruptions of lava occurred in the LERZ. They noted that as an inflation period ended there was an increase in seismicity that was attributed to the stress accumulation in the summit from the intrusion of magma. Similarly, they attribute the decrease in seismicity during deflation to stress relaxation as magma was transported along the rift zone to the eruption site. Inflation occurred in one or more magma chambers beneath the Kīlauea summit caldera and was concentrated near Halema‘uma‘u Crater. However, no systematic sequence of episodic caldera collapse events occurred as in the 2018 eruption.

3. Methods

3.1. Data Selection

In this study, we analyze the earthquake data from the USGS Earthquake Catalog that occurred on the Island of Hawaii between 4 May 2018 and 15 August 2018. The following sections explain our initial
investigation of this full data set as well as our methods to select a subset of this data to apply our technique to. All times considered here are Greenwich Mean Time. We begin counting time \( t \) (in days) at the time of occurrence of the \( M_{\text{w}} = 6.9 \) tectonic earthquake as this is a well-defined and significant event at the beginning of the whole sequence of heightened activity. This earthquake occurred at 22:32:54 on 4 May 2018, which will be \( t = 0 \). The timeline concludes with the occurrence of the last collapse event at \( t = 89.97 \) days, on 2 August 2018. During this entire sequence 62 collapse events occurred with most events radiating seismic energy equivalent to a magnitude \( M_{\text{w}} = 5 \pm 0.3 \) earthquake (Neal et al., 2019).

### 3.1.1. Magnitude

We consider the frequency-magnitude statistics of the earthquakes in the study region from 4 May to 2 August 2018. The cumulative number of earthquakes \( N_c \) with a magnitude greater than or equal to \( M \) is given as a function of \( M \) in Figure 2. In many cases the frequency-magnitude scaling of earthquakes is well approximated by the Gutenberg–Richter relation given by

\[
\log_{\text{10}}(N_c) = a - bM
\]

where \( a \) is a measure of seismic intensity and the \( b \) value is the scaling relating the number of small events to large events and is generally near 1 (Gutenberg & Richter, 1954). The smaller event magnitudes are given in local or duration magnitude, and the larger events are given in moment magnitude.

We give the least squares fit of equation (1) to the data in Figure 2 over the magnitude range \( 2.5 \leq M \leq 4.0 \) and find that \( a = 8.40 \) and \( b = 1.66 \). The rollover of the data at small magnitudes, \( M \leq 2.5 \), is attributed to the incompleteness of the catalog data. The sensitivity of the network has a considerably lower cutoff, but the very high rate of seismicity saturates the seismic records and causes the observed rollover. For this reason, the analysis carried out in this study uses only events \( M \geq 2.5 \).

### 3.1.2. Temporal

We introduce a timeline, illustrated in Figure 3, to provide a basis for explaining the temporal evolution of seismicity associated with the collapse events. We show the accumulation of earthquakes, including collapse events, from the \( M_{\text{w}} = 6.9 \) earthquake on 4 May 2018 (\( t = 0 \)) to the last collapse event on 2 August 2018 (\( t = 89.97 \)). In Figure 3a we give the cumulative number \( N_c \) of earthquakes with \( M \geq 4.7 \) (the minimum magnitude of large collapse events) as a function of time \( t \). The large aftershocks of the \( M_{\text{w}} = 6.9 \) earthquake can be observed in the first cluster of events, and the remainder of the data is collapse events (Neal et al., 2019). The rate of occurrence of collapse events becomes quasiperiodic in early June, about one per day, and slowly decreases until the sequence terminates on 2 August 2018. In Figure 3b, we give the cumulative number \( N_c \) of earthquakes with \( M \geq 2.5 \) as a function of time \( t \). As the collapse events become more periodic, you can see in Figure 3b that the rate of small seismicity greatly increases. The shaded red region of Figures 3a and 3b, 4 June to 2 August 2018, which contain this heightened period of small seismicity among 47 quasiperiodic collapse events, was selected as the study period we focus on in this paper.

### 3.1.3. Spatial

We now turn to the spatial dependence. This study is focused on temporal patterns so we use the available locations from the USGS Earthquake Catalog. The distribution in space of the epicenters of the seismicity is qualitatively very similar for the 46 interevent periods from 4 June to 2 August. We illustrate the distribution for a typical interevent period. The summit distribution of the epicenters of \( M \geq 2.5 \) earthquakes between the collapse events at \( t = 53.42 \) and \( t = 54.68 \) days is given in Figure 4a as an example. It can be seen that the epicenters are concentrated in the summit caldera. The seismicity is mainly concentrated at the summit but becomes more diffuse downslope and to the rest of the island (not pictured).

In order to quantify the spatial distribution of epicenters in Figure 4a, we give the distribution of radial distances from the center of the caldera. The center we take is the red star in Figure 1, and the distribution is given in Figure 4b. We see that 95% of the total number of earthquakes with \( M \geq 2.5 \) that occurred on the
island of Hawai‘i during the interval considered in Figure 4a lie within a circle, centered at the red star, with radius of \( r = 4.15 \) km. They are concentrated near the summit. The seismicity becomes more diffuse downslope, but there is no well-defined bound on this. We use this statistic to justify using the seismicity for the entire island of Hawai‘i in our study. Using the lower cutoff of \( M \geq 2.5 \) eliminates a lot of the smaller seismicity associated with other activity downrift.

### 3.2. Interevent Seismicity

The focus of this study is on the smaller seismicity occurring during 46 interevent periods between 47 collapse events. A subset of the timeline of seismicity and collapse events is given in Figure 5. Seismic behavior between collapse events was remarkably similar. A typical example of an interevent period is given in Figure 6 for the time between the collapse events that occurred in late June at \( t = 53.42 \) and \( t = 54.68 \) days (same interval illustrated in Figure 4 for spatial data selection). Following a collapse event, there is a relatively quiescent period. This is followed by a gradual buildup of seismicity into an active period with a near-constant rate of seismicity that continues until the next collapse event. The first period, the quiescent time, clearly has a different behavior than the latter period, the active time. By splitting the total interevent time and isolating these time periods, we look at immediate precollapse and immediate postcollapse dynamics in the seismicity.

The boundary between these two time periods was determined quantitatively. We began with a small window of time at the end of an interevent period and fit a straight line to this subset of data with a least squares linear regression. We iteratively increased the length of time included in the regression, extending to earlier times, until the correlation coefficient began to decrease. This was taken as the point of curvature of the data. We used the slope of this linear regression as the rate of seismicity, earthquakes per day, and the \( x \)-intercept of the line to divide the quiescent period and the active period. This was done manually for each of the 46 interevent periods.

In order to look at the precollapse and postcollapse event activity throughout the sequence as a whole, five main characteristics of each interevent period were measured. For each interevent period, we measured the total interevent time between collapse events (\( \Delta t \)), duration of quiescent time (\( t_q \)), duration of active time (\( t_a \)), rate of seismicity during the active time (\( \frac{dN}{dt} \)), and the total number of events that occurred during the interevent time (\( N_c \)) (Figure 6). We also used Gutenberg-Richter statistics on each interevent time, quiescent time, and active time to look for trends in magnitude distributions (\( b \) values).

### 4. Results

Overall, the pattern of collapse event, quiescent time, and active time repeated itself 46 times between the 47 collapse events within our study period. In Figure 7 we give the time series of the smaller seismicity statistics throughout our study period. These time series can be classified as weakly antipersistent, with the cumulative number of events displaying the strongest antipersistence. An antipersistent time series has alternating highs and lows (sequential values are negatively correlated), whereas a persistent series would have values that consistently increase or consistently decrease (sequential values are positively correlated) (Turcotte, 1997). This is nonunique in general eruptive behavior in that Newman et al. (2012) illustrate, for example, that a shorter interevent time between eruptions of the Old Faithful geyser in Yellowstone National Park follows a longer interevent time, and a longer interevent time follows a shorter interevent time and thus classify it as antipersistent.
Although there was variable scatter in the data, some overall trends were clear. First, looking at the overall interevent time, $\Delta t$, a best fit line through the data reveals a very shallow positive slope. Although antiper- sistent, with values ranging from less than 1 day to just over 2 days, we consider the interevent times fairly constant throughout the sequence with only a small general increase (Figure 7a). The active time, $t_a$, showed an overall general increase throughout the sequence as well (Figure 7c). In contrast to these monotonic trends, the quiescent time, $t_q$, had a significant shift in trend during the sequence around $t = 40$ days, 14 June. The quiescent time decreases for about the first 10 days of our study period before remaining relatively consistent for the rest of the sequence (Figure 7b). After the collapse event of 17 June, there was only one interevent time whose quiescent time was longer than its active time. The cumulative number of earthquakes, $N_c$, and the rate of seismicity during the active time, $\frac{dN_c}{dt}$, both had significant changes in trend at this early-middle June point in the sequence too. The cumulative number of earthquakes fluctuates around 100 for the first 10 days before increasing to variable but consistent rates fluctuating around 325 earthquakes per interevent time for the remainder of sequence (Figure 7d). The final variable analyzed was the rate of seismicity during the active time. These rates were remarkably linear with an average correlation coefficient of

**Figure 4.** (a) The spatial distribution of the epicenters of $M \geq 2.5$ events that occurred in the interval between the summit seismic events of $t = 53.42$ and $t = 54.68$ days. The red and yellow stars indicate the centers of the summit caldera and Halema’uma’u Crater, respectively. (b) The cumulative number of these epicenters found at a radial distance from the center of the summit caldera (red star in (a)). We find that 378 earthquakes lie within a circle with radius $r = 4.15$ km. This represents 95% of all earthquakes on the Island during this period.

**Figure 5.** A subset of the 46 interevent periods which illustrates the repetitive pattern of seismicity observed between the 47 large summit seismic events. The cumulative number $N_c$ of $M \geq 2.5$ earthquakes is given as a function of time $t$. The vertical lines indicate the occurrence of a large collapse event and its magnitude is noted. The cumulative count of earthquakes resets to zero after each large event.
The rates were fairly low around 250 earthquakes per day, increasing slightly for the first 10 days before steeply increasing to over 500 earthquakes per day. After this jump in rate of seismicity, there was a gradual decrease in rates throughout the rest of the sequence as the rates fell back toward 250 earthquakes per day (Figure 7e). The rates were generally decreasing and returned to the level of seismicity before the jump in rates around 14 June. It is unclear if this is a coincidence or if it might be indicative of the physical system's behavior.

We note that the paper Shelly and Thelen (2019), published while this paper was under review, suggests that further work to improve the earthquake catalog is needed before analyzing magnitudes of events. We have included the $b$ value analysis results that we had already completed and qualitatively contribute to our study. However, we caution the reader that these $b$ values could change if further work on the earthquake catalog leads to significant changes in earthquake magnitudes. The Gutenberg-Richter scaling for our entire study period shown in Figure 2 shows that the $b$ value ($b = 1.66$) is quite high compared with tectonic earthquakes in general (generally $b = 1$), but the fit of the data to the scaling is quite good. The larger $b$ value is not atypical for volcanic settings where larger numbers of smaller earthquakes are often seen, especially during eruptive phases (Roberts et al., 2015). The Gutenberg-Richter scaling was applied to the seismicity of each interevent time. The average interevent $b$ value was 1.67 with a minimum of 1.29 and a maximum of 2.06. There were no significant temporal trends observed in $b$ values throughout the study period (Figure S1 in the supporting information).

Not only did the quiescent and active times behave differently in terms of rates of activity but also in magnitudes of activity. As seen in Figure 8, the quiescent times comprised smaller magnitude and fewer overall events in comparison to the active times. Even though the number of events was low, the Gutenberg-Richter scaling was applied to each interevent's quiescent time and active time. The average interevent $b$ value for quiescent times was 2.04, and the average for active times was 1.65. The active time $b$ values fluctuated similarly to the total interevent times between 1.23 and 2.23. As the majority of the earthquakes occurred in the active time, it makes sense that the $b$ values of this time period are more closely aligned with the $b$ values of the total interevent times (Figure S1). The quiescent time saw much more variation in $b$ values ranging from 1.07 up to 3.43.

Although there were continually decreasing rates of seismicity during the active times as the sequence progressed, there was no clear signal indicative of the abrupt termination of this sequence. In early August, the active seismicity in the system as a whole appeared to cease. The last large collapse event occurred on 2
August. An initial quiescent period followed by an active period of constant seismicity typical of interevent times is seen. However, instead of culminating in another collapse event, the rate of seismicity simply decays (Figure 9).

5. Discussion

The type of analysis presented in this study could aid in improving our understanding of the Kilauea volcanic system itself and caldera collapse of basaltic systems. The analysis reveals changes in activity that could be associated with changes to the physical system, which we discuss in the context of Kilauea and other recorded caldera collapse events. Though they have been previously studied, the 2018 set of events provide

Figure 8. These plots show how the characteristics we studied changed throughout the study period. Panels (a–e) have the same x axis which is time, t, for the days of our study period. Each round marker represents 1 of the 46 interevent periods. The y axes are each a different variable of the interevent periods: (a) length of interevent time, (b) length of quiescent time, (c) length of active time, (d) rates of seismicity during the active times, and (e) cumulative number of earthquakes during the interevent time.

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Figure 9. As in Figure 5, the cumulative number $N_c$ of $M \geq 2.5$ earthquakes is given as a function of time $t$. The gray lines indicate the occurrence of a large collapse event and its magnitude notated. The cumulative count of earthquakes resets to zero after each large event. The final three collapse events are shown, and the far-right sequence of earthquakes shows the seismicity for 5 days following the last large seismic event that occurred on 2 August 2018 ($t = 89.97$).
opportunities to revisit the relationships within the system between the summit and the LERZ with modern instrumentation data as well as this recorded earthquake data and analysis.

The steady drainage of magma from Kilauea’s summit magma chamber from 2 May until 2 August 2018 was clearly connected to the sequence of collapse events including those that we study. Neal et al. (2019) estimated that over this period of time, the volume of collapse at the summit was 0.825 km$^3$. This value was similar to their estimates of erupted material in the LERZ during this time. The pattern of seismicity we observed is part of this complex process, but as a first approximation we suggest a periodic failure of the floor of the Halema’uma’u Crater as also suggested by Neal et al. (2019) and following the piston model proposed in other caldera collapse events such as Miyakejima (Kumagai et al., 2001) and Bárðarbunga (Gudmundsson et al., 2016). At the start of the eruption, the crater floor was made up of solidified magma and rubble from the walls of the crater. After a collapse event, the floor of the crater rests on the top of the magma chamber. The floor has some strength and remains in place as magma withdrawal continues. The loss of magma reduces the basal support of the floor. The required support comes from the surrounding floor and walls of the summit caldera. As magma continues to be lost from the magma chamber and drains toward the LERZ, its support of the crater floor is reduced, but it is held in place by the transfer of stress to the surrounding rock in the caldera. As the stresses increase, small earthquakes begin to occur as illustrated in Figure 4 (during the quiescent time). The continued withdrawal of magma results in a further increase in stresses that reaches a critical point causing a transition to high levels of seismicity (the active time), until the lateral support of the floor fails. The collapse of walls and descent of the floor onto the lowered level of magma results in the collapse event and the release of seismic energy in the VLP events. The collapse event results in a further deposition of rubble from the walls of the crater onto the floor and an increase in the size and depth of the crater. The process then repeats in the observed episodic manner as magma is drained from the reservoir and moved downrift until the next collapse event occurs. The analysis of the interevent seismicity shows that the process of stress buildup is consistent and repeatable between collapse events.

Our focus at Kilauea on precollapse and postcollapse conditions and breaking down the interevent seismicity into the quiescent and active times revealed some interesting characteristics of the seismicity, which could be related to the failure process leading to collapse. The decrease in duration of quiescent time after the first few pattern cycles indicates that the critical value of stress in the caldera floor and walls was reached in shorter amounts of time after a collapse event. The Gutenberg-Richter frequency-magnitude scaling results indicated that these shorter quiescent times had a higher relative number of smaller magnitude events to larger magnitude events (indicated by the overall higher b values; see Figure S1). Although the sample size was small because this was a time of quiescence, this was a fairly consistent characteristic. The larger magnitude events between collapse events occurred closer in time to the approaching collapse event, rather than to the previous collapse events as indicated by the lower b values calculated for the active times. After the large collapse events, time is needed again to reach the critical stress build up needed for the larger earthquakes. The larger earthquakes happen as the floor is starting to reach failure, but this built-up stress still culminates in the collapse event. The built-up stresses are not large enough during the quiescent time to cause these mid- and larger magnitude interevent earthquakes. The mid-June changes in interevent seismicity statistics also seem to suggest a physical change in the collapse events. These changes could be related to changes in degrees of inflation and deflation, effusion volume and rates into the LERZ, magma supply from below, and/or geographic locations of fissures, which all have been studied as proxies for physical system changes during previous eruptions in Kilauea and are discussed here. Some of these physical characteristics have been similarly utilized for collapse events elsewhere and are also discussed below.

The interpretation of the interevent seismicity presented above appeals to changes in magma supply and withdrawal which in turn affect the stress state of the caldera floor. Therefore, comparison to independent observation that constrains magma supply to and removal from the caldera would provide further support for this interpretation. As the inflation-deflation events were episodic with the collapse events, the degree to which the summit inflated and deflated (using tiltmeters) could be analyzed in a similar time series approach to look for significant changes during the sequence. For example, Epp et al. (1983) proposed an inverse relationship between Kilauea’s summit deformation, measured by tiltmeter, and the elevation of actively erupting fissures in the LERZ. They concluded that there was an increase in the amount the tilt changed with decreasing elevation of fissures. Similarly, Eaton and Murata (1960) discuss the interplay between erupted lava volumes, fissure location/elevation, and changes in tilt. Though much of the activity was
focused at Fissure 8, the 2018 events had a total of 24 active fissures in the LERZ (Neal et al., 2019). The geographic locations and durations of activity may correlate with not only the extent of tilt changes but also potentially the summit seismic activity such as that of the intercollapse times studied in this paper. As more lava output and effusion rate data become available, this could provide more insight into systematic changes that could correlate with (or not) the mid-June change in activity we see in the seismicity rates and quiescent time durations.

Previous caldera collapse studies have also focused on the pressure changes and relationships between the summit and rift zone eruptions as a way to approach collapse dynamics. The Bárdarbunga volcano in Iceland experienced caldera collapse from 2014–2015. Gudmundsson et al. (2016) studied this event using many data types including seismicity, GPS displacements, magma flow rates, and geobarometric and subaerial gas analysis. Through their analysis of these and modeling of the system, Gudmundsson et al. (2016) concluded that this collapse event was initiated by drainage of magma away from the summit and continued in stages as the product of a pressure feedback between the magma path flowing away from the summit and the block (“piston”) on top of the summit magma chamber. In the past at Kilauea, insight into the magma chamber pressure conditions has been interpreted using lava lake levels (Patrick et al., 2015). In the case of the 2018 events, the lava lake had drained extensively to depths that were no longer visible by the start of the large collapse events. Neal et al. (2019) reference tilt signals detected downrift in their suggestion that collapse events and pressure changes are linked through the summit magma plumbing system and the LERZ. As detailed tilt data come out and are analyzed, this could be examined with our seismicity analysis to further examine the piston model pressure feedback explanation that was presented for the Icelandic caldera collapse.

Other volcanoes with less instrumentation such as Miyakejima in Japan have also displayed VLP signals during caldera-forming events (Kumagai et al., 2001). In 2000, there were VLP seismic signals recorded once to twice a day for almost a month, but in contrast to the 2018 Kilauea events, the magnitudes of the events were inconsistent (Kumagai et al., 2001). There were other obvious differences with the 2000 Miyakejima events such as the fact that the erupted materials only amounted to 1% of the collapse volume (Geshi et al., 2002), whereas the erupted volume of Kilauea was estimated by Neal et al. (2019) to be close to the volume of collapse at the summit. There were earthquake “preswarms” before the VLP events as studied by Kobayashi et al. (2003). The four preswarms they studied though contained much fewer earthquakes than the interevent times observed at Kilauea. If available, the full catalog of small seismic events throughout the sequence of VLP events may be able to be studied in a similar way to this paper to learn more about the Miyakejima event. Investigating this and other caldera-forming events, for which there is available seismic data, could lead to a better understanding of both the quasiperiodic and nonepisodic caldera-forming collapse sequences at active volcanoes.

Just as the beginning trigger of the 2018 sequence of events was described as enigmatic by Neal et al. (2019), the end of the sequence also is poorly understood. Although the rates of interevent seismicity were generally decreasing in the latter part of the sequence as discussed above, there was no diagnostic signal within this data set that indicated that the sequence was coming to an end or pause in activity. Further research into the characteristics of the smaller seismicity or other data types may provide insight into this abrupt end of heightened activity and this periodic sequence as a whole. Neal et al. (2019) do point out that in some correlation to the final collapse event occurring on 2 August, that by 4 August the subsidence at the summit mostly stopped as well as the LERZ effusion. These terminal dates, along with duration of the whole process, are not always correlated. As Michon et al. (2011) point out at Piton de la Fournaise, the collapse process only lasted 2 days, but the eruption continued on for about a month after. Michon et al. (2011) attribute these differences to underlying factors of the physical system, concluding that one of the main factors in changes to these trends at the three different systems that they studied (Piton de la Fournaise, Fernandina, and Miyakejima) was magma outflow rates. This detailed type of interevent study using eruption rates, tilt steps, and displacement measurements, among others, could be reapplied and revisited using the further broken down interevent times and the trends of these specific time intervals where available/possible.

### 6. Conclusions

We have presented an approach for statistical analysis of the interevent seismicity behavior occurring between volcanic summit caldera collapse events. In this approach, we isolate the quiescent and active
times to look at immediate precollapse and postcollapse seismic activity. For Kilauea, we find that the statistical nature of the intercollapse seismicity is generally antipersistent with some overall trends and a significant change in behavior occurring during mid-June. During mid-June there were significant changes in the quiescent time lengths (decreased), the number of earthquakes during the interevent times (increased), and the rates of seismicity during the active times (increased). While it is inferred that these changes are related to a change in the physical state of the volcanic system, the exact nature of the change remains unknown.

The statistical behavior of the small magnitude seismicity, however, does provide an important data set that describes a very regular, repeatable process occurring between collapse events, which may also be sensitive to larger-scale changes linked to magma flow away from the summit region. Due to the very recent occurrence of the events, the utility of the analysis we have presented here may become more clear as new and ongoing data sets and studies are published, and new physical models for collapse events are explored that can more explicitly link changes in stress state to magma supply and collapse mechanics. New detailed studies on the modeling of the caldera collapse mechanics, the lava effusion behavior at the fissures, the East Rift Zone’s feedback system with the summit, and magma sources and geochemistry have been published while this paper was in review and provide further context and insight to the Kilauea system as a whole (e.g., Anderson et al., 2019; Gansecki et al., 2019; Patrick et al., 2019). An example of another recent intercollapse seismicity study on these events is Butler (2020), which analyzes the interevent seismicity as “foreshocks” of the collapse events. The low number of caldera collapse events that have occurred globally requires full exploration of each system’s properties and characteristics in order to gain insight into the underlying physical processes within these volcanic systems as well as general process of caldera collapse.

Data
Maps were made using the National Map and National Elevation Dataset (NED) proved by the U.S. Geological Survey (https://www.usgs.gov/core-science-systems/ngp/tm-delivery/). Earthquake data were acquired on 22 August 2018 from the U.S. Geological Survey Earthquake Catalog (https://earthquake.usgs.gov/earthquakes/search/). Magnitudes, epicenter locations, dates and times were all downloaded from USGS Earthquake Catalog. Analysis and figures done using Python 3.6.4. ArcGIS and QGIS were also used in making maps.

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