**Shallowly driven fluctuations in lava lake outgassing (gas pistoning),
Kīlauea Volcano**

Matthew R. Patrick^{1*}, Tim Orr¹, A.J. Sutton¹, Einat Lev², Wes Thelen¹, David Fee³

¹ Hawaiian Volcano Observatory—U.S. Geological Survey, PO Box 51, Hawai‘i National Park,
HI, 96718

² Lamont-Doherty Earth Observatory, 61 Rte. 9w, Palisades, NY, 10964

³ Wilson Infrasound Observatories, Geophysical Institute, University of Alaska Fairbanks, 903
Koyukuk Drive, Fairbanks, AK, 99775

*Corresponding author:

mpatrick@usgs.gov

Phone: 1-808-345-0485

Fax: 1-808-967-8890

Abstract

Lava lakes provide ideal venues for directly observing and understanding the nature of outgassing in basaltic magmatic systems. Kīlauea Volcano's summit lava lake has persisted for several years, during which seismic and infrasonic tremor amplitudes have exhibited episodic behavior associated with a rise and fall of the lava surface ("gas pistoning"). Since 2010, the outgassing regime of the lake has been tied to the presence or absence of gas pistoning. During normal behavior (no gas pistoning), the lake is in a "spattering" regime, consisting of higher tremor amplitudes and gas emissions. In comparison, gas piston events are associated with an abrupt rise in lava level (up to 20 m), during which the lake enters a "non-spattering" regime with greatly decreased tremor and gas emissions. We study this episodic behavior using long-term multidisciplinary monitoring of the lake, including seismicity, infrasound, gas emission and geochemistry, and time-lapse camera observations. The non-spattering regime (i.e. rise phase of a gas piston cycle) reflects gas bubbles accumulating near the top of the lake, perhaps as a shallow foam, while spattering regimes represent more efficient decoupling of gas from the lake. We speculate that the gas pistoning might be controlled by time-varying porosity and/or permeability in the upper portions of the lava lake, which may modulate foam formation and collapse. Competing models for gas pistoning, such as deeply sourced gas slugs, or dynamic pressure balances, are not consistent with our observations. Unlike other lava lakes which have cyclic behavior that is thought to be controlled by deeply sourced processes, external to the lake itself, we show an example of lava lake fluctuations driven by cycles of activity at shallow depth

and close to the lake's surface. These observations highlight the complex and unsteady nature of outgassing from basaltic magmatic systems.

Keywords: lava lake, Kilauea, volcano monitoring, gas emissions

1. Introduction

Persistent lava lakes provide a stable window into magmatic processes such as convection and outgassing dynamics. In recent years numerous studies have focused on a handful of lava lakes, including Erebus (Oppenheimer et al., 2009), Erta 'Ale (Oppenheimer and Yirgu, 2002; Harris et al., 2005; Spampinato et al., 2008) and Nyiragongo (Spampinato et al., 2013). With the reappearance of lava lake activity in Halema'uma'u Crater, on Kilauea Volcano, Hawai'i, over the last several years (Patrick et al., 2013), there is a new opportunity to conduct multidisciplinary studies on lava lake behavior. The existing robust monitoring network on Kilauea, augmented by regular visual observations of the lava lake, provides a diversity and abundance of data to test models of lava lake behavior.

The current eruption in Halema'uma'u Crater began in March 2008 (Wilson et al., 2008; Fee et al., 2010; Patrick et al., 2013), with the opening of the "Overlook" crater (Fig. 1). Ephemeral lava ponds were present deep in the crater (~200 m below the Overlook crater rim) during 2008 and 2009, with a larger, continuously active lava lake appearing in February 2010. By 2013 the lake measured about 160×200 m in size, and was normally about 30–60 m below the Overlook crater rim. The lake surface consisted of large, black crustal plates separated by narrow,

incandescent cracks. Lake surface migration was normally from north to south, with downwelling along the southern margin and spattering commonly active at a point along that edge. Rockfalls occasionally impacted the lake and triggered small explosive events (Orr et al., 2013). The SO₂ emission rate from the lava lake ranged between 500 and 5000 t d⁻¹, with the plume lofting up to a kilometer above the volcano as it was carried southwest by the prevailing tradewinds (Elias and Sutton, 2012).

Episodic tremor was first observed in April 2008, just a month after the start of the eruption, as occasional cigar-shaped tremor bursts lasting a few minutes (Patrick et al., 2008). Through 2008 this episodic behavior became more intense and periodic, occurring every 5–10 minutes, and was associated with a rise and fall of the lava lake surface. Following the establishment of the continuously active lava lake in early 2010, these joint fluctuations in tremor and lava level were more sporadic (a few per day), and longer lasting (several hours each) (Patrick et al., 2010, 2014). We consider this behavior a type of gas pistoning, which is a cyclic rise and fall of the lava surface commonly observed on Kīlauea (Swanson et al., 1979; Tilling, 1987; Orr and Rea, 2012). This study describes and interprets the gas pistoning between 2010 and 2015. There was occasional variability in the styles of gas pistoning during this period, and we focus on the most common style.

2. Background

We consider a gas piston event to consist of a quiescent rise of the lava surface, terminated by intense spattering that accompanies an abrupt drop of the lava surface. Gas pistoning was first

described in detail by Swanson et al. (1979), at Mauna Ulu, where cycles began with the quiescent rise of a crusted lava surface within the conduit, taking 10–15 minutes to reach maximum height (30–50 m rise). Spattering and outgassing would disrupt the surface, and the lava level would rapidly drop (1–2 minutes). Swanson et al. (1979) interpreted this as gas accumulating beneath an impermeable crust, building to a critical point when the crust failed and gas was released, with lava draining back to fill the void.

Jaupart and Vergnolle (1988) and Vergnolle and Jaupart (1990) conducted analogue models to suggest that gas-piston behavior was consistent with the periodic rise of large gas slugs. The rise and expansion of the gas slug in the conduit would lift the lava surface and terminate with bursting of the slug at the lava free surface and a rapid drop in lava level. Edmonds and Gerlach (2007) analyzed gas composition during a purported gas-piston event at Pu‘u ‘Ō‘ō, the vent area for Kīlauea’s ongoing East Rift Zone eruption. The high CO₂ content of the gas led them to infer that the gas pistoning was driven by deeply-sourced gas slugs, supporting the Jaupart and Vergnolle (1988) model and arguing against Swanson et al. (1979). Whitham et al. (2006) used an analogue model to show that cyclic fluctuations in lava level might be produced by dynamic pressure equilibration at the base of the conduit. Peters et al. (2014) show lava level fluctuations at Erebus that may relate to this process.

Patrick et al. (2011a) showed that gas pistoning occurred in a perched lava channel on Kīlauea’s East Rift Zone in late 2007. With the perched channel removed from a deep magmatic system, the shallow gas accumulation model was the only reasonable explanation for that gas-pistoning, supporting Swanson et al. (1979). Patrick et al. (2010) analyzed observations of the

Halema‘uma‘u lava lake and interpreted the behavior as due to shallow gas accumulation, which was also suggested by Patrick et al. (2011b). Orr and Rea (2012) analyzed gas piston events in a lava pond at Pu‘u ‘Ō‘ō and attributed them to episodic growth and failure of a shallow foam layer at the top of the lava column, irrespective of the presence of a surface crust. Chouet and Dawson (2015) presented a model for Halema‘uma‘u gas pistoning in which foam formation occurred within a narrow conduit, which is different than the lava lake scenario we describe here.

Thus, three general models have been presented to explain gas pistoning: 1) shallow gas accumulation, either due to gas trapped by the surface crust (Swanson et al., 1979) or due to gas trapped within a near-surface foam layer (Orr and Rea, 2012; Chouet and Dawson, 2015), 2) deeply sourced gas slugs (Jaupart and Vergnolle, 1988) and 3) dynamic pressure balance (Whitham et al., 2006).

3. Methods

We characterized the lava lake activity using five primary data sources: 1) imagery from field cameras, 2) seismicity, 3) infrasound, 4) SO₂ emission rates and 5) gas geochemistry.

We augmented direct visual observations of the lake with imagery from three cameras, two visible/near-infrared and one thermal, all located on the rim of Halema‘uma‘u Crater roughly 150-250 m from the lava lake surface. The two visible/near-infrared cameras captured images at varying rates, with one having a frame rate of 1–4 frames per second (Orr et al., 2013) and the other capturing an image every 10 s (Patrick et al. 2015a). Both operated continuously in near-

infrared mode, which improves their ability to see through fume in the crater. The thermal camera (HTcam) was a Mikron M7500 acquiring an image every 5 s with an image size of 320×240 pixels (Patrick et al. 2014). Lava lake crust velocity was measured from the thermal images using the technique of Lev et al. (2012) (Appendix). Lava level was measured using the thermal images (Appendix), which provided a continuous view of the lake surface through thick fume. The lava level was measured in pixels from the images manually and converted to absolute height in meters (above sea level, a.s.l.) either using the camera viewing geometry and measured geometry of the Overlook crater or using an empirical fit to sporadic laser rangefinder measurements (Appendix).

Seismic data came primarily from broadband station NPT, located ~ 700 m from the vent, but we also used station OTL (~ 2 km from vent) when NPT was not operational. Infrasound data came from two sources: for the 2010 activity we used data from the University of Hawai‘i Infrasound Laboratory infrasound array 6.8 km east of the vent (Fee and Garces, 2007); for activity during 2013 and 2014 we used data from station AHUD, positioned 4.1 km southeast of the vent.

SO₂ emission rates from Kīlauea caldera emission sources, principally the Overlook crater, were measured by vehicle-based FLYSPEC DOAS UV spectrometer according to the method described by Elias and Sutton (2012). To provide a more continuous time series reflective of SO₂ emission rate changes, we used data from an in-situ SO₂ sensor located 200 m nominally downwind of the vent. We monitored the chemistry of the principal gases released from the lake in discrete, several-hour-long campaigns, by directing a MIDAC M4402 Open Path FTIR spectrometer fitted with a Stirling-cooled InSb detector at the lake surface. The gas data time

series provides a nearly continuous record of contemporaneous abundances of H₂O, CO₂, SO₂, CO, HCl, and HF.

4. Observations and data

4.1. 2010 activity

Gas pistoning was common throughout much of 2010, and events in November-December are evident as spikes in lava level superimposed on a gradually rising lava level baseline (Fig. 2a). Each event was associated with tremor dropping to very low levels, a phenomenon we call “tremor stagnation” that was consistently tied to gas piston events during our study period. Between November 8 and December 6 there were 67 gas piston events (average of 2.4 per day), ranging from 1.6 to 7.8 hours in duration (from start of rise to end of fall) with a mean of 3.4 hours (std. 1.1 hour). Between November 8 and 24 (after which the top of the gas piston cycles went above the top of the images), gas piston events had lava level changes of 11–22 m, with a mean of 15.7 m (std. 2.5 m). Starting in mid-November, the baseline lava level began rising as the summit inflated. Baseline lava level change has been tied to summit magma reservoir pressure fluctuations, with the gas-driven level changes shown in this study superimposed on these longer-term pressure-driven changes (Patrick et al., 2015b).

Figure 3 shows data from two gas piston events from November 20, 2010 (Supplementary Video 1), which are representative of activity from late 2010. The periods before and after the two gas piston events (between 4:00 to 8:00 and 18:00 to 22:00 HST) show typical baseline behavior,

with a relatively steady lava level (baseline level of 868 m a.s.l.) and a steady amplitude envelope of moderate seismic and infrasonic tremor. The two gas piston events were associated with dramatically reduced tremor amplitudes (tremor stagnation) that dropped within a minute of the onset of rapid lava level rise. The rise in lava level lasted tens of minutes and slowed exponentially into a lava level plateau (13–14 m above baseline lava level) that lasted several hours. Inevitably, intense spattering would start within the lake, usually at the lake margin, and corresponded with a rapid drop in lava level and a burst in seismic and infrasonic tremor. The surface crust velocity showed systematic changes that correlated with lava level and tremor amplitude. During steady behavior, the crust moved at a relatively constant velocity of about 0.4 m s⁻¹. For both events, the crust velocity dropped to about half of this steady velocity during the rise phase, and then attained a relatively steady, yet reduced, velocity during the plateaus. Fall phases were characterized by surging crust motion, with crust “plunging” towards the spattering sources.

4.2. *Outgassing behavior and SO₂ emissions*

Repeated visual observations indicate that during rise and plateau phases (i.e., tremor stagnation), the outgassing plume becomes unusually thin, weak and wispy, and during the fall phases (tremor burst) the plume becomes unusually thick, robust and pulsating. This difference has been consistent and observed in many weather conditions, indicating the changes in plume appearance are not simply driven by atmospheric conditions. In contrast, baseline lava level (moderate tremor) corresponds to moderate plume vigor. Figure 4a-c shows a representative example from 2013, with the same general relationship as that observed in 2010. The

fluctuations in plume vigor suggest that gas emissions fluctuate concordantly with tremor. This is supported by downwind SO₂ concentration, used as a proxy for SO₂ emission rate. Figure 5 shows gas piston events on November 24–27, 2010. Baseline lava level varies but is generally between 870 and 875 m a.s.l. The baseline level is interrupted by six major gas piston events, lasting between 1.9 and 4 hours, and all but one of these had lava levels that extended slightly above the top of the image (equivalent to about 892 m a.s.l.). SO₂ concentration is variable but is generally between about 5 and 25 ppm when the lava level is at its baseline level, and plummets during each rise and plateau phase to undetectable levels (less than 1 ppm). During the fall phase of the gas piston cycles the SO₂ concentration briefly spikes to high levels. The relative changes in SO₂ emission rate implied by these SO₂ concentration data are in agreement with SO₂ camera observations of Nadeau et al. (2014).

Explicit measurements of SO₂ emissions from vehicle-based traverses are consistent with the in-situ ambient SO₂ concentration data and confirm that gas pistoning is associated with significant changes in SO₂ emission rates. Elias and Sutton (2012) showed significantly lower SO₂ emission rates during tremor stagnation phases. We focus here on more recent data, recalibrated for more accurate absolute values. Figure 4d,e shows representative emission rate changes bracketing transitions between normal tremor and tremor stagnation. Tremor stagnation phases in these examples have SO₂ emission rates that were 23 and 38% of the values during normal tremor phases, suggesting that SO₂ emissions are roughly a third of that during normal tremor phases. These emission rate data are again broadly consistent with the SO₂ camera data of Nadeau et al. (2014) and point to significantly reduced gas emissions during lava rise and plateau phases of gas piston events.

4.3. Gas geochemistry

FTIR data collected on January 14, 2011, captured relatively short-term, quasi-periodic gas pistonning (similar to that shown in Supplementary Video 2), with 10 cycles occurring between 10:15 and 16:15 HST (Fig. 6; Appendix). Lava level changes were 15–20 m above baseline (Fig. 6a), with each cycle lasting about 30 minutes. Rise phases corresponded with a weak and wispy gas plume, characterized by lower pathlength-concentrations of all gas species measured by FTIR (Appendix). Fall phases were associated with a vigorous, pulsating plume and higher pathlength concentrations for all species. SO_2/CO_2 drops to very low and steady values during the rise phase (Fig. 6c), while during fall phases SO_2 and H_2O release dominates with high and chaotic SO_2/CO_2 and $\text{H}_2\text{O}/\text{CO}_2$ shown in the exsolved gases. SO_2/HCl ratios spike at the onset of the fall phases (Fig. 6e).

4.4. 2013–2015 activity

By 2013, gas piston events still consisted of long periods (hours) of tremor stagnation, but lava level fluctuations were smaller in amplitude and less conspicuous. In 2013–2015, gas piston events were most conspicuous by changes in tremor and spattering in the lake, and we referred to lake outgassing behavior as either “spattering” (normal, moderate tremor and spattering) or “non-spattering” (tremor stagnation and no spattering) phases. Non-spattering phases corresponded with the rise and plateau phases of gas pistonning. Analysis of 900 non-spattering phases between February 2012 and November 2013 reveals a range of durations between 4

minutes and 15.8 hours, with a mean of 2.3 hours (std. 1.7 hours). During these 22 months, the lava lake was in a non-spattering phase 13% of the time.

Figure 7 shows a one day period (April 5, 2014), representative of 2013–2015. The non-spattering phases lasted between 1.3 and 2.6 hours, shown by mirrored reductions in seismic and infrasonic tremor amplitudes. Non-spattering phases were each associated with an abrupt rise in lava level by about 3 m. The non-spattering phase that begins around 15:00 was unusual in that lava level abruptly rose 53 minutes before the onset of tremor stagnation. Nevertheless, this lava level rise corresponds in time with a sharp reduction in seismic tremor amplitudes (if not a stagnation), which in that sense is typical. The overall higher lava levels in 2013–2015, compared to 2010, permitted a view of most of the lake perimeter, thus allowing a count of the number of spatter sources active through the day. Spattering phases consist of one or more spattering sources in the lake; multiple spattering sources correspond to the periods with the highest seismic tremor. Non-spattering phases correspond with a complete absence of spattering sources in the lake. The surface crust velocity was relatively steady through the day and did not appear to consistently drop during tremor stagnation as it did in the 2010 events. This lack of obvious change in surface velocity during non-spattering phases was confirmed by examining several dozen other events through 2013 and 2015.

During 2013 and up to the time of writing in early 2015, lake surface migration was normally from its upwelling area at the north margin towards the south margin where it downwelled. A spatter source was common at the southeast margin of the lake during spattering phases. During spattering, the surface crust would be locally drawn towards the spatter sources, with crust

seeming to “plunge” into the spattering area. Rockfalls which impacted the lake at the margin often initiated spattering phases by triggering minor spattering at the point of impact that grew into a large sustained spatter source. Typically, these spatter sources would migrate along the margin towards the south, presumably carried by the prevailing circulation (akin to the “traveling” fountains of early Halema‘uma‘u (Perret, 1913) and in the East Rift Zone in 2007 (Patrick et al., 2011a); Supplementary Video 3). Occasional spattering that appeared near the center of the lake, not triggered by rockfalls, would also be carried south in the current.

4.5. Relation with rockfalls

An important aspect of the gas pistoning in 2010–2015 was the common association with rockfalls from the Overlook crater walls (Fig. 8). Based on webcam and visual observations, rockfalls often terminated or, more rarely, initiated gas piston events. Small rockfalls (even single rocks <1 m diameter) often pierced the surface of the lava lake during a rise or plateau phase. Weak spattering would begin at the impact point and gradually expand in size and intensity, further disrupting the crust and causing the lake surface to undulate as the level dropped, terminating the gas piston event and restarting a spattering phase. This continuity of increasing spattering intensity at the puncture point indicated that the rockfalls triggered these fall phases, and were not merely coincidences. This observation is similar to that in Swanson et al. (1979), who found that they could trigger spattering and gas piston fall phases by piercing the lava surface with thrown objects. More rarely, larger rockfalls would impact the lake, triggering a very long period seismic signal (Orr et al. 2013), followed within minutes by the onset of a rise phase and cessation of spattering (Fig. 8a-c).

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300 We also observed an apparent correlation with longer term lava level drop and non-spattering
301 activity. During summit deflation, the overall lava level would drop; more frequent small
302 rockfalls were common during low lava levels as the veneer of juvenile lava adhered onto the
303 crater walls detached and fell into the lake. At these times, non-spattering phases seemed to be
304 more common (Fig. 8d), producing short-term gas-driven lava level fluctuations superimposed
305 on the longer term lava level change (Patrick et al. 2015b) that relates to ground tilt (Fig. 8e).

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307 **5. Discussion**

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309 *5.1. Gas pistoning: shallowly or deeply sourced?*

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311 Published explanations for gas piston behavior include 1) shallow gas accumulation, trapped by
312 the crust or within a foam (e.g., Swanson et al., 1979, Patrick et al., 2010; Orr and Rea, 2012), 2)
313 deeply sourced gas slugs (e.g., Jaupart and Vergnolle, 1988), and 3) dynamic pressure balance
314 (Whitham et al., 2006). Shallow gas accumulation, at or near the surface of the lava lake,
315 appears to drive the gas piston events in this study based on the following observations:

316 1) *Seismic and infrasonic tremor, gas emissions and visual observations are consistent with a*
317 *“trapping” process.* Figures 3 and 7 show that rise phases begin with an abrupt decrease in
318 seismic and infrasonic tremor amplitudes, and gas emissions (Fig. 5,7) relative to steady
319 background levels. Likewise, these measurements increase dramatically above background
320 levels during fall phases. The instantaneous and inverse correspondence between outgassing

and lava level implies a shallow build-up and release process, rather than an injection of additional gas (i.e., a gas slug) from depth.

2) *Changes in SO_2/CO_2 ratio exclude deep CO_2 -rich gas:* The FTIR data show a decrease in CO_2 relative to SO_2 during fall phases (Fig. 6c), consistent with a process dominated by SO_2 and H_2O exsolution originating at depths of several hundred meters or less (Appendix). The data do not show evidence of CO_2 enrichment relative to the other gases, as would be found with deeply sourced gas slugs (Edmonds and Gerlach, 2007; Burton et al., 2007).

3) *Triggering by rockfalls suggests a shallow process:* Small rockfalls triggering the fall phases (termination of gas pistons) suggest that gas is accumulating just beneath the surface during gas piston events. Likewise, their occasional triggering by rockfalls also suggests a shallow process.

4) *Spattering activity is shallowly rooted in the lake:* The observations that spattering a) migrates with the lake current, b) is not tied to the upwelling area in the north portion of the lake, and c) can be triggered by small rockfalls, suggest that spattering in general is shallowly rooted in the upper portions of the lake.

5) The gas-pistoning in the 2007 East Rift Zone perched lava channel shows that the shallow gas accumulation model can drive gas piston activity, providing a clear precedent for the shallow accumulation model (Patrick et al., 2011a).

We envision that shallow gas accumulation occurs near the top of the lava lake (depths of several tens of meters or less), well above the depths of significant SO_2 and H_2O exsolution (Gerlach, 1986; Appendix). We therefore expect that SO_2 and H_2O -rich bubbles rise upwards continuously from their exsolution depths of several hundred meters into the shallow portions of the lake.

Spattering normally releases this gas from the lake, but gas pistoning occurs when this rising SO₂ and H₂O-rich gas accumulates near the surface. The role of exsolution at very shallow (tens of meters) depths appears to be minor, as shown by the increase in SO₂ relative to HCl at the onset of fall phases (Appendix).

The gas slug model is not consistent with our observations for several of the reasons above. In addition, the rise phases during 2010 lasted tens of minutes to over an hour, which is unrealistically long for the terminal ascent phase of a slug (James et al., 2008). Second, the lava level plateaus (Fig. 3) would require the slug to pause at a shallow level for the duration of the plateau phase (several hours) prior to bursting and lava level fall. Third, the volume change of the lake during gas pistons in 2010 was $\sim 10^5 \text{ m}^3$, which is several thousand times larger than the estimated slug volumes at Stromboli (Ripepe and Marchetti, 2002), and seem implausibly large for a gas slug. Fourth, the episodically high SO₂/CO₂ and H₂O/CO₂ ratios during fall phases are consistent with a process dominated by SO₂ or H₂O rather than a very deep one driven by CO₂, and is contrary to the CO₂ enrichment reported for deeply sourced gas slugs (Edmonds and Gerlach, 2007; Burton et al., 2007).

The dynamic pressure balance model (Witham et al., 2006) does not apply to the Halema'uma'u gas piston events in this study, because the gas release timing predicted by that model is opposite to what is observed. In that model, increased gas flow occurs during the rise phase, and gas flow is inhibited during the fall phase. In contrast, SO₂ concentration data and webcam observations show the rise phase at Halema'uma'u represents a pronounced decrease in outgassing, plume vigor and spattering (Fig. 4), and the fall phase ushers in an increase in these parameters.

5.2. Outgassing regimes

Based on our observations of lava lake activity at Halema'uma'u, we identify two dominant styles of outgassing from the lake (Fig. 9): 1) *passive outgassing* and 2) *spattering*. Passive outgassing consists of many small bubbles releasing gas through the lake surface (at the incandescent cracks and through points in the crustal plates) in a scattered fashion (Fig. 10). Passive outgassing accounts for roughly a third of the total SO₂ emission during normal tremor periods. Spattering consists of a train of larger bubbles bursting at the margin of the lake, feeding one or more spattering sources. Spattering is responsible for roughly two-thirds of SO₂ emissions during normal tremor periods. A third outgassing style was associated with occasional small slug bursts at the upwelling area (Orr et al., 2014), though this is presumably a very minor contributor.

At any given time, overall lake behavior is determined by the dominance of the above outgassing styles, and can belong to one of two regimes: a *spattering* regime, and a *non-spattering* regime. During spattering regimes, outgassing consists of both 1) passive outgassing and 2) spattering styles. Seismic and infrasonic tremor and total gas output are at normal levels, and the plume is robust. Non-spattering regimes exhibit only passive outgassing, where the lake is quiet and tremor amplitudes are low, and the lava lake level rises due to gas pistonning. The gas emissions rates are low (SO₂ is roughly a third of that during spattering regimes), and the plume is thin and wispy. Lava upwelling and surface crust migration continues during non-spattering regimes. In

the absence of spattering during non-spattering phases, gas accumulates at the top of the lake, leading to gas pistoning.

Nadeau et al. (2014) presented data suggesting an apparent gas “deficit” exists with respect to SO₂ during non-spattering phases. It appeared that the pulse of gas released during the brief vigorous spattering that terminated non-spattering phases (and presumably represented the accumulated gas driving the gas piston) was insufficient to account for the total gas mass that would be expected for that time interval based on emission rates during spattering phases. Given the uncertainties in their data, they were not able to establish this deficit conclusively. Our lava level data confirm this deficit. The lava level plateau common to gas piston events indicates that net gas accumulation only occurs during the rise phase, but ceases during the plateau phase. The plateau phase represents equilibrium between a) gas supply beneath the surface and b) outflux from the surface - albeit at an overall outgassing rate much lower than that during spattering regimes (SO₂ emission roughly a third of that during spattering).

5.3. *Gas pistoning controls*

Our data show convincingly that gas pistoning and non-spattering behavior are driven by gas accumulation near the top of the lava lake, but the precise mechanism which modulates this process is more difficult to constrain. We favor a general model which follows that of Orr and Rea (2012), in which the gas pistoning represents the growth and failure of a shallow foam layer at the top of the lake (Fig. 10), irrespective of a surface crust. We envision that a continuous supply of SO₂- and H₂O-rich gas bubbles rises upwards from exsolution depths of several

hundred meters or less. Non-spattering phases (i.e. the rise and plateau phases of gas pistonning) occur when these rising bubbles accumulate near the top of the lake, creating a foam. The foam evolves through time as drainage, diffusion and bubble coalescence ensue (Mangan and Cashman, 1996; Orr and Rea, 2012), and may mature to a porosity and/or permeability state that encourages large scale coalescence, gas decoupling and spattering, which collapses the foam.

Rockfalls trigger some, but not all, spattering phases. In the absence of rockfalls, what triggers spattering phases and foam collapse? Carbone et al. (2013) showed that the depth-averaged bulk density of the Halema'uma'u lake was quite low (about 950 kg m^{-3}), equivalent to a depth-averaged porosity of 62%. If we assume that gas accumulation is focused near the upper surface of the lake, this implies that the porosity in the upper portions of the lake could be much higher than 62%. Previous studies have highlighted that significant permeability is achieved at porosities >70% (e.g., Mangan and Cashman, 1996; Namiki and Manga, 2008). The upper portions of the lake may therefore often be close to such a threshold, if one exists, with gas pistonning and spattering/non-spattering transitions representing the lake fluctuating around the threshold. Spattering might be triggered by the foam intrinsically evolving to a state of sufficient porosity and/or permeability that large scale gas decoupling ensues and the foam breaks down (Orr and Rea, 2012). Small rockfalls are an extrinsic mechanism to increase local permeability.

What triggers non-spattering phases and foam formation? The observation that large rockfalls seem to trigger some gas piston events may suggest that impact nucleation could be one trigger for foam formation (Carey et al. 2012). However, most gas piston events are not preceded by large rockfalls. Besides impact nucleation, an alternate trigger may relate to the observation that

non-spattering phases also appear to be more common during summit deflation phases, when baseline lava level drop encourages more frequent small rockfalls into the lake (Fig. 8d,e). Both large and small rockfalls tend to trigger intense spattering (i.e., excess outgassing), and this may exhume sufficient gas from the upper portion of the lake that the shallow lake porosity drops to a less permeable state, hindering coalescence and decoupling and shutting off spattering – building a foam instead.

What explains the lava level plateau? Plateaus occur during non-spattering regimes, when gas release from the lake is limited to passive outgassing. The steady lava level implies a stable foam thickness, maintaining a rough balance between the passive outgassing at the lake surface and the supply of bubbles into the base of the foam. Foam stability depends on a number of factors, including drainage, surface tension, bubble radius and gas velocity (Pilon et al. 2001). The gas piston heights of 2010 (as much as 20 m) vs. 2013–2015 (<5 m) suggest a large difference in stable foam thickness for these periods, albeit roughly consistent within a given time period. A coarse sampling of gas piston heights from 2012 to 2013 indicates that piston heights dropped to a few meters after the lake’s baseline lava level abruptly rose in early 2013, leading to an enlargement of the lake surface area. We speculate that the enlargement of the lake was responsible for the smaller gas piston amplitudes. A primary control on stable foam thickness is superficial gas velocity, defined as gas volumetric flux (m^3/s) divided by container cross-sectional surface area (m^2) by Pilon et al. (2001), with a lower velocity resulting in a thinner foam layer. Given that overall SO_2 outgassing rates did not have an obvious trend between 2010 and 2013, this suggests that the superficial gas velocity, by that definition, would have decreased over this period with the increase in lake surface area.

458
459 Why is there a gas deficit during non-spattering regimes? The plateau is linked to the gas deficit
460 suggested by Nadeau et al. (2014); the balanced outgassing and steady lava level occur in a
461 regime of significantly reduced overall outgassing rates, compared to spattering regimes. To
462 explain the deficit, either the supply of gas from the deeper system has slowed, or some gas that
463 has already entered the lake is circulated back into the deeper system due to the presence of foam
464 at the top of the lake. The reduced velocities during gas piston events in 2010 (Fig. 3) might
465 support the former mechanism, but 2013–2014 data do not show consistently lowered surface
466 velocities during gas piston events (Fig. 7). Instead, the 2014 data suggest a mechanism of gas
467 “recycling”, shown to be viable by Carey et al. (2013), who found that bubbles that had entered
468 the lake were being carried back to a deeper level.

469
470 Why were surface velocities different in 2010 and 2013–2015? One possible explanation is lake
471 size. We have observed that surface crust velocity is determined, in part, by proximity to
472 spattering sources, with increased surface velocities closer to an active spattering source (nearby
473 surface crust plunges towards spattering areas). With the smaller lake in 2010, the surface
474 velocity may have been more strongly influenced by the presence or absence of a spatter source,
475 resulting in lowered surface velocities during non-spattering phases. In 2013–2015, the
476 relatively steady surface velocities throughout the spattering and non-spattering phases might
477 represent less sensitivity due to the larger lake area (and overall greater distances from the
478 spattering source), with 2013–2015 surface velocities more closely reflecting the deeper
479 convective motion of the lake. Another explanation for the difference in surface velocity
480 fluctuation may be due to the different gas piston heights. In 2010, the gas piston heights, which

may correspond to the thickness of the shallow foam layer, were much higher than those in 2013–2015, and this thicker foam layer may have imparted a rheological resistance to surface movement.

5.4. Comparison with other lava lakes

Cyclic activity appears to be common at persistent lava lakes. At Erta ‘Ale, Harris et al. (2005) described two modes of activity, “sluggish” and “vigorous”, each lasting tens of minutes to several hours. Sluggish behavior consisted of low velocities and cooler crust with fewer incandescent cracks. Vigorous activity had higher velocities and a crust more disrupted by incandescent cracks. They attributed these modes of activity to changing convective regimes in the lake, but could not determine if the ultimate cause was shallow (internal to the lake) or more deeply (externally) sourced. Spampinato et al. (2008) tracked fluctuations at Erta ‘Ale and explained them as having a deep source, based on the modeling of Whitham et al. (2006). The lava lake at Erebus exhibits fluctuations in surface velocity, radiative heat output and SO₂/CO₂ ratio (Oppenheimer et al., 2009; Peters et al. 2014), which is explained by pulses of H₂O- and SO₂-rich magma from the deeper magmatic system into the lake. Spampinato et al. (2013) showed that the Nyiragongo lava lake had oscillations in lava lake level with a change of a few meters over several days, attributed to variations in the deep system based on the precedent of previous studies such as Whitham et al. (2006) and Oppenheimer et al. (2009).

The behavior we observe in Halema‘uma‘u is distinct from that described by previous studies in two major aspects. First, the Halema‘uma‘u lake exhibits more abrupt transitions than those at

Erta ‘Ale or Erebus. The Halema‘uma‘u activity we show here can be considered an end-member on a transition scale from gradual (Erebus), to moderately abrupt (Erta ‘Ale) to extremely abrupt (this study). The abrupt—and extreme—changes at Halema‘uma‘u result in a kind of binary outgassing behavior, with the lake switching between full (spattering regime) and dramatically subdued (non-spattering regime) outgassing. Second, the changes at Erta ‘Ale, Erebus and Nyiragongo, are attributed to deeply-sourced, conduit-driven, processes that are external to the lakes themselves. In contrast, we show that changes in lake behavior at Halema‘uma‘u are consistent with shallow processes that are internal to the lake.

Our study highlights the potential for a lava lake to modulate its own outgassing independent of deeper processes. Lake size, and the resulting lava residence time in the lake, is a possible explanation for this difference — with an area of roughly 25,000 m², Halema‘uma‘u is the second largest lava lake on Earth, second only to Nyiragongo (Spampinato et al., 2013). Given its depth (>100 m in 2011, Carbone et al., 2013), the lake represents a large repository of gas-charged lava, in which gas is released in an unsteady, episodic manner. By reconciling the magma supply rate with the estimated lake volume, Oppenheimer et al. (2009) estimated a residence time for magma in the Erebus lava lake at around four hours. For Halema‘uma‘u, reconciling the rough magma supply rate (3 m³/s dense rock, Edmonds et al., 2013) with the lake’s total lava mass (volume of 2.5×10^6 m³ at a density of 1000 kg/m³, Carbone et al., 2013), we estimate an average lava residence time of about four days. This internal “momentum” may allow for lake circulation and outgassing cycles which are independent, on short timescales, of conduit processes.

Finally, seismic and infrasonic tremor amplitudes closely follow trends in outgassing, suggesting that tremor is a good proxy for gas emission rates at Halema‘uma‘u (also shown by Nadeau et al. 2014). At Stromboli Volcano, tremor has been tied to bubble bursting at the lava free surface (Ripepe et al. 1996), and our data indicate that the tremor at Halema‘uma‘u reflects spattering intensity on the lake surface. This follows other recent studies that demonstrate tremor can be a useful gauge for outgassing behavior at basaltic volcanoes (Nadeau et al., 2011; Palma et al., 2008, Fee et al., 2010).

6. Conclusions

Cycles of lava level rise and fall (gas piston events), associated with tremor, lake surface velocities, and outgassing levels, have been observed at Halema‘uma‘u since mid-2008. We use multidisciplinary data to characterize the activity in 2010–2015, and reach the following conclusions:

- 1) The lava lake abruptly switches between “spattering” and “non-spattering” regimes. Spattering phases consist of both spattering and passive outgassing from the lake, as well as elevated tremor and a vigorous outgassing plume. Non-spattering phases are associated with only passive outgassing from the lake (no spattering), with greatly reduced tremor and a weak outgassing plume. Non-spattering phases last several hours and correspond with the lava lake level abruptly rising, in some cases 20 m, in a process called “gas pistoning”.

- 2) Gas pistoning (non-spattering) is caused by the accumulation of gas near the top surface of the lava lake, perhaps as a shallow foam. Our data show that gas pistoning at Halema‘uma‘u is not consistent deeply sourced gas slugs or dynamic pressure balances.
- 3) We speculate that the gas pistoning might be controlled by time-varying porosity and/or permeability in the upper portions of the lava lake, which may modulate bubble coalescence and spattering.
- 4) An outgassing “deficit” exists during non-spattering phases, and may imply gas “recycling” in the lake during these periods.
- 5) Seismic and infrasonic tremor amplitudes closely mimic outgassing trends, probably due to the intensity of spattering on the lava surface, suggesting that seismic and infrasonic tremor may be a rough proxy for gas emissions at Halema‘uma‘u and possibly other open-vent basaltic volcanoes.
- 6) Outgassing fluctuations in Halema‘uma‘u are controlled by shallow processes, internal to the lake itself, in contrast with other lakes where cyclic activity is thought to be more deeply driven.
- Our study illustrates the value of multidisciplinary monitoring for constraining the diverse aspects of open-vent activity. In particular, camera observations are vital for measuring activity on the surface (Orr and Rea, 2012), and complement the geophysical data that track changes below (seismic) and above (infrasound) the ground. The gas piston events, and spattering/non-spattering regimes, highlight the complex and unsteady nature of outgassing from basaltic systems. These observations should serve as a valuable basis for quantitative modeling of gas segregation and loss at lava lakes and other open-vent basaltic systems.

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Figure captions

Figure 1. Location of Kīlauea's summit eruption. (a) Halema'uma'u Crater is in the southwest portion of Kīlauea's summit caldera. The lava lake is contained within the Overlook crater, formed at the onset of the eruption in March 2008 and enlarging within the southeast portion of Halema'uma'u. HVO marks the location of the Hawaiian Volcano Observatory. NPT and OTL are seismic stations, yellow lines are roads. (b) Oblique aerial photograph of Halema'uma'u Crater, looking west, on May 14, 2010. The Overlook crater is filled with thick fume, and emits an outgassing plume that normally drifts southwest in the trade winds. The cameras and FTIR were positioned at the Halema'uma'u (HMM) Overlook, 85 m above the rim of the Overlook crater. (c) View of the Overlook crater from Halema'uma'u Crater rim, looking north, on June 1, 2010. The Overlook crater at this time was about 150 m wide, and the lava lake was about 140 m below the Overlook crater rim (i.e., same distance below the floor of Halema'uma'u). (d) View of the Overlook crater from Halema'uma'u Crater rim, looking northeast, on February 1, 2014, when the lake was roughly 50 m below the Overlook crater rim. The upwelling area is along the north margin of the lake, whereas the downwelling is spread across the south margin. At the southeast margin, a spattering source is commonly active and associated with the most vigorous focus of downwelling.

Figure 2. About one month of activity in late 2010. (a) Lava level shows numerous gas piston events superimposed upon a baseline lava level that began rising in mid-November. The baseline lava level tracks summit ground tilt, indicating that the long-term lava level is closely

775 tied to the pressure state of the summit magma reservoir (Patrick et al., 2015b). Each gas piston
776 event was associated with a drop (during rise and plateau phases) in (b) seismic tremor
777 amplitude, typically followed by a high-amplitude burst in tremor (during the fall phase).

778
779 **Figure 3.** An 18-hour period showing two gas piston events representative of those in late 2010.
780 (a-c) Thermal images showing lava lake level and surface activity. Lake is ~80 m diameter. (d)
781 Lava level fluctuations during the two events, with each event consisting of a rise phase, a
782 plateau phase, and a fall phase. These gas piston events interrupt normal baseline lava level. (e-
783 f) The rise and plateau phases correspond to seismic and infrasonic tremor dropping to unusually
784 low amplitudes (tremor stagnation) compared to those during normal, baseline lava level. The
785 fall phases are associated with intense spattering, corresponding to bursts of seismic and
786 infrasonic tremor. (g) The rise phases correspond to a decrease in lake surface velocity, and the
787 plateau phases also appear to be associated with lower velocities. The fall phases are associated
788 with surges in the lake velocity, as the lava surface plunges towards the intensified spatter
789 source.

790
791 **Figure 4.** Variation of gas emission with tremor. (a-c) Example shown is from September 1,
792 2013, but similar behavior was observed throughout the study period. During periods of
793 unusually low tremor (tremor stagnation), the plume becomes weak, wispy and translucent,
794 suggesting decreased gas emissions. During normal behavior, the plume is more robust,
795 suggesting higher gas emissions. Red lines show time of images. (d) Comparison of seismic
796 tremor and SO₂ emission rates for April 14, 2014, showing decreased emission during low
797 tremor (tremor stagnation). (e) Similar measurements during May 12, 2014.

798

799 **Figure 5.** Several gas piston events in late November, 2010, exhibiting changes in (a) lava level,
800 (b) downwind SO₂ concentration and (c) seismic tremor. Rise and plateau phases of a gas piston
801 event (and tremor stagnation) are associated with dramatically reduced downwind SO₂
802 concentration, implying that SO₂ emission rates plummet during these phases. Brief peaks in
803 SO₂ concentration during the fall phases suggest that a burst in SO₂ emission occurs at this time.
804 The close correspondence between SO₂ concentration (and inferred SO₂ emission) and seismic
805 tremor amplitude suggests that the tremor amplitude is closely correlated with surface outgassing
806 intensity.

807

808 **Figure 6.** Gas geochemistry for gas piston events on January 14, 2011. (a) Relative lava level
809 (b) RSAM and (c-e) gas ratios for several of the gas piston events. Elevated SO₂/CO₂ and
810 H₂O/CO₂ during fall phases contradicts a CO₂-rich gas slug mechanism and indicates average
811 exsolution depths shallower than 1 km. SO₂/HCl is consistent with an average exsolution depth
812 greater than a few tens of meters.

813

814 **Figure 7.** Typical gas piston activity in 2013-2015. The lake fluctuated between spattering (a)
815 and non-spattering (b) regimes, with gas pistoning corresponding to non-spattering phases. Gas
816 piston activity in 2013-2015 had very minor lava level changes (c), and was better identified by
817 the changes in spattering (d) and seismic (e) and infrasonic (f) tremor. Unlike 2010 when
818 significant changes in surface crust velocity were associated with tremor stagnation (Fig. 3),
819 during 2013-2015 there was no obvious changes in velocity with gas piston events (g). The lake
820 is (a-b) is about 200 m long, and 50 m below the crater rim.

Figure 8. Relation of rockfalls to gas piston. Rockfalls often impacted the lake, with larger ones triggering a very long period seismic signal (a) and subsequent gas piston (non-spattering) phase, shown by tremor stagnation (b) and lava level rise (c). During periods of summit deflation, the overall lake level would drop (e), and this was often associated with more frequent small collapses from the crater walls, and non-spattering phases (d, e) appeared to be more frequent during these phases. The gas piston (non-spattering) lava level fluctuations were superimposed on the broader baseline lava level change that correlated with tilt. RSAM is from station NPT.

Figure 9. Summary of observations and interpretation. Gas piston cycles consist of elevated lava level that may last for several hours, during which time seismic and infrasonic tremor amplitudes, SO₂ emission, plume optical thickness and nighttime glow at the crater drop to unusually low levels (well below steady, background, levels). The SO₂/CO₂ ratio also drops during high lava levels. During the fall phase of a gas piston, these indicators increase to unusually high levels briefly, before dropping to normal, steady values. We interpret this behavior in the context of outgassing behavior in the lake. During normal, steady behavior the lake is in a spattering regime, and there is both passive outgassing and spattering. During the elevated lava level of a gas piston cycle, the spattering shuts down and the lake is in a “non-spattering” regime. The intense spattering associated with the lava fall phase returns the lake to a spattering regime.

Figure 10. Conceptual model for the gas piston and spattering/non-spattering regimes. During spattering regimes, both passive outgassing (accounting for roughly a third of total SO₂ emissions) and spattering (roughly two-thirds of total SO₂ emissions) are present, with spattering representing the release of large, coalesced bubbles. During non-spattering regimes, the shutdown of spattering is associated with gas accumulation at the top of the lake, perhaps as a shallow foam, driving the rise of a gas piston. Only passive outgassing is present during non-spattering regimes. The lack of spattering in this phase reduces total SO₂ emission and also the associated tremor and SO₂/CO₂ ratio.

866 reduced RSAM (tremor stagnation). Several brief episodes (e.g., 17:18 and 20:14) of additional
867 spattering produce RSAM spikes, with the spattering carried by lake circulation towards the
868 normal spattering source location. A large episode of increased spattering around 05:50
869 produces a brief reversal in flow direction, and precedes the subsequent non-spattering phase.

Figure 1

Figure 2

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