Continuous gravity and tilt reveal anomalous pressure and density changes associated with gas pistoning within the summit lava lake at Kīlauea Volcano, Hawai‘i

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ABSTRACT

Gas piston events within the summit eruptive vent of Kīlauea Volcano, Hawaiʻi, are characterized by increases in lava level, and by decreases in seismic energy release, spattering, and degassing. During 2010–2012, gas piston events were especially well manifested, with lava level rises of tens of meters over the course of several hours, followed by a sudden drop to pre-event levels. The changes in lava level were accompanied by directly proportional changes in gravity, but ground deformation determined from tilt was anticorrelative. The small magnitude of the gravity changes, compared to the large changes in volume within the vent during gas pistons, suggests that pistoning involves the accumulation of a very low-density (100–200 kg/m^3) foam at the top of the lava column. Co-event ground tilt indicates that rise in lava level is paradoxically associated with deflation (the opposite is usually true), which can be modeled as an increase in the gas content of the magma column between the source reservoir and the surface. Gas pistoning behavior is therefore associated with not only accumulation of a shallow magmatic foam, but also more bubbles within the feeder conduit, probably due to the overall decrease in gas emissions from the lava lake during piston events.

1.0 INTRODUCTION

Since its onset on March 19, 2008, the ongoing summit eruption at Kīlauea Volcano, Hawaiʻi, has afforded unparalleled opportunities to examine the behavior of an active lava lake. One of the two largest lava lakes on Earth (Patrick et al., 2016), the lava lake within a pit in the floor of Halemaʻumaʻu Crater has been the subject of intensive multidisciplinary investigations that have taken advantage of detailed records of gas geochemistry and emissions, tephra deposition, lava level fluctuations, seismicity, and deformation. Such work has substantially elucidated knowledge of lava lake dynamics by providing insights into, for example, the mechanisms of very-low-frequency earthquakes (Patrick et al., 2011; Chouet and Dawson, 2013, 2015; Dawson and Chouet, 2014); characteristics and driving forces of small explosive eruptions (Houghton et al., 2011, 2013; Orr et al., 2013); the occurrence of gas pistoning (Nadeau et al., 2015; Patrick et al., 2016); the dynamics of bubble nucleation and resorption (Carey et al., 2012, 2013, 2015); volatile content and degassing (Mather et al., 2012; Edmonds et al., 2013); and the relation between lava lake activity and the volcano's East Rift Zone (ERZ) eruption (Patrick et al., 2015).

Kīlauea's summit lava lake is the uppermost expression of an interconnected magma plumbing system. The shallow summit magma system is known to consist of at least two reservoirs, one beneath the east margin of Halemaʻumaʻu Crater at ~1.5 km depth and with a volume on the order of 1 km^3, and another beneath the south caldera, at 3–5 km depth and with a volume on the order of 10 km^3 (Poland et al., 2014; Anderson et al., 2015). The lava lake is linked to the shallower reservoir, as indicated by seismicity as well as the coincidence of reservoir inflation/deflation with changes in lava level (Chouet and Dawson, 2013, 2015; Dawson and Chouet, 2014; Anderson et al., 2015; Patrick et al., 2016), while the deeper reservoir is connected to the ERZ eruptive vent, which has been the site of ongoing eruptive activity since 1983 (Poland et al., 2014; Orr et al., 2015). A hydraulic connection between the summit and ERZ vents via the subsurface magma storage and transport system is demonstrated by the compositional similarity of erupted products at the two sites (Rowe et al., 2015), gas compositions and emission rates (Elias and Sutton, 2012), and coincidence of changes in eruptive activity at the summit and ERZ vents (Patrick et al., 2015).

Summit eruptive activity at Kīlauea is occurring in an easily accessible area and within an existing (and readily expandable) framework of geophysical, geochemical, and geological monitoring. This has not only allowed for tracking of eruptive activity through such manifestations as deformation and seismicity, but also afforded the opportunity to deploy new instruments, like continuously recording gravimeters. Gravity has proven to be a particularly useful tool, suggesting that the upper ~100 m of the summit lava lake has a density of about 1000 kg/m^3 and is thus extremely rich in bubbles (Carbone et al., 2013; Poland and Carbone, 2016), and also providing evidence for rapid convection in the subsurface magma reservoir that feeds the lava lake (Carbone and Poland, 2012).

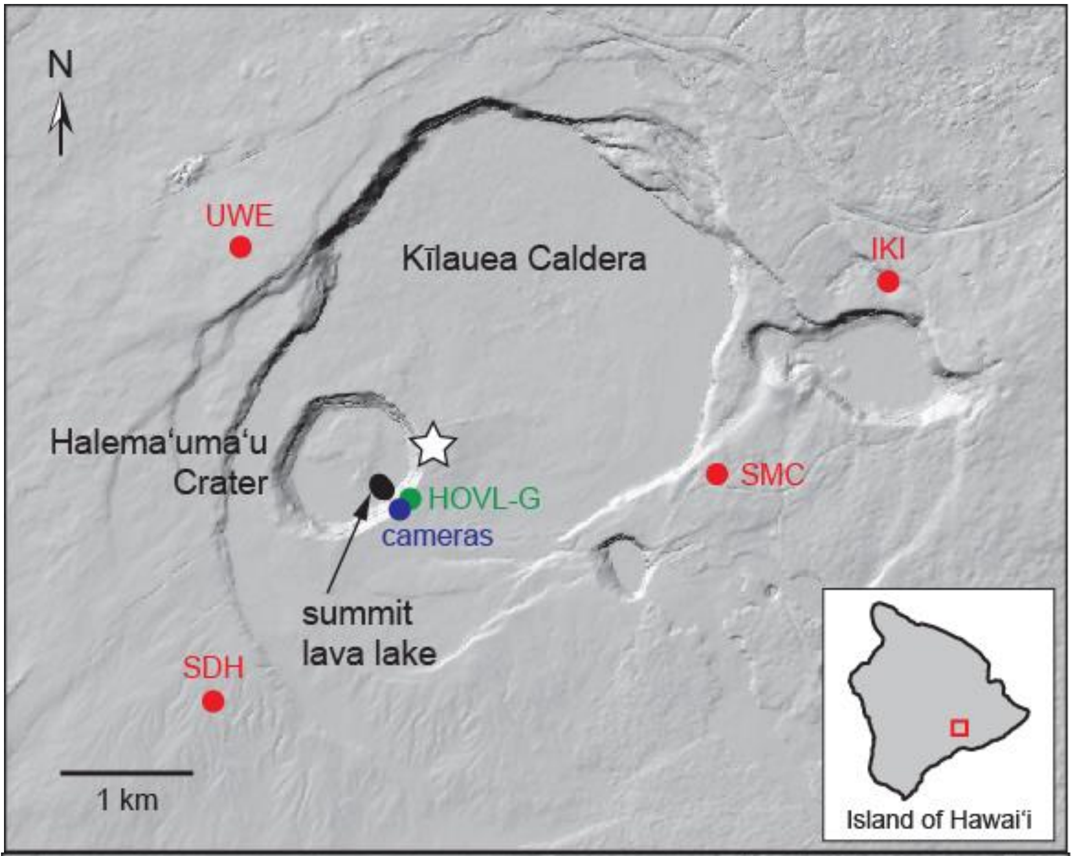
Here, we examine subtle gravity and deformation signals associated with gas pistoning events—transient, minutes- to hours-long changes in lava level and spattering activity thought to be driven by shallow gas accumulation in the upper part of the lava lake (Orr and Rea, 2012; Patrick et al., 2016)—with the goal of better understanding their driving mechanisms and accompanying physical processes. Gravity data confirm that gas pistons are associated with very low-density magmatic foams, while deformation data record what at first glance would seem to be a paradoxical anticorrelation between magma reservoir pressure and lava level. Geodetic data collected during gas pistons thus highlight the importance of volatile accumulation in both the lava lake and conduit—information that cannot be measured directly. Indeed, geodetic data offer powerful constraints on the properties and activity of the lava lake, which are important boundary conditions for models of its dynamic behavior.

2.0 DATA AND OBSERVATIONS

Our work focuses on the 2010–2011 time period, when gas piston events at Kilauea's summit lava lake were most strongly manifested by tens-of-meters change in lava level. During that period, the upper part of the lava lake had dimensions of approximately 160 × 220 m (although the vent narrowed with depth) and varied from about 60 to more than 200 m below the floor of Halemaumau Crater (Carbone et al., 2013; Patrick et al., 2015, 2016).

2.1 Geodetic and lava level data

Kīlauea's summit is host to a variety of instruments, including cameras that track lava level changes within the eruptive vent (Patrick et al., 2014), a continuously recording gravimeter on the rim of Halemaʻumaʻu Crater (Carbone and Poland, 2012), and borehole tilt stations around the caldera (Anderson et al., 2015) (Fig. 1). Gravity data used in this study were collected at a rate of 2 Hz from a site about 80 m above the floor of Halemaʻumaʻu Crater and about 150 m east of the center of the eruptive vent (green dot in Fig. 1). Although gravity measurements are influenced by instrumental drift over time, changes that occur over minutes to a few days have been shown to mostly reflect volcanic processes (Poland and Carbone, 2016). No free-air adjustments were applied to the data because the small amount of tilt associated with gas piston events (~0.1 μrad) measured at a site 2 km to the northwest of the summit vent suggests that the vertical deformation is negligible (previous studies have found that many tens of μrad of tilt at the same site correspond to only about 10 cm of vertical deformation; e.g., Poland et al., 2008; Lundgren et al., 2013). We removed the effects of Earth tides, and a first-order linear regression model was used to approximate the instrumental drift. To isolate the component of gravity that is directly related to the gas pistoning events, we applied a band-pass filter with cutoff frequencies of 0.08 and 8 mHz (corresponding to periods of between 2 and 200 min).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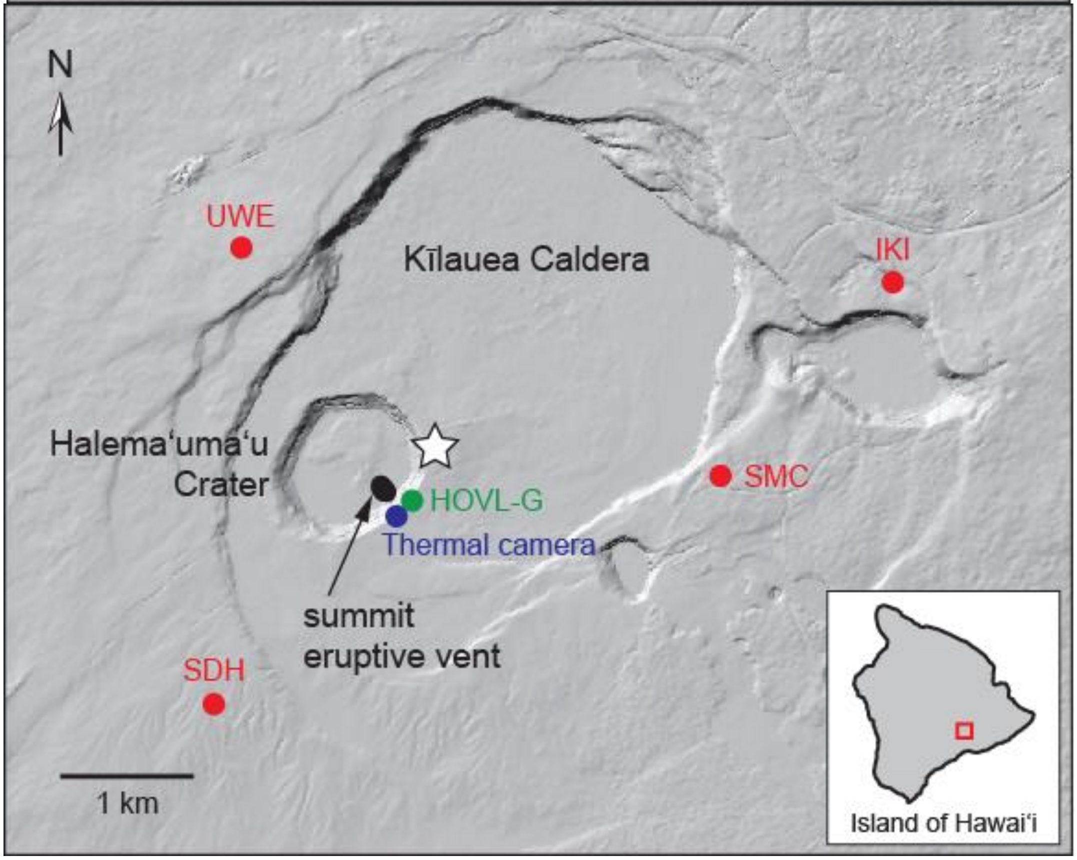
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Figure 1. Map of the summit region of Kīlauea Volcano, Hawai‘i, showing the locations of the continuous gravimeter (green dot), thermal camera used to derive lava levels (blue dot), borehole tilt stations (red dots), and the summit lava lake (black area). White star indicates location of 1.5-km-deep Halema‘uma‘u magma reservoir.

Tilt measurements, collected every 60 s, were made by a network of four borehole stations that surround the summit vent at distances of 2–4 km (red dots in Fig. 1). Like gravity, tilt data may also be subject to drift and environmental factors, but, over minutes to weeks, they provide a reliable record of ground deformation (e.g., Anderson et al., 2015).

Lava level changes were measured in images acquired by near-infrared and thermal cameras located on the rim of Halema‘uma‘u Crater just above the summit eruptive vent (blue dot in Fig. 1). Although tracking lava level automatically from camera imagery is possible (Patrick et al., 2014), better accuracy is achieved by determining the lava level by eye in individual images, which was done at approximately 2-minute intervals by M. Patrick (pers. comm., 2017).

2.2 Geodetic change associated with gas piston events

Over the course of Kīlauea’s current summit eruption, deformation, gravity change, and lava level have generally acted in concert—inflation is accompanied by gravity increase and lava level rise, and deflation with gravity decrease and lava level drop (Patrick et al., 2015; Poland and Carbone, 2016). This correlation is especially apparent during rapid lava drainage due to rift zone intrusive and eruptive activity (Carbone et al., 2013; Orr et al., 2015; Patrick et al., 2015) and hours- to days-long deflation-inflation events (Anderson et al., 2015; Patrick et al., 2015), and it suggests that lava level fluctuations are driven by pressure changes in the shallow magma reservoir that feeds the eruptive vent. Patrick et al. (2015) calculated that 1 m of lava level change was equivalent to 0.01–0.02 MPa of pressure change in the known 1.5-km-deep magma reservoir by assuming the lava lake behaves as a piezometer.

Rapid (seconds to hours) changes in lava level occur most commonly as a result of gas pistoning, and also occasionally are associated with small explosions and very-long-period earthquakes. Gas pistons are characterized by a rise in the lava surface within the vent (Fig. 2a), accompanied by a decrease in spattering activity, degassing, and seismic tremor (Fig. 2b), followed, after tens of minutes to a few hours, by an abrupt drop in lava level with increases in spattering, seismic energy, and gas emissions (Nadeau et al., 2015; Patrick et al., 2016). Pistoning appears to be a result of bubble accumulation at or near the top of the lava lake, possibly due to a transient decrease in porosity/permeability in a thin layer near the surface that traps rising bubbles beneath a largely impermeable cap (Orr and Rea, 2012; Nadeau et al., 2015; Patrick et al., 2016).

Unlike changes in lava level that last hours to days, ground tilt is anticorrelated with lava level during gas pistons (Fig. 2c). Deflationary tilt occurs as lava level rises, and tilt is inflationary (typically with a magnitude of ~0.1 μrad) during the sudden drop in lava level at the end of a gas piston. The seemingly paradoxical behavior implies that short-term changes in lava level are driven by shallow processes related to gas accumulation and release (Patrick et al., 2015).

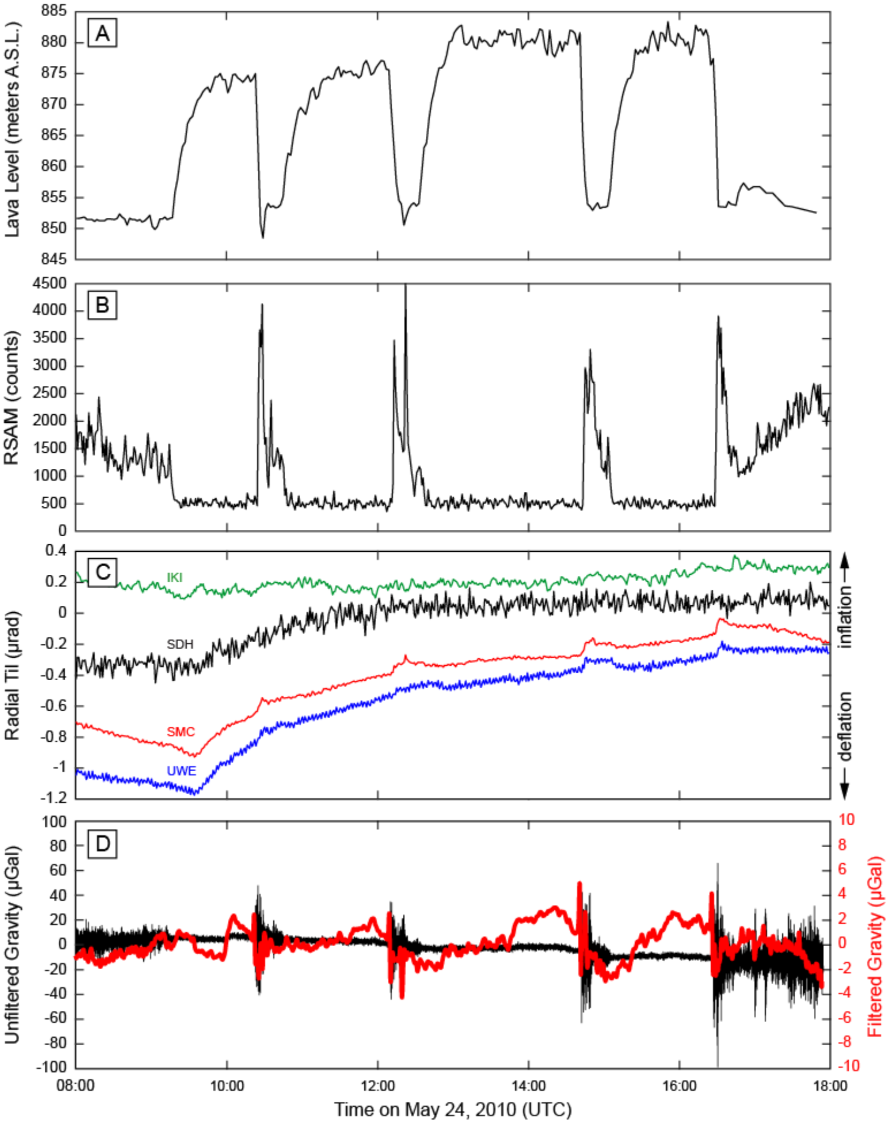

Figure 2. Manifestations of gas pistons in (A) lava level; (B) seismic tremor (expressed in terms of RSAM counts from a broadband seismometer on the northern edge of Halemaʻumaʻu Crater); (C) ground tilt (station locations given in Fig. 1); and (D) gravity (black is raw signal, and red is band-pass filtered with cutoff frequencies of 0.08 and 8 mHz and y axis 10x exaggerated for clarity).

Gas pistons generally show a direct correlation between gravity (Fig. 2d) and lava level (Fig. 2a). Rising lava level during the onset of gas pistons is not always associated with a clear change in gravity, owing to the noise inherent in the gravity time series over the minutes to hours of lava level change, but subtle gravity increases are sometimes apparent. Drops in lava level at the end of gas pistons are more obviously associated with sudden decreases in gravity, however, because that activity occurs over the course of a few minutes, over which time small changes in gravity are easier to resolve. Gravity variations are presumably due to movement of mass within the lava lake towards (gravity increase) and away from (gravity decrease) the gravimeter. The magnitudes of gravity decreases associated with the ends of gas piston events are typically 2–4 μGal (Fig. 2d).

Gas piston events in 2010 and early 2011 were characterized by particularly large changes in lava level and well manifested in the tilt and gravity record (Fig. 2). Many of these events were associated with lava level fluctuations of 20–30 meters during a time when the lava lake was about 150 m below the floor of Halemaʻumaʻu Crater (which, prior to May 2015, was at an elevation of 1023 m). By 2012, changes in lava level during gas pistons were much smaller (a few meters at most), perhaps due to the increased diameter of the lava lake as it rose within the flared conduit (Patrick et al., 2016); associated tilt and gravity changes could not be resolved. The 2010–2011 time period thus represents a unique period of Kīlauea’s summit eruption when multidisciplinary datasets can be used to track and elucidate the manifestations and mechanisms of gas piston events.

3.0 MODELING GEODETIC CHANGE ASSOCIATED WITH GAS PISTON EVENTS

3.1 Density of the fluid involved in gas piston events

We used the numerical model of Carbone et al. (2013) to constrain the density of that part of the lava lake that was changing level during gas pistoning, focusing on the end of the piston events, which are most obvious in the gravity time series. Given the low signal-to-noise ratio, we did not attempt to invert the data for a best fitting density. Instead, we forward calculated the expected gravity changes based on observed variations in lava level (Fig. 3a). Results indicate that the density of that part of the lava lake involved in gas pistoning is between 100 and 200 kg/m^3—5 to 10 times smaller than the density of the upper ~100 m of the lake inferred from gravity time series data over 2011–2015 (Poland and Carbone, 2016) and during the March 2011 lava lake draining (Carbone et al., 2013). This value is consistent over various episodes of gas pistoning, for example, May 2010 (Fig. 3a) and November 2010 (Fig. 3b) and supports the hypothesis that gas pistons are associated with the formation of a magmatic foam at the top of the lava lake (Patrick et al., 2016). Assuming an undegassed magma density of 2500 kg/m^3, the foam has a porosity of 92–96%. Such a value may seem extreme, but it is consistent with the densities of clasts ejected from the vent during explosive eruptions, which can be as low as 310 kg/m^3 (Carey et al., 2012, 2015), as well as the porosities measured in Kīlauea reticulites (Mangan and Cashman, 1996) and modeled for lunar basaltic eruptions (Wilson and Head, 2017).

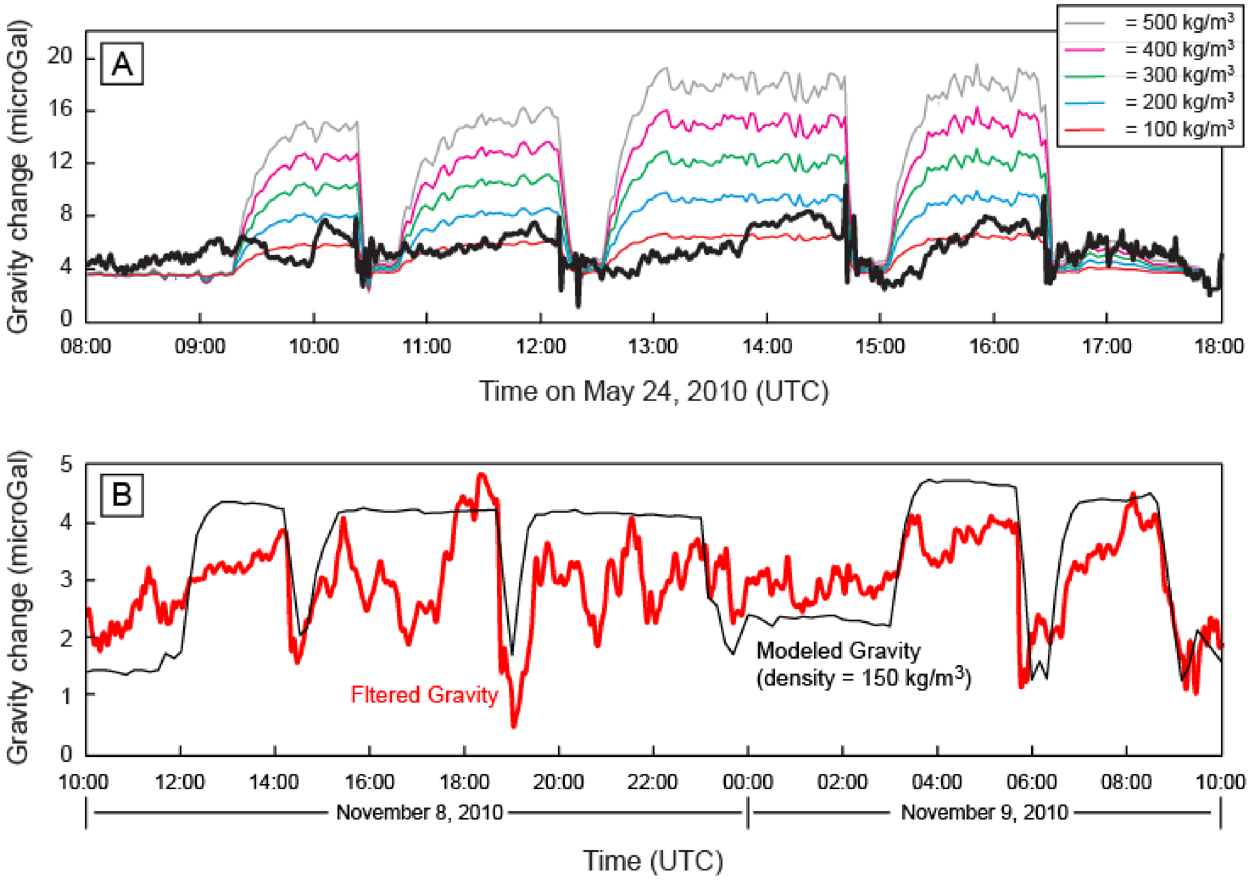

Figure 3. Observed and modeled gravity for gas piston events in May 2010 (A) and November 2010 (B). Modeled gravity change forward calculates gravity using the lava lake geometry of Carbone et al. (2013) and the observed lava level changes. The density of that portion of the lava lake that changes elevation during gas piston events appears to be between 100 and 200 kg/m^3.

3.2 The source of tilt change

The source of the tilt variations during gas pistons is difficult to constrain owing to the small magnitude of tilt and the limited number of tiltmeters in the summit region. Changes in tilt recorded at the UWE instrument, 2 km from the eruptive vent, during gas pistons were generally on the order of 0.1 μrad in 2010 and 2011. Tiltmeter SMC, located 2.5 km from the vent, also recorded fluctuations of about 0.1 μrad for the same events. Changes at SDH, 2.2 km from the vent, are suggested by trends in the data but impossible to resolve owing to higher noise and smaller signal at that instrument, and there is no detectable manifestation of the events at IKI, 4 km from the vent (Fig. 2c).

Modeling such small tilt at only a few stations is not practical, since a variety of source models and locations could fit the data. Instead, we consider the tilt signals in light of the known geometry of Kīlauea’s shallow magma plumbing system, which is relatively well constrained by geophysical data (e.g., Chouet and Dawson, 2011; Dawson and Chouet, 2014; Poland et al., 2014; Anderson et al., 2015). The source of tilt variations must either be the lava lake and its associated conduit, or the known magma storage area located about 1.5 km beneath the east margin of Halemaʻumaʻu Crater (Anderson et al., 2015). All potential sources are axisymmetric to a first order, and tilt magnitude decays with distance in all cases (except for the area in close proximity to the lava lake in an open pipe model (Lisowski, 2007), but this area is closer to the summit vent than any of the tiltmeters at Kīlauea). Source location can therefore be inferred from the relative magnitudes of the signals across the tilt network.

That tilt associated with gas pistons is most strongly manifested at UWE and SMC suggests that the source of the deformation is the ~1.5-km-deep magma reservoir (star in Fig. 1). This reservoir is closest to those two stations (about 2.1 km and 2.2 km, respectively, compared with 2.5 km to SDH and 3.6 km to IKI) and should produce the largest signal at those sites, consistent with observations (Fig. 2c). The summit vent, in contrast, is located closer to SDH, where the largest tilt signal would be expected if the tilt source was coincident with the lava lake and conduit. Indeed, the relative magnitudes of tilt at UWE, SMC, and SDH during gas piston events are similar to those of the much more strongly manifested deflation-inflation events, which also have a source in the 1.5-km-deep reservoir (Anderson et al., 2015). Transient tilt associated with gas pistons, therefore, appears to be associated with pressure fluctuations within the shallow magma reservoir that feeds the summit eruptive vent.

4.0 THE PROCESS OF GAS PISTONING

Regardless of the location of the deformation source, a fundamental question remains: why would a rise in lava level be associated with deflationary tilt that indicates a decrease in magma pressure within Kīlauea's summit magmatic system, and vice versa? Especially given that, with the exception of gas pistons, changes in lava level and deformation are correlative?

Gas piston events are hypothesized to be driven by a decrease in the porosity and/or permeability of the upper part of the lava lake, which prevents gas from escaping and thereby causes the observed decreases in spattering, degassing, and seismic tremor (Nadeau et al, 2015; Patrick et al., 2016). Accumulation of bubbles at the top of the lava lake is clearly supported by gravity data (see section 3.1); the lack of surface degassing may also result in an increase in the overall bubble volume throughout the conduit. Insight into how this condition can result in a decrease in pressure within the reservoir may be gleaned by idealizing the shallow summit magmatic system as a lava lake connected via a conduit to a reservoir at ~1.5 km depth (Fig. 4a). Under hydrostatic conditions and during non-pistoning behavior, the pressure P at the top of the reservoir is:

$$P = \rho g h \qquad (1)$$

where g is acceleration due to gravity, ρ is the height-averaged density of the material filling the conduit and lake, and h is the height of the magma column (from the base of the reservoir to the top of the lava lake). During a gas piston event (Fig. 4b), when the flux of gas out of the magma diminishes (Nadeau et al., 2015; Patrick et al., 2016), more bubbles will accumulate in the conduit. For simplicity, if we assume that these additional bubbles are concentrated in a single "slug" (the bubbles are actually distributed throughout the conduit, but can be approximated as a slug for this calculation) that occupies a portion of the conduit of length h_1, the rise in the level of lava in the lake (h_1') due to the formation of the slug will be:

$$h_1' = h_1(a/A) \qquad (2)$$

where a and A are the cross-sectional areas of the conduit and lava lake, respectively. Assuming that the density of the gas in the "slug" is negligible, the pressure at the reservoir top during a gas piston (P_{gp}) will be:

$$P_{gp} = \rho g((h-h_1)+ h_1') = \rho g(h-h_1(1-a/A)) \qquad (3)$$

Because the conduit area is much smaller than the lava lake area (i.e., $a/A << 1$) (e.g., Edmonds et al., 2013), P_{gp} must be lower than P, and deflation would occur during a gas piston event. In other words, as gas accumulates in the narrow conduit, the overall density of the conduit decreases, but the lava level rises by a disproportionately small amount because the level increase occurs over the wide area of the lava lake. Inflation accompanies the end of gas piston events as bubbles escape through the top of the lava lake, the level drops, the overall density of the conduit increases, and pressure returns to pre-event levels. The difference in pressure, ΔP, due to gas piston events is:

$$\Delta P = P - P_{gp} = \rho gh - \rho g((h-h_1)+ h_1') = \rho g(h_1 - h_1') \qquad (4)$$

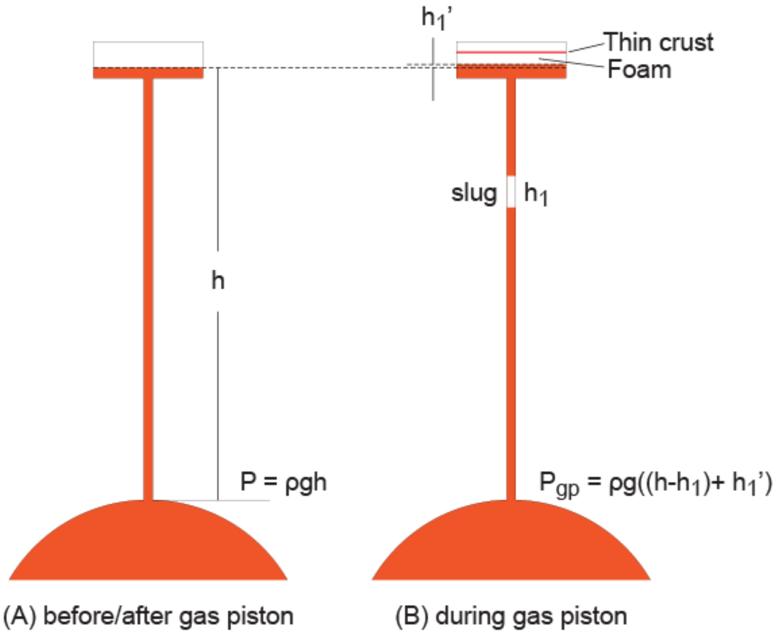

Figure 4. Conceptual model of lava levels and pressure conditions during normal (A) and gas piston (B) conditions.

Under the assumption that the Halemaʻumaʻu magma reservoir behaves as a point-pressure source (Anderson et al., 2015) and that the volume (approximated by a sphere) and depth of the reservoir are ~1 km^3 and 1.5 km, respectively (Poland et al., 2009; Anderson et al., 2015), the observed tilt changes during gas piston events (on the order of 0.1 μrad at UWE and SMC; Fig. 2c), imply a pressure change at the top of the reservoir of between 0.2 and 0.02 MPa (for a rigidity of between 3 and 30 GPa; Johnson, 1992). Through eq. (4), these pressure changes suggest that, during a gas piston event, the difference between h_1 and h_1' ranges between about 1 and 10 m, and, since $a/A << 1$, h_1' must be much smaller than that (eq. 2), probably on the order of a few to a few tens of cm. The gravity effect due to the h_1' lava level change is thus far below the resolution limit of the gravimeter, implying that the small gravity changes observed during the gas piston events are solely due to the accumulation of the magmatic foam in the uppermost part of the lava lake (Fig. 4b).

Our analysis of gravity, tilt, and lava level therefore suggests that two coupled processes accompany the onset of gas piston events, both of which are related to changes in gas flux through the summit eruptive vent: (1) accumulation of a foam layer beneath the lava lake surface, which drives the lake level upward and is associated with a very small gravity increase; and (2) overall increase of gas volume throughout the conduit, which causes (i) a negligible rise of the lava level in the lake, and (ii) a decrease in the overall density of the material in the conduit, both of which result in a decrease in the magmastatic pressure at the top of the reservoir (producing deformation that is anticorrelative with lava level).

The above observations imply that, during gas piston events, the shallow magma reservoir is reacting passively to magmastatic pressure changes in the overlying magma plumbing system. In contrast, lava level fluctuations and ground deformation during days- to weeks-long periods, including deflation-inflation events, long-term inflation/deflation, and sudden deflation with lava lake drainage due to rift zone intrusions (Anderson et al., 2015; Patrick et al., 2015), are actively driven by pressure changes in the shallow magma reservoir.

CONCLUSIONS

Subtle geodetic signals manifested in gravity and tilt time series provide important constraints on the nature of summit eruptive activity at Kīlauea Volcano, including gas pistons.

Gravity data not only confirm that gas piston events are associated with accumulation of bubbles near the top of the lava lake, but constrain the porosity of the resulting magmatic foam to be >90%. Small changes in ground tilt are the opposite of what would be expected from short-term variations in lava level during gas pistons—decreases in magma pressure within the 1.5-km-deep reservoir that feeds the summit eruptive vent occur during lava rise, and vice versa. The inverse relation between deformation and lava level is probably driven by accumulation of bubbles in the conduit that feeds the summit vent, causing a decrease in the overall density of the magma in the conduit but only a small increase in lava level, resulting in a lowering of the magmastatic pressure on the magma reservoir. Both the increase of the gas volume fraction in the conduit and the accumulation of a foam at the top of the lava lake appear to be driven by a change in permeability of the upper part of the lava lake, as hypothesized by Orr and Rea (2012), Nadeau et al. (2015), and Patrick et al (2016). The combination of high-temporal-resolution geodetic and lava level measurements clearly provides a powerful tool for elucidating shallow magmatic processes at Kīlauea.

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