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Magma degassing triggered by static decompression at Kīlauea Volcano, Hawai‘i

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[1] During mid-June 2007, the summit of Kīlauea Volcano, Hawai‘i, deflated rapidly as magma drained from the subsurface to feed an east rift zone intrusion and eruption. Coincident with the deflation, summit SO_2 emission rates rose by a factor of four before decaying to background levels over several weeks. We propose that SO_2 release was triggered by static decompression caused by magma withdrawal from Kīlauea's shallow summit reservoir. Models of the deflation suggest a pressure drop of 0.5–3 MPa, which is sufficient to trigger exsolution of the observed excess SO_2 from a relatively small volume of magma at the modeled source depth beneath Kīlauea's summit. Static decompression may also explain other episodes of deflation accompanied by heightened gas emission, including the precursory phases of Kīlauea's 2008 summit eruption. Hazards associated with unexpected volcanic gas emission argue for increased awareness of magma reservoir pressure fluctuations.

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1. Introduction

[2] Increased SO_2 emissions at active volcanoes are often interpreted as a sign of ascending magma, since this gas tends to remain dissolved in the melt at depths greater than several hundred meters [*Gerlach*, 1986]. Episodes of heightened SO_2 emission at the summit of Kīlauea Volcano, Hawai‘i, during 2007–2008, however, occurred during periods of deflation and minor earthquake activity, which are not usually considered indicative of rising magma.

[3] *Johnson* [1992] proposed that SO_2 degassing at Kīlauea is favored when magma pressure within the shallow summit reservoir is low, for example, in 1981 and 1983, when magma withdrew from the summit to feed rift zone intrusions/eruptions. Rapid deflation and an accompanying four-fold increase in summit SO_2 emissions in mid-June 2007, related to magma drainage from the summit to feed an intrusion and small eruption on Kīlauea's east rift zone (ERZ) [*Poland et al.*, 2008], provided an opportunity to test this hypothesis. Our results demonstrate that static decompression of Kīlauea's shallow reservoir with no magma ascent probably caused increased gas emission, which has implications for volcano monitoring and hazards assessment.

2. Father's Day 2007

[4] Throughout the first 20 years of the 1983–present Pu‘u ‘Ō‘ō-Kupaianaha eruption, deformation at the summit of Kīlauea (Figure 1) was dominated by deflation, with only minor fluctuations in the rate and/or style over time [*Cervelli and Miklius*, 2003]. In late 2003, however, the summit began a period of inflation as magma accumulated beneath the caldera [*Poland et al.*, 2008]. The inflation continued at varying rates until 1216 UTC on 17 June 2007 (Father's Day holiday in the USA), when sudden deflation occurred (Figure 2a) as magma drained from the summit to feed an intrusion and small eruption on the ERZ, 8 km from the summit (Figure 1). The activity, referred to as "Father's Day 2007" (FD07), ended at about 2030 UTC on 19 June when summit inflation resumed. Inflation abruptly switched to deflation on 21 July 2007, when a new eruptive vent opened on the ERZ, 19 km from the summit [*Poland et al.*, 2008]. Deflation continued throughout the rest of 2007 and 2008 (Figure 2a).

[5] An increase and subsequent decay in summit SO_2 emissions and seismic tremor also characterized FD07. SO_2 emission rates have been measured regularly at Kīlauea since 1979 [*Sutton et al.*, 2001], and background levels at the summit from 2 April to 17 June 2007 averaged 113 ± 11 tonnes/day. Background SO_2 degassing at Kīlauea's summit results from equilibration of magma within the shallow summit reservoir [*Greenland et al.*, 1985; *Gerlach and Graeber*, 1985; *Gerlach*, 1986]. Analysis of SO_2 emission and magma supply rates indicates that excess volatile components are degassed as quickly as magma is supplied to the summit reservoir [*Greenland et al.*, 1985]. During FD07, SO_2 emissions rose abruptly, peaking at 402 ± 108 tonnes/day on 19 June and decaying to background levels by 19 July (Figure 2b). Based on the background emission rate, the integrated excess SO_2 emitted during 17 June–19 July 2007 was 1560 tonnes. Seismic tremor at the summit also increased to 30–times background on 18 June before decaying to pre-FD07 levels by about 23 June. Only a minor increase in the number of located summit earthquakes occurred during FD07 (Figures 2c and 2d).

3. Decompression-Driven Volatile Exsolution

[6] Following *Johnson* [1992], we propose that the predominant cause of elevated summit tremor and SO_2 emissions during and immediately following FD07 was volatile exsolution caused by static decompression of the

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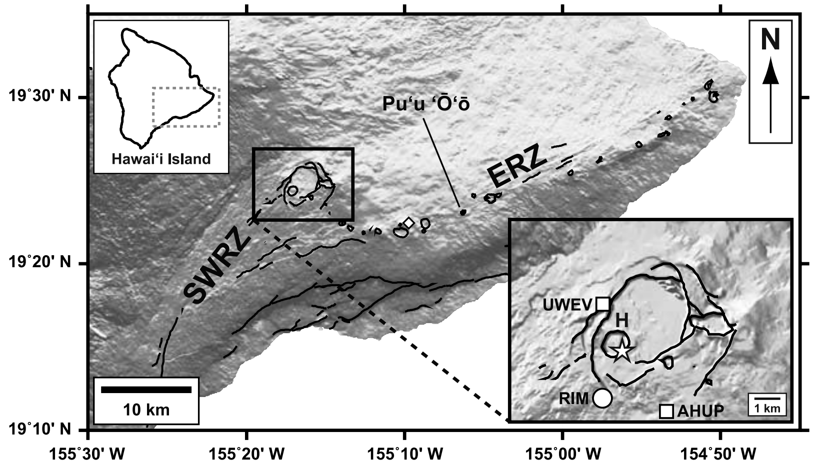

Figure 1. Location map of Kīlauea Volcano showing summit, rift zones (SWRZ, southwest rift zone; ERZ, east rift zone), and Pu‘u ‘Ō‘ō eruptive vent. White diamond gives location of FD07 eruption. Zoomed area of Kīlauea's summit includes locations of 2008 summit eruptive vent (star), GPS stations UWEV and AHUP (squares), and seismic station RIM (circle). H, Halema‘uma‘u Crater. Major faults and craters are outlined.

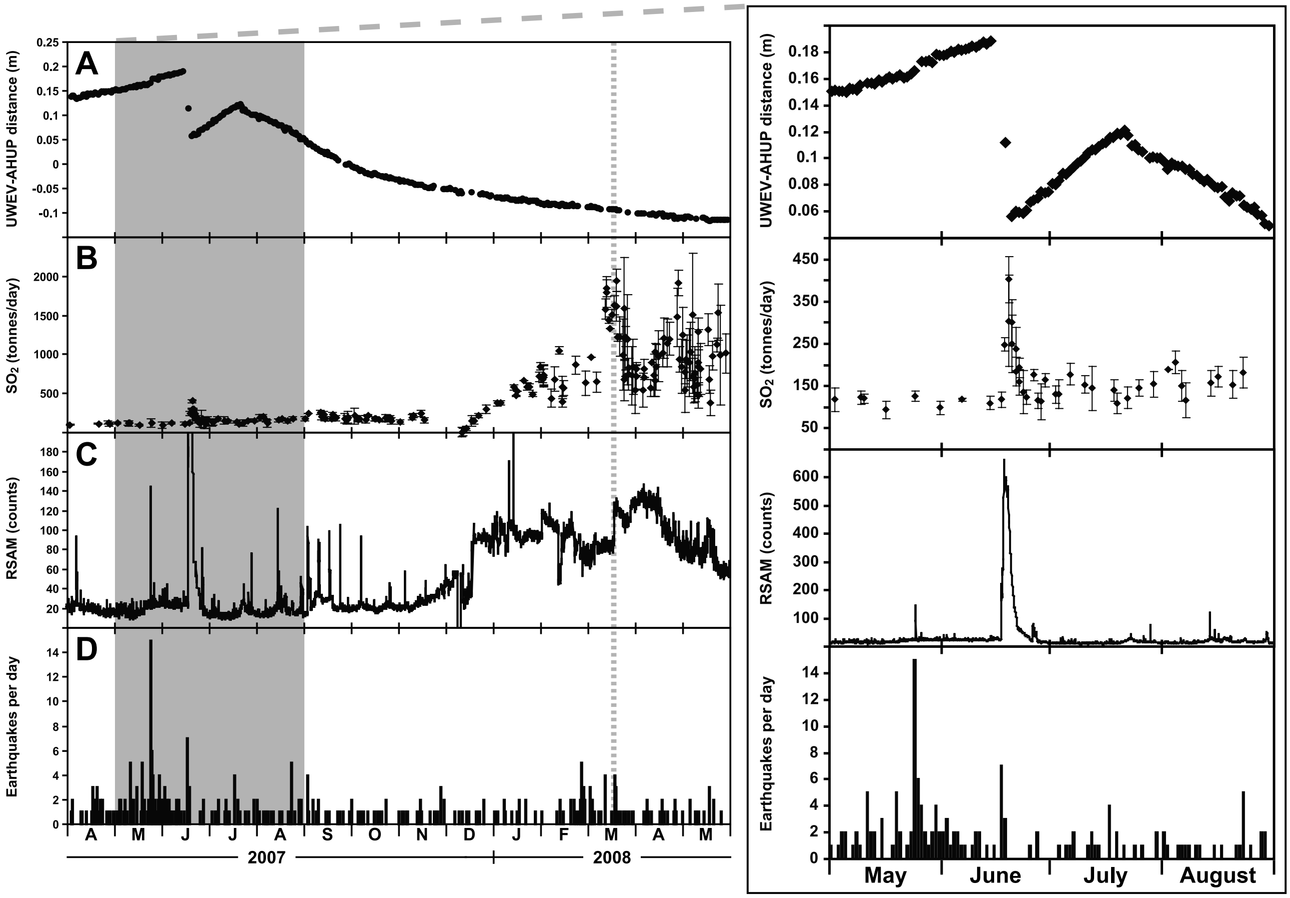

Figure 2. April 2007–June 2008 time series of (a) distance change between GPS stations UWEV and AHUP (used as a proxy for summit inflation/deflation, positive indicates inflation), (b) summit SO_2 emission rate, (c) hourly average Real-time Seismic Amplitude Measurements (RSAM) from seismic station RIM, and (d) number of located summit earthquakes per day. Grey box shows time spanned by zoomed plots (right) that give detail of FD07. Dotted line marks 19 March 2008 summit explosion. Locations of seismic and GPS stations are given in Figure 1. Spike in earthquake counts on 24 May 2007 reflects normal faulting in the upper ERZ and is not related to intrusive/eruptive activity. Decrease in SO_2 emissions and outage of seismic station RIM during December 2007 are artifacts of heavy rainfall and do not signify changes in volcanic activity.

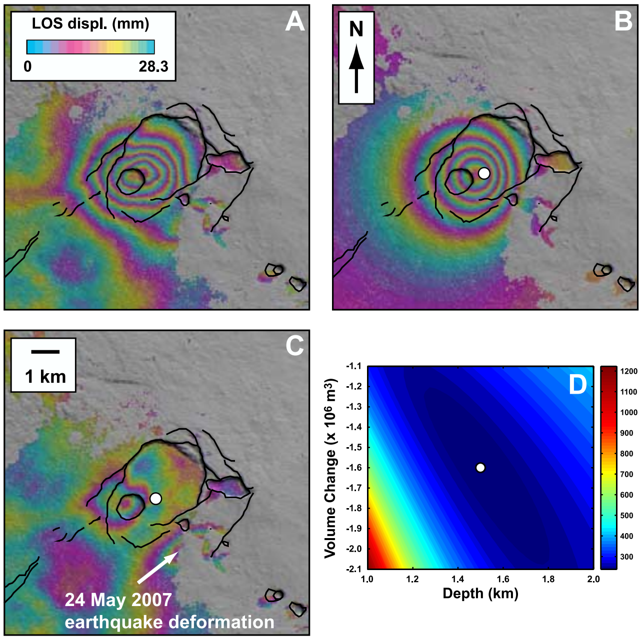

Figure 3. Model results of a point source of volume change beneath Kīlauea's summit fit to line-of-sight (LOS) displacements from an ENVISAT interferogram (beam mode 4, track 136) spanning 12 April–21 June 2007 UTC. (a) Observed LOS displacements. (b) Modeled LOS displacements. White circle shows location of best-fitting point source. (c) Residual (observed minus modeled) LOS displacements. Deformation signal southwest of the caldera is due to 24 May 2007 normal faulting event. (d) Contours of mean standard error (in mm^2) for models of different volume changes and depths. Best fit model (white circle) is at 1.5-km depth, with a volume loss of $1.6 \times 10^6\ \mathrm{m}^3$.

summit magma reservoir, with no change in magma depth. We estimated the pressure drop within Kīlauea's shallow magma reservoir by modeling satellite radar interferometry data spanning FD07. Using data acquired by the ASAR instrument on the ENVSAT satellite and a Shuttle Radar Topography mission digital elevation model [*Farr and Kobrick*, 2000], we processed a radar interferogram spanning 12 April–21 June 2007 (Figure 3a). This time period includes minimal inflation before and immediately after FD07 (Figure 2a); therefore, we attribute the deformation in the interferogram to 17–19 June 2007 deflation.

[7] A point source [*Mogi*, 1958] centered just east of Halemaʻumaʻu Crater at a depth of 1.5 km and with a volume loss of $1.6 \times 10^6\ \mathrm{m}^3$ provides a good fit to the deflation (Figures 3b and 3c). Modeled depth and volume change are highly correlated, however; the deflation can be fit by sources spanning 1.2–km depth and $1.2 \times 10^6\ \mathrm{m}^3$ volume loss to 1.8–km depth and $2.0 \times 10^6\ \mathrm{m}^3$ volume loss (Figure 3d). *Johnson* [1992] calculated a magma pressure to modeled subsurface volume change ratio of $0.43–1.66\ \mathrm{Pa/m}^3$ for source volume changes at similar magnitudes and slightly greater depths (but probably not significantly so given limitations of *Johnson*'s [1992] model depth resolution) to FD07. Applied to our range of modeled volume change for FD07 subsidence, the ratio indicates a magma pressure drop of 0.5–3 MPa.

[8] To assess whether the modeled pressure drop could result in the observed excess SO_2, we updated the S, H_2O, and CO_2 exsolution model proposed specifically for Kīlauea by *Gerlach* [1986] by calculating H_2O and CO_2 exsolution using VolatileCalc [*Newman and Lowenstern*, 2002]. This multicomponent exsolution model predicts S degassing in agreement with observations from submarine basalts at various water depths [*Gerlach*, 1986]. Starting with the melt concentrations for reservoir-equilibrated magma from *Gerlach and Graeber* [1985] (0.27 wt% H_2O, 0.02 wt % CO_2 and 0.07 wt% S), we assumed a starting magma depth and that all exsolved gas leaked away, then imposed a pressure drop on the magma (for details on depth-dependent variations of the volatile content of the melt, the composition of the gas phase, and the bubble content of the magma, see *Gerlach* [1986]). The decrease in pressure resulted in a release of mixed gases including SO_2, which we scaled up to compute the corresponding volume of magma at the starting depth required to release the 1560 tonnes of excess SO_2 measured during 17 June –19 July 2007. We conducted this procedure for pressure drops of 0.5 and 3.0 MPa and starting depths ranging from 0.2 to 2.0 km in 0.2 km increments (Figure 4), assuming average shallow overburden and magma densities of $2550\ \mathrm{kg/m}^3$ to constrain starting and ending pressure and depth (similar results are obtained at densities ranging from 2300 to $2800\ \mathrm{kg/m}^3$). Some investigations indicate that reservoir-equilibrated magma can have higher H_2O and S contents than those assumed here [e.g., *Dixon et al.*, 1991], but such results require even smaller volumes of magma (relative to our results) to account for the 1560 tonnes of SO_2 for pressure drops of 0.5 and 3.0 MPa; thus, our results represent high end-members for the volume of magma required.

[9] We neglect modeling gas transport because the tight temporal correspondence between changes in SO_2 emission rates, deformation, and tremor imply that gas transport

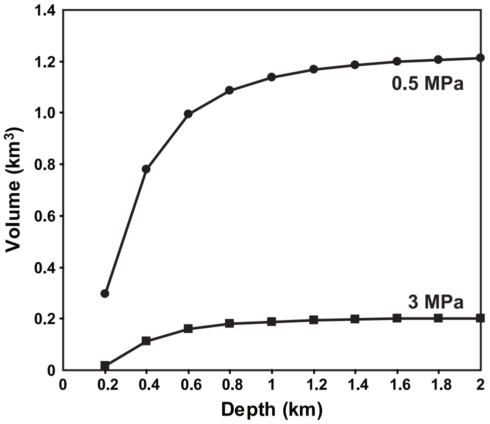

Figure 4. Combination of magma volume and depth required to generate the 1560 tonnes of excess SO_2 exsolved during 17 June–19 July 2007 based on the degassing model of *Gerlach* [1986] (which was updated using VolatileCalc [*Newman and Lowenstern*, 2002]) and assuming magma pressure drops of 0.5 and 3 MPa. For example, a magma volume of $1.1\ \mathrm{km}^3$ at a depth of 1 km must experience a pressure drop of 0.5 MPa to exsolve 1560 tonnes of SO_2. The same amount of SO_2 could also be produced by a pressure drop of 3.0 MPa in $0.2\ \mathrm{km}^3$ of magma at 1-km depth.

processes (i.e., bubble ascent, permeable gas flow, gas channel flow) were not a rate-limiting step in FD07 degassing. Degassing of SO_2 at Kīlauea's summit occurs from thousands of small fumaroles (typically $\leq 95°C$) spread over 6–7 km^2 [*Gerlach et al.*, 2002]. The fumaroles are fed by bubble transport from the magma directly into the fractured crust of the summit, leading to nearly instantaneous degassing, as indicated by past measurements of SO_2 emissions associated with volcanic events [*Greenland et al.*, 1985]. We focus, therefore, on the fundamental question of whether the exsolution capacity of a reasonable volume of magma can account for the observed SO_2 emission.

[10] The pressure/volume/depth relations in Figure 4 indicate that 1560 tonnes of SO_2 could be released by a 0.5 MPa pressure drop in about 1.2 km^3 of magma, or a 3 MPa pressure drop in about 0.2 km^3 of magma, at 1.2–1.8 km depth (above about 1 km, variations in volume between these depths are small; Figure 4). Both volumes are comparable to estimates of magma storage beneath the eastern margin of Halema'uma'u Crater, inferred by *Johnson* [1992] to be at least 1.6 km^3 on the basis of gravity and deformation data, and by *Ohminato et al.* [1998] to be about 0.5 km^3 from broadband seismic data (which images a spherical source with a radius of 0.5 km). Magma stored at shallower depths requires static decompression of even smaller volumes to produce the observed excess SO_2 (Figure 4), and geophysical evidence suggests that magma is stored as shallow as a 1 km to few hundred meters depth [*Ohminato et al.*, 1998; *Dawson et al.*, 1999; *Battaglia et al.*, 2003; *Cervelli and Miklius*, 2003]. We therefore conclude that a pressure drop with no change in magma depth can explain the increase and subsequent decay in SO_2 emissions during 17 June–19 July 2007.

[11] The decompression-triggered exsolution mechanism discussed herein requires that gas-saturated magma accumulated beneath Kīlauea's summit prior to FD07, during the 2003–2007 inflation. Because magma is compressible [e.g., *Johnson*, 1992; *Rivalta and Segall*, 2008], its accumulation caused an increase in pressure within the magma reservoir that could reasonably have suppressed exsolution of the additional magmatic SO_2; thus, no substantial changes in summit SO_2 emissions were observed during pre-FD07 inflation [*Elias and Sutton*, 2007]). Summit deflation events not preceded by increases in magma pressure would not, therefore, be accompanied by significant SO_2 emission rate increases. For example, rapid summit subsidence events in 1997 [*Owen et al.*, 2000] and 1999 [*Cervelli et al.*, 2002] were not associated with changes in summit SO_2 emissions [*Sutton et al.*, 2001; *Elias and Sutton*, 2002], probably because magma had not previously accumulated beneath the summit (indicated by long-term deflation prior to the 1997 and 1999 events [*Cervelli and Miklius*, 2003]).

4. Application to Other Events

[12] Sudden decreases in pressure within a shallow magma reservoir, with no change in magma depth, may also explain other periods of degassing associated with deflation at Kīlauea and elsewhere. Summit deflation at Kīlauea coincident with both the start of the Pu'u 'Ō'ō-Kupaianaha eruption in 1983 and intrusion into the southwest rift zone in 1981 was accompanied by increased summit SO_2 emissions [*Johnson*, 1992], and both events were preceded by magma accumulation [*Cayol et al.*, 2000]. In Japan, small phreatic explosions and a "gigantic SO_2 emission" followed caldera collapse as magma drained from beneath Miyakejima Volcano to feed a dike intrusion in 2000 [*Kazahaya et al.*, 2004]. Although *Kazahaya et al.* [2004] propose that the SO_2 emission was enhanced by development of pathways between the surface and magma reservoir, static decompression of a shallow magma reservoir due to rapid magma withdrawal might have contributed to SO_2 exsolution.

[13] The 2008 summit eruption at Kīlauea could also have been triggered, at least in part, by static depressurization-induced volatile exsolution. In late 2007, seismic tremor and SO_2 emission rates at Kīlauea's summit began to increase, rising well above background by early 2008 (Figures 2b and 2c). The activity culminated a small explosion from the east wall of Halema'uma'u Crater (star in Figure 1) on 19 March 2008 [*Wilson et al.*, 2008]. Surprisingly, the eruption occurred without the expected precursory earthquake swarms and inflation. In fact, the summit deflated prior to, and throughout, the eruption (Figure 2a) as magma drained from beneath the summit to feed the ongoing ERZ eruption. Although more complex than FD07, the 2007–2008 coincidence of heightened tremor, increased SO_2 emissions, few located earthquakes, and deflationary deformation is consistent with observations from FD07 and argues that static depressurization might have played a role in the 2008 eruption buildup.

5. Conclusions

[14] The coincidence of deflationary deformation and increased SO_2 emissions at the summit of Kīlauea Volcano during 2007–2008 suggests that static decompression is an undervalued factor contributing to shallow magma degassing. Heightened summit SO_2 emissions during and after a period of magma withdrawal in mid-June 2007 can be explained by a minor pressure drop in a reasonable volume of magma at a depth indicated by deformation models. Magma reservoir decompression may also have contributed to elevated SO_2 emissions prior to the 2008 summit eruption of Kīlauea Volcano, as well as other periods of heightened degassing and unrest at Kīlauea and elsewhere.

[15] Triggering of volatile exsolution by magma decompression has important implications for volcano monitoring and hazard mitigation. Increases in SO_2 emissions are often interpreted as a sign of ascending magma. Results from Kīlauea, however, indicate that variations in SO_2 emission rates also reflect changes in magma reservoir pressurization. Hazards posed by static decompression of a shallow magma reservoir range from low, long-term, and distributed (e.g., heightened downwind SO_2 concentrations) to extreme, short-term, and localized (e.g., volcanic explosions). Gas emissions should therefore be considered in combination with deformation and other geophysical data in monitoring and hazards analysis. Further, static decompression-triggering of SO_2 emission, and potentially small explosions, should be included in hazards assessments at basaltic volcanoes, where reservoir decompression events are most likely.

[16] **Acknowledgments.** Data presented were collected by the staff of the USGS Hawaiian Volcano Observatory. SAR images are from European Space Agency Cat-1 project 2765. Figure 1 was created using the Generic Mapping Tools (GMT) software [*Wessel and Smith*, 1998]. We are grateful for reviews and comments from Tom Sisson, Cynthia Werner, Larry Mastin, Jane Takahashi, Jim Kauahikaua, and two anonymous reviewers.

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