Shallow magma accumulation at Kīlauea Volcano, Hawai‘i, revealed by microgravity surveys

Daniel J. Johnson*, Albert A. Eggers[1], Marco Bagnardi[2†], Maurizio Battaglia[2,3], Michael P. Poland[4§], and Asta Miklius[4]
[1]Geology Department, University of Puget Sound, Tacoma, Washington 98416, USA
[2]Department of Earth Sciences, Sapienza, University of Rome, Italy
[3]Volcano Science Center, U.S. Geological Survey, Menlo Park, California 94025, USA
[4]Hawaiian Volcano Observatory, U.S. Geological Survey, Hawai‘i Volcanoes National Park, Hawaii 96718, USA

ABSTRACT

Using microgravity data collected at Kīlauea Volcano, Hawai‘i (United States), between November 1975 and January 2008, we document significant mass increase beneath the east margin of Halema‘uma‘u Crater, within Kīlauea's summit caldera. Surprisingly, there was no sustained uplift accompanying the mass accumulation. We propose that the positive gravity residual in the absence of significant uplift is indicative of magma accumulation in void space (probably a network of interconnected cracks), which may have been created when magma withdrew from the summit in response to the 29 November 1975 M = 7.2 south flank earthquake. Subsequent refilling documented by gravity represents a gradual recovery from that earthquake. A new eruptive vent opened at the summit of Kīlauea in 2008 within a few hundred meters of the positive gravity residual maximum, probably tapping the reservoir that had been accumulating magma since the 1975 earthquake.

INTRODUCTION

The use of geodetic techniques to measure the displacement of points on the surface of a volcano is well established as a means of identifying the locations and dynamics of subsurface magma reservoirs (e.g., Dzurisin, 2003). At Kīlauea Volcano, Hawai‘i (United States; Fig. 1), deformation studies have been critical to identifying zones of subsurface magma storage, magma supply to the volcano, relations between magmatism and tectonism, and changes in behavior preceding and accompanying intrusions and eruptions (e.g., Fiske and Kinoshita, 1969; Dzurisin et al., 1980, 1984; Owen et al., 2000). Deformation measurements alone, however, are sensitive only to changes in the pressure (and, by inference, volume) of a reservoir and not to changes in reservoir content. In contrast, microgravity measurements on a volcano can indicate changes in subsurface mass. The combination of deformation and microgravity data provides a powerful tool for characterizing subsurface volcanic processes (Battaglia et al., 2008).

Gravity measurements at Kīlauea directed toward monitoring changes over time have led to insights into magma reservoir dynamics and magma storage (e.g., Jachens and Eaton, 1980; Johnson, 1992; Kauahikaua and Miklius, 2003). During 1975, gravity and leveling surveys were completed just before (serendipitously) and following a M = 7.2 earthquake on 29 November on Kīlauea's south flank. Results indicated changes in maximum elevation and residual gravity (i.e., gravity change corrected for vertical displacement) at the summit of about −1.3 m and −160 μGal, respectively. The volume of magma lost (based on gravity data and assuming a reasonable magma density) exceeded the volume of summit collapse, suggesting the creation of 40–90 × 10^6 m^3 of void space due to magma drainage from beneath the summit into the east and southwest rift zones (Dzurisin et al., 1980; Jachens and Eaton, 1980). The void space was probably not contained in one area, but rather represented by a network of interconnected cracks, similar to the summit magma storage geometry suggested by Dawson et al. (1999) based on seismic data. The creation of void space due to magma withdrawal was also hypothesized by Furuya et al. (2003) at Miykejima Volcano, Japan, on the basis of gravity data.

Summit deformation at Kīlauea reflects a combination of rifting due to steady southward motion of the volcano's south flank and inflation and/or deflation of multiple magma reservoirs. Following the 1975 earthquake and until 1983, summit deformation was variable due to magma accumulation and withdrawal related to eruptive and intrusive activity (Dzurisin et al., 1984). Upon the start of the Pu‘u‘Ō‘ō-Kupaianaha eruption on Kīlauea's east rift zone (Fig. 1) in 1983, contraction and subsidence dominated at the summit, with a maximum net subsidence of ~1.5 m by 2003 (Miklius et al., 2006). The summit switched to extension and uplift in 2003 owing to an inferred increase in magma accumulation beneath the summit and reverted back to deflation and contraction in mid-2007 (Fig. 2), when a new eruptive vent formed on the east rift zone (Poland et al., 2008).

In early 2008, an explosion occurred at Kīlauea's summit, leading to the formation of a new eruptive vent, the first at Kīlauea's summit since 1982, on the east edge of Halema‘uam‘u Crater (Fig. 1; Wilson et al., 2008). The eruption continues (as of October 2010), with the vent hosting a lava column and emitting large quantities of volcanic gas and minor amounts of ash.

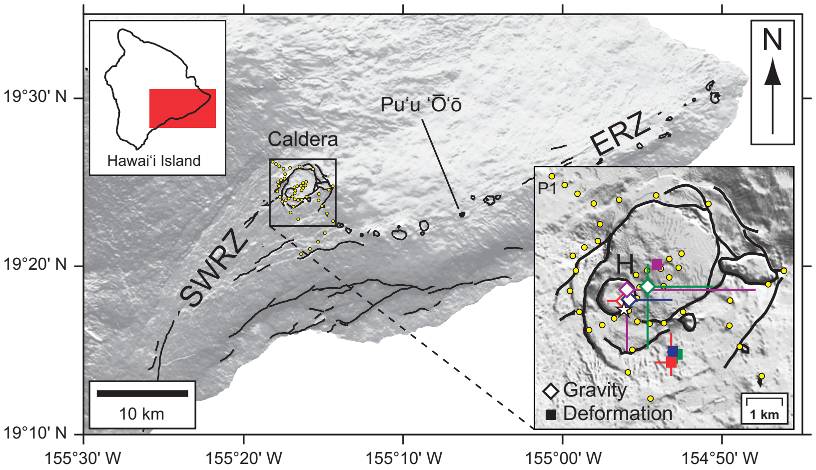

Figure 1. Location map of Kīlauea Volcano showing summit caldera, rift zones (SWRZ is southwest rift zone; ERZ is east rift zone), and Pu‘u ‘Ō‘ō eruptive vent. Inset shows Halema‘uma‘u Crater (H) and summit eruptive vent (white star) with modeled source locations to residual gravity (diamonds) and leveling (squares) data for 1975–1981 (red), 1981–1998 (green), 1998–2003 (blue), and 2003–2008 (purple). Error bars indicate one standard deviation of uncertainty. Major faults and craters are outlined. Yellow dots indicate gravity stations that were measured in 2003 and 2008; location of benchmark P1 is indicated in inset.

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*Deceased

†Current address: Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida 33149, USA.

§E-mail: mpoland@usgs.gov.

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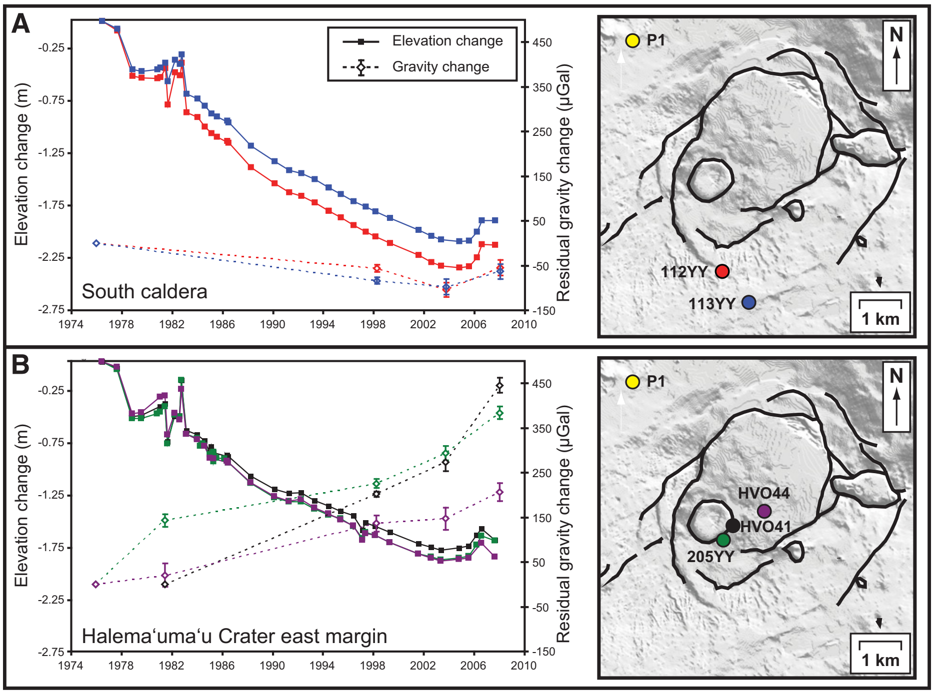

Figure 2. Vertical deformation (solid lines and boxes) and residual gravity change (dashed lines and diamonds). A: Sites located in south caldera. B: Sites located near east margin of Halemaʻumaʻu Crater. Map view is same as inset in Figure 1. Plot colors correspond to station colors on maps. Error bars indicate one standard deviation of uncertainty and are smaller than symbols for vertical deformation results. Vertical deformation and residual gravity change scales are same in both plots to highlight differences in behavior of two areas. Vertical deformation is from all leveling surveys completed between 1975 and 2008, not just those completed during gravity surveys.

GRAVITY DATA

Microgravity data were collected from a network of measurement sites around Kīlauea's summit region (Fig. 1) following the 1975 earthquake and in 1981, 1998, 2003, and 2008 (see Table 1 for specific information about each measurement campaign). All gravity measurements are relative to a benchmark (P1) located 4 km northwest of the caldera center (Figs. 1 and 2; Fig. DR1 in the GSA Data Repository[1]). P1 is assumed to be stable, although that benchmark does participate in summit deformation. The assumption of stability is justified because the rate of vertical deformation there is less than a few centimeters per year (based on leveling and global positioning system data; Delaney et al., 1998; Kauahikaua and Miklius, 2003), which would contribute a gravity signal of no more than a few tens of μGal, <10% of the maximum residual gravity anomaly. Data were collected along closed loops using five different G-model LaCoste and Romberg gravimeters (Table 1), and every station was occupied at least twice during a survey. Measurements along a calibration line spanning similar elevations as Kīlauea's summit area, but on the south flank of Mauna Loa volcano, were used to adjust for inherent calibration differences between gravimeters.

Gravity data reduction followed well-documented procedures for the removal of solid Earth tides, instrumental gravimeter drift, and tares (Jachens et al., 1981). Relative gravity measurements were averaged using a least-squares method to obtain one gravity value at each station for each survey; the average standard error for the individual surveys varied from 4 to 17 μGal (Table 1). Residual gravity change in μGal (Δg_r) at each site for each epoch was determined by $\Delta g_r = \Delta g - 308.6 \times \Delta h$, where Δg is the gravity change in μGal, Δh is the elevation change (in meters, determined by leveling surveys completed at approximately the same time as the gravity surveys), and –308.6 μGal/m is the free-air correction (LaFehr, 1991; see the Data Repository for additional information). Because the January 2008 gravity survey was not concurrent with a leveling survey, elevation changes between the 2003 and 2008 gravity surveys were determined by leveling data between 2003 and 2007, adding the vertical deformation derived from multiple look angles of interferometric synthetic aperture radar data (determined following the procedure of Yun et al., 2006) between the times of the 2007 leveling survey and 2008 gravity survey.

Variations in the height of the water table can contribute to changes in residual gravity (e.g., Battaglia and Hill, 2009). The water table at Kilauea is ~500 m beneath the surface, and drilling and resistivity data suggest only minor spatial fluctuations and no perched aquifers (J. Kauahikaua, U.S. Geological Survey, 2010, personal commun.). Water-level measurements in a deep well in the south part of Kīlauea caldera indicate that gravity changes due to the rise and fall of the water table might amount to a few tens of μGal, which is an order of magnitude less than the maximum residual gravity anomaly (for additional information, see the Data Repository); therefore, we ignore water-table variations in our analysis.

TABLE 1. GRAVITY SURVEYS AT KILAUEA'S SUMMIT 1975–2008

Date of survey	Surveyor	Meters	Measured stations	Average standard error (mGal)
December 1975	R. Jachens	G-8, G-192	45	0.010
June 1981	J. Kienle	G-248	89	0.013
April 1998	D. Johnson	G-248	65	0.004
October 2003	D. Johnson, A. Eggers	G-209, G-69	45	0.017
January 2008	A. Eggers	G-209	45	0.008

GRAVITY AND LEVELING RESULTS

Leveling and residual gravity data from Kīlauea spanning 1975–2008 reveal unexpected and contradictory results (Fig. 2; see the Data Repository). Major changes during the time period are confined to two areas: (1) the south caldera, which is a known region of long-term magma storage (e.g., Delaney et al., 1998; Cervelli and Miklius, 2003), and (2) the eastern margin of Halemaʻumaʻu Crater, which is the location of an inferred shallow (~1 km depth) magma reservoir (Dawson et al., 1999; Battaglia et al., 2003; Cervelli and Miklius, 2003).

During 1975–2003, surface motion in the summit region was dominated by subsidence, which reached a maximum in the south caldera of 2.4 m over the period. The subsidence was associated with a negative residual gravity anomaly of ~100 μGal in the south caldera (Fig. 2A; see the Data Repository), indicative of mass loss. This result is consistent with previ-

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[1] GSA Data Repository item 2010307, descriptions of analysis strategies, as well as the gravity and height change data modeled in the accompanying manuscript, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

ous studies that suggested that summit subsidence was due to a combination of subsurface volume loss, which would be accompanied by decreasing mass, and extension, which would have no significant residual gravity signature (e.g., Delaney et al., 1998; Cervelli and Miklius, 2003; Kauahikaua and Miklius, 2003). During 2003–2008, subsidence was negligible in the south caldera, although activity during that time included both inflation and deflation of several distinct subsurface magma sources (Miklius et al., 2006). Residual gravity change in the south caldera during 2003–2008 was marked by a small increase of 35–50 μGal (Fig. 2A; see the Data Repository), which is on the same order as potential water-table effects (see the Data Repository) and is therefore probably not significant. Overall, residual gravity changes in the south caldera generally track vertical deformation, as might be expected in areas that undergo magma accumulation and withdrawal.

In contrast, the east margin of Halemaʻumaʻu Crater is characterized by a positive gravity anomaly during 1975–2008, with a maximum change of almost 450 μGal over the 33 yr period (Fig. 2B; see the Data Repository). Deformation in this area is dominated by subsidence associated with south caldera deflation, so a localized residual gravity high is unexpected. Sustained positive residual gravity change throughout 1975–2008 implies mass increase beneath the east margin of Halemaʻumaʻu Crater.

DISCUSSION

Gravity and Deformation Sources

We inverted changes in residual gravity and vertical elevation from each discrete time period (i.e., 1981 relative to 1975, 1998 relative to 1981, 2003 relative to 1998, and 2008 relative to 2003) for the best-fit finite spherical source using an interior point algorithm with random grid search (Byrd et al., 1999), and we applied a bootstrap method for estimating confidence intervals on source parameters (e.g., Battaglia and Hill, 2009). While the source geometry is probably more complex, a spherical source model has been shown to be a good approximation for basaltic magma reservoirs (e.g., Cervelli and Miklius, 2003), and is certainly justified given the spatial sparseness and nonuniform distribution of gravity and leveling sites (several areas in Kīlauea's summit are completely devoid of measurement locations; Fig. 1).

Modeled source locations for both deformation and residual gravity change are remarkably consistent over the 1975–2008 period, with the locus of maximum volume change at ~2 km beneath the south caldera (squares in Figs. 1 and 3) and the source of mass change at ~1 km depth beneath the east margin of Halemaʻumaʻu Crater (diamonds in Figs. 1 and 3). The only significant deviation from this general pattern was during 2003–2008, when the modeled deformation source was located beneath the center of Kīlauea caldera (Fig. 1). This anomalous source location reflects the cumulative effects of inflation and deflation of three distinct summit magma sources, including the same south caldera source that dominated surface deformation prior to 2003 (Miklius et al., 2006; Poland et al., 2008). The deformation source model for 2003–2008 therefore does not represent a discrete source of subsurface volume change, but rather the net signal from a complex period of variable deformation. Our limited temporal and spatial resolution does not allow us to decipher short-term changes or test the possibility of models involving more than a single deformation source during any period of Kīlauea's recent history. The main source of residual gravity change, in contrast, remains consistent during all four time intervals.

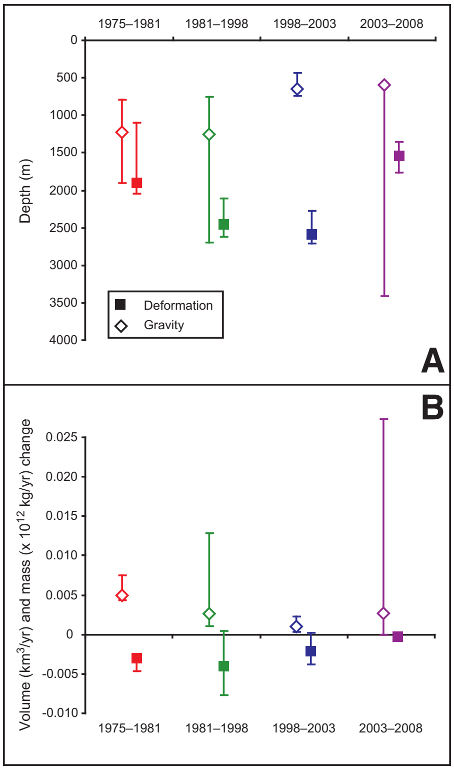

Figure 3. A: Modeled depths for residual gravity (diamonds) and deformation (squares) sources during 1975–1981 (red), 1981–1998 (green), 1998–2003 (blue), and 2003–2008 (purple). B: Volume and mass change. Depth is relative to average station elevation, which is ~1100 m above mean sea level. Mass (for residual gravity sources) and volume (for deformation sources) changes are given as annual rates to facilitate comparison, even though rates of change were probably not steady during any time period. Source parameters are given in the Data Repository (see footnote 1) and source locations are shown in Figure 1. Error bars indicate one standard deviation of uncertainty.

As suggested by the loci of maximum vertical deformation and residual gravity change, modeled source locations for deformation and residual gravity do not overlap significantly (Figs. 1 and 3), indicating an apparent contradiction: that the major deformation source beneath the summit was characterized by changes in volume but not mass, while the major residual gravity anomaly was characterized by changes in mass but not volume. The lack of a large negative residual gravity anomaly in the south caldera, where subsidence due to contraction of a source modeled at ~2 km depth reached 2.4 m during 1975–2003, implies that changes in volume beneath the south caldera were at least partially controlled by processes that do not require major mass loss. If the 1975–2003 subsidence was completely due to mass loss, the predicted residual gravity decrease at south caldera gravity stations based on the modeled source depth and volume change is ~300 μGal (assuming that the lost mass has a density of 2800 kg/m^3), 3 times greater than the 100 μGal negative anomaly observed over that period. Previous gravity investigations at Kīlauea have also concluded that subsidence of the south caldera was not associated with significant mass change (Johnson, 1992; Kauahikaua and Miklius, 2003), although we note that these studies did not extend into the area of maximum subsidence in the south caldera, or into the caldera near Halema’uma’u Crater, and instead rely on a benchmark nearly equidistant to these two source areas.

Positive residual gravity change along the east margin of Halemaʻumaʻu Crater without accompanying uplift implies that low-density material is being replaced by higher density material with minor net change in source volume. The region beneath the east rim of Halema’uma’u Crater is a known area of shallow magma storage, on the basis of both geodetic (e.g., Fiske and Kinoshita, 1969; Johnson, 1992; Cervelli and Miklius, 2003) and seismic (e.g., Ohminato et al., 1998; Dawson et al., 1999; Battaglia et al., 2003) data, and is located near the site of several historical summit eruptive vents, including that of 2008 (Wilson et al., 2008). Models of geodetic and seismic data suggest a source depth of 0.5–1 km (Battaglia et al., 2003; Cervelli and Miklius, 2003), coincident with the location and depth of our residual gravity change model. The total modeled mass accumulation beneath the east margin of Halema’uma’u Crater during 1975–2008 is 6–33 × 10^{10} kg (95% confidence bounds). The rate of mass accumulation was almost certainly variable during this time period (Fig. 2B), given the occurrence of several rift intrusions that caused drainage and subsequent refilling of this source over time scales of days to months at various times during the study interval (e.g., Poland et al., 2008), but the temporal resolution of our data is not sufficient to distinguish rate changes during 1975–2008.

Source Mechanism of Gravity Change

Mass increase of the Halema’uma’u source in the absence of notable surface deformation could be caused by at least three mechanisms: (1) replacement of magma by olivine cumulates, (2) progressive assimilation of roof rock by an upward-advancing magma body, or (3) filling of void space by magma. Replacement of magma (2800 kg/m^3) by denser olivine cumulates (3320 kg/m^3) is unlikely, as accumulation of olivine over time would require continual recirculation of fresh magma into the reservoir and would gradually fill that reservoir, causing the magma to move toward the surface and resulting in significant deformation. The residual gravity signal could be generated if ascending, high-density magma gradually assimilated and replaced lower density country rock (composed mostly of subaerially erupted vesicular lava flows), but there is no geophysical evidence to support upward migration of magma beneath the caldera.

Filling of subsurface void space by magma is the simplest and most likely mechanism of the positive residual gravity anomaly without significant uplift along the east margin of Halema’uma’u Crater. The same mechanism was also invoked by Carbone et al. (2003) to explain gravity increases without expected deformation at Mount Etna, Italy. The magma probably fills a network of interconnected cracks hypothesized to exist on the basis of seismic data (Dawson et al., 1999). The modeled mass increase during 1975–2008 (6–33 × 10^{10} kg) is equivalent to a volume of 21–120 × 10^6 m^3 (assuming a magma density of 2800 kg/m^3) and is on the same order as the void space inferred to have been created as a result of the 1975 earthquake (40–90 × 10^6 m^3; Dzurisin et al., 1980). We therefore view the 1975–2008 residual gravity increase as a refilling of space that was vacated during and following the 1975 earthquake. The onset of summit eruptive activity in 2008 may indicate that the void space was mostly filled by that time. Future gravity and deformation measurements within Kilauea caldera will test this hypothesis.

CONCLUSIONS

Gravity and deformation surveys of Kīlauea from November 1975 to January 2008 revealed a significant positive residual gravity anomaly indicative of addition of mass at a depth of no more than 1 km beneath the southeast rim of Halema’uma’u Crater. The residual gravity increase was not accompanied by significant uplift, suggesting magma accumulation in void space (probably a network of interconnected cracks) that may have been initially created by magma drainage from the summit in response to the M = 7.2, 29 November 1975, south flank earthquake. On 19 March 2008, a new eruptive vent formed at Kīlauea’s summit along the southeast margin of Halema’uma’u Crater, within 1 km of the surface projection of the Halema’uma’u residual gravity anomaly. The eruptive activity was apparently preceded by decades of magma accumulation that gradually filled void space, and that was detected by gravity measurements but unknown from deformation monitoring alone.

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REFERENCES CITED

Battaglia, M., and Hill, D.P., 2009, Analytical modeling of gravity changes and crustal deformation at volcanoes: The Long Valley caldera, California, case study: Tectonophysics, v. 471, p. 45–57, doi: 10.1016/j.tecto.2008.09.040.

Battaglia, J., Got, J., and Okubo, P.G., 2003, Location of long-period events below Kilauea Volcano using seismic amplitudes and accurate relative relocation: Journal of Geophysical Research, v. 108, 2553, 16 p., doi: 10.1029/2003JB002517.

Battaglia, M., Gottsmann, J., Carbone, D., and Fernandez, J., 2008, 4D volcano gravimetry: Geophysics, v. 73, p. WA3–WA18, doi: 10.1190/1.2977792.

Byrd, R.H., Hribar, M.E., and Nocedal, J., 1999, An interior point algorithm for large-scale nonlinear programming: SIAM Journal on Optimization, v. 9, p. 877–900, doi: 10.1137/S1052623497325107.

Carbone, D., Budetta, G., and Greco, F., 2003, Bulk processes prior to the 2001 Mount Etna eruption, highlighted through microgravity studies: Journal of Geophysical Research, v. 108, 2003, doi: 10.1029/2003JB002542.

Cervelli, P.F., and Miklius, A., 2003, The shallow magmatic system of Kilauea Volcano, *in* Heliker, C., et al., eds., The Pu`u `O`o-Kupaianaha eruption of Kilauea Volcano, Hawai`i: The first 20 years: U.S. Geological Survey Professional Paper 1676, p. 149–163.

Dawson, P.B., Chouet, B.A., Okubo, P.G., Villasenor, A., and Benz, H.M., 1999, Three-dimensional velocity structure of the Kilauea Caldera, Hawaii: Geophysical Research Letters, v. 26, p. 2805–2808, doi: 10.1029/1999GL005379.

Delaney, P.T., Denlinger, R.P., Lisowski, M., Miklius, A., Okubo, P.G., Okamura, A.T., and Sako, M.K., 1998, Volcanic spreading at Kilauea, 1976–1996: Journal of Geophysical Research, v. 103, p. 18,003–18,023, doi: 10.1029/98JB01665.

Dzurisin, D., 2003, A comprehensive approach to monitoring volcano deformation as a window on the eruption cycle: Reviews of Geophysics, v. 41, 1001, doi: 1010,1029/2001RG000107.

Dzurisin, D., Anderson, L.A., Eaton, G.P., Koyanagi, R.Y., Lipman, P.W., Lockwood, J.P., Okamura, R.T., Puniwai, G.S., Sako, M.K., and Yamashita, K.M., 1980, Geophysical observations of Kilauea Volcano, Hawaii; 2, Constraints on the magma supply during November 1975-September 1977: Journal of Volcanology and Geothermal Research, v. 7, p. 241–269, doi: 10.1016/0377-0273(80)90032-3.

Dzurisin, D., Koyanagi, R.Y., and English, T.T., 1984, Magma supply and storage at Kilauea Volcano, Hawaii, 1956–1983: Journal of Volcanology and Geothermal Research, v. 21, p. 177–206, doi: 10.1016/0377-0273(84)90022-2.

Fiske, R.S., and Kinoshita, W.T., 1969, Inflation of Kilauea Volcano prior to its 1967–1968 eruption: Science, v. 165, p. 341–349, doi: 10.1126/science.165.3891.341.

Furuya, M., Okubo, S., Sun, W., Tanaka, Y., Oikawa, J., Watanabe, H., and Maekawa, T., 2003, Spatiotemporal gravity changes at Miyakejima Volcano, Japan; caldera collapse, explosive eruptions and magma movement: Journal of Geophysical Research, v. 108, 2219, doi: 10.1029/2002JB001989.

Jachens, R.C., and Eaton, G.P., 1980, Geophysical observations of Kilauea Volcano, Hawaii; 1, Temporal gravity variations related to the 29 November, 1975, M=7.2 earthquake and associated summit collapse: Journal of Volcanology and Geothermal Research, v. 7, p. 225–240, doi: 10.1016/0377-0273(80)90031-1.

Jachens, R.C., Spydell, D.R., Pitts, G.S., Dzurisin, D., and Roberts, C.W., 1981, Temporal gravity variations at Mount St. Helens, March–May 1980, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 175–181.

Johnson, D.J., 1992, Dynamics of magma storage in the summit reservoir of Kilauea Volcano, Hawaii: Journal of Geophysical Research, v. 97, p. 1807–1820, doi: 10.1029/91JB02839.

Kauahikaua, J.P., and Miklius, A., 2003, Long-term trends in microgravity at Kilauea’s summit during the Pu’u ‘O’o-Kupaianaha eruption, *in* Heliker, C., et al., eds., The Pu`u `O`o-Kupaianaha eruption of Kilauea Volcano, Hawai`i: The first 20 years: U.S. Geological Survey Professional Paper 1676, p. 165–171.

LaFehr, T.R., 1991, Standardization in gravity reduction: Geophysics, v. 56, p. 1170–1178, doi: 10.1190/1.1443137.

Miklius, A., Poland, M., Desmarais, E., Sutton, A., Orr, T., and Okubo, P., 2006, Recent inflation of Kilauea Volcano: Eos (Transactions, American Geophysical Union), v. 87, abs. G43C–01.

Ohminato, T., Chouet, B.A., Dawson, P.B., and Kedar, S., 1998, Waveform inversion of very long period impulsive signals associated with magmatic injection beneath Kilauea Volcano, Hawaii: Journal of Geophysical Research, v. 103, p. 23,839–23,862, doi: 10.1029/98JB01122.

Owen, S., Segall, P., Lisowski, M., Miklius, A., Denlinger, R., and Sako, M., 2000, Rapid deformation of Kilauea Volcano; global positioning system measurements between 1990 and 1996: Journal of Geophysical Research, v. 105, p. 18,983–18,998, doi: 10.1029/2000JB900109.

Poland, M.P., Miklius, A., Orr, T., Sutton, A.J., Thornber, C.R., and Wilson, D., 2008, New episodes of volcanism at Kilauea Volcano, Hawaii: Eos (Transactions, American Geophysical Union), v. 89, p. 37–38, doi: 10.1029/2008EO050001.

Wilson, D., Elias, T., Orr, T., Patrick, M., Sutton, J., and Swanson, D., 2008, Small explosion from new vent at Kilauea’s summit: Eos (Transactions, American Geophysical Union), v. 89, p. 203.

Yun, S., Segall, P., and Zebker, H., 2006, Constraints on magma chamber geometry at Sierra Negra volcano, Galapagos, based on InSAR observations: Journal of Volcanology and Geothermal Research, v. 150, p. 232–243, doi: 10.1016/j.jvolgeores.2005.07.009.

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