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A mantle-driven surge in magma supply to Kīlauea Volcano during 2003–2007

Michael P. Poland[1]*, Asta Miklius[1], A. Jeff Sutton[1] and Carl R. Thornber[2]

The eruptive activity of a volcano is fundamentally controlled by the rate of magma supply. At Kīlauea Volcano, Hawai'i, the rate of magma rising from a source within Earth's mantle, through the Hawaiian hotspot, was thought to have been relatively steady in recent decades. Here we show that the magma supply to Kīlauea at least doubled during 2003–2007, resulting in dramatic changes in eruptive activity and the formation of new eruptive vents. An initial indication of the surge in supply was an increase in CO_2 emissions during 2003–2004, combined with the onset of inflation of Kīlauea's summit, measured using the Global Positioning System and interferometric synthetic aperture radar. Inflation was not limited to the summit magma reservoirs, but was recorded as far as 50 km from the summit, implying the existence of a connected magma system over that distance. We also record increases in SO_2 emissions, heightened seismicity, and compositional and temperature variations in erupted lavas. The increase in the volume of magma passing through and stored within Kīlauea, coupled with increased CO_2 emissions, indicate a mantle source for the magma surge. We suggest that magma supply from the Hawaiian hotspot can vary over timescales of years, and that CO_2 emissions could be a valuable aid for assessing variations in magma supply at Kīlauea and other volcanoes.

Determining the rate of magma supply to a volcano requires knowing the volumes of storage in subsurface reservoirs and lava erupted[1]. Magma supply rates over millions of years can be calculated from the volumes and ages of erupted products[2] or can be approximated indirectly, for example, by models of magma volume needed to sustain heat flow measured at the surface[3]. On timescales of years, magma-supply estimates are based on geochemical[4,5], geophysical[6] and eruption-rate[7] data. With near-continuous eruptive activity and long-term geological, geochemical and geophysical monitoring, Kīlauea Volcano, Hawai'i, is an ideal location to investigate magma supply to an active volcano.

Kīlauea, at the southeast front of a linear chain of volcanoes and seamounts that extends 6,000 km across the Pacific Ocean, formed as the Pacific Plate passed over a mantle melting anomaly, referred to as a hotspot. Plate motion of $\sim$9 cm yr^{-1} gradually moves each growing volcano off the hotspot and causes a new volcano to form at the front of the chain, so that the islands and seamounts increase in age toward the northwest[8]. Hawai'i is the type example of hotspot volcanism, and studies of Hawaiian volcanoes have, to a great extent, deepened our understanding of how volcanoes work[8,9].

The general model of Kīlauea's magmatic system as proposed in 1960 (ref. 9) remains largely unchanged today. Melt is generated at more than 80 km depth in the Earth's mantle and ascends through a subvertical conduit[8] to a storage area beneath Kīlauea's summit (Fig. 1; refs 8,10–13). Increasing pressure within the summit reservoirs can result in a summit eruption or transport of magma into rift zones that radiate to the east and southwest (Fig. 1), possibly leading to an eruption tens of kilometres from the summit[8].

Magmatic intrusions in the rift zones generally occur within $\sim$3 km of the surface[14–16]. Below $\sim$3 km, magma accumulation is hypothesized on the basis of surface deformation indicative of deep rift opening[17]. The base of the deep rift system is defined by a low-angle detachment fault at $\sim$10 km depth. Motion along this plane occurs through steady creep[18,19], aseismic slip events[20,21] and strong earthquakes[22], and causes seaward motion of Kīlauea's south flank.

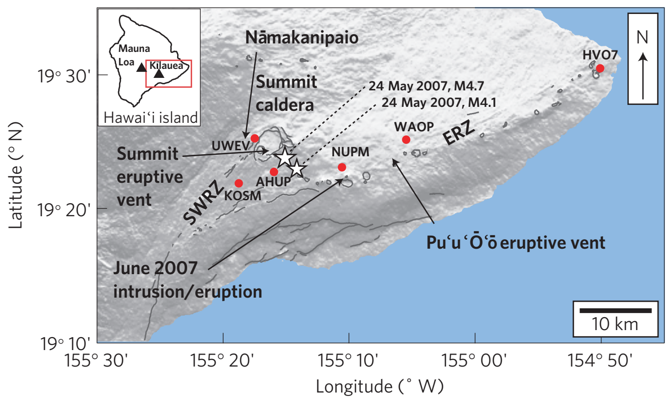

Figure 1 | Map of Kīlauea Volcano, Hawai'i. Red dots are GPS stations with data shown in Figs 2–4, and stars with dates and magnitudes are earthquakes discussed in the text. Major craters and faults are outlined, and geographic features mentioned in the text are labelled. Inset: Location of map on the Island of Hawai'i, with the summits of Kīlauea and Mauna Loa volcanoes indicated. ERZ, east rift zone; SWRZ, southwest rift zone; UWEV, KOSM, AHUP, NUPM and WAOP, GPS stations.

Magma supply to Kīlauea

The first modern estimate of the contemporary rate of magma supply to Kīlauea that accounted for volumes of both magma storage and eruption was 0.11 km^3 yr^{-1} (ref. 7; all supply rates reported are dense rock equivalent) for 1952–1971 based on the effusion rate during three long-term eruptions at times of little or no summit deformation (that is, times when all of the magma supplied to the volcano was being erupted). Since that work, numerous authors have used geophysical, geochemical and geological data to infer magma supply rates to Kīlauea for different time periods (Supplementary Table S1). Most of these studies are consistent with the original calculation, suggesting a relatively

[1]US Geological Survey—Hawaiian Volcano Observatory, PO Box 51, Hawai'i National Park, Hawai'i 96718-0051, USA, [2]US Geological Survey—Cascades Volcano Observatory, 1300 SE Cardinal Ct., Suite 100, Vancouver, Washington 98683-9589, USA. *e-mail: mpoland@usgs.gov.

constant magma supply rate since 1952 (when an 18-year period of repose ended). Minor variations in supply may be due to pulses of magma generation in the mantle source[23] or magma withdrawal from beneath Kīlauea's summit that unloads the magma plumbing system and triggers magma ascent from depth[24].

In addition to storage in reservoirs beneath the summit, magma may accumulate in Kīlauea's deep rift zones. Models of surface deformation suggest creation of ~0.06 km^3 yr^{-1} due to deep rift opening, which may be filled by magma[17–19,25]. Adding the volumes of possible deep rift storage, summit storage and eruption yields a relatively constant magma supply rate of ~0.18 km^3 yr^{-1} during 1961–1991 (ref. 25).

Surge in magma supply during 2003–2007

Geological, geophysical and gas geochemical data indicate that the magma supply rate to the shallow magmatic system (that is, not including the deep rift zones) increased by at least a factor of two during 2003–2007, before decaying to background levels by 2008 (Fig. 2). Since the start of the ongoing Puʻu ʻŌʻō–Kupaianaha eruption on Kīlauea's east rift zone (ERZ; Fig. 1) in 1983 (ref. 26) and until 2003, the mode of summit deformation was predominantly deflation (Fig. 3b; refs 12,27). The deflation was coincident with a decrease in incompatible element ratios in erupted lavas that suggests progressive flushing of resident magma in Kīlauea's plumbing system by hotter, more primitive, mantle-derived melt[28,29]. The eruption rate from the Puʻu ʻŌʻō–Kupaianaha vent system during 1983–2002 was 0.12 km^3 yr^{-1} (ref. 26), essentially the same as the magma supply rate since 1952 (Supplementary Table S1).

In late 2003, deformation at Kīlauea's summit changed to inflation (Fig. 2c), centred beneath the caldera (Fig. 3c–d). Previous periods of summit inflation during long-term ERZ eruptions were of short duration and associated with decreased effusion from ERZ eruptive vents, implying a backup in Kīlauea's magma plumbing system[30–32]. During the inflation that started in 2003, however, lava effusion rates, suggested by ERZ SO_2 emissions (Fig. 2b) and observations, did not decrease.

SO_2 gas exsolves from magma mostly within a few hundred metres of the surface[33] and, as the source composition is relatively homogeneous[23,34,35], can be used as a proxy for the amount of magma being delivered from the summit to Kīlauea's ERZ eruption site[36]. The nearly constant SO_2 emission rate through the onset of summit inflation (Fig. 2b) suggests transport of ~0.11 km^3 yr^{-1} of lava from the summit to the ERZ, so the inflation was not caused by a backup in the ERZ but instead an increase in magma supplied from depth. In early 2005, a pulse of magma from the summit to the ERZ resulted in temporary increases in SO_2 emissions and lava effusion from the Puʻu ʻŌʻō vent, accompanied by several weeks of summit deflation as magma drained to feed the effusive surge. By mid-2005, summit inflation had resumed (Figs 2c and 3d) and average SO_2 emissions had increased (Fig. 2b), indicating that ~0.18 km^3 yr^{-1} of magma were being delivered to the ERZ. The 2005 effusive surge apparently represents an adjustment that enabled the ERZ plumbing system to transport a higher magma flux from the summit to the eruption site.

Continued summit inflation following 2005 is a sign that more magma was being supplied than the ERZ conduit could accommodate. The rate of summit inflation increased rapidly in early 2006 (Fig. 2c), and uplift was centred beneath the southern part of the caldera (Fig. 3e). By mid-2006, uplift was also occurring along Kīlauea's southwest rift zone (SWRZ; Fig. 1), indicating magma accumulation in that area of the volcano as well (Fig. 2c).

We modelled the volume change in subsurface magma reservoirs during 2006—the time period of most rapid summit inflation—to estimate the quantity of magma stored beneath the summit and SWRZ. Results suggest a volume increase of about 0.01 km^3 (Supplementary Fig. S1). Combining this volume with the amount

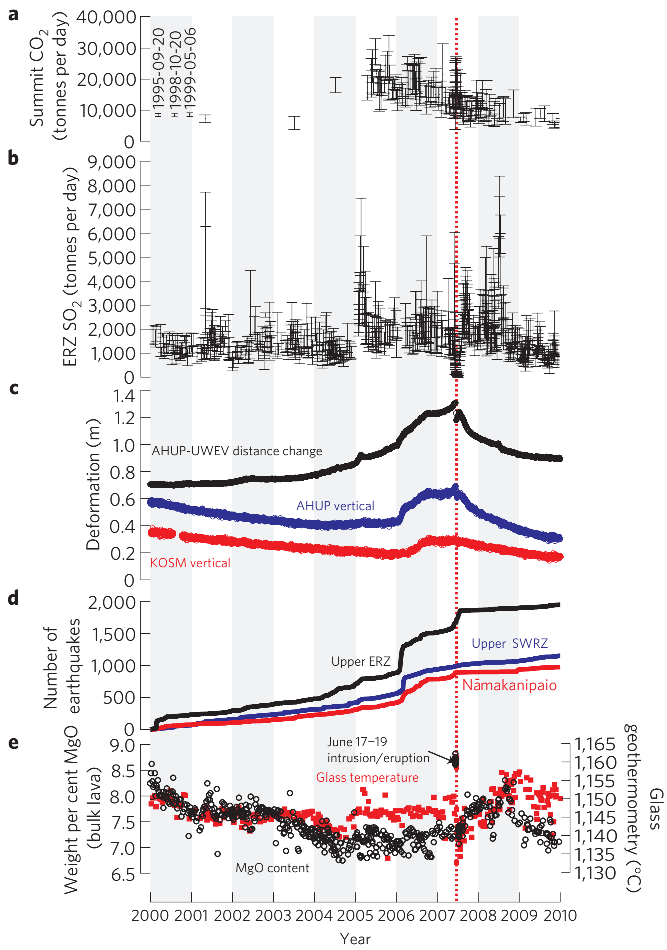

Figure 2 | Geophysical and geochemical data from Kīlauea Volcano during 2000–2009. a, Summit CO_2 emissions (error, s.d. of multiple daily measurements). **b**, ERZ SO_2 emissions (error same as for **a**). **c**, AHUP–UWEV distance change (black; positive = extension); AHUP vertical change (blue; positive = uplift); KOSM vertical change (red). **d**, Cumulative earthquakes in upper ERZ (black), upper SWRZ (blue) and Nāmakanipaio (red). **e**, MgO weight per cent and eruption temperatures of ERZ lava. The red dotted line indicates 17–19 June 2007 ERZ intrusion/eruption. Station locations and geographic areas are given in Fig. 1. Error in **c**,**e** smaller than symbols.

of magma transported from the summit to the ERZ (0.18 km^3 yr^{-1}) implies that at least 0.19 km^3 yr^{-1} of magma was being supplied to Kīlauea's shallow system in 2006—approximately twice previous estimates (Supplementary Table S1).

Our calculated supply rate is probably a minimum because of limitations in the modelling (Supplementary Information), and our treatment of magma as an incompressible fluid. In reality, magma is compressible because it contains exsolved volatiles. Our models will therefore underestimate the volume change by as much as a factor of five[37,38], implying a volume increase and supply rate of up to 0.05 km^3 and 0.23 km^3 yr^{-1}, respectively. Further, continuous Global Positioning System (GPS) measurements during 2003–2007 indicate uplift along the ERZ between the summit and about 5 km downrift of Puʻu ʻŌʻō (Fig. 4a), and campaign GPS results suggest a possible cessation of decades-long ERZ subsidence ~50 km downrift of the summit (Fig. 4b,c). Even though the last eruption in this distal part of the ERZ was in 1960, the presence of magma at shallow levels was confirmed by geothermal drill holes[39]. As there was no apparent change in the amount of deep rift opening during 2003–2007 (Supplementary Fig. S2), the downrift uplift probably represents

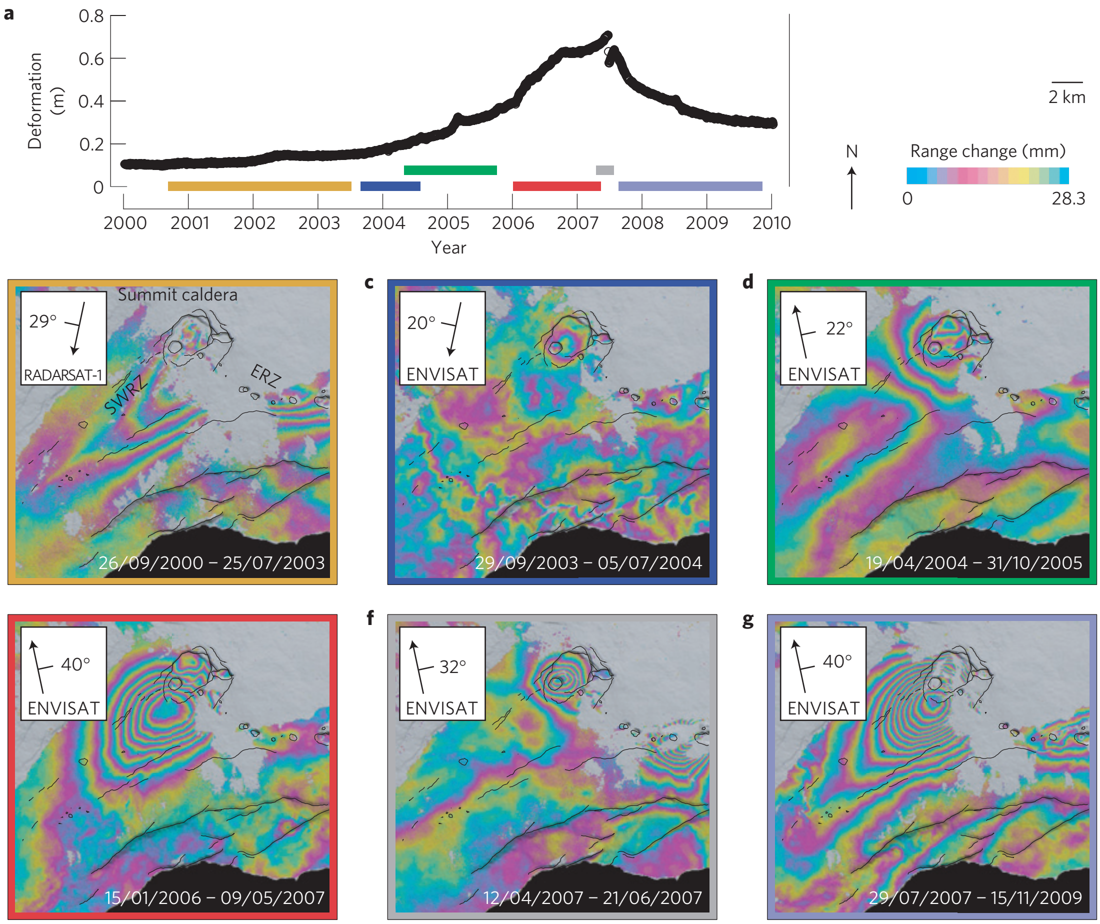

Figure 3 | Interferograms of Kīlauea's summit area. a, AHUP–UWEV GPS distance change (same as Fig. 2c). Coloured bars correspond to borders of interferograms in parts **b**–**g**. **b**, Caldera and rift-zone subsidence. One fringe is 28.3 mm of range change (positive for ground motion away from satellite). Orthogonal arrows give satellite flight/look directions. **c**, Uplift focused within caldera. **d**, Caldera-wide uplift. **e**, Uplift centred in south caldera. **f**, Caldera subsidence and ERZ uplift during 17–19 June 2008 intrusion/eruption. **g**, Subsidence centred in south caldera and upper rift zones.

magma storage within the shallow ERZ (≤3 km depth) that is not accounted for in our modelling (Supplementary Information).

Summit CO_2 emissions provide an estimate of magma supply that is independent of deformation and ERZ SO_2 emissions. The saturation depth for CO_2 is ~30 km, and nearly all CO_2 carried in magma ascending beneath Kīlauea degasses through the summit; therefore, the CO_2 emission rate is a direct indication of the magma supply rate[34,35] given consistency of the source[23]. Five intermittent measurements during 1995–2003 indicated an emission rate of about 8,000 tonnes per day, but a measurement in mid-2004 was 18,200 ± 2,500 tonnes per day (Fig. 2a). More frequent measurements began in mid-2005 and averaged ~20,000 tonnes per day for several months. The increase in CO_2 emissions began sometime between the 15 July 2003 and 16 July 2004 measurements—coincident with the onset of summit inflation[35] but months before the highest rates of summit inflation, which implies that the CO_2 ascended faster than the magma from which it exsolved.

Consequences of magma supply increase

The increase in magma supply resulted in dramatic changes in volcanic activity at Kīlauea. During 2003–2007, Kīlauea's summit extended and uplifted by 55 cm and 30 cm, respectively (Fig. 2c). Swarms of short-period earthquakes, associated with rock breakage and heightened stress in the summit region, occurred in the upper parts of the ERZ and SWRZ (that is, within 5 km of the summit), as well as in the northwest part of the caldera in the Nāmakanipaio area, in 2005–2006 (Fig. 2d). A pair of shallow (≤3 km depth) M4+ earthquakes along the outermost caldera faults on 24 May 2007 (Fig. 1) provided further indication of the critical pressure build-up within the summit magma system.

Less than a month later, on 17 June, the summit suddenly began to deflate (Figs 2c, 3f) as magma drained to feed an intrusion and small eruption between the summit and Puʻu ʻŌʻō (Fig. 1) that lasted until 19 June[40]. Some past ERZ intrusions were passive responses to rift-zone extension due to seaward motion of Kīlauea's south flank[14,15]. The 17–19 June activity, however, started with summit deflation and erupted high-temperature, high-MgO lava characteristic of freshly supplied magma (Fig. 2e), which indicates forcible intrusion driven by high magma pressure at the summit[40]. Increased compressive stress on Kīlauea's south flank due to ERZ opening during 17–19 June apparently triggered an aseismic slip event on the basal detachment fault shortly after the onset of the intrusion[41], which, in turn, may have facilitated continued shallow dike opening[16] but does not seem to have caused changes to any existing deep magma storage. A new long-term ERZ eruptive vent formed on 21 July and eventually sent lava into populated areas along Kīlauea's south coast. Summit deflation commenced at that time (Figs 2c and 3g), as more magma was erupted than was supplied to the volcano[40].

Petrologic changes in lava erupted from the ERZ are consistent with an increase in magma supply to Kīlauea. ERZ lava is a hybrid mix of high-MgO, high-temperature magma supplied from the hotspot and somewhat degassed, lower-MgO, lower-temperature resident magma that has partially crystallized owing to storage at shallow levels[28,29]. Before the magma supply surge, MgO content and lava temperature had been steadily declining from values of 9.5% and 1,168 °C in 1998 to 7–7.5% and 1,140–1,150 °C by 2003, reflecting an increase in the proportion of the lower-temperature component (Fig. 2e). In addition, the mineralogical composition of the lava changed from predominantly high-temperature olivine to a non-equilibrium assemblage of high-temperature olivine plus low-temperature clinopyroxene, olivine and plagioclase. These petrologic and mineralogic signs of shallow mixing between hotter recharge magma and shallow resident magma persisted throughout 2003–2007, indicating that cooler portions of the magma storage and transport pathways in Kīlauea's summit and ERZ were being stirred and flushed by an influx of new magma. Lavas erupted on 19 June 2007 were the hottest and most primitive since 1998 and represent the recharge-magma component. After June 2007, MgO content and temperature increased steadily until mid-2008 (Fig. 2e), suggesting that heightened magma supply introduced more of the high-temperature magmatic component to Kīlauea.

The onset of the first summit eruption at Kīlauea since 1982 may also be attributable to the magma supply surge. On 19 March 2008, a small explosion occurred from Halema'uma'u Crater within Kīlauea's caldera (Fig. 1), forming an eruptive vent that has produced persistent emissions of gas and ash, with occasional small explosive events[42,43]. The start of this eruption has been attributed to decompression of the inflated summit due to formation of the 21 July 2007 ERZ eruptive vent[44].

By the end of 2008, geological, geophysical and geochemical data indicated a return to pre-2003 rates of magma supply to Kīlauea. CO_2 emission rates, which began to decline in 2006, reached pre-2003 levels (Fig. 2a), deflation dominated the summit after formation of the new ERZ vent on 21 July 2007 (Figs 2c and 3g) and SO_2 emissions from the ERZ began dropping towards pre-2003 rates (Fig. 2b). Summit seismicity returned to background levels following the June 2007 intrusion and eruption (Fig. 2d); however, tremor levels increased in the months before the start of the 2008 summit eruption[44]. Finally, the MgO content and temperature of lava erupted from the ERZ began to decline in mid-2008 (Fig. 2e), indicating a decrease in the proportion of freshly supplied magma.

Implications of 2003–2007 magma supply surge

The increase in magma supply to Kīlauea from 2003 to 2007 started in Earth's mantle and was not triggered by pressure changes in the shallow magmatic system. The increase in CO_2 emissions indicates that the source of the magma surge was at least ~30 km beneath the surface[34], and the trend towards increasing MgO content and temperature of erupted lavas is evidence for an increasing proportion of primary magma[23]. The constant velocity of GPS stations on Kīlauea's south flank during 2000–2009 indicates that there was no change in the rate of deep rift opening (Supplementary Fig. S2), so the magma surge neither came from, nor contributed volume to, the deep rift system. All of these data suggest a pulse of magma from the mantle as the source of the supply increase.

Surface deformation during the increase in magma supply has led to new insights into the ERZ magma plumbing system. Magma accumulation within the ERZ, certainly in the vicinity of Pu'u 'Ō'ō and perhaps as far as 50 km from the summit (Fig. 4), during the supply surge suggests a hydraulic connection between the summit and the ERZ that may extend downrift of Pu'u 'Ō'ō towards populated areas. Such a connection has important implications for volcanic hazards and argues for increased geophysical monitoring of this area.

Curiously, increased magma supply may also have manifested at Mauna Loa volcano, Kīlauea's older and much larger neighbour (Fig. 1). Following nearly a decade of deflation, Mauna Loa began to inflate in 2002 (refs 31,45). The inflation rate increased more than fivefold in 2004, accompanied by a swarm of long-period

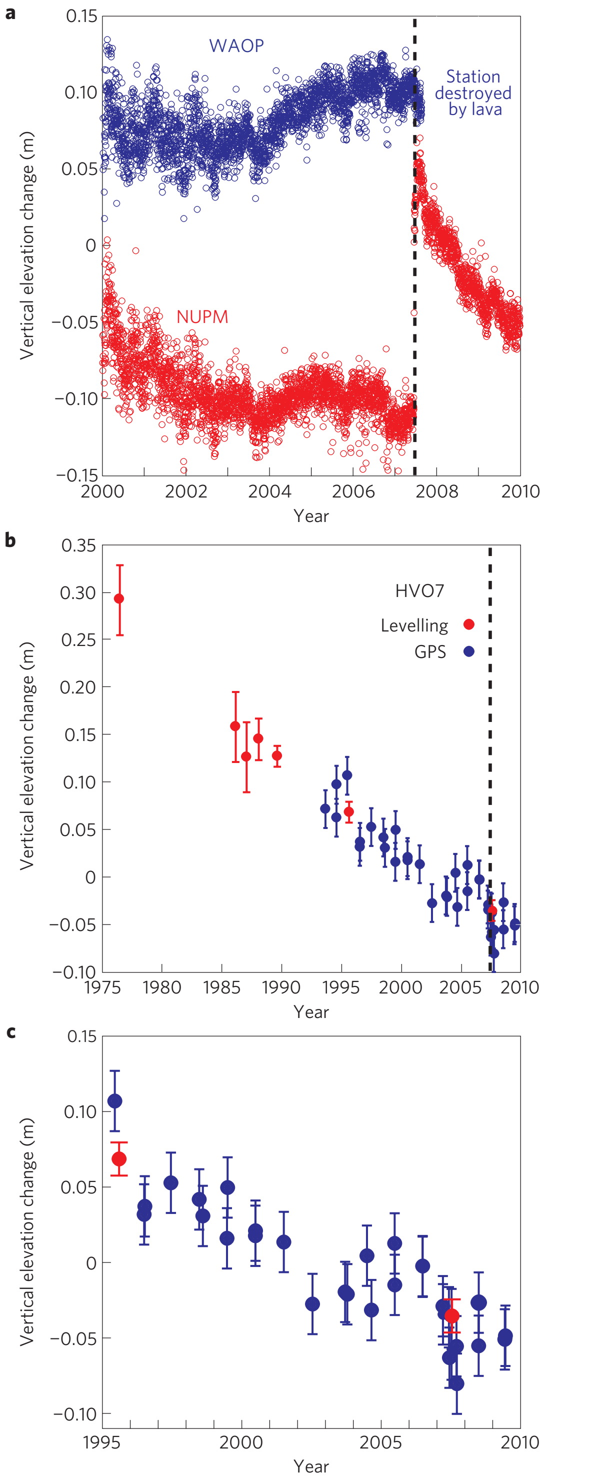

Figure 4 | Vertical deformation at sites along Kīlauea's ERZ. a, Elevation change at GPS stations NUPM (located between the summit and Pu'u 'Ō'ō) and WAOP (~5 km downrift of Pu'u 'Ō'ō) showing a transition from subsidence to uplift in late 2003. **b**, Vertical elevation change at site HVO7 from levelling and campaign GPS with 2σ error bars suggesting cessation of subsidence during the 2003–2007 magma-supply increase. Station locations are given in Fig. 1. Dashed lines indicate 17–19 June 2007 intrusion and eruption. **c**, Zoom of 1995–2010 time period from **b**.

earthquakes at more than 30 km depth[46], then gradually waned (Supplementary Fig. S3). That the bulk of Mauna Loa inflation occurred at approximately the same time as a surge in magma supply to Kīlauea (albeit with overall inflation starting earlier and lasting longer at Mauna Loa) suggests that the increase in magma supplied from the mantle affected both volcanoes. Mauna Loa lavas are isotopically distinct from those erupted at Kīlauea, indicating that the two volcanoes have different mantle source regions[47], but their common response to the magma supply surge supports the possibility raised by previous workers[48] of a shared supply.

Lessons learned

The increase in magma supply to Kīlauea during 2003–2007 was a transient phenomenon caused by a pulse of magma from the mantle that resulted in changes in volcanic activity and indicates that the supply of magma from the hotspot can vary on timescales of years. The lack of sustained changes in magma supply in the preceding 50 years (Supplementary Table S1) suggests that the increase in 2003–2007 was a relatively unusual event. Similar variations in supply have not been documented at other volcanoes during continuous eruptive activity, but monitoring should be tuned to identify such changes given the demonstrated link between magma supply and volcanism.

An especially important lesson of the supply surge to Kīlauea is the value of CO_2 emissions in tracking magma supply changes[34,35]. CO_2 emission rates at Kīlauea more than doubled about a year before increased magma supply was strongly manifested in deformation, seismicity and eruptive activity. In addition to geophysical techniques, monitoring of magma supply should include CO_2 emission rate as a diagnostic indicator. Given the elusive nature of intermediate-term (that is, months to years) indicators of potential volcanic activity[49], changes in CO_2 emission rate provide particularly valuable input in forecasting future activity.

Methods

Full details on the collection methods for deformation, seismic, gas geochemistry and petrology are included in Supplementary Information.

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Author contributions

M.P.P. processed the interferometric synthetic aperture radar data and wrote the manuscript. A.M. processed the GPS data. A.J.S. collected and analysed the gas geochemistry data. C.R.T. analysed the petrologic data. All authors discussed the data and developed the interpretations jointly.

Additional information

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Supplementary information for "A Mantle-Driven Surge in Magma Supply to Kīlauea Volcano During 2003–2007"

This supplement contains information on data collection methods, magma supply estimates for Kīlauea, deformation results from Mauna Loa and Kīlauea's south flank, and deformation modeling procedures and results.

METHODS

All data were collected by staff of the Hawaiian Volcano Observatory (HVO). Processing and analysis methods are detailed below.

Gas emissions

SO_2 emission rate data are collected with an ultraviolet spectrometer (COSPEC or FLYSPEC) during repeated vehicle-based transects beneath gas plumes from Kīlauea's summit and east rift zone (ERZ). Persistent trade winds from the northeast blow the plumes across roads 1 km and 9 km from the summit and ERZ source vents, respectively. Average transect values are combined with wind-speed data to derive emission rates, and error is calculated as the standard deviation of repeated transects. Procedures are given in [refs. 50–52].

CO_2 emissions are constrained using the SO_2 emission rate E_{SO2} and synchronously quantified volcanic CO_2-to-SO_2 molar ratio CO_2/SO_2 measured across the summit plume. The emission rate of CO_2 in tonnes per day is computed as 0.69 x $(CO_2)/(SO_2)$ E_{SO2}. Methodology is described in [ref. 34].

SO_2 emission rates from the ERZ can be used to assess the volume of magma that has degassed, which indicates the volume of magma that has been transported from the summit to the

ERZ. This calculation, based on knowledge of the CO_2/SO_2 molar ratio from eruptive gas samples from the ERZ, indicates that 1.49 kg of SO_2 is emitted per tonne of lava degassed[36].

Petrology

Samples of eruptive products, collected throughout the ongoing Puʻu ʻŌʻō-Kupaianaha eruption, generally consist of rapidly quenched near-vent tephra and spatter, and lava collected from surface flows, ponds, and tubes (through skylights). Bulk lava major-element analyses (including MgO wt. %) are obtained by wavelength dispersive x-ray fluorescence. Procedures are detailed in [refs. 28,53]. Eruption temperatures are based on geothermometry of MgO glass contents[54]. MgO content and glass temperatures generally track one another, but a noteworthy exception is the time period immediately following the June 19, 2007 ERZ eruption, when samples collected from Puʻu ʻŌʻō had some of the coolest glass temperatures during the 2000–2009 time period. This is most likely caused by a combination of two factors: 1) the samples were spatter, which tend to have lower glass temperatures than quenched molten lava, and 2) the lava erupted within Puʻu ʻŌʻō during the July 1–21, 2007, time period of lowest glass temperatures had clearly been resident beneath Puʻu ʻŌʻō (based on the low gas emissions) and was therefore cooler than if it had been transported from the summit more recently.

Seismicity

Earthquake locations were determined from data collected by seismometers of HVO's permanent network. The seismic network, data processing, and location procedures are described in [ref. 55].

Deformation

GPS data are collected by a network of continuous instruments, as well as annual (or as activity warrants) surveys of fixed benchmarks. Dual-frequency GPS data are processed using the GIPSY/OASIS II software[56] with non-fiducial orbits and a precise point positioning strategy[57]. A complete description of the GPS network and processing strategy are in [ref. 58].

The distance between GPS stations AHUP and UWEV includes a small amount of tectonic motion (a few cm/yr) because station AHUP moves seaward with the south flank[18,19]; however, this motion is minor compared to extension and contraction due to inflation and deflation of subsurface magma reservoirs during the 2003–2007 magma supply surge.

Leveling data (Fig. 4b) give elevation changes of fixed benchmarks over time. Procedures are described in [ref. 12].

Campaign GPS and leveling data indicate subsidence of benchmark HVO7 (Fig. 4b), about 50 km from Kīlauea's summit along the ERZ (Fig. 1), since the mid-1970s. The subsidence rate at this site is not a function of geothermal production at a power plant ~6.5 km to the west. The power plant came on line in 1993, and no change in the subsidence rate is apparent on or around this time, and power production has been steady. From late 2003 to mid-2007 a stalling of the subsidence is suggested by the GPS and leveling data. The coincidence of the apparent stalling of subsidence and the 2003–2007 increase in magma supply suggests that some magma may have been stored within the lower ERZ during the magma supply surge.

InSAR data are from the ASAR instrument on the ENVISAT satellite, operated by the European Space Agency, and RADARSAT-1, operated by the Canadian Space Agency. Data are processed using the GAMMA software, and topographic phase is corrected using a 30-m-resolution digital elevation model derived from the Shuttle Radar Topography Mission[59].

Coherence in resulting interferograms is improved using an adaptive filtering technique[60], and unwrapping is done using a minimum-cost approach[61].

DEFORMATION MODELING

We modeled deformation data to infer the geometry of magma sources beneath the summit and upper southwest rift zone of Kīlauea Volcano. Modeling was restricted to radar interferometry data, which offers the best spatial resolution of any technique (only 3 GPS stations were present in the summit area in 2006, so adding GPS would not significantly impact the model result). The interferogram selected for modeling is from ENVISAT beam mode 6, track 179, and spans 11 December 2005 to 31 December 2006. Data were inverted to determine the best-fitting point source[62], approximating a magma reservoir, and horizontal uniform-opening rectangular dislocation[63], approximating a sill, in an elastic, isotropic half-space. The best-fitting model (supplementary fig. 1) includes a point source 2.9 km beneath the south caldera, with a volume increase of about 0.009 km^3, and a 4.8 km x 1.2 km sill at 3.8-km depth beneath the upper SWRZ, with an opening of 0.65 m (equivalent to a volume of about 0.004 km^3). The total modeled volume increase during 2006 is therefore about 0.013 km^3.

Our modeling results are approximate for several reasons. Perhaps most importantly, we treat the magma as an incompressible fluid, which may result in an underestimate in volume change by as much as a factor of 5[37,38]. Other factors that can result in different depth and volume change estimates include model geometry (for example, an ellipsoid instead of a point source)[64,65], layering or the presence of weak materials[66,67], non-elastic rheologies[68,69], and degassing and gas ascent[70]. While important to a few factors, the effects of such variables on the calculated magma supply are of second order, since the volume of extrusion is an order of magnitude larger than the volume of storage beneath the summit and SWRZ.

DEFORMATION OF KĪLAUEA'S SOUTH FLANK

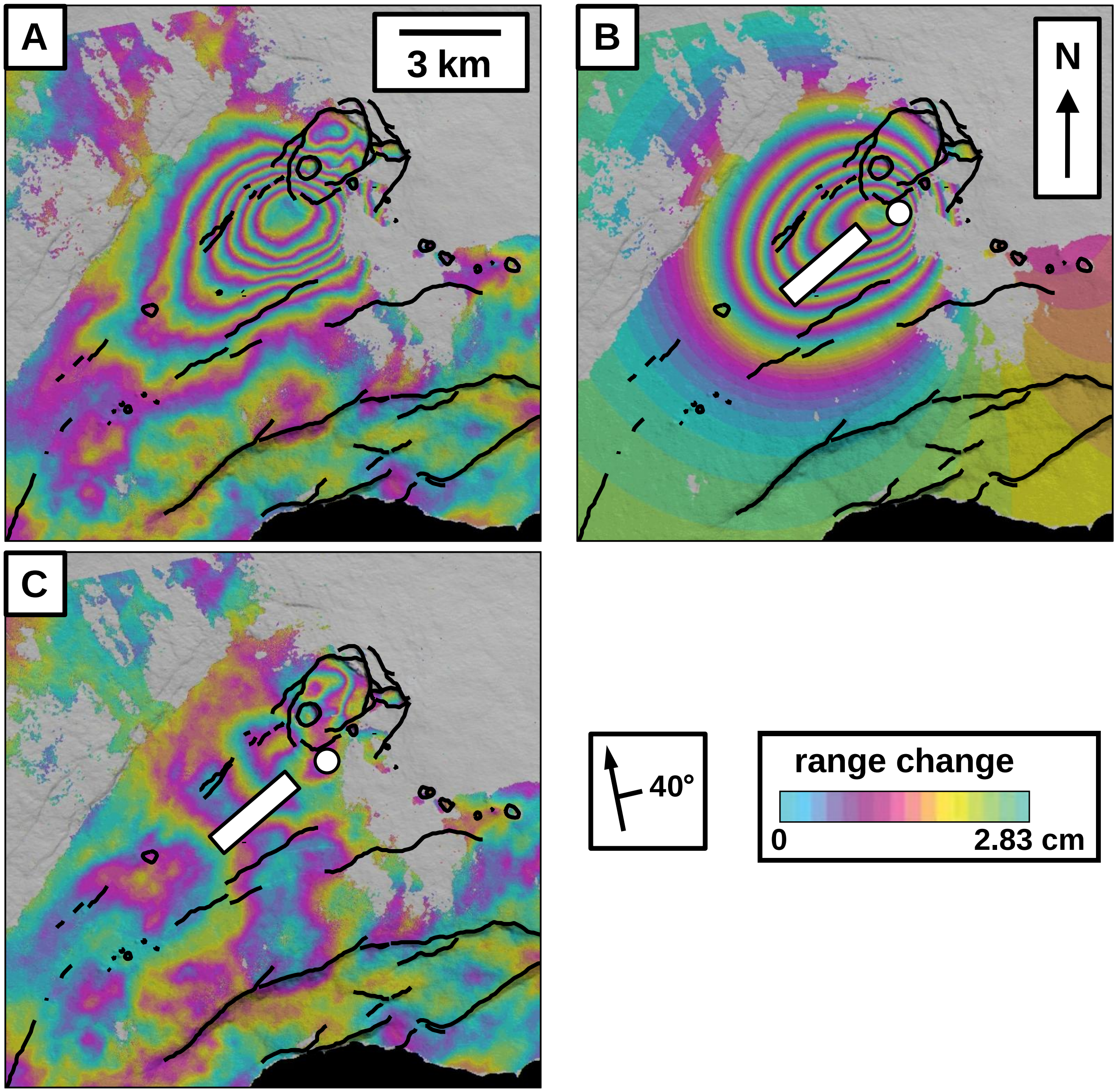
Deformation data indicate opening of Kīlauea's deep rift system between about 3-km and 10-km depth, possibly due to magma accumulation coupled with seaward sliding of the volcano's south flank along a low-angle detachment fault[17–19,71]. During 2003–2008, the rate of south flank motion remained constant (supplementary fig. 2), suggesting that magma was neither stored nor withdrawn from the deep rift zone.

DEFORMATION OF MAUNA LOA

After several years of deflation, GPS results indicated inflation of Mauna Loa volcano, starting in mid-2002[31]. The inflation rate decreased, but remained steady, from late 2002 through early 2004, increased several-fold during mid-2004 to mid-2005, waned, and changed to deflation in late 2009 (supplementary fig. 3). The time period of inflation at Mauna Loa bookends the inflation at Kīlauea, *i.e.*, the magma supply increase that affected Kīlauea was also manifested at Mauna Loa. The two volcanoes erupt isotopically distinct magmas, indicating distinct mantle sources[47], but a surge from the hotspot that feeds both volcanoes could travel through different regions of the mantle before reaching the surface.

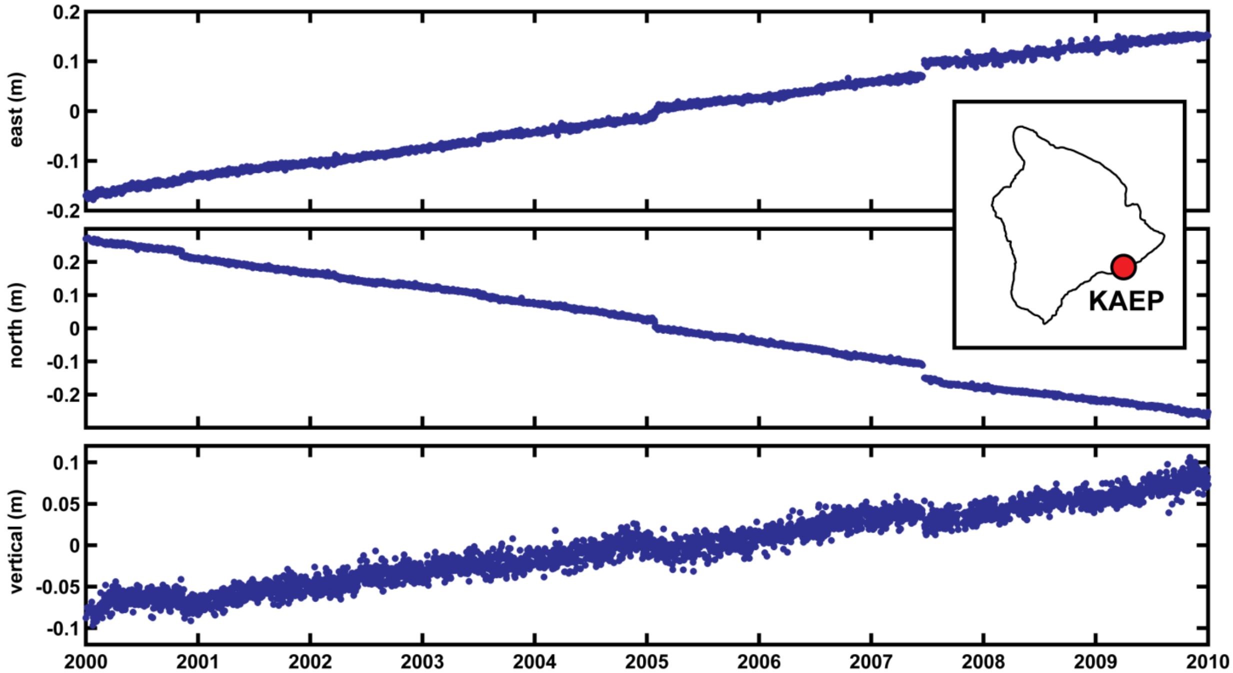
PREVIOUS ESTIMATES OF MAGMA SUPPLY TO KĪLAUEA

Since the first estimate of the contemporary magma supply rate to Kīlauea Volcano was published by Swanson[7], many authors have quantified magma supply to Kīlauea over various time periods, using different techniques. Table S1 details a selection of estimates made for magma supply to Kīlauea's shallow magmatic system (*i.e.*, magma erupted or stored in the summit and shallow rift zones). Magma supply estimates that include the deep rift zones[25] are not included; whether or not magma accumulates in this area of the volcano is uncertain, and no evidence for a change in deep rift opening was found in the current study.

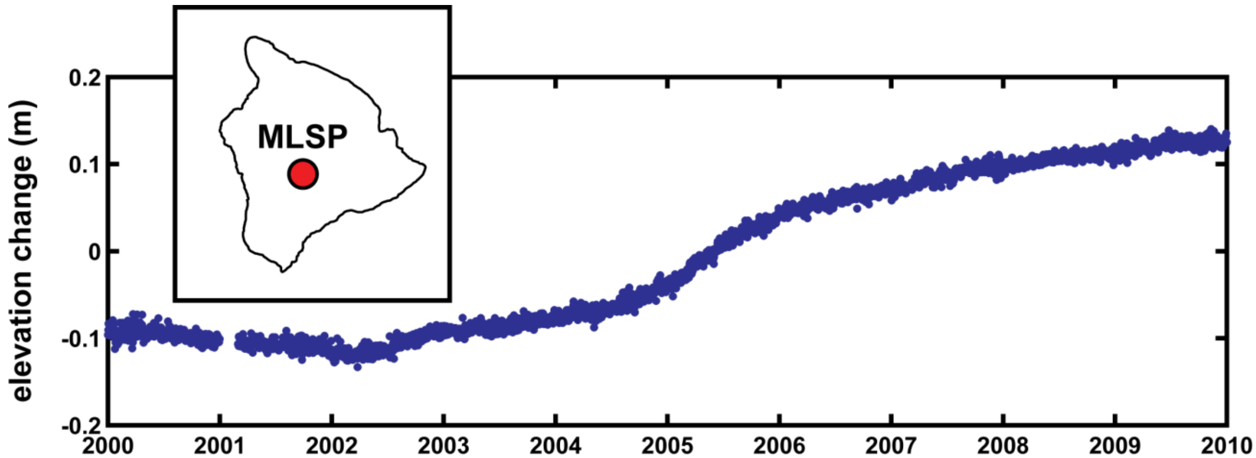


Supplementary Figure 1. Model of deformation during 2006. **a**, Line-of-sight displacements (scale bar at lower right) recorded by an ENVISAT radar interferogram (with azimuth direction to the north-northwest and an incidence angle of 40°, as indicated by the legend) spanning 15 December 2005 to 31 December 2006. **b**, Displacements predicted by a model that includes a point source[62] (white circle) beneath the south caldera at a depth of 2.9 km that expanded by

0.009 km^3, and a rectangular sill[63] (white rectangle) beneath the upper SWRZ, with dimensions of 4.8 km x 1.2 km at a depth of 3.8 km, that opened by about 0.65 m (for a volume increase of 0.004 km^3). Total volume increase in both model sources is 0.013 km^3. **c,** Residual displacements (observed minus modeled) are relatively small compared to the size of the observed signal, demonstrating that the model accounts for most of the deformation. The residual signal probably does not imply a large difference from the modeled volume change given uncertainties inherent in the modeling (see text for discussion).



Supplementary Figure 2. Deformation of Kīlauea's south flank. East (top), north (middle), and vertical (bottom) components of deformation at GPS station KAEP, which is located on the south flank of Kīlauea Volcano (location given in inset). Linear deformation suggests no change in the opening rate of the deep rift zone during 2000–2009. Small offsets in the time series are related to aseismic slip events on the south flank[20,21].



Supplementary Figure 3. Deformation of Mauna Loa. Vertical elevation change at a GPS station MLSP, located on the south side of Mauna Loa's summit caldera (location given in inset). Uplift and inflation began in 2002, accelerated in 2004–2005, and gradually waned to no deformation by the end of 2009[31,45].

Time period	Supply (km^3/yr)	Method	Reference
1918–1979	0.08	Ratio between repose times and erupted volumes	48
1919–1990	0.09	Effusion rate of several sustained eruptions	1
1952–1971	0.11	Effusion rate of three sustained eruptions	7
1956–1983	0.09	Average summit and rift deformation and eruption volumes	24
1959–1990	0.06	Average based on deformation and eruption volumes	1
1960–1967	0.02–0.18	Deformation-inferred refilling of summit reservoir	1
1966–1970	0.07	Deformation and eruption volumes	72
1967-1975	0.05–0.18	Deformation and eruption volumes	73
1971–1972	0.08	Deformation and erupted volumes	32
1975–1977	0.07–0.16	Microgravity and deformation	74
1975-1982	0.08	Deformation and erupted volumes	75
1983–1984	0.12	First 20 episodes of Pu`u `O`o eruption	76
1983–2002	0.12	Pu`u `O`o eruption volumes	26
1983–2002	0.13	SO_2 emissions from ERZ	36
1991	0.08	Deformation and effusion rates	77

Table S1. Magma supply rates to the shallow magma system of Kīlauea Volcano, as determined by previous studies. Estimates that include deep rift opening, for example, [ref. 25]. Calculated supply, time period over which the calculation was made, data used to determine supply, and reference number are given.

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VOLCANOLOGY

Opening wide the magma spigot

The supply of magma to Kīlauea Volcano was relatively stable for 50 years. But between 2003 and 2007, the volcano experienced a surge in the supply of magma from the mantle that implies short-term changes in the underlying Hawaiian hotspot.

Matthew Pritchard

The Big Island of Hawai'i is home to many tourist attractions, but the ongoing lava eruptions of Kīlauea Volcano are the most visited. The Hawaiian archipelago's six active volcanoes have been attracting scientific visitors for more than a century. They led to the creation of the Hawaiian Volcano Observatory in 1912 — the oldest of its kind in the United States and second oldest in the world. Because it is so well studied, Kīlauea is considered by many volcanologists as a type example for interpreting similar volcanism around the world and on other planets. The potential causes and consequences of variations in magma supply to Kīlauea are therefore of global interest. Writing in this issue of *Nature Geoscience*, Poland *et al.*[1] combine a variety of different volcano-monitoring techniques to show that the supply of magma to Kīlauea was approximately constant between 1952 and 2002, but then underwent a four-year surge that caused changes in the magma plumbing system.

The flux of magma to a volcano helps control the type and rate of eruptive activity. However, magma flux is tricky to measure. A long-term average eruptive rate can be estimated through measurement of the ages and volumes of lava flows and ash beds from earlier eruptions. But these volcanic deposits can be obscured by the sea or lost through erosion. Even if the volume of erupted material could be accurately determined, it would not be a complete measure of the magma flux because some of the magma that is fed into the volcano from the mantle never erupts at the surface.

Hawai'i is one of the few places on Earth where the total magma flux — magma intruded into the volcano combined with magma extruded at the surface as lava — can be approximated well in real time because the magmatic plumbing system here is relatively well known and well monitored. The ultimate source of the volcanism in Hawai'i is an area of melting in the Earth's mantle that extends at least 1,500 km below the surface[2] — part of a so-called hotspot. The Hawaiian hotspot has been active for at least 70 million years. As the Pacific plate moves above it, the hotspot has created a chain of islands that spans more than 6,000 km (ref. 3). Magma starts in the mantle and travels upwards to magma reservoirs within the summit of either Kīlauea or the neighbouring volcano, Mauna Loa (Fig. 1). In the subsurface of the volcano, the magma then flows downwards into rift zones — linear fissures that cut the flanks of the volcano and connect the subsurface magmatic plumbing system to the surface — where it can either be stored or erupt at the surface[3]. The entire southern flank of the Big Island of Hawai'i is moving away from the island towards the ocean[4], creating openings that allow magma to enter the rift zones on the flanks without first travelling through the summit reservoirs. Although the composition of the lavas erupted from Mauna Loa and Kīlauea are distinct[5], implying different source regions, there are several lines of evidence to suggest that the two volcanoes share a common magma flux[1,6].

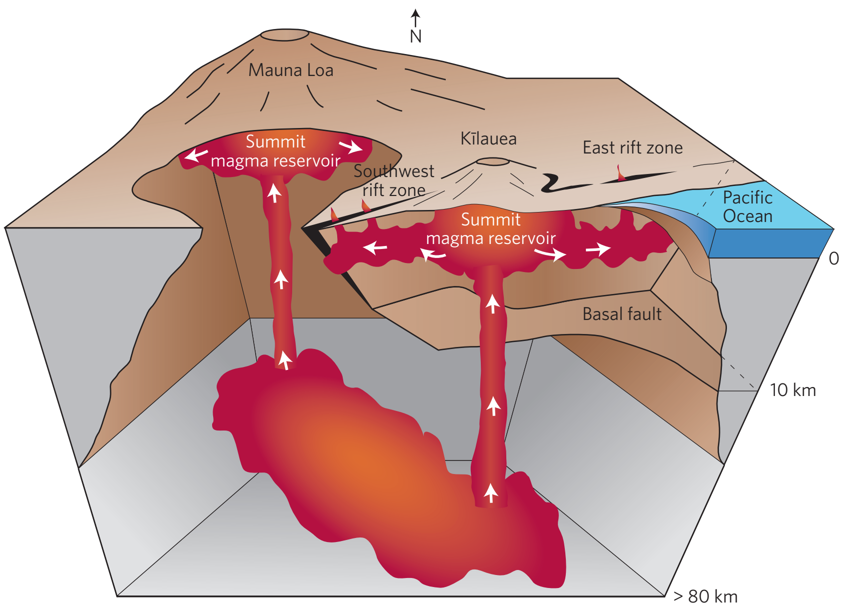

Figure 1 | The magmatic plumbing system at Kīlauea, Hawai'i. Magma (red-orange) rises from the Hawaiian hotspot, travels through a volcanic conduit to the summit of Kīlauea where it can remain, erupt, or flow down the flanks of the volcano in the subsurface. Linear fissures — rift zones — that cut through the flanks of the volcano can facilitate both magma storage and eruption. Poland *et al.*[1] use a variety of volcano-monitoring techniques to show that Kīlauea Volcano experienced a surge in magma supply from the hotspot between 2003 and 2007. Figure adapted from ref. 11.

Poland *et al.*[1] use five different types of observations to show that Kīlauea experienced a surge in magma supply between 2003 and 2007. They measure an increase in the volume of lava erupted at the surface, recorded by raised emissions of sulphur dioxide[7]. They also detect inflations and deflations of the volcanic surface, observed using satellites and ground sensors, which were caused by the magma as it moved into and out of the summit reservoirs and rift zones. Minor deformation was recorded on the southern flank of Kīlauea, implying that very little of the magma from the surge was channelled directly to the rift zones from the mantle source. Instead, most of the magma flux went through the summit reservoirs. The migration of the magma and the speed of flow were tracked by locating small earthquakes that are generated as magma moves through the rock. Finally, measurements of an increased flux of carbon dioxide, which escapes from magma while it is in the mantle at about 30 km depth, as well as inferences about the lava temperature and composition, indicate that the magma surge was sourced from the mantle.

The results indicate that after around 50 years of nearly uniform flow, the supply of magma from the mantle beneath Hawai'i changed over a timescale of just a few years. This observation is interesting in itself, but Poland *et al.*[1] further illuminate some important consequences. A new eruption at the summit of Kīlauea started in 2008 and is ongoing in 2012. The study shows that the volcano summit and the easternmost extent of the Kīlauea rift zone 50 km away share a hydraulic connection. Thus, some of the magma flowing to the summit could move over large distances near populated areas. The entire volcanic system, including the Pu'u 'Ō'ō eruptive vent on the East Rift Zone, should therefore be monitored to mitigate the volcanic hazard. Furthermore, the neighbouring Mauna Loa volcano also experienced an injection of magma, the first in about 20 years, around May 2002[8]. Thus, there could also be some interconnection between Kīlauea and Mauna Loa, the two most active Hawaiian volcanoes in recent centuries.

It is unclear why the flux of magma from the Hawaiian hotspot to Kīlauea increased in 2003. Future work will search for detailed geochemical variations in the magmas[9] that could indicate whether the increased flux was due to a temporary change in the temperature or compositional structure of the mantle hotspot that is otherwise difficult to probe.

Importantly, the observed increase in carbon dioxide flux occurred about one year before the other manifestations of the increased magma flux, such as the increased emissions of sulphur dioxide, seismicity, surface deformation and lava temperatures. In the future, it is possible that measurements of carbon dioxide flux could be used as a predictive tool of changing magma flux and impending volcanic hazards.

Poland *et al.*[1] show that Kīlauea Volcano experienced a sudden surge in magma supply after 50 years of almost constant flux. Kīlauea has been continually erupting for almost 30 years and the characteristics of its eruption have changed frequently. These findings will inspire researchers, and possibly students, to investigate the beautiful and sometimes surprising behaviour of erupting volcanoes further — some of the data are available online in near-real time[10]. ❐

Matthew Pritchard is in the Department of Earth and Atmospheric Sciences, Snee Hall, Cornell University, Ithaca, New York 14850, USA.
e-mail: pritchard@cornell.edu

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PALAEOCLIMATE

Fossils from above

Despite only faint light from the young Sun, the early Earth enjoyed fairly equable climates. These balmy temperatures could be explained by extremely high levels of carbon dioxide and other greenhouse gases. Measurements of carbon isotopes in 2.7-billion-year-old palaeosols, however, suggest that the carbon dioxide concentrations would only have been high enough to maintain a temperate climate if the atmospheric nitrogen concentration was twice that of today's levels.

The nitrogen hypothesis is attractive, but without any measurements of atmospheric pressure during the Archaean eon, it remains speculative. Sanjoy Som of the University of Washington, Seattle, and colleagues (*Nature* http://dx.doi.org/10.1038/nature10890; 2012) propose that fossilized raindrop imprints allow a reconstruction of ancient atmospheric pressure from the rock record. They identified raindrop imprints in a layer of 2.7-billion-year-old volcanic tuff found near Prieska, South Africa.

The size of a raindrop is independent of atmospheric pressure. However,

the terminal velocity of the raindrop is controlled by air density, and thus can provide bounds on atmospheric pressure. The team experimented on two different types of volcanic ash — the precursor to tuff — to identify the relationship between raindrop terminal velocity and the imprint left. Using the assumption that rain during the Archaean followed the same size distribution as modern rainfall, they find that the absolute upper limit of air density is 2.3 kg m^{-3}, sufficient for the nitrogen hypothesis to be plausible.

However, the most probable estimate for Archaean air density is less than 1.1 kg m^{-3}, similar to modern values, a pressure that precludes a nitrogen-enhanced efficacy of greenhouse gases. These atmospheric pressure values also rule out exceedingly high concentrations of carbon dioxide. There are, of course, other ways to explain Archaean warmth. A hazy atmosphere consisting of the greenhouse gas methane and fractal hydrocarbons would allow ammonia — a potent greenhouse gas — to persist in quantities sufficient to promote warming (*Science* **328,** 1266–1268; 2010). The search is on for other greenhouse gases that, although readily broken down in today's oxygenated atmosphere, may have been stable under more reducing conditions.

Identifying the components of the atmosphere billions of years ago is challenging, at best. And so it seems that despite decades of scientific effort, the faint young Sun paradox may remain just that for the foreseeable future.

ALICIA NEWTON