LETTERS
PUBLISHED ONLINE: 21 OCTOBER 2012 | DOI: 10.1038/NGEO1612
nature geoscience

Coupling at Mauna Loa and Kīlauea by stress transfer in an asthenospheric melt layer

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The eruptive activity at the neighbouring Hawaiian volcanoes, Kīlauea and Mauna Loa, is thought to be linked[1–3], despite both having separate lithospheric magmatic plumbing systems. Over the past century, activity at the two volcanoes has been anti-correlated, which could reflect a competition for the same magma supply[1,2]. Yet, during the past decade Kīlauea and Mauna Loa have inflated simultaneously[3]. Linked activity between adjacent volcanoes in general remains controversial[4–6]. Here we present a numerical model for the dynamical interaction between Kīlauea and Mauna Loa, where both volcanoes are coupled by pore-pressure diffusion, occurring within a common, asthenospheric magma supply system. The model is constrained by measurements of gas emission rates[7,8], indicative of eruptive activity, and it is calibrated to match geodetic measurements of surface deformation at both volcanoes, inferred to reflect changes in shallow magma storage. Although an increase in the asthenospheric magma supply can cause simultaneous inflation of Kīlauea and Mauna Loa, we find that eruptive activity at one volcano may inhibit eruptions of the adjacent volcano, if there is no concurrent increase in magma supply. We conclude that dynamic stress transfer by asthenospheric pore pressure is a viable mechanism for volcano coupling at Hawai‘i, and perhaps for adjacent volcanoes elsewhere.

An understanding of the processes responsible for the spatiotemporal distribution of volcanic activity is of global significance (Fig. 1). Its relevance was illustrated recently by the eruption of Ejyafjallajökull Volcano, Iceland, and associated speculation about the increased likelihood of a subsequent and related eruption at nearby Katla Volcano[9]. Global analyses indicate that the number of eruptions at volcanoes spaced closer than 200 km and erupting within days of each other increases significantly (approximately 4 standard deviations above the average)[4,5]. This is commonly attributed to stress transfer due to earthquakes or aseismic fault displacements[10], and requires that both volcanoes are in a critical state and primed for activity[5]. Global positioning system (GPS) records for Mauna Loa and Kīlauea (see Methods), which are located within a distance of a few tens of kilometres from each other, reveal that Kīlauea, which was actively erupting, and Mauna Loa, which has not erupted since 1984, inflated concurrently during the past decade. This raises the questions of whether and how both volcanoes might be dynamically connected[1–3], and if an eruption of Mauna Loa could be more likely in the near future.

Volcanism in Hawai‘i is the consequence of hot upwelling mantle and partial melting at depths >80 km, centred approximately 20 km south of Kīlauea[11]. Melt segregation by compaction of the asthenospheric partial melt zone[12] may result in porous melt accumulation within a layer of high permeability beneath the lithosphere–asthenosphere boundary[13,14], where large changes in rheology favour a transition from porous melt flow through intergranular spaces and veins to focused upward flow in dikes[15,16]. As Kīlauea and Mauna Loa erupt isotopically distinct magmas from geochemically distinct parts of the same mantle source[11,17], they are thought to have two independent lithospheric magmatic systems, consistent with long-period earthquakes[18].

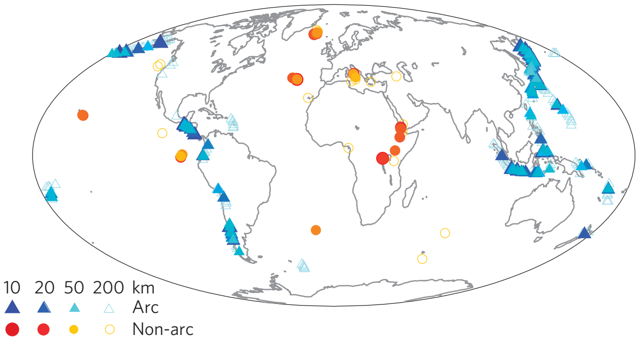

Figure 1 | Global distribution of volcanoes in close proximity. Shown are subaerial, historically active volcanoes (source: Smithsonian Institution, Global Volcanism Program). Symbols denote volcanoes that are located within the specified distance of one another.

The nearly contemporaneous and similar pattern of inflation at Mauna Loa and Kīlauea requires pressure increases of the summit reservoirs in the range of 1–10 MPa (refs 19,20), orders of magnitude larger than would be expected from static stress transfer between both volcanoes[10]. After accounting for motion of Kīlauea's south flank and storage of magma in its deep rift zone[21] (see Methods), patterns of inflation and deflation at Kīlauea's summit result primarily from an imbalance between the incoming mantle magma supply and temporally variable rates of magma outflow to its east rift zone[22] (ERZ). Although Kīlauea's inflation during late 2001 is thought to be caused by a decrease in outflow[3], subsequent inflation and increased activity have been explained by an increase in mantle magma supply[22]. Mauna Loa's inflation began approximately six months after Kīlauea started to inflate in 2001 and the accompanying long-period earthquake swarms in the mantle suggest that it was fed by magma originating from ≥45 km depth[18]. Although some form of static stress transfer between Kīlauea and Mauna Loa might facilitate inflation by opening of deep magmatic pathways, it is unclear whether this mechanism could explain temporally

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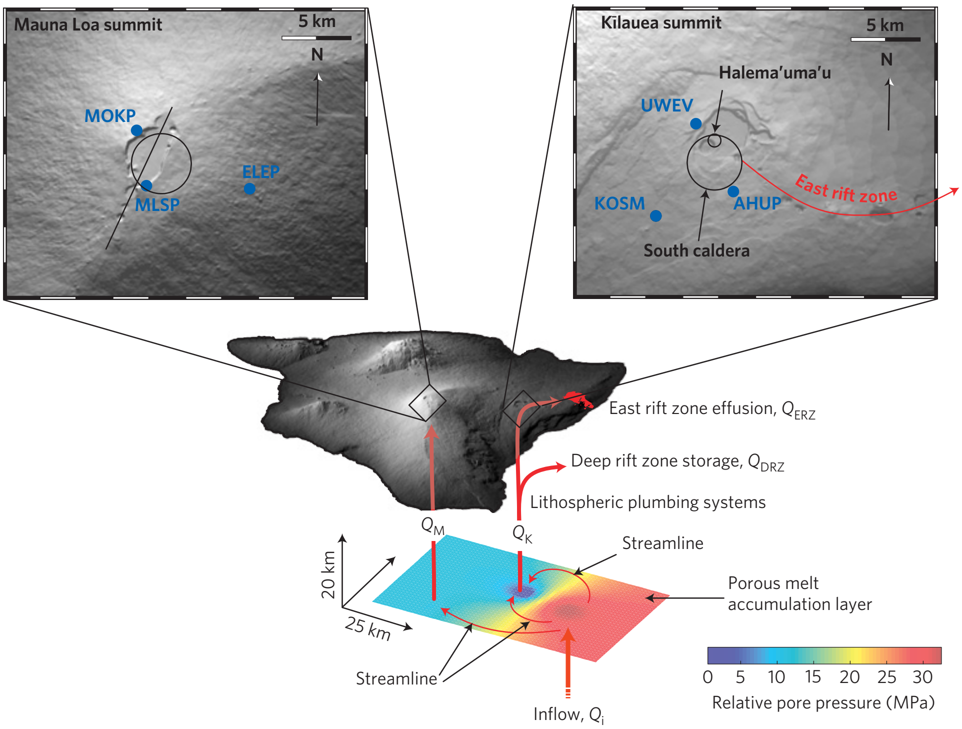

Figure 2 | Dynamic coupling model. View of Hawai'i with relative pore pressure in the porous melt accumulation layer. Thick vertical red arrows indicate melt supply into the porous layer or lithospheric plumbing systems. Streamlines (thin red arrows) follow pressure gradients, illustrating that Mauna Loa and Kīlauea capture different parts of the melt source. Insets indicate locations of GPS stations used (blue dots with station names in blue letters). Deformation sources are indicated by black circles for spherical sources and a line for Mauna Loa's tabular deformation source. Q_M and Q_K are the rates of upward flow into Mauna Loa's and Kīlauea's lithospheric plumbing systems, respectively.

correlated variations in inflation over the past decade without a related surge in deep magma supply[22].

We show here that the inflation at Kīlauea and Mauna Loa can be well explained by stress transfer through pore-pressure variations in a thin asthenospheric melt accumulation layer. To erupt isotopically distinct magmas, each volcano's relatively open lithospheric plumbing system[13,15] has to sample melt from different parts of an isotopically heterogeneous melt accumulation layer[11,17]. This idea is consistent with porous melt flow, where each volcano's lithospheric plumbing system captures geochemically distinct regions of melt. Changes in pore pressure may affect the rates of upward flow into each volcano's plumbing system without significantly altering horizontal flow paths within the porous layer. Likewise, changes in summit magma storage will affect pressures within the lithospheric magma system and eventually within the porous layer.

We treat the coupled system of asthenospheric melt accumulation layer, lithospheric magma transport and crustal magma storage as a lumped parameter model, with magma supply to the asthenospheric layer and magma flow to Kīlauea's ERZ as time-dependent boundary conditions (Fig. 2). The melt accumulation layer is modelled as an idealized layer with melt flow governed by pore-pressure diffusion[23] and a diffusivity, $c = 50\,\mathrm{m^2\,s^{-1}}$, that is representative of the field-scale permeability of a dual porosity zone (see Supplementary Information) consisting of a low-permeability matrix and melt-rich bands[16]. The governing equation for the melt accumulation layer is

$$\dot{p}(\mathbf{x},t) = c\,\nabla^2 p(\mathbf{x},t) + S^{-1} q(\mathbf{x},t)$$

where p is pore pressure, $S = 10^{-11}\,\mathrm{Pa^{-1}}$ is the storage coefficient, q is the volumetric rate of melt in- or outflow per unit volume, $\mathbf{x}$ is the spatial coordinate vector and t denotes time. The volumetric rate of melt supply (all supply rates reported are dense rock equivalent and the magma is treated as incompressible) from the underlying mantle, $Q_I = \int_x q$, is uniformly distributed over an area of 30 km in diameter[11]. The rates of upward flow into Kīlauea's and Mauna Loa's lithospheric plumbing systems, $Q_K = \alpha(p_K - P_K)$ and $Q_M = \alpha(p_M - P_M)$, respectively, are proportional to the difference in reduced pressure between each volcano's summit reservoir, P_K and P_M, and the pressure in the porous layer directly beneath each volcano, p_K and p_M. The constant of proportionality, $\alpha = 0.02\,\mathrm{km^3\,MPa^{-1}\,yr^{-1}}$, is identical for both volcanoes and accounts for viscous pressure loss, with overall model results not significantly sensitive to reasonable choices thereof (see Supplementary Information).

As changes in stored magma volume cause surface deformation, they can be constrained from GPS deformation data. In the absence of an outflow source, Mauna Loa's deformation provides a direct measure of Q_M. In contrast, volume changes in Kīlauea's summit storage reservoirs are due to an imbalance between Q_K, magma stored in the deep rift zone, Q_{DRZ}, and outflow to the ERZ, Q_{ERZ}. The first of these is thought to be constant, as there are no observations to suggest otherwise[21,22], whereas Q_{ERZ} can be estimated from SO_2 emissions[22,24] (see Methods), leaving the temporal changes in Q_I to be obtained from a model calibration.

Before 2001 we assume that both volcanoes are in a steady state (see Supplementary Information), during which no magma ascends beneath Mauna Loa and $Q_M = 0$. At Kīlauea we assume that $Q_K = Q_{DRZ} + Q_{ERZ}$, with $Q_{DRZ} = 0.06\,\mathrm{km^3\,yr^{-1}}$ corresponding to the long-term average[21,22] and mid-2001 values of $Q_{ERZ} = 0.14\,\mathrm{km^3\,yr^{-1}}$ obtained from SO_2 emissions[24]. At Mauna Loa, any increase in asthenospheric pore pressure will result in $Q_M > 0$ and inflation due to an increase in the volume of stored magma. As Q_{DRZ} is constant, a rise in asthenospheric pore pressure will increase Q_K, and if not balanced by Q_{ERZ}, magma will be added to the summit reservoir causing inflation. The associated rise in P_K will feedback

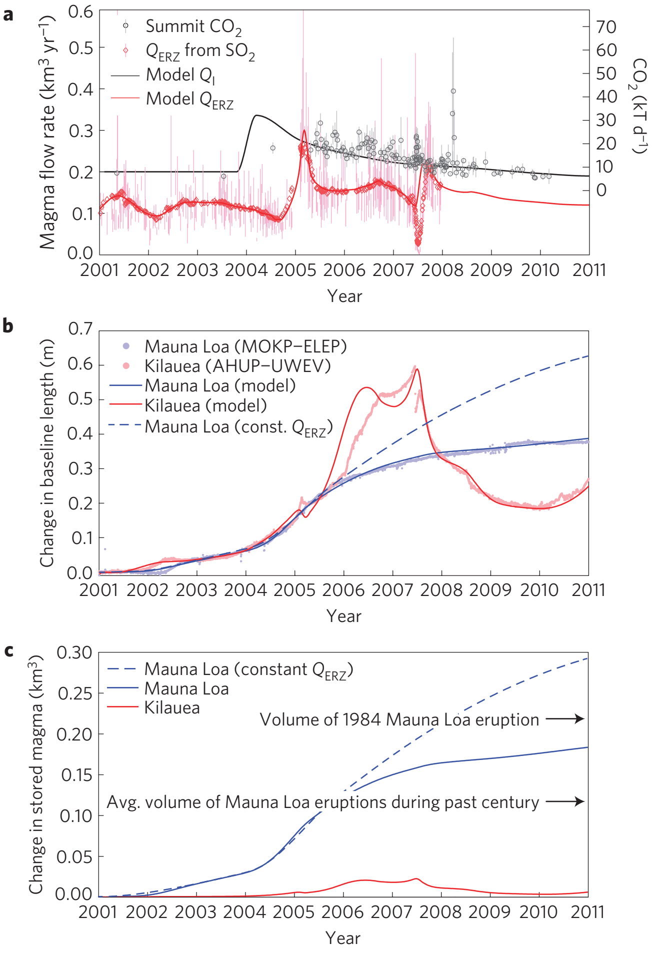

Figure 3 | Model results. a, Kīlauea summit CO$_2$ emission rates (circles) and smoothed ERZ effusion rates (diamonds) with 1 standard deviation error bars. Modelled inflow to porous zone (black line) and modelled outflow to ERZ (red line). **b**, Measured (dots) and modelled (lines) baseline changes at Kīlauea (red) and Mauna Loa (blue; blue dashed for $Q_{ERZ} = 0.12\,\text{km}^3\,\text{yr}^{-1}$ after 2002 to illustrate the effect of Kīlauea's activity on Mauna Loa). **c**, Modelled volume changes at Kīlauea's (red) and Mauna Loa's (blue) summit reservoirs (dashed line is for $Q_{ERZ} = 0.12\,\text{km}^3\,\text{yr}^{-1}$ after 2002).

to cause Q_K to decline until a new balance is achieved. Similarly, if $Q_{DRZ} + Q_{ERZ}$ exceeds Q_K, there will be a loss in stored summit magma and deflation. The resultant drop in P_K will increase Q_K and decrease p_K, until a new balance is attained.

Magma storage and associated surface deformation are modelled assuming a linearly elastic crust and an incompressible magma. Changes in volume and pressure of stored magma are proportional and can be calculated from Q_M and $Q_K - Q_{DRZ} - Q_{ERZ}$, using analytical solutions for surface displacements (see Supplementary Information). Mauna Loa's summit storage reservoir, known to be an elongate body underlying its caldera and upper rift zones, can be modelled as a combined tabular and spherical body[19]. At Kīlauea, magma storage and surface deformation are associated with a shallow reservoir, located beneath the eastern edge of Halemaʻumaʻu Crater[25], and a deeper and larger reservoir, located beneath the southern part of Kīlauea's caldera[25]. They can be modelled as two distinct, but interconnected, spherical bodies[20,22,25] (see Supplementary Information).

Model results (Fig. 3) indicate that the interplay between Q_{ERZ} and Q_I can self-consistently explain deformation of both Kīlauea and Mauna Loa. Late in 2001 a temporary blockage between Kīlauea's summit and the ERZ caused a decrease in Q_{ERZ} and produced inflation at Kīlauea[3,7]. The associated increase in summit magma pressure was transmitted down Kīlauea's plumbing system and diffused horizontally within the porous layer, contributing to an increase in pore pressure beneath Mauna Loa and resultant inflation. The time delay of approximately six months between inflation at Kīlauea and at Mauna Loa represents the characteristic pore-pressure diffusion time, $\tau \sim \sqrt{L^2/c}$, where $L \approx 34\,\text{km}$ is the horizontal distance between Kīlauea and Mauna Loa. In late 2003, a sudden increase in Q_I, that gradually decayed during subsequent years, caused another increase in pore pressure and renewed inflation at both Kīlauea and Mauna Loa.

Magma rising through Kīlauea's plumbing system becomes saturated in CO$_2$ at ~30 km depth and buoyant CO$_2$-rich bubbles rise through Kīlauea's summit to the surface. Consequently, summit CO$_2$ emission rates track Kīlauea's magma supply[22,26]. Variations in Q_I, obtained from our model calibration, agree with independent CO$_2$ emissions from Kīlauea's summit (Fig. 3), substantiating the plausibility of our model. Interestingly, we find that the 2005 increase in Q_{ERZ} caused a corresponding waning in the inflation rate of Mauna Loa by withdrawing more melt from the accumulation layer and thereby reducing pore pressures (Fig. 3).

Although dynamical interactions between nearby volcanoes are controversial, they seem to occur in some circumstances[1,2,4–6,9]. Our study provides a quantitative model that can explain observations of direct volcano coupling. Our results illustrate that pore-pressure diffusion in the asthenosphere constitutes a potential mechanism for dynamic stress transfer between Kīlauea and Mauna Loa volcanoes. This stress transfer is at least two orders of magnitude faster than the predicted flow of melt within the porous zone (see Supplementary Information), consistent with pore velocities estimated from U-series disequilibria[27]. At the same time, predicted changes in pore pressure cause only small changes in flow paths, and are insufficient to significantly affect the isotopic composition of melt flowing to Kīlauea and Mauna Loa, respectively.

Over the past decade, the estimated volume of magma added to Mauna Loa's crustal reservoir is similar to historical eruptions at Mauna Loa[28], suggesting that Mauna Loa is perhaps poised for eruption (Fig. 3c). The model predicts higher pressures within the asthenospheric melt accumulation zone and within Mauna Loa's summit reservoir, had Kīlauea not gone through a period of heightened eruptive and intrusive activity. Although more than 100 active volcanoes are within a similar distance of one another as Kīlauea and Mauna Loa (Fig. 1), many of them are arc volcanoes with magmas of relatively high viscosities and with plumbing systems that are probably more complex and less amenable to hydrodynamic stress transfer. Perhaps the combination of prolific melt production and a lithospheric structure that allows for an unusually high degree of connectivity between asthenosphere and shallow reservoirs is exceptional to Hawaiʻi. Nevertheless, spatiotemporal relations of volcanic centres in arc settings remain a topic of debate and, furthermore, laterally extensive asthenospheric melt zones have been proposed beneath some volcanic arcs[29] and other ocean islands[30]. Consequently, asthenospheric stress transfer through pore-pressure diffusion is a mechanism that should be taken into consideration elsewhere.

Methods

GPS data. Daily batches of 30-s sampled GPS observations were processed to form baselines between sites, which removes many of the effects of coherent noise/extraneous signals. Baseline length estimates across the summit of Mauna Loa, at an elevation of 4,200 m, have errors of approximately 2.5 mm, whereas the errors for the similar length baseline across the 1,200 m elevation summit of Kīlauea are approximately 5 mm. Kīlauea's GPS sites record displacements due to combined summit inflation/deflation and south flank motion. Consequently, the modelled baseline time series across Kīlauea's summit includes a length change of approximately 1.3 cm yr^{-1} caused by slip on Kīlauea's south flank decollement.

ERZ magma effusion and SO_2 emission rates. During the past decade, magma leaving Kīlauea's summit has mostly been supplying eruptions to the ERZ (ref. 22). As SO_2 exsolves on eruption, ERZ SO_2 emission rates, E_{SO_2}, correlate with magma effusion rates, V_m, before the 2007 Father's Day diking event[22,24]. We constrain Q_{ERZ} using the empirical formulation $V_m = E_{SO_2} K_{SO_2}$, where $K_{SO_2} = 233 \pm 80\,m^3$ of lava per ton of SO_2 is an empirical constant[24]. The values of V_m shown in Fig. 3a were obtained after smoothing the measured SO_2 emission rates[7,8] with a Savitzky–Golay filter, a generalized moving average that can accept non-uniform data with filter coefficients determined by an unweighted linear least-squares regression and a polynomial model.

Modelling of pore-pressure diffusion. We model pore-pressure diffusion in the porous melt accumulation layer using an alternating direction implicit finite difference scheme. Please see Supplementary Information for details about model parameters.

Received 2 April 2012; accepted 21 September 2012; published online 21 October 2012

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Acknowledgements

The Kīlauea and Mauna Loa GPS networks are supported by grants from the USGS, NSF and NASA and operated in collaboration by the USGS, Stanford University and the Pacific GPS Facility at the University of Hawaiʻi. The authors thank J. Sutton for providing access to the CO_2 data and S.E. Ingebritsen for constructive comments. H.M.G. thanks A. M. Jellinek and T. Fournier for constructive discussions. This work was supported by the USGS and by the NSF Geophysics and Volcanology & Petrology programmes.

Author contributions

All authors contributed to the design of this study; H.M.G. developed the model; H.M.G. led the writing of the paper; C.J.W. significantly contributed to the writing of the paper; M.P.'s knowledge about Mauna Loa and Kīlauea were of critical importance to the model development; B.B., J.F., M.P. and A.M. have been involved in installation of GPS stations and in data acquisition; J.F. analysed the GPS data and produced the GPS time series; M.P. and A.M. have been involved in daily monitoring of the eruptive activity.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to H.M.G.

Competing financial interests

The authors declare no competing financial interests.