Relative seismic velocity variations correlate with deformation at Kīlauea volcano

Clare Donaldson, Corentin Caudron, Robert G. Green, Weston A. Thelen, Robert S. White

Seismic noise interferometry allows the continuous and real-time measurement of relative seismic velocity through a volcanic edifice. Because seismic velocity is sensitive to the pressurization state of the system, this method is an exciting new monitoring tool at active volcanoes. Despite the potential of this tool, no studies have yet comprehensively compared velocity to other geophysical observables on a short-term time scale at a volcano over a significant length of time. We use volcanic tremor (~0.3 to 1.0 Hz) at Kīlauea as a passive source for interferometry to measure relative velocity changes with time. By cross-correlating the vertical component of day-long seismic records between ~230 station pairs, we extract coherent and temporally consistent coda wave signals with time lags of up to 120 s. Our resulting time series of relative velocity shows a remarkable correlation between relative velocity and the radial tilt record measured at Kīlauea summit, consistently correlating on a time scale of days to weeks for almost the entire study period (June 2011 to November 2015). As the summit continually deforms in deflation-inflation events, the velocity decreases and increases, respectively. Modeling of strain at Kīlauea suggests that, during inflation of the shallow magma reservoir (1 to 2 km below the surface), most of the edifice is dominated by compression—hence closing cracks and producing faster velocities—and vice versa. The excellent correlation between relative velocity and deformation in this study provides an opportunity to understand better the mechanisms causing seismic velocity changes at volcanoes, and therefore realize the potential of passive interferometry as a monitoring tool.

INTRODUCTION

Seismic noise interferometry as a monitoring tool

Measurement of seismic velocity by passive interferometry using seismic noise is a promising monitoring tool at volcanoes (1, 2), potentially being sensitive to magma pressurization and redistribution of melt within a subsurface plumbing system. The continuous nature of seismic noise provides better temporal resolution than earthquake interferometry and means that the technique is not dependent on the occurrence and location of seismicity. Furthermore, some authors (1) have postulated that ambient noise may be sensitive to changes at depth that do not deform the volcano surface and hence may be missed by measurements from interferometric synthetic aperture radar (InSAR), Global Positioning System (GPS), and tiltmeters. Monitoring successes include detection of precursory eruptive signals of relative velocity at Piton de la Fournaise (1, 3) and mapping of pressurized volcanic fluids in Japan (4). Detection of signals due to short-term (months to hours) changes in magma pressurization or transport before eruptions is an exciting result. However, these short-term velocity changes have often been seemingly unrelated to other observables at volcanoes during intereruptive periods and over long periods of time (years). In particular, surface deformation—a traditional indicator of volcano pressurization—has not yet been found to correlate consistently with seismic velocity, except for long-term changes that occur over many years (5). This lack of definitive correlation has limited our understanding of the mechanisms causing the velocity changes of the shallow subsurface. Kīlauea is an extremely well-monitored volcano with continuous summit activity since 2008 and clear, repetitive deformation transients. This feature provides an excellent opportunity to compare measurements of deformation to seismic velocity changes and to test the possibility of noise interferometry as a monitoring tool. We studied relative velocity variations in the subsurface at Kīlauea volcano over the period of June 2011 to November 2015 using seismic noise interferometry with volcanic tremor as the passive noise source. Over this 4-year period, we find a remarkably consistent correlation of relative velocity and deformation on time scales of days to weeks.

Kīlauea volcano

An eruptive vent has existed at Kīlauea summit (Fig. 1) in the southeast corner of Halemaʻumaʻu caldera since it opened in March 2008 (6). The summit plumbing system is thought to consist of a shallow magma reservoir located on the east side of Halemaʻumaʻu caldera at 1- to 2-km depth below the surface [the Halemaʻumaʻu reservoir (HMMR)] and a larger, deeper reservoir at 3- to 5-km depth below the southern side of Kīlauea caldera (7). This magmatic system is linked to the East Rift Zone—in which Puʻu ʻOʻo vent, 20 km from the summit, has been erupting since 1983—and the Southwest Rift Zone. Deformation at Kīlauea is the result of both long- and short-term processes. Longer-term deformation includes contributions from volcanic and tectonic sources, such as pressurization of the summit magma system and seaward motion of Kīlauea’s south flank. Deformation at Kīlauea’s summit on the time scale of hours to days is dominated by transient deflation-inflation (DI) events (8). They are measured to varying degrees by InSAR, tiltmeters, GPS, and strainmeters and are strongly correlated with changes in surface height of the summit lava lake (8–10). Inverse modeling of DI events shows that the deformation is generated by pressure transients in the HMMR, located beneath the eastern margin of Halemaʻumaʻu caldera (8).

Seismic noise interferometry and volcanic tremor

Cross-correlation of the diffuse noise wave field measured at a pair of stations extracts coherent seismic energy arriving at both stations. Small perturbations to the arrival times of the phases in noise cross-correlation functions (NCFs) can then be measured to construct a temporal variation of the seismic velocity relative to a reference

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1Bullard Laboratories, Department of Earth Sciences, University of Cambridge, Madingley Road, Cambridge CB3 0EZ, UK. 2U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, WA 98661, USA.
3Corresponding author. Email: cgd27@cam.ac.uk
†Present address: Department of Geosciences, Environment and Society, Université Libre de Bruxelles, Brussels, Belgium.

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The volcanic tremor source used in this study can be seen above ~0.3 Hz in the amplitude spectrogram for station Uwekahuna Vault (UWE) shown in Fig. 2C. This tremor, brightest at ~0.5 Hz, is associated with degassing and spattering of the lava lake surface (10, 18–21). The lava lake is described as undergoing normal behavior during periods of spattering (Fig. 2A), associated with higher tremor amplitudes (Fig. 2, C to E) and gas emissions (10, 21). During a nonspattering regime (Fig. 2B), tremor and gas emissions greatly decrease, and the level of the lake rises (Fig. 2F). Nonspattering phases typically last ~2 hours during the period of this study (21). This episodic behavior associated with the rise and fall of the lava lake surface (“gas pistoning”) results from gas bubbles accumulating near the top of the lake, followed by more efficient decoupling of gas from the lake (21). The tremor over the entire period of study can be seen in the amplitude spectrogram shown in Fig. 3A.

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RESULTS

Stability of tremor source

Volcanic tremor can be seen above ~0.3 Hz in Fig. 3A, as well as the oceanic secondary microseism at ~0.1 to 0.3 Hz, displaying typical seasonal variation. Figure 3B demonstrates the ability to extract consistent NCFs with coherent coda arrivals in the frequency band (0.33 to 1.0 Hz) for almost the entire period of study. Coherent energy is seen in the coda of the NCF at negative lag times up to 120 s.
We use the differential arrival time of the direct ballistic wave (first arrival in the NCF) to estimate the location of the tremor source in two-dimensional space and to investigate how stable this location is through time (17). Figure 4 shows that the most likely location of the noise source is in Halemaʻumaʻu caldera at the closest grid point to the lava lake (small red square). We performed a jackknife test to investigate the effects of the network configuration on this location and to give an estimate of the error. The best source location was calculated 1000 times from the reference functions for randomly chosen network configurations using half the number of stations. More than 90% of results locate in the larger red square in Fig. 4 (approximately 1 km across). The robust estimate of location at or below Halemaʻumaʻu caldera agrees with our suggestion that the source of tremor is spattering in the lava lake. The location has also been calculated from overlapping 10-day moving window stacks through the whole time period (June 2011 to November 2015) and is always found within the region of error (larger red square) in Fig. 4. This shows that the tremor source location is stable and validates the continuous use of this noise source. Source effects on our measurement of $\frac{dv}{v}$ are still an important consideration, so we further examine this in Discussion.

**Correlation between $\frac{dv}{v}$ and radial tilt on the time scale of days to weeks**

A network-averaged relative velocity variation is found by taking the median $\frac{dv}{v}$ of the pairs of the 22 closest stations from the eruptive vent (circled in Fig. 1; 231 pairs) and by stacking over 3-day moving windows. A linear trend from the raw $\frac{dv}{v}$ time series in Fig. 5A (blue curve) is removed to estimate the short-term velocity variations shown in Fig. 5B.

Radial ground tilt, as recorded at site UWE (Fig. 5, gray curves), and the level of the lava lake both change in response to pressurization of the HMMR (8–10). An increase in UWE radial tilt corresponds to an inflation of Kilauea summit and a rise in the level of the lava lake. We choose to study radial tilt here because tiltmeters offer better sensitivity and temporal resolution during DI events in comparison to other instrumentations (for example, GPS) at Kilauea (8). The short-term variations in radial tilt have also been estimated by removing a linear trend from the raw time series (Fig. 5A).

A breakout eruption at Puʻu ʻŌʻō (episode 60), as highlighted in Fig. 5, began on 3 August 2011 and Puʻu ʻŌʻō drained and then re-filled. A marked reduction and recovery of radial tilt at Kilauea summit are also seen in $\frac{dv}{v}$ (Fig. 5C). Figure 5 (D and E) shows large DI...
Sensitivity of noise cross-correlation functions to changes in the medium

NCFs are sensitive to changes in both \( dv/v \) and the structure of the medium. The coherence (correlation coefficient) between the NCFs and the reference NCFs (Fig. 5H) can indicate whether the waveform has fundamentally changed, for example, because of a structural change in the medium (3). Coherence remains above 0.9 for almost the entire study period but drops temporarily during the breakout eruption at Pu‘u Ō‘ō in August 2011. During the overflow of the lava lake in April/May 2015, the coherence drops and does not recover to the same preceding value. This suggests that the complex NCFs containing many scattered phases have changed subtly because of a permanent change to the scatterers and reflectors in the edifice structure, presumably related to the addition of a layer of lava at the free surface. Therefore, \( dv/v \) and radial tilt may no longer correlate at this time because the reference NCF being used is not representative of the medium. The error in \( dv/v \) also permanently increases after the overflow. The decrease in coherence in February 2012 is roughly synchronous with a weakening of amplitude of the source, visible in Fig. 3 (A and B).

Correlation between \( dv/v \) and radial tilt on the time scale of years

The long-term variations in both radial tilt and \( dv/v \) can be seen in the raw time series (Fig. 5A). Radial tilt increases steadily in the long term from 2011 to 2015, suggesting overall inflation of the summit, whereas \( dv/v \) decreases. Vertical displacement measured by GPS at the summit also measures a long-term inflation (23). These raw time series of radial tilt and \( dv/v \) are anticorrelated over the 4-year period, with a cross-correlation coefficient of \(-0.73\) at zero lag between them.

DISCUSSION

We have shown a correlation between the time series of \( dv/v \) using noise interferometry and of surface deformation at a volcano. On the time scale of days to weeks, radial tilt and \( dv/v \) are positively correlated. We believe that this is the first time a correlation between \( dv/v \) and deformation has been found at this time scale consistently over a period of several years. In contrast, on the scale of years, radial tilt and \( dv/v \) are anticorrelated. Radial tilt at UWE is strongly correlated with the level of the lava lake (9), demonstrating a clear link between the magmatic system at Kilauea and the summit deformation. During DI events, as the level of the lava lake rises, UWE radial tilt increases (and vice versa), resulting from pressure changes in the HMHR (8).

We propose that the changes in magma pressurization associated with the continual deflations and inflations of the summit also cause the changes in \( dv/v \). When the magma pressurization increases, compression closes up cracks in the surrounding rock, and the elastic modulus and seismic velocity of the medium increase (24).

Several existing studies have also attributed seismic velocity changes to magma pressurization but have found the opposite trend, that is, seismic velocity decreases as a volcano inflates (1, 3, 25). Precursory seismic velocity drops were measured before several eruptions at Piton de la Fournaise volcano (1, 3). Brenguier et al. (1) attributed this to an increase in magma pressurization causing dilatation and an opening of fractures at the edifice surface. Processes of pressurization due to heated and vaporized hydrothermal water have also been used to explain these short-term signals (26, 27). At Merapi volcano in Indonesia, both increases and decreases in seismic velocity were measured during the same deformation events (28). The authors suggest that, because of topography and heterogeneity of Merapi volcano, both tensional and compressional stresses occur at different locations on the edifice. Similarly, for a deflation event at Miyakejima volcano, both velocity increases and decreases were detected (29). Velocity increases were attributed to deflation of two pressure sources, and velocity decreases were attributed to dilatation because of caldera collapse. Increases in seismic velocity were measured...
during inflation of a volcano, as seen in this study, at Merapi volcano before eruptions in 1992 (30) and 1998 (31). However, it has been suggested that these could be partly or entirely due to seasonal changes in groundwater level (28).

We suggest a model based on strain theory at volcanoes to reconcile some of these observations (Fig. 7). The pattern of deformation at a volcano due to a deforming source greatly depends on the depth of that source; a deeper source results in a greater region in the shallow subsurface undergoing extension. We assume that a change in velocity is proportional to a change in strain (29, 32–34). For a point pressure source at depth $d$, the sign of the strain field changes at a distance $r = d\sqrt{2}$ at the surface of the elastic half-space (that is,

![Fig. 5. Results of $dv/v$ and its relationship with radial tilt. (A) Raw relative velocity variations, $dv/v$ (blue). Light blue shading indicates the error in the measurement, calculated from the linear regression of $dt$ against $t$. Raw radial tilt measured at UWE (gray). The radial component of tilt is calculated with respect to the eruptive vent in Halema’uma’u caldera. (B) Short-term $dv/v$ and radial tilt, estimated by linearly detrending the raw series. The gray-green bar shows the correlation coefficient between $dv/v$ and radial tilt in 30-day moving windows with an overlap of 6 days. Times highlighted in yellow correspond to (from left to right) a breakout eruption at Pu’u ‘O’ō (episode 60), a large deflation and an “anomalous” deflation event (see text), and an overflow of the lava lake onto Halema’uma’u caldera floor. (C to G) Enlargements of time periods in (B). (E) is a large DI event. (H) Coherence (correlation coefficient) between current 3-day moving window NCF and reference NCF.](image-url)
Fig. 6. Evidence for the positive correlation between $d\nu/v$ and radial tilt. (A) Example of period in 2014 when radial tilt and $d\nu/v$ track each other closely (gray-green bar as in Fig. 5B). (B) Histogram of the correlation coefficients calculated between radial tilt and $d\nu/v$ for 30-day moving windows with an overlap of 6 days over the whole time period, as shown in Fig. 5B.
relative path lengths between the source and stations, which would be relevant if body waves make up a significant part of the NCF (42), we would measure the opposite trend in $dv/v$. Let us consider a pair of stations on the surface and limiting cases of the tremor source at the surface and infinite depth. The differential interstation distance (see Materials and Methods) is at a maximum when the tremor source is at the surface and tends to zero for a tremor source getting infinitely deep. Therefore, shallow and deep tremor sources correspond to measurements of the slowest seismic velocity and an infinitely fast seismic velocity, respectively. This trend is opposite to the measured trend of faster velocity at a higher elevation of the lava lake (that is, a shallow tremor source). We thus conclude that our measurements of $dv/v$ reflect real changes in seismic velocity and are not spuriously produced by vertical movement of the tremor source in the conduit.

The result of $dv/v$ correlating with radial tilt is consistent when measured at different time lags in the NCFs, when using a window length of at least 20 s on both sides of the NCFs and when averaged over many pairs. Given that some stations lie in the inner region of strain suggested in our model, one might expect to measure a $dv/v$ time series that negatively correlates with radial tilt using these stations. Further, the magnitude of strain change is greater within the inner region than in the outer, so we suggest testing this theory at other volcanoes with a shallow deformation source. However, we do not find this negative correlation at Kīlauea and we suggest the following two reasons for this. First, we believe that the coda of the NCFs is sensitive to a wide area extending outside the inner region of strain because of scattering of the seismic waves. It is difficult to avoid measuring the coda; limiting measurements to the early ballistic arrivals means that a short window length for the frequency of study must be used, and we then measure a noisy time series. We further note that the area of extension at the surface is also undergoing compression at depth (for an inflation, see Fig. 7C). Therefore, even phases—probably surface waves, as suggested above—traveling in the region of near-surface extension could be sensitive to the compression at depth (Fig. 7D). Second, if we limit our average of $dv/v$ to the stations closest to the source, there are very few pairs. We find that time series become much noisier when the number of pairs decreases, and ideally, a minimum of ~40 pairs is needed. However, when we include more stations to increase the number of pairs, we start to sample the outer strain region.

![Fig. 7. Model of volumetric strain due to inflation of point sources at 1-km depth (Kīlauea, left) and 2.6-km depth (Piton de la Fournaise, right).](image-url)
Because the long-term trends of radial tilt and $dv/v$ are oppositely correlated to those in the short term, the same mechanism cannot be at play. The source of long-term inflation could be deeper than the HMMR, and so a greater area of extensional strain would exist at the surface. If the summit reservoir at 3- to 5-km depth (7) inflates, then extension could be seen over an area with a radius as large as 7 km. Another suggestion is that inflation of the summit could be accompanied by an increase in the presence of magma and/or hydrothermal fluids within the pore spaces of the summit (43). It is also possible that the seaward motion of Kilauea’s south flank results in crust relaxation and opening of the pore space. Flank movement has been suggested to account for a velocity drop measured at Piton de la Fournaise before an eruption in April 2007 (44).

To our knowledge, we have shown for the first time a consistent correlation between a daily time series of relative velocity, $dv/v$, and daily surface deformation measurements. Having a reliable record of $dv/v$ at this time scale is an important step forward in terms of volcano monitoring with noise interferometry. This result also provides an opportunity to understand better the dominant mechanism controlling the seismic velocities at volcanoes, which has been difficult in previous work, particularly during eruptive periods. The clear link with deformation associated with DI events suggests that pressurization of the shallow reservoir at Kilauea summit is also affecting seismic velocity across the summit region.

**MATERIALS AND METHODS**

**Seismic network**

The seismometers used in this study are maintained by the Hawaiian Volcano Observatory, U.S. Geological Survey. Twenty-seven instruments around Kilauea summit were used: 16 broadband and 11 short-period instruments. All stations mentioned in this paper are broadband: PAUD (T120, 120-s corner), RIMD (T120, 120-s corner), and UWE (STS2, 120-s corner).

**Seismic noise interferometry to measure $dv/v$**

We used the freely available program MSNoise to measure $dv/v$ (45). The data were stored in day-long, 100-Hz miniSEED files. Only vertical components were used. The data from each station were preprocessed individually. An initial bandpass was applied (0.01 to 8.0 Hz), and the waveforms were demeaned, tapered, and downsampled to 20 Hz. The waveforms were then temporally normalized (by clipping at the root mean square multiplied by 1.5) and spectrally whitened in 30-min windows (46).

NCFs were calculated for every pair in the network in 30-min windows for time lags of ±120 s. The NCFs were stacked for each day, and then the daily NCFs were stacked over 3-day moving windows. A reference NCF was also calculated for each pair by stacking the daily NCFs over the whole period.

The Moving-Window Cross-Spectral (MWCS) method, also known as the doublet method, was used to measure the dephasing between the NCF and the reference NCF through time (47). The MWCS method works in the frequency domain and measures a delay time ($dt$) at different lag times ($t$) in the current NCF, relative to the reference NCF. Only points with an error of less than 0.1 s, a coherence of more than 0.65 and a $dt$ of less than 0.1 s were accepted. A weighted linear regression was calculated in a 30-s window in the NCF to calculate $dt/t$. The minimum time lag of this window was chosen by dividing the differential interstation distance from the tremor source by a velocity of 0.8 km/s. The differential interstation distance from the source for a pair A-B refers to

$$\text{distance(source→A) − distance(source→B)}$$

This is shown diagrammatically in the Supplementary Materials. This distance is required because the source of seismic energy is not external and isotropic to the network. A velocity of 0.8 km/s—slower than the ballistic arrivals in the NCF—allows measurement of the coda of the waves. This technique was originally used in earthquake coda interferometry (12). Then, the relative velocity change was calculated using

$$\frac{dv}{v} = -\frac{dt}{t}$$

assuming a homogeneous relative velocity change (30). We averaged $dv/v$ for the closest 22 stations from the source (231 pairs). We rejected a pair’s results for a day if the error from the linear regression of $dt$ against $t$ is greater than 0.01%.

It is possible to spuriously measure apparent $dv/v$ variations because of a change in frequency content of the noise source (48) using the “stretching technique” (11). The MWCS method, in contrast, is theoretically relatively unaffected by this problem because the amplitude spectrum and phase spectrum are separated before making the measurements. Further discussion of possible changes in frequency content affecting the measurement of $dv/v$ can be found in the Supplementary Materials.

**Tremor source location method**

The NCFs are asymmetrical because the noise wave field is not isotropic, but it mainly originates in one location. We exploit this fact to locate the noise source, following the method of Ballmer et al. (17). We constructed a 0.005° (c. 500 m) geographical grid and considered each point to be a potential source location. Arrival times were estimated in the NCFs for each pair of stations for each grid point, assuming a lateral propagation velocity of 1 km/s. By testing velocities of 0.5 to 3.3 km/s, we find that the estimate of source location is relatively insensitive to the assumed velocity. The total absolute amplitudes in 4-s windows around the expected arrival times in the NCFs (using the differential interstation distance) for each pair were added together. This then represents the likelihood of the source being located at that grid point. The estimate of source location in Fig. 4 was calculated from the reference NCFs for all the pairs.

**Strain modeling**

Strain modeling used routines from the freely available package Coulomb 3.3 (49, 50). Depth sensitivity kernels were calculated with the program surf96 (51) and published velocity models (38, 39).

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/6/e1700219/DC1

Differential interstation distance from source
Coda arrivals in NCFs
Two reference functions
Expected change in $dv/v$ from strain data
Frequency variations in the volcanic tremor source

REFERENCES AND NOTES


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