



HAL
open science

Earthquake-volcano interaction imaged by coda wave interferometry

Jean Battaglia, Jean-Philippe Métaxian, Esline Garaebiti

► **To cite this version:**

Jean Battaglia, Jean-Philippe Métaxian, Esline Garaebiti. Earthquake-volcano interaction imaged by coda wave interferometry. *Geophysical Research Letters*, 2012, 39 (11), pp.L11309. 10.1029/2012GL052003 . hal-00720269

HAL Id: hal-00720269

<https://hal.science/hal-00720269v1>

Submitted on 20 May 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Earthquake-volcano interaction imaged by coda wave interferometry

Jean Battaglia,^{1,2,3} Jean-Philippe Métaxian,⁴ and Esline Garaebiti⁵

Received 11 April 2012; revised 14 May 2012; accepted 15 May 2012; published 8 June 2012.

[1] Large earthquakes are often assumed to influence the eruptive activity of volcanoes. A major challenge to better understand the causal relationship between these phenomena is to detect and image, in detail, all induced changes, including subtle, non-eruptive responses. We show that coda wave interferometry can be used to image such earthquake-induced responses, as recorded at Yasur volcano (Vanuatu) following a magnitude 7.3 earthquake which occurred 80 km from its summit. We use repeating Long-Period events to show that the earthquake caused a sudden seismic velocity drop, followed by a slow partial recovery process. The spatial distribution of the response amplitude indicates an effect centered on the volcano. Our result demonstrates that, even if no major change in eruptive activity is observed, volcanoes will be affected by the propagation of large amplitude seismic waves through their structure, suggesting that Earthquake-volcano interaction is likely a more common phenomenon than previously believed. **Citation:** Battaglia, J., J.-P. Métaxian, and E. Garaebiti (2012), Earthquake-volcano interaction imaged by coda wave interferometry, *Geophys. Res. Lett.*, 39, L11309, doi:10.1029/2012GL052003.

1. Introduction

[2] A wide variety of volcano responses have been recorded following large earthquakes, depending on the earthquake magnitude, distance that separates the volcano from the earthquake as well as the type of on-going eruptive activity or state of equilibrium of the magmatic system. Such interactions occur at short distances by static stress diffusion [Walter and Amelung, 2006; Walter, 2007] as well as at distances of several hundred kilometers or more by dynamic stress transfer [Hill et al., 2002; Gomberg and Johnson, 2005]. They may result in the triggering of new effusive or explosive eruptions or bring changes to the dynamics of ongoing eruptions. Most commonly, increases in local tectonic or volcanic micro-seismicity have been observed

following the passage of seismic waves, sometimes leading to swarms of local seismic events [Moran et al., 2004; West et al., 2005; Okubo and Wolfe, 2008] which may end in a new eruptive sequence [Cannata et al., 2010]. Several global studies found a statistically significant increase in the number of eruptions following large earthquakes [e.g., Linde and Sacks, 1998]. For volcanoes with on-going eruptive activity, large earthquakes may bring changes to the eruption dynamics leading to increases in heat flux [Harris and Ripepe, 2007; Delle Donne et al., 2010], degassing [Cigolini et al., 2007] or extrusion rate [Walter et al., 2007]. More subtle changes have also been observed such as changes in tremor activity [Moran et al., 2004; Speranza and Carniel, 2008] or increases in fumarolic emissions [Walter et al., 2007]. In many cases, however, large earthquakes occur without apparently influencing activity at nearby volcanoes, showing that interactions are not systematic and/or that insufficient data are available to understand the cause-effect relationship. Moreover, because triggering may occur with variable time delays, ranging from a few minutes to several days, weeks, months or years [Delle Donne et al., 2010; Manga and Brodsky, 2006; Marzocchi, 2002], the causal relationship is sometimes difficult to establish or is, at best, controversial.

[3] To understand the effects of large earthquakes on volcanoes we need to have quantitative measurements to image the full array of induced changes. While modifications in surface activity or new eruptions may be detected by visual observations, changes in the eruptive dynamics or subtle sub-surface modifications to the volcanic system, require monitoring of appropriate geophysical and geochemical parameters. The use of similar seismic signals and coda wave interferometry (CWI) technique [Poupinet et al., 1984; Snieder et al., 2002] has proved to be an efficient tool for identifying subtle sub-surface changes like increases of the propagation velocity of seismic waves preceding volcanic eruptions [Brenquiere et al., 2008] or velocity decreases, near the epicenter of large earthquakes [Schaff and Beroza, 2004]. The technique relies on the comparison of similar seismic signals whose source can be natural (earthquakes) or artificial (explosions), or which may be generated by seismic noise correlation [Campillo, 2006; Shapiro and Campillo, 2004]. Changes in the medium (shallow subsurface) induce changes in the travel times of seismic waves and distortions in the waveforms which can be detected by comparing the seismic signals. The technique has previously been used to monitor temporal changes in volcanic interiors [Ratdomopurbo and Poupinet, 1995; Snieder and Hagerty, 2004; Grêt et al., 2005]. However, a major drawback in most studies is the limited, and irregular, temporal coverage of the similar signals.

[4] In this paper, we use highly repetitive seismic events and CWI to monitor rapid temporal changes in the structure of Yasur volcano during a period of two months including

¹Clermont Université, Université Blaise Pascal, Laboratoire Magmas et Volcans, BP 10448, F-63000 CLERMONT-FERRAND, France.

²CNRS, UMR 6524, LMV, F-63038 CLERMONT-FERRAND, France.

³IRD, R 163, LMV, F-63038 CLERMONT-FERRAND, France.

⁴ISTerre, IRD R216, CNRS, Univ. de Savoie, Le Bourget du Lac, 73376, France.

⁵Vanuatu Meteorology and Geohazards Department, P.M.B 9054, Port Vila, Vanuatu.

Corresponding author: J. Battaglia, Laboratoire Magmas et Volcans, 5, rue Kessler, 63038 Clermont-Ferrand, France. (battag@opgc.univ-bpclermont.fr)

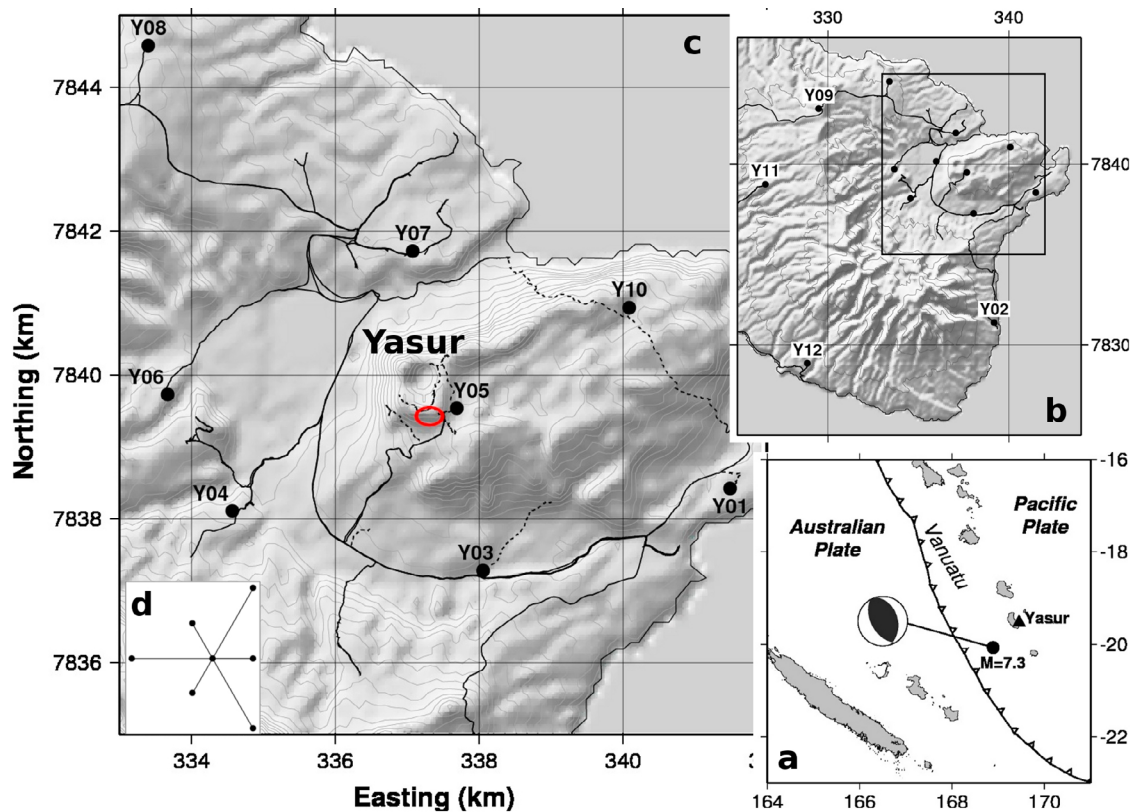


Figure 1. Geological settings and layout of the seismic network. (a) Location of Yasur volcano and epicentral location of the magnitude 7.3 subduction earthquake which occurred at a depth of about 35 km on April 9, 2008 (longitude-latitude coordinates in degrees). (b) Location of the seismic stations in the Southern part of Tanna island and (c) around Yasur volcano (UTM coordinates in km). The epicentral location of LP events is indicated by a red ellipse. (d) Typical sensor distribution for a 7-sensor seismic station: one 3-component sensor surrounded by 6 vertical sensors at distances of 20 or 40 meters. Stations with four sensors (Y11 and Y02) only include 3 peripheral seismometers.

a $M = 7.3$ subduction earthquake which occurred 80 km from the volcano.

2. Data and Methods

[5] Yasur volcano is a small scoria cone (360 m a.s.l.) located on Tanna island, in the southern part of Vanuatu Archipelago. The volcano is characterized by permanent Strombolian (repeated, low intensity) explosive activity, experiencing events at rates of up to several explosions per minute. Between January 2008 and February 2009, we operated a temporary seismic network around Yasur. This included 12 short period seismic stations (Figure 1): 9 composed of 7 sensors, 2 composed of 4 sensors (Y02 and Y11) and 1 with a single 3-component sensor (Y12). The instruments recorded intense seismicity dominated by numerous explosion quakes directly generated by surface (explosive) activity, but also including LP events [Chouet, 1996] related to deeper (sub-surface, conduit) processes. This seismicity comprised families of events with similar waveforms. One family of LP events in particular occurred regularly during the whole study period at a rate of about 10 events per hour (Figure 2a). According to two independent methods based on the use of (a) seismic antennas techniques [Perrier, 2011] and (b) first arrival times picked using stacks with well identified onsets, source locations for LP events are found

below the southeastern part of the crater rim at a depth ranging from 400 to 800 m b.s.l. depending on location parameters and technique. The high rate of occurrence of these events provides us with an unprecedented sampling rate for applying the CWI technique to examine the effect on the volcano of the $M=7.3$ subduction earthquake which occurred 80 km to the southeast on April 9, 2008 at 12:46 UT (T_0 , the time of occurrence of the earthquake).

[6] To compare waveforms, and identify distortions, we used the cross-correlation moving window technique in which we calculated delays along the waveforms by cross-correlating 5.12 s sliding windows. We selected 8500 similar LP events between March 1 and May 10 which were identified by cross-correlating, to detect the similar signal windows, continuous data from a station that clearly recorded LP waveforms (Y07 in Figure 1) with a reference LP trace. To identify suitable reference events to apply the CWI technique (with high quality signal-to-noise ratios), we generated, for each station and component, several synthetic stacks, before and after T_0 , by summing the 30 largest events recorded on any one day. Comparing these daily stacks to the 8500 LP events with the moving window technique, we commonly observed drops in similarity for the later part of the signals, and a progressive dephasing of the waveforms with an almost linear trend whose slope (dt/t) we determined by linear regression (Figure 2b). Among the

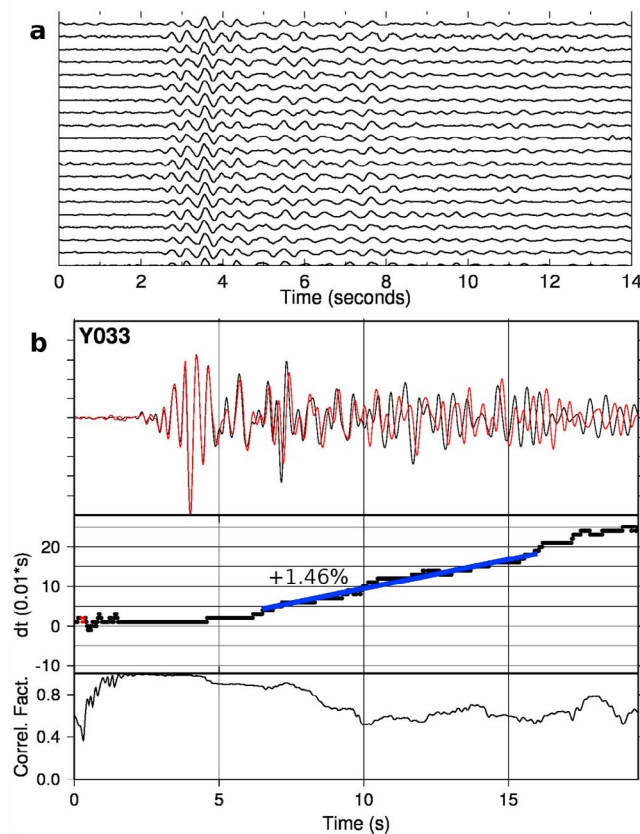


Figure 2. Similar waveforms and application of the cross-correlation moving window technique. (a) Example of similar LP events recorded at station Y05. (b) Correlation Moving Window technique applied to two stacks for station Y03 (vertical component 3): a stack composed of events collected during the hours preceding T_0 and a stack of events after T_0 . The upper part shows the waveforms aligned on their onsets, middle part shows delays along the waveform calculated using 512-point windows, with linear interpolation and evaluation of the slope dt/t , and lower part shows corresponding correlation value.

comparisons, we selected the results providing a good linear fit and plotted them as a function of time.

3. Changes Induced by the $M = 7.3$ Earthquake

[7] Figure 3a shows examples of temporal variations in dt/t for two reference stacks, collected before and after T_0 , at two vertical components of stations Y01 and Y03. These curves are representative of those obtained at all stations. Variations for each time frame (before or after T_0) are better recovered using stacks collected during the corresponding period. Nevertheless, the resulting curves outline a clear increase in the value of dt/t at T_0 , indicating a quasi-instantaneous response to the distal earthquake. During the days following T_0 , we detected a partial relaxation process, characterized by a decrease in dt/t , whose values did not return to their initial pre- T_0 levels. Apart from the rapid step observed at T_0 , dt/t displayed rather smooth variations, especially prior to T_0 . However, we note for several stations a significant change in the trend began about 4 days before T_0 (Y011 for example in Figure 3a), prior to the first $M =$

5.1 foreshock which occurred on April 6. To examine the spatial distribution of the amplitude of the step observed at T_0 , we compared, for each station and component, a stack composed of LP events collected during the hours before T_0 to a stack composed of events collected after the same event. The distribution shows a maximum value for station Y05 and a rough decay as a function of distance to the summit (Figure 3b).

[8] CWI theory directly relates dt/t to changes in the average seismic velocity (dv/v) of the medium sampled by the seismic waves, where $dv/v = -dt/t$ [Poupinet *et al.*, 1984]. In the present case, we favor the hypothesis of a medium change as compared to a source change [Haney *et al.*, 2009] because in the later case we would expect comparable variations to be observed at all stations. Therefore our data indicate that the distant earthquake induced

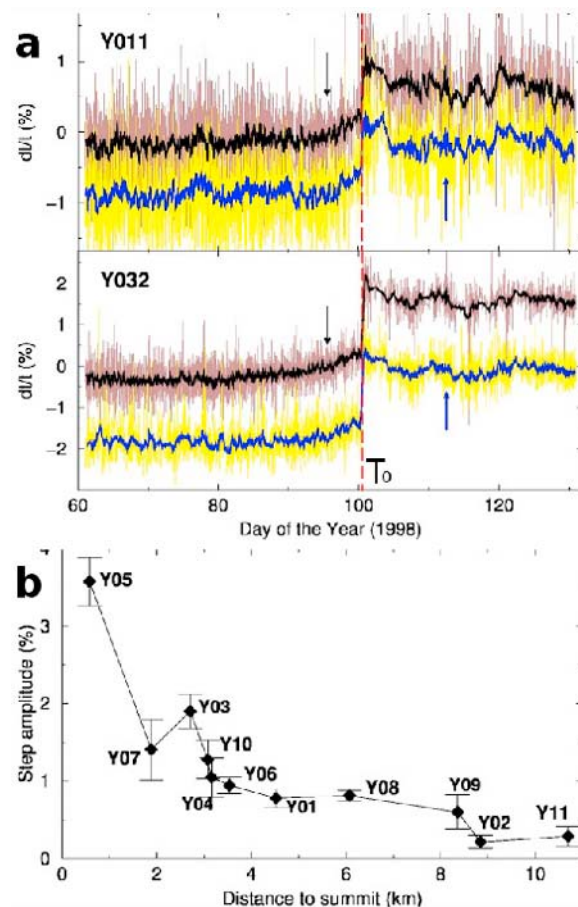


Figure 3. Temporal and spatial variations of dt/t , the slope of the linearized delay between similar events. (a) dt/t between 2 reference stacks collected at dates indicated by black and blue arrows and 8500 LPs for stations Y01 (component 4) and Y03 (component 7). Vertical dashed line is drawn at the time of occurrence of the $M=7.3$ earthquake (T_0). Individual measurements are shown in light color, in foreground are average curves calculated over 20 point moving windows. (b) dt/t between stacks of LP events collected during the hours before and after T_0 . Slopes have been calculated at each station for all vertical components providing for each station a mean value and standard deviation. Results are plotted as a function of the distance to the summit of the volcano.

a sudden velocity drop, by a few percent, at the volcano. The fact that the amplitude of the drop was maximum near the summit suggests that the induced change affected mostly the medium in the vicinity of the volcanic conduit. While the seismic waves reaching stations close to the summit mostly sampled the medium surrounding the conduit and are strongly delayed, waves reaching more distant stations sampled increasingly less affected media and therefore show reduced distortions. Calculations done using Coulomb 3.3 software [e.g., *Toda et al.*, 2005] indicate normal and shear stresses induced by the $M=7.3$ earthquake at the location of Yasur volcano on the order of 10 kPa. These low values for static stress suggest that the interaction mode was rather by dynamic stress transfer. The opening of cracks or the exsolution of gas from the conduit due to enhanced permeability caused by large amplitude shaking [*Rojstaczer et al.*, 1995] could be a possible explanation for the rapid medium change.

4. Conclusions

[9] The earthquake which occurred 80 km from Yasur did not bring any clear change to the seismic activity of the volcano in terms of radiated energy or number of generated transient events, nor did it bring any clear modification to its morphology. Despite this apparent lack of impact on the eruptive dynamics, examination of waveforms for LP events around the event shows that the distal earthquake induced measurable changes to the medium of the volcano. Here we demonstrate that repeating seismic events and CWI are an efficient tool to image these changes. Because similar events are commonly observed at volcanoes around the world, the technique could provide important information on the effect of large tectonic earthquakes on the internal structure of volcanoes, thereby providing important clues on the nature of earthquake-volcano interaction and eruption triggering.

[10] **Acknowledgments.** All the data used in this study were collected during a temporary experiment carried with seismic stations from the French seismic networks IHR and RISC (Isterre, Grenoble, France). We are grateful to D. Nakedau and R. Yatika who helped significantly in field work and A. Harris and J.-L. Got who helped improving the quality of the paper. We are grateful to D. P. Hill and an anonymous reviewer for constructive reviews. This work has been supported by the ANR (France) contract ANR-06-CATT-02 Arc-Vanuatu.

[11] The Editor thanks David Hill and an anonymous reviewer for assisting in the evaluation of this paper.

References

Brenguier, F., N. M. Shapiro, M. Campillo, V. Ferrazzini, Z. Duputel, O. Coutant, and A. Nercessian (2008), Towards forecasting volcanic eruptions using seismic noise, *Nat. Geosci.*, *1*, 126–130, doi:10.1038/ngeo104.

Campillo, M. (2006), Phase and correlation in random seismic fields and the reconstruction of the Green function, *Pure Appl. Geophys.*, *163*, 475–502, doi:10.1007/s00024-005-0032-8.

Cannata, A., G. Di Grazia, P. Montalto, M. Aliotta, D. Patanè, and E. Boschi (2010), Response of Mount Etna to dynamic stresses from distant earthquakes, *J. Geophys. Res.*, *115*, B12304, doi:10.1029/2010JB007487.

Chouet, B. (1996), Long-period volcano seismicity: Its source and use in eruption forecasting, *Nature*, *380*, 309–316, doi:10.1038/380309a0.

Cigolini, C., M. Laiolo, and D. Coppola (2007), Earthquake–volcano interactions detected from radon degassing at Stromboli (Italy), *Earth Planet. Sci. Lett.*, *257*, 511–525, doi:10.1016/j.epsl.2007.03.022.

Delle Donne, D., A. J. L. Harris, M. Ripepe, and R. Wright (2010), Earthquake-induced thermal anomalies at active volcanoes, *Geology*, *38*, 771–774, doi:10.1130/G30984.1.

Gomberg, J., and P. Johnson (2005), Dynamic triggering of earthquakes, *Nature*, *437*, 830, doi:10.1038/437830a.

Grêt, A., R. Snieder, R. C. Aster, and P. R. Kyle (2005), Monitoring rapid temporal change in a volcano with coda wave interferometry, *Geophys. Res. Lett.*, *32*, L06304, doi:10.1029/2004GL021143.

Haney, M. M., K. van Wijk, L. A. Preston, and D. F. Aldridge (2009), Observation and modeling of source effects in coda wave interferometry at Pavlof volcano, *Leading Edge*, *28*, 554–560, doi:10.1190/1.3124930.

Harris, A. J. L., and M. Ripepe (2007), Regional earthquake as a trigger for enhanced volcanic activity: Evidence from MODIS thermal data, *Geophys. Res. Lett.*, *34*, L02304, doi:10.1029/2006GL028251.

Hill, D. P., F. Pollitz, and C. Newhall (2002), Earthquake–volcano interactions, *Phys. Today*, *55*(11), 41–47, doi:10.1063/1.1535006.

Linde, A. T., and I. S. Sacks (1998), Triggering of volcanic eruptions, *Nature*, *395*, 888–890, doi:10.1038/27650.

Manga, M., and E. E. Brodsky (2006), Seismic triggering of eruptions in the far field: Volcanoes and geysers, *Annu. Rev. Earth Planet. Sci.*, *34*, 263–291, doi:10.1146/annurev.earth.34.031405.125125.

Marzocchi, W. (2002), Remote seismic influence on large explosive eruptions, *J. Geophys. Res.*, *107*(B1), 2018, doi:10.1029/2001JB000307.

Moran, S. C., J. A. Power, S. D. Stihler, J. J. Sánchez, and J. Caplan-Auerbach (2004), Earthquake triggering at Alaskan volcanoes following the 3 November 2002 Denali Fault earthquake, *Bull. Seismol. Soc. Am.*, *94*(6B), S300–S309, doi:10.1785/0120040608.

Okubo, P. G., and C. J. Wolfe (2008), Swarms of similar long-period earthquakes in the mantle beneath Mauna Loa Volcano, *J. Volcanol. Geotherm. Res.*, *178*, 787–794, doi:10.1016/j.jvolgeores.2008.09.007.

Perrier, L. (2011), Apport de l'étude des sources sismo-volcaniques à la connaissance des processus éruptifs du volcan Yasur, Vanuatu, PhD thesis, Univ. de Grenoble, Saint Martin d'Hères, France.

Poupinet, G., W. L. Ellsworth, and J. Fréchet (1984), Monitoring velocity variations in the crust using earthquake doublets: An application to the Calaveras Fault, California, *J. Geophys. Res.*, *89*, 5719–5731, doi:10.1029/JB089iB07p05719.

Ratdomopurbo, A., and G. Poupinet (1995), Monitoring a temporal change of seismic velocity in a volcano: Application to the 1992 eruption of Mt. Merapi (Indonesia), *Geophys. Res. Lett.*, *22*(7), 775–778, doi:10.1029/95GL00302.

Rojstaczer, S., S. Wolf, and R. Michel (1995), Permeability enhancement in the shallow crust as a cause of earthquake-induced hydrological changes, *Nature*, *373*, 237–239, doi:10.1038/373237a0.

Schaff, D. P., and G. C. Beroza (2004), Coseismic and postseismic velocity changes measured by repeating earthquakes, *J. Geophys. Res.*, *109*, B10302, doi:10.1029/2004JB003011.

Shapiro, N. M., and M. Campillo (2004), Emergence of broadband Rayleigh waves from correlations of the ambient seismic noise, *Geophys. Res. Lett.*, *31*, L07614, doi:10.1029/2004GL019491.

Snieder, R., and M. Hagerty (2004), Monitoring change in volcanic interiors using coda wave interferometry: Application to Arenal Volcano, Costa Rica, *Geophys. Res. Lett.*, *31*, L09608, doi:10.1029/2004GL019670.

Snieder, R., A. Grêt, H. Douma, and J. Scales (2002), Coda wave interferometry for estimating nonlinear behavior in seismic velocity, *Science*, *295*, 2253–2255, doi:10.1126/science.1070015.

Speranza, F. F., and R. Carniel (2008), Structural changes of volcanic tremor at Stromboli volcano, *J. Volcanol. Geotherm. Res.*, *171*, 103–117, doi:10.1016/j.jvolgeores.2007.11.003.

Toda, S., R. S. Stein, K. Richards-Dinger, and S. Bozkurt (2005), Forecasting the evolution of seismicity in Southern California: Animations built on earthquake stress transfer, *J. Geophys. Res.*, *110*, B05S16, doi:10.1029/2004JB003415.

Walter, T. R. (2007), How a tectonic earthquake may wake up volcanoes: Stress transfer during the 1996 earthquake–eruption sequence at the Karymsky Volcanic Group, Kamchatka, *Earth Planet. Sci. Lett.*, *264*, 347–359, doi:10.1016/j.epsl.2007.09.006.

Walter, T. R., and F. Amelung (2006), Volcano–earthquake interaction at Mauna Loa volcano, Hawaii, *J. Geophys. Res.*, *111*, B05204, doi:10.1029/2005JB003861.

Walter, T. R., R. Wang, M. Zimmer, H. Grosse, B. Lühr, and A. Ratdomopurbo (2007), Volcanic activity influenced by tectonic earthquakes: Static and dynamic stress triggering at Mt. Merapi, *Geophys. Res. Lett.*, *34*, L05304, doi:10.1029/2006GL028710.

West, M., J. J. Sánchez, and S. R. McNutt (2005), Periodically triggered seismicity at Mount Wrangell, Alaska, after the Sumatra earthquake, *Science*, *308*, 1144–1146, doi:10.1126/science.1112462.