

Geology

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Geology 2010;38:771-774
doi: 10.1130/G30984.1

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Notes

Earthquake-induced thermal anomalies at active volcanoes

Dario Delle Donne¹, Andrew J.L. Harris², Maurizio Ripepe¹, and Robert Wright³

¹Dipartimento di Scienze della Terra, Università di Firenze, via La Pira 4, 50121, Florence, Italy

²Laboratoire Magmas et Volcans (LMV), Université Blaise Pascal, 5 Rue Kessler, 63038 Clermont Ferrand, France

³Hawai'i Institute of Geophysics and Planetology, School of Ocean and Earth Science and Technology (HIGP/SOEST), University of Hawai'i, 1680 East-West Road, Honolulu, Hawaii 96822, USA

ABSTRACT

Answering the question whether a regional earthquake can trigger or enhance volcanic activity requires a systematic measure of volcanic activity. One such measure is heat flux. The availability since A.D. 2000 of a satellite-derived heat flux inventory for global volcanism allows us to explore how earthquakes and volcanic activity may be linked. Examination of 7 yr of global volcanic heat flux data reveals 37 volcanic responses to regional earthquakes. Each response is expressed by an increase in heat flux within 1–21 days of the triggering earthquake. Whether a volcano responds depends on earthquake magnitude, distance to the epicenter, and orientation of the earthquake focal mechanism in respect to the volcano: the focal mechanism has to align with the responding system. Of the 7 global major increases of seismic energy during 2000–2006, 4 were followed by a global volcanic heat flux increase. The largest response involved a 300% increase and followed the largest earthquake in the period, the 2004 Sumatra-Andaman (Indonesia) earthquake, moment magnitude, $M_w = 9.3$.

INTRODUCTION

Many have demonstrated that volcanic and tectonic activity can be linked at various temporal and spatial scales (e.g., Linde and Sacks, 1998; Hill et al., 2002; Manga and Brodsky, 2006; Walter et al., 2009; Watt et al., 2009; Eggert and Walter, 2009). Triggering of volcanic eruptions by regional earthquakes has been observed for both effusive and explosive eruptions; Kilauea's (Hawaii) November 1975 eruption (Tilling et al., 1976), Pinatubo's (Philippines) 1991 eruption (Bautista et al., 1996), and Cordón Caulle's (Chile) 1960 eruption (Lara et al., 2004) have all been linked with large regional earthquakes. In Harris and Ripepe (2007) it was shown that responses could be realized at systems where eruptions were already underway, postulating coupled responses at two Javanese volcanoes active during a Local Magnitude 6.3 earthquake that occurred just offshore Java. Likewise, Fattori Speranza and Carniel (2007) noted that tectonic earthquakes can influence tremor associated with persistent volcanic activity at Stromboli (Italy).

Satellite-based volcano monitoring has evolved rapidly over the past decade; thermal infrared sensors flown on geostationary and polar orbiting satellites now provide regional- to global-scale information for volcanic hotspots on an hourly to daily basis (e.g., Harris et al., 2000a; Wright et al., 2004). Such a capability has allowed construction of global heat flux inventories for all erupting volcanoes (e.g., Wright and Flynn, 2004), as well as decade-scale time series detailing trends resulting from repeated explosive and effusive activity at individual, persistently active, volcanoes (e.g., Harris and Stevenson, 1997; Harris et al., 2000b). Such heat flux time series can, in turn, be used to assess earthquake-induced changes in heat flux at systems where eruptions are underway (e.g., Harris and Ripepe, 2007). Global, satellite-based, heat flux inventories can thus be used with global earthquake databases to test the commonality of earthquake-induced changes in heat flux at erupting volcanoes and to increase our understanding as to how earthquakes and volcanoes interact.

We use data from the moderate resolution imaging spectroradiometer (MODIS) sensor flown aboard the National Aeronautic and Space Administration's Terra and Aqua satellites. The MODIS sensors on these two satellites pass over every point on the planet four times a day, allowing

detection of thermal anomalies associated with ongoing volcanic activity. The MODVOLC detection algorithm allows automated global hotspot detection in MODIS data and provides a global inventory for volcanic hotspots dating back to February 2000 (Wright et al., 2004). Spectral radiance data recovered for hotspots detected by MODVOLC can be converted to heat flux for all terrestrial eruptions (Wright and Flynn, 2004). The MODVOLC database does not provide complete information for all global volcanic activity because, being an algorithm designed to locate global hotspots with minimal false alarms, it is simply not intended to detect low intensity activity (open vent degassing, fumarolic activity, Strombolian activity). However, for effusive events (lava flows, lakes, and domes), MODVOLC is effective in detecting the associated thermal anomaly (Wright et al., 2004), with variation in resulting radiance time series providing a good proxy for the level of effusive activity (Wright and Flynn, 2004). This database thus constitutes a record of volcanic thermal activity that can be used to assess whether regional earthquakes can trigger a change in effusive activity, and to identify those conditions necessary if a change is to be felt. To do this we have correlated the MODVOLC-derived heat flux time series with the record of global earthquake activity reported by the U.S. Geological Survey Global Seismic Network (<http://earthquake.usgs.gov/regional/ncic/>).

METHOD

During 2000–2006, MODVOLC detected thermal anomalies at 65 volcanoes across the globe (Table DR1 in the GSA Data Repository¹). Thermal radiance data for each detected anomaly were converted to heat flux, in units of watts or joules per second, following the method of Wright and Flynn (2004). For each earthquake in the U.S. Geological Survey Global Seismic Network catalogue with a local magnitude (M_L) >4.5 (the catalogue is only complete for $M_L > 4.5$), we cross-checked the volcanic heat flux time series searching for increases in heat flux immediately following each earthquake. We did this at two spatial scales, regional and global. The regional check involved finding all volcanic hotspots active within 750 km of the earthquake epicenter. For each located hotspot, the heat flux inventory was tested for a response. Response was defined using a 30-day-long window centered on the earthquake. The duration of this search window was based on evidence from Merapi and Semeru (Indonesia), where this was the typical time scale of response (Harris and Ripepe, 2007). If the mean heat flux for an individual volcano was at least twice as high in the 15 days after the earthquake as it was in the 15 days before, then the volcano was classified as responding. The global search involved the correlation between global seismic energy release for magnitudes higher than 4.5, and the global heat flux, calculated merging all the data relative to the active volcanoes. All the coherent fluctuations between the two data sets were then analyzed more in detail. In addition, we generated dummy earthquake and hotspot databases in which random temporal distributions of earthquakes and hotspots were generated for cross-correlation with the heat flux inventory to test if the same results could be obtained by chance.

¹GSA Data Repository item 2010218, Table DR1 (list and details of the 37 earthquake-triggered volcano heat flux responses found in the MODVOLC data set), is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Finally, analysis of earthquake focal mechanisms, as given by the Harvard Centroid Moment Tensor Project (<http://www.globalcmt.org>), allowed us to define the orientation (strike) of the fault plane and the azimuth between earthquake epicenter and responding volcano. The focal mechanism gives two possible solutions, where we select the fault plane most consistent with the regional tectonic framework.

RESULTS 1: EARTHQUAKE-VOLCANO INTERACTION AT A REGIONAL SCALE

From the 40,483 earthquakes with $M_L > 4.5$ that occurred during our study period, we found 37 earthquake-volcano interactions in the 7 yr spanning 2000–2006 at 24 different volcanoes (Table DR1). This means that 37% of the 65 volcanoes at which hotspot activity was detected by MODVOLC during 2000–2006 had a heat flux response to a regional earthquake. Of these responses, 22 (59%) occurred at volcanoes where activity was ongoing at the time of the earthquake; the remaining 15 cases were recorded at volcanoes that started to erupt only after the earthquake had occurred. The response of Augustine volcano (Aleutian Islands, U.S.), as given in Figure 1A, was typical of the response recorded for a vol-

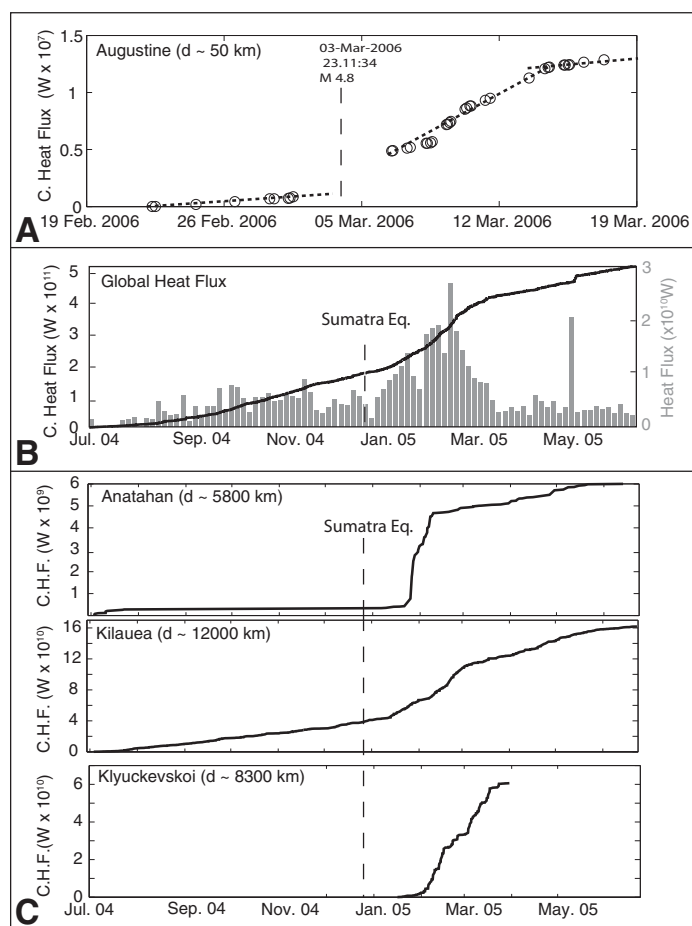


Figure 1. A: Cumulative heat flux recorded for Augustine volcano (Aleutian Island, Alaska) during February and March 2006. Time of magnitude 4.8 earthquake that occurred at 50 km (d, distance) from volcano is marked by vertical dashed line. **B:** Cumulative volcanic heat flux generated by all active volcanoes across globe during 1 yr period centered on date of the Sumatra-Andaman earthquake (Eq.). Global heat flux time series are plotted using 7-day-long bins. **C:** Cumulative heat flux (C.H.F.) for Klyuchevskoi, Anatahan, and Kilauea volcanoes for 1 yr period, centered on date of Sumatra-Andaman earthquake (vertical dashed line).

cano where activity was ongoing. On 3 March 2006, a M_L 4.8 earthquake occurred 50 km from the volcano. At the time of the earthquake, activity was ongoing at Augustine, where 9 hotspot detections had been recorded by MODVOLC over the 15 days prior to the earthquake. The increase in heat flux from 20 to 50 MW prior to the earthquake to 200–800 MW after was matched by an increase in volcanic tremor amplitude and in the frequency of small volcano-tectonic earthquakes (as reported in Siebert and Simkin, 2008). After 14 March, heat flux returned to the pre-response levels (Fig. 1A), in agreement with ground-based reports of decreased activity (see Siebert and Simkin, 2008).

All heat flux responses recorded by us follow the Augustine-type trend, and match the heat flux response recorded (Harris and Ripepe, 2007) at Merapi and Semeru to a $M_L = 6.3$ earthquake that occurred 50 and 300 km from the two volcanoes, respectively.

A generic three-stage heat flux response can thus be defined. First, we record a steady level of low heat fluxes, or no thermal anomaly at all, prior to the earthquake. Second, a sudden, but short-lived increase in heat flux is recorded beginning shortly after the earthquake. Third, the response is completed by a return to low heat fluxes typical of the pre-earthquake levels.

For the cases recorded by us and documented in Table DR1, the response lasts 4–50 days. All responses occurred within 21 days of the triggering earthquake, but most (67%) responses occurred within 5 days (Fig. 2A), the median delay time being 3 days.

We assess the response proportion in terms of a cumulative response ratio, $P(>M_L)$, which considers the ratio between the number of positive responses, $N_{\text{trig}}(\geq M_L)$, and the total number of earthquakes $N_{\text{tot}}(\geq M_L)$ with magnitude greater than M_L , that occurred within 750 km of the volcano. We find that the response ratio increases exponentially with earthquake magnitude (Fig. 2A), so that $\log P(>M_L) = 0.67M_L - 3.86$ ($R^2 = 0.99$). As a result, the response ratio increases from <0.1% for $M > 4.5$, to 15%

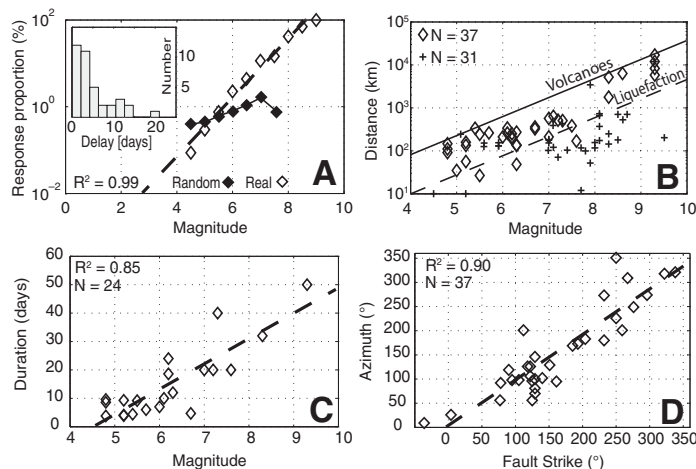


Figure 2. A: Correlation between response proportion and earthquake magnitude obtained from real (white diamonds) and random (black diamonds) data sets. Response proportion obtained from random test is always between 0.3% and 2% for every magnitude class and shows decreasing trend for magnitudes above 7. Inset: Frequency distribution of lag between earthquake occurrence and response. **B:** Correlation between earthquake magnitude and distance from responding volcano. Diamonds—data from our study; crosses—results of Bautista et al. (1996), Lara et al. (2004), West et al. (2005), Linde and Sacks (1998), Brodsky and Prejean (2005), Gresta et al. (2005), Cigolini et al. (2007), and Walter et al. (2009). Bold lines—linear relation defined from these data ($M = -6.4 + 2.17 \log R$; see text); dashed line—linear relation identified for earthquake-induced soil liquefaction. **C:** Correlation between earthquake magnitude and response duration. **D:** Correlation between earthquake fault strike and volcano azimuth.

for $M > 7.5$, reaching 100% for $M > 8.5$. We could not generate the same results using our randomly generated earthquake temporal distributions. Our random distribution, in contrast to the real results, did not produce the same interactions, but the response ratio is almost the same for all the magnitude classes (Fig. 2A).

As shown in Figure 2B, the distance between the earthquake epicenter and responding volcano also correlates positively with the magnitude of the triggering earthquake ($R^2 = 0.89$).

Likewise, we find positive correlations between earthquake magnitude and response duration (Fig. 2C), as well as fault strike direction and azimuth of the responding volcano in relation to the location of the epicenter for the triggering earthquake.

RESULTS 2: GLOBAL RESPONSES

The plots of global cumulative seismic energy and global volcanic heat flux during 2000–2006 show that the main positive inflections in the volcanic heat flux follow the inflections in the cumulative seismic energy plot (Fig. 3). Responses are seen in the global volcanic heat flux plot following four of the seven major increases in the global seismic energy (Fig. 3). The greatest heat flux response followed the highest magnitude earthquake of the period, the 26 December 2004 Sumatra-Andaman earthquake (Indonesia, $M_w = 9.3$) earthquake, a megathrust event that involved an ~1000-km-long fault segment. Following this event, the heat flux generated by global volcanic activity, which was already at relatively high level since April 2004, underwent a 300% increase (Fig. 1B). The response persisted for four months, with pre-earthquake global volcanic heat flux levels being returned to in late April 2005. In the first 2 months following the earthquake, ~12.5% of the total heat flux measured on Earth during the 7-yr-long investigation period was released. As in the other global responses recorded in Figure 3, responses were witnessed at volcanoes located thousands of kilometers from the earthquake epicenter.

Within 21 days of the Sumatra-Andaman event responses were realized at 4 volcanoes (Fig. 1C): Kilauea (delay = 1 day, distance = 12,000 km), Anatahan (Northern Mariana Islands; delay = 11 days, distance = 5800 km), Popocatepetl (Mexico; delay = 13.2 days, distance = 17,000 km), and Klyuchevskoi (Russia; delay = 21 days, distance = 8300 km).

Of the seven events of major seismic energy increase occurring between 2000 and 2006, only those related to the 25 September 2003

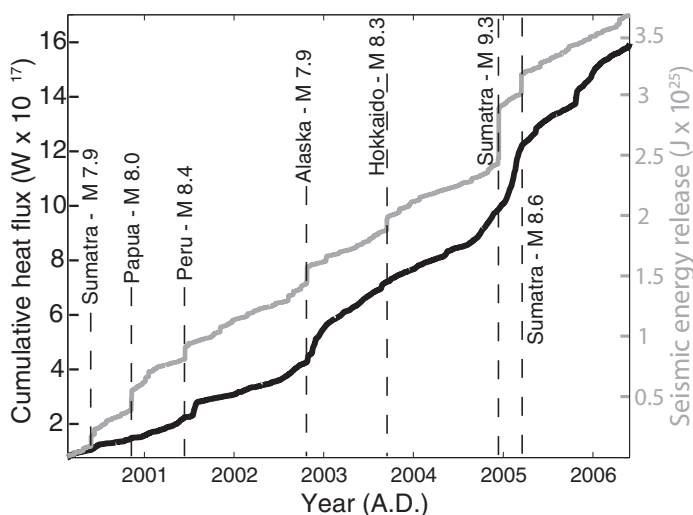


Figure 3. Cumulative seismic energy (thin line) and heat flux (bold lines) from all global earthquake ($M > 4.5$) and volcanic activity during 2000–2006. All major increments in seismic energy correspond to earthquakes of $M > 7.8$ and are indicated by dashed lines.

Hokkaido (Japan; $M = 8.3$), the 28 March 2005 Northern Sumatra (Indonesia; $M_w = 8.6$), and the 26 November 2000 Papua New Guinea ($M = 8.0$) events were not associated with a clear global heat flux responses. Of these three events, the second occurred when the global heat flux was still responding to the Sumatra-Andaman earthquake, which may have masked any possible response. The only one of the five major increases in the global volcanic heat flux that is not related to an evident increase in the global seismic energy release occurred in October 2005 and is related to the onset of the activity of the Sierra Negra volcano (Mexico).

DISCUSSION: TRIGGERING CONDITIONS

Can earthquakes really induce enhanced volcanic heat flux, or is what we observed a random coincidence? Our tests argue for the former, and show that factors involved in generating a response are many and varied, with many earthquakes not being associated with a heat flux response. However, regional earthquakes appear to play a role in determining the conditions that favor eruption or change in the heat fluxes during ongoing activity in some cases.

Conditions That Favor Response

Static stress change induced by an earthquake decays rapidly ($1/R^3$), so that it can be considered significant only at small distances (Walter and Amelung, 2007). In contrast, dynamic stresses, due to passage of seismic surface waves with period of 20–50 s, can be felt at greater distances, with the stress decaying less rapidly ($1/R^{1.66}$) (Brodsky and Prejean, 2005; Hill, 2008). Thus, given the large distances (typically >100 km) of many of our responding volcanoes from the triggering epicenter, a dynamic stress model appears more appropriate as an explanation for the earthquake-volcano interaction.

In Figure 2B we also consider all other cases reported in the literature. This allows us to define an empirical relationship:

$$M = -6.4 + 2.17 \log R_{\max}, \quad (1)$$

where R represents a distance limit, expressed in meters, beyond which, for a given magnitude earthquake, no response may be expected. Rearranging equation 1 allows the maximum distance for interaction (R_{\max}) to be obtained. This relationship agrees well with the empirical limits defined between earthquake R_{\max} and M defined by Wang et al. (2005) and Montgomery and Manga (2003) in order for earthquake-induced liquefaction to occur, as shown in Figure 2B. The similar slopes of these linearly defined triggering limits (2.26 herein; 2.17 in Wang et al., 2005) suggest that magma chambers, magma-filled conduits, and saturated soils undergo similar stress-induced fluid-dynamical processes when subjected to the passage of seismic waves.

Nevertheless, there are many cases where erupting volcanoes in the vicinity of a regional earthquake did not respond, so that distance cannot be considered as the only factor controlling the earthquake-volcano interaction. However, we also find a positive correlation between the earthquake magnitude and thermal anomaly response duration (Fig. 2C): higher magnitude earthquakes generate longer responses than lower magnitude events. For all responses reported here, the volcano azimuth is within 30° of the fault strike for the associated earthquake (Fig. 2D). Thus, volcanoes may preferentially be triggered at locations aligned with the fault plane orientation. The 80% of the focal mechanisms of the triggering earthquakes show large strike-slip and vertical dip-slip components. This is consistent with a scenario whereby the radiation pattern of Love waves are larger along the fault strike (Kanamori, 1970). Moreover, the propagation of fault rupture thus may also have a fundamental role in focusing the stress in a well-defined direction and could determine whether a response will be realized or not, with rupture directivity being a major factor in focusing radiated energy in a strike-parallel direction.

CONCLUSION

Our analysis shows that whether a volcano will respond to a regional earthquake depends on the magnitude and distance of the earthquake, but also may depend on the fault orientation in relation to the location of the volcano. Rupture directivity thus seems to be a good candidate to explain why volcanoes do not always respond to earthquake-induced dynamic stress, even when the magnitude of the earthquake is high and the epicenter close to the erupting volcano. The orientation of the fault plane could be thus an additional factor that may favor the response of a volcano to an earthquake. The duration of the response seems dependent on the magnitude of the earthquake, so that higher-magnitude earthquakes can induce longer lasting periods of enhanced heat flux at more distant volcanoes. However, many questions, for example, why we saw no proximal responses to the Sumatra-Andaman earthquake, remain. We cannot answer this question with our data, but we do note that our investigation mostly considers responses at effusive systems, and does not fully consider responses in fumarolic emission, explosive activity, or volcano seismicity. However, our analysis allows us to propose that dynamic stress changes induced by seismic waves can accelerate volcanic unrest processes underway at the time of the triggering earthquake. Seismic waves alone may not have sufficient energy to wake up a quiescent volcano, but may trigger a response if the volcano is in a critical state.

ACKNOWLEDGMENTS

This manuscript was improved by the useful and constructive reviews of Corrado Cigolini and two anonymous reviewers. Delle Donne and Ripepe were partially funded by an Italian Department of Civil Protection—DevNet grant.

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Manuscript received 21 December 2009

Revised manuscript received 22 March 2010

Manuscript accepted 27 March 2010

Printed in USA