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Frequency dependence of mud volcano response to earthquakes

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[1] Distant earthquakes can trigger the eruption of mud volcanoes. We document the response of the Davis-Schrimpf mud volcanoes, California, to two earthquakes and non-response to four additional events. We show that the Davis-Schrimpf mud volcanoes are more sensitive to long period seismic waves than to shorter period waves of the same amplitude. Our observations are consistent with models for dislodging bubbles and particles by time varying flows produced by seismic waves. Mobilizing trapped bubbles or particles increases permeability or fluid mobility, increasing discharge. **Citation:** Rudolph, M. L., and M. Manga (2012), Frequency dependence of mud volcano response to earthquakes, *Geophys. Res. Lett.*, *39*, L14303, doi:10.1029/2012GL052383.

1. Introduction

[2] Changes in crustal stress generated by earthquakes affect geological and hydrological processes at distances that exceed several times the length of the ruptured fault. Examples of triggered phenomena include other earthquakes, the eruption of magmatic and mud volcanoes, the eruption of geysers, changes in permeability of the crust, and increased discharge at springs and in streams. A review of these phenomena and compilation of observations are presented in *Wang and Manga* [2010].

[3] The eruption of mud volcanoes in response to earthquakes has a long history of being documented [e.g., *Pliny*, 1855; *Chigira and Tanaka*, 1997; *Manga and Brodsky*, 2006; *Mellors et al.*, 2007; *Bonini*, 2009; *Rudolph and Manga*, 2010]. Figure 1 shows the relationship between earthquake magnitude and the distance of the triggered eruption from the earthquake. There is a clear pattern in that larger earthquakes can trigger eruptions at greater distances. Also shown in Figure 1 is an estimate of the energy dissipated by the seismic waves at the eruption location [*Wang*, 2007]. Eruptions appear to be triggered for energy densities as small as 10^{-1} J/m^3. To put this number in perspective, sediments prone to liquefaction require energy densities >30 J/m^3 [*Green and Mitchell*, 2004] to liquefy by undrained consolidation, the mechanism thought to be responsible for liquefaction in the near-field [*Wang*, 2007]. Thus, the eruption of previously existing mud volcanoes is not likely to arise from the processes that create the small mud and sediment eruptions produced by liquefaction of shallow sediments. The mechanism or mechanisms responsible for mud volcano responses remain uncertain. Possible explanations include an increase in permeability or fluid mobility resulting from the mobilization of trapped colloidal particles [e.g., *Roberts and Abdel-Fattah*, 2009] or bubbles [e.g., *Beresnev*, 2006] by the time-varying flows produced by the passage of seismic waves.

[4] Here we investigate whether the frequency of seismic waves, in addition to their amplitude, plays a role in triggering eruptions. Our interest in establishing the presence or absence of a frequency-dependence is that it may be used to distinguish between triggering mechanisms. With a better understanding of how earthquakes trigger eruptions, it should be possible to more reliably assess whether any given eruption is the result of an earthquake. A prominent application is the ongoing eruption of mud at the Lusi eruption in Indonesia [*Davies et al.*, 2007] that has continued for >5 years and caused billions of dollars of economic losses [*Richards*, 2011]. In this case, the eruption has been attributed to an earthquake [e.g., *Mazzini et al.*, 2007, 2012], not an earthquake [e.g., *Manga*, 2007], or to drilling operations at a gas exploration well [e.g., *Davies et al.*, 2007, 2008].

2. Data

[5] Since March 2010, we have been monitoring the eruption of mud and CO_2 gas at subaerial hydrothermal vents in the Imperial Valley, California, at a set of features locally known as the Davis-Schrimpf mud volcanoes [*Lynch and Hudnut*, 2008]. Figure 2 shows the location of the Davis-Schrimpf seep field and the numbering scheme we use to identify each mud volcano. Their tectonic context, geochemistry, and geomorphology are described by *Lynch and Hudnut* [2008], *Svensen et al.* [2009] and *Onderdonk et al.* [2011], respectively. *Rudolph and Manga* [2010] documented their response to the 4 April 2010 magnitude 7.2 El Mayor-Cucapah earthquake and described the grain size distribution and rheology of the erupting mud. Since then, we have continued to monitor responses to large regional and small local earthquakes. Table 1 lists the earthquakes following which we collected measurements.

[6] We made campaign measurements several times per year and as soon as possible (always between 1 and 2 days) following local and regional earthquakes that may have produced shaking strong enough to trigger a response based on the empirical energy dissipation curves in Figure 1 and strain records from the nearby Wildlife Liquefaction Array. During each visit we measured gas discharge, mud temperature, and counted the number of fresh flows on the flanks of the mounds of mud. We measured gas discharge using a funnel (diameter 22 cm) attached to a Cole-Parmer gas flowmeter with stated accuracy ±5% and repeatability ±0.5%. The gas discharge was manually read from the flowmeter gauge, with uncertainty less than 10%. Temperature was measured using a thermistor. *Rudolph and Manga* [2010] show pictures of the mud volcanoes and fresh flows,

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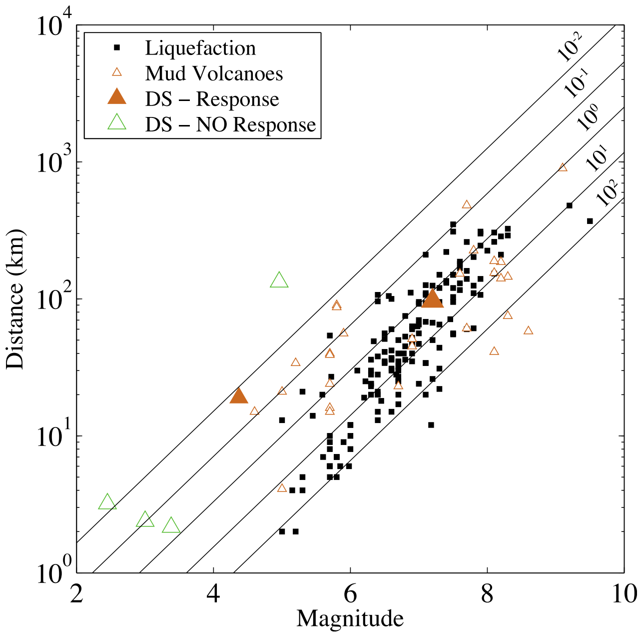

Figure 1. Occurrence of liquefaction and triggered eruption of mud volcanoes. Epicentral distance is the distance between the observation and earthquake epicenter. Magnitude is moment magnitude. Data tabulated in *Wang and Manga* [2010]. The four open green triangles indicate the four documented non-responses of the Davis-Schrimpf mud volcanoes. Labeled contour lines show seismic energy density is units of J/m^3 based on the model of *Wang* [2007].

defined as being active or having a moist surface appearance, indicating activity within a few days prior to the field visit. The first two field visits occurred prior to any of the earthquakes; at least three visits occurred prior to the start of construction at the nearby Hudson Ranch I geothermal facility; all visits occurred prior to the plant's commissioning on March 9, 2012 (M. Cichon, 49.9-MW Hudson Ranch I Geothermal Plant Unveiled in California, 2012, http://www.renewableenergyworld.com/rea/news/article/2012/05/49-9-mw-hudson-ranch-i-geothermal-plant-unveiled-in-calif).

Table 1. Attributes of six earthquakes for which we document responses

Date	Time (UTC)	Magnitude	Epicentral Distance	PGV (cm/s)	SCEC Catalog Number
April 4, 2010	22:40:42	7.2	96.6 km	14.4	14607652
September 14, 2010	10:52:18	4.96	133 km	0.12	10798005
December 15, 2010	19:16:47	4.37	18.97 km	0.17	14898996
April 2, 2011	02:32:51	2.45	3.19 km	0.07	14961412
February 11, 2012	09:46:47	3.0	2.46 km	0.08	11065613
February 29, 2012	17:35:55	3.4	2.16 km	0.25	15116321

[7] In order to assess the ground motion, we used data recorded at station CI.RXH, maintained by the Southern California Seismic Network, sited 4.5 km ESE from the mud volcanoes. The instrument is a CMG-3T broadband seismometer with response from 120 s to 50 Hz. Figure 2 shows the location of the instrument relative to the mud volcanoes and the 6 earthquakes for which we have gas discharge data. Because the broadband seismometer at CI.RXH clipped during the El Mayor-Cucapah event, we integrated acceleration data recorded at station NP.5062, which has a FBA-D instrument, to assess ground motion for this event only.

3. Results

[8] Figure 3 shows the measured gas flux and the number of fresh mud flows. We use vertical lines to indicate the time of earthquakes. At some volcanoes there are multiple data points as there are sometimes multiple vents. Responses to earthquakes are observed as increases in gas discharge. The

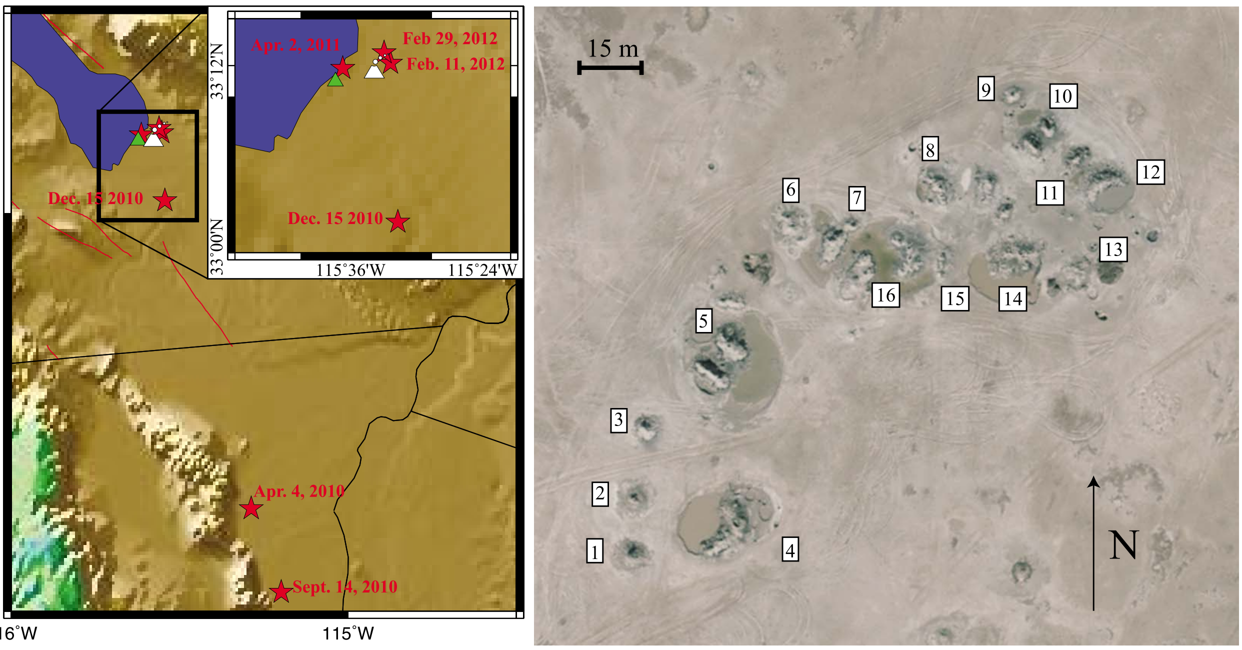

Figure 2. (left) Location of Davis-Schrimpf mud volcanoes (white volcano glyph), seismometer CI.RXH (green triangle), and the epicenters of earthquakes we consider (red stars). (right) Location and numbering convention of the mud volcanoes.

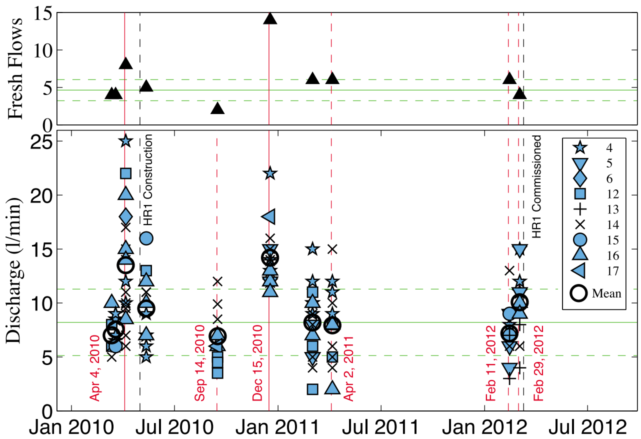

Figure 3. Number of (top) fresh mud flows observed and (bottom) gas discharge measured at mud volcanoes between March 2010 and March 2012. The legend associates symbols with individual mud volcanoes (locations shown in Figure 2). On a given day, there may be multiple data points at a given volcano if there are multiple active vents. Earthquakes that triggered a response are indicated by vertical solid lines and those that did not are indicated with vertical dashed lines. Dark circles indicate mean discharge on each date. The solid and dashed horizontal green lines indicate the mean and standard deviation of all data except those collected immediately following the April 4, 2010 and December 15, 2010 events. Vertical black dashed lines indicate start of construction and commissioning of the nearby Hudson Ranch I geothermal plant. Note that measurements were collected on two different dates prior to the 4 April, 2010 event.

mean discharge measured after the El Mayor-Cucapah and December 15, 2010 earthquakes was more than one standard deviation greater than the mean discharge computed from measurements collected on all other dates (Figure 3). There are no clear changes after the other four earthquakes. Temperature did not change following any of the earthquakes.

4. Discussion

[9] Larger earthquakes produce longer period seismic waves and the duration of shaking is longer as well. Thus the observation in Figure 1 that small earthquakes with large seismic energy densities do not increase eruption rate implies that short period waves or short shaking durations are less effective at influencing eruptions than long period waves. This is confirmed by spectrograms (Figure 4) of velocity waveform data. The key feature of the spectrograms in Figure 4 is that the two events to which the mud volcanoes responded have more power at low frequency than the four events that produced no response. The duration and amplitude of shaking during the September 14, 2010 event are greater than expected based on empiricisms (Figure 1), highlighting the importance of event-specific information.

[10] The earthquakes that produced responses differ from those that did not in that they had greater power spectral density (PSD) at low frequencies (0–1.3 Hz). Figure 5a shows that, in general, mean discharge increases with increasing (PSD) in the 0–1.3 Hz band. Low-frequency PSD was greater for those earthquakes that produced a response than those that did not by at least 3.5 dB/Hz, corresponding to a difference in amplitude at these frequencies of ~1.5 (Figure 5b). There is no correspondence between PSD at higher frequencies and mud volcano response (Figure 5b). Figure 5c shows the duration of shaking at low frequency with PSD greater than 10% of the maximum value. The duration of low frequency shaking during the September 14, 2010 event, which did not produce a response, was ~3 times greater than the December 15, 2010 event that did produce a response. This argues for frequency, rather than duration, as the more important factor in determining whether a response occurs.

[11] Our conclusion that long period seismic waves have a greater influence on mud eruptions is consistent with that reached in *Manga et al.* [2009] from an analysis of the reported responses of the Niikappu mud volcanoes in Japan to earthquakes [*Chigira and Tanaka*, 1997]. The present study adds quantitative measurements about the nature of the responses and the triggering ground motions, which were not available at Niikappu.

[12] Some other geological and hydrological responses to earthquakes also appear to be more sensitive to long period waves: triggered earthquakes in a geothermal setting [*Brodsky and Prejean*, 2005], non-volcanic tremor [*Guilhem et al.*, 2010], and field observations of liquefaction [e.g., *Wong and Wang*, 2007; *Holzer and Youd*, 2007]. However, as concluded in a recent review, "the data supporting this conclusion are still extremely sparse" [*Manga et al.*, 2012].

[13] Our primary objective in monitoring the Davis-Schrimpf mud volcanoes is to obtain observations that might provide insight into the mechanisms that trigger or modify eruptions. In this light we now assess which mechanisms

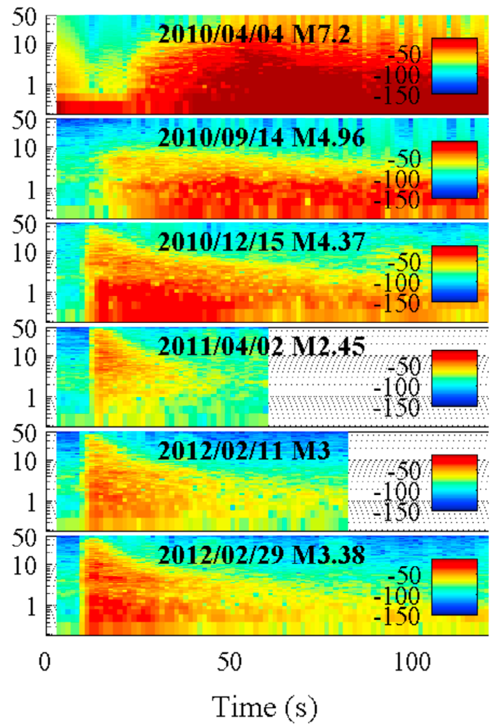

Figure 4. Spectrograms of East ground velocity for the 6 earthquakes listed in Table 1. Color scale represents power spectral density (dB/Hz). Spectrograms were calculated using a window length of 5.12 s, a Hamming mask, and window overlap of 384 samples.

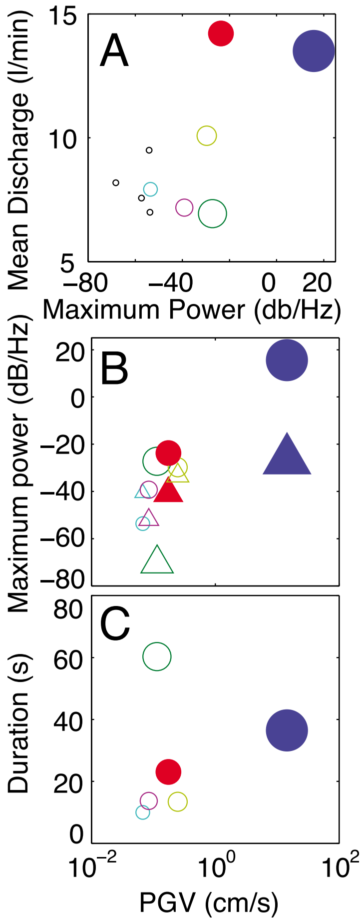

Figure 5. (a) Relationship between all mean discharge measurements and maximum PSD in the 0–1.3 Hz band. Size of symbols is proportional to earthquake magnitude. Filled symbols indicate earthquakes to which the mud volcanoes responded. Black circles indicate measurements that were not preceded by an earthquake. We used records from the two days preceding the measurement to compute PSD for these data. (b) Maximum PSD in the 0–1.3 Hz band (circles) and at 10 Hz (triangles). (c) Duration of shaking with power spectral density (PSD) in the 0–1.3 Hz band greater than 10% of the maximum recorded PSD, as a function of peak ground velocity (PGV).

are sensitive to the period of forcing. We consider only mechanisms that arise from time varying stress as these were 6 orders of magnitude larger than the static stress changes produced by the El Mayor-Cucapah earthquake [*Rudolph and Manga*, 2010]. We do not consider the possibility of subcritical crack growth because the system is already erupting and we document increases in eruption rate, not new eruptions. We also do not consider bubble pressurization as a mechanism because *Ichihara and Brodsky* [2006] have shown that it is not effective, and further, this mechanism is not frequency-dependent [*Brodsky and Prejean*, 2005].

[14] Dislodging particles and bubbles by fluid flow induced by time-varying stresses are mechanisms that depend on the frequency of deformation [e.g., *Beresnev*, 2006]. The pressure gradients created by inhomogeneous poroelastic properties will be proportional to strain amplitude. The time available to mobilize particles or bubbles by the flow induced by these pressure gradients will be proportional to the period of the seismic waves. Thus long period waves with a given amplitude should be more effective at mobilizing trapped bubbles and particles that may be limiting permeability and the otherwise free flow of fluids and gas. Laboratory experiments confirm that oscillatory flows mobilize particles [e.g., *Beckham et al.*, 2010] and trapped droplets [e.g., *Beresnev et al.*, 2011].

[15] Our observations do not provide new insight into the Lusi eruption in Indonesia. They are, however, consistent with previous compilations of observations that relate earthquake magnitude and distance over which triggered eruptions occur [*Mellors et al.*, 2007; *Manga et al.*, 2009; *Bonini*, 2009]. The magnitude-distance relationship shown in Figure 1 does not support an earthquake-trigger for the Lusi eruption.

5. Conclusion

[16] The Davis-Shrimpf mud volcanoes, like other mud eruptions, appear to be more sensitive to long period waves than shorter period waves with similar amplitudes. Mobilization of particles or bubbles by oscillatory flows induced by seismic waves is consistent with this observation.

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