Did an Earthquake Trigger the May 2006 Eruption of the Lusi Mud Volcano?

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On 29 May 2006, a mud volcano, unofficially named 'Lusi,' erupted in the Indonesian city of Sidoarjo, in eastern Java, covering an area of several square kilometers with mud [*Davies et al.*, 2007] and displacing more than 24,000 people [*Cyranoski*, 2007]. Two days earlier, a magnitude 6.3 earthquake occurred approximately 250 kilo-meters to the southeast. A 2800-meter-deep exploratory gas well, located about 200 meters from the mud eruption, experienced control problems within 5–7 hours of the earthquake (R. J. Davies, personal communication, 2007) indicating changes in fluid pressures soon after this earthquake. This earthquake is coincident with changes in eruptive behavior at nearby magmatic volcanoes [*Harris and Ripepe*, 2007; *Walter et al.*, 2007]. Did the earthquake trigger the eruption of the Lusi mud volcano?

The eruption of mud volcanoes is one of several possible subsurface hydrological responses to earthquakes. Within less than one or two fault lengths from the ruptured surface, static stress changes cause expansion or contraction of the crust which in turn can change pore pressure. Because static stress changes decay with the cube of the distance away from the main shock, at the distance of the mud volcano (about 30 fault lengths away from the epicenter), static stress changes are negligible. However, dynamic stress changes caused by propagating seismic waves will be much larger at such large distances. In unconsolidated sediments, if these transient stresses are large enough and there are sufficient cycles of deformation, grains can be rearranged into a more compact arrangement leading to an increase in pore pressure. If pore pressure increases to the point that it can bear the weight of the overburden, the sediment will lose strength and behave in a liquid-like manner. Such liquefaction is one way to create mud volcanoes.

Figure 1 shows the relationship between the distance of hydrological responses from earthquake epicenters as a function of the earthquake magnitude. These responses include changes in stream discharge, the occurrence of liquefaction, and the eruption of mud volcanoes from depths greater than a few hundred meters. The mechanisms that lead to these responses are varied, including liquefaction and changes in permeability [*Montgomery and Manga*, 2003]. Nevertheless, all responses likely involve a permanent change in subsurface properties. The black line is an empirically drawn upper bound for these hydrologic responses that also corresponds to a line of constant seismic energy density [*Wang et al.*, 2006]. This line is best interpreted as the maximum distance over which the indicated types of hydrologic response to an earthquake have been documented, and, presumably, these responses require optimal subsurface conditions and source properties: At distances below the line, no hydrological response is still the most common observation for most earthquakes.

Superimposed on this plot are data from the Lusi mud volcano. The star in Figure 1 shows the distance between the magnitude 6.3 earthquake and the Lusi mud volcano. This earthquake occurred at a distance well above the line in Figure 1, that is, at distances greater than we would expect to see the types of hydrologic response shown in Figure 1. A more convincing case that the earthquake did not trigger the eruption can be made by considering its noneruption in response to previous earthquakes. The solid circles in Figure 1 show the magnitudes and epicentral distances of regional earthquakes of magnitude greater than 6 since 1974. Only earthquakes with epicentral depths greater than 200 kilometers are included. Importantly, there were two earthquakes (in 1976 and 1998) that were larger and closer to the Lusi eruption, yet none, to my knowledge, triggered a mud-volcano eruption. In addition, there was a more distant magnitude 7.8 earthquake that falls below the empirical maximum-distance-for-hydrologic-response line plotted in Figure 1. No eruption was triggered.

The natural eruption of mud volcanoes does not require earthquakes, and most eruptions are probably not triggered by earthquakes [*Mellors et al.*, 2007]; tectonic compression, gas or fluid migration, and even ocean waves can lead to liquefaction or can fluidize unconsolidated sediments [e.g., *Maltman and Bolton*, 2003]. All these processes lead to overpressure developing on the (long) timescales that characterize the relevant geological process [*Kopf*, 2002]. If the system was so close to critical that it began erupting in 2006, it is surprising that none of the events closer to the empirical threshold line in Figure 1 triggered an eruption.

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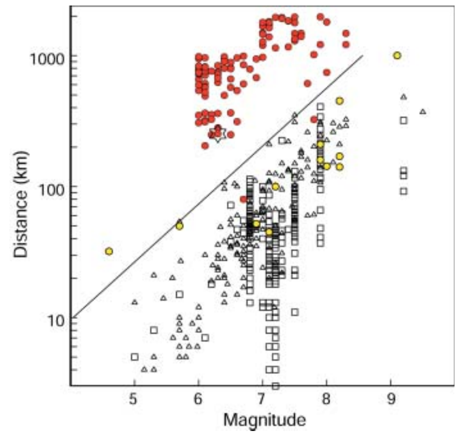

Fig. 1. Distance between the earthquake epicenter and hydrologic response as a function of earthquake magnitude. Increases in stream discharge, shallow liquefaction, and eruption of mud volcanoes are shown with open squares, triangles, and yellow circles respectively; data are from compilations and references presented by Montgomery and Manga *[2003] and* Wang et al. *[2005, 2006], with mud volcano data compiled by* Manga and Brodsky *[2006] and from Table 1 of* Mellors et al. *[2007]. The red circles show the distance between regional earthquakes and the location of the Lusi volcano. The star represents the distance between the Lusi mud volcano and the earthquake 2 days prior to the eruption. Earthquake locations and properties are obtained from the U.S. Geological Survey's National Earthquake Information Center catalog (http://neic.usgs.gov/neis/epic/epic.html).*

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