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Is the 2006 Yogyakarta Earthquake Related to the Triggering of the Sidoarjo, Indonesia Mud Volcano?

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Abstract

We examine the possible effect of shaking from the May 26, 2006 Yogyakarta earthquake (M_W 6.3) on the triggering of the Sidoarjo, Indonesia mud volcano, which is located about 250 km from the earthquake. The mud volcano has been erupting since May 2006. There seems to be indications from the timing of pressure changes in the neighborhood of the mud volcano and the earthquake occurrence, that the seismic waves may have affected the local fluid conditions. The level of stress changes from the earthquake waves is inferred from data of other similar sized earthquakes. The stress changes are quite small (0.005 to 0.010 MPa), but in the range of values that have triggered small earthquakes in other regions. There appeared to be pressure changes in the well drilling several minutes after the earthquake, suggesting a fluid response to the earthquake shaking. Although it seems possible that the 2006 Yogyakarta earthquake triggered small fluid pressure changes at the mud volcano, it is difficult to evaluate if there is any direct relation to the initiation of the mud eruption.

Key words: mud volcano, Sidoarjo, triggering, Yogyakarta earthquake, fluid pressure

I. Introduction

Since May 29, 2006 the large mud volcano LUSI (Lumpur Sidoarjo) has been erupting within the town of Sidoarjo, East Java in Indonesia (Davies *et al.*, 2007; Mazzini, *et al.*, 2007; Abidin *et al.*, 2008). In addition to the scientific interest in observing this event, the eruption has become an important social crisis because of the devastating impact on the local population. The mud and water flooding has destroyed over 10,000 buildings, including schools and factories. 4 people have been killed and over 15,000 evacuated. Since the initiation of the mud eruption, there has been heated debate about its relation to the drilling operations and the 2006 Yogyakarta earthquake (M_W 6.3) which occurred in central region of Java about the same time that the activity at LUSI began.

There is little seismic or other continuously recorded geophysical data during this time, so it is difficult to make conclusive statements about possible connections to the earthquake. Most of the reasoning for or against a direct relation between the earthquake and mud eruption comes from analogies to other examples. In this paper, we summarize available information and present our views on this issue.

II. Observations and Results

1) Inferred Level of Ground Motion in Sidoarjo

The Yogyakarta earthquake (M_W 6.3) of May

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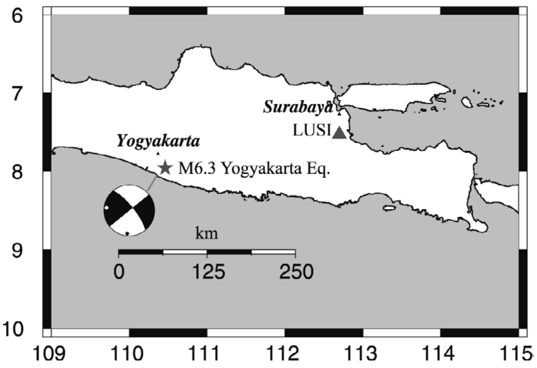

Fig. 1 Map showing locations of the mud volcano, LUSI (triangle) and 2006 Yogyakarta earthquake (star). The focal mechanism diagram shows a strike-slip earthquake.

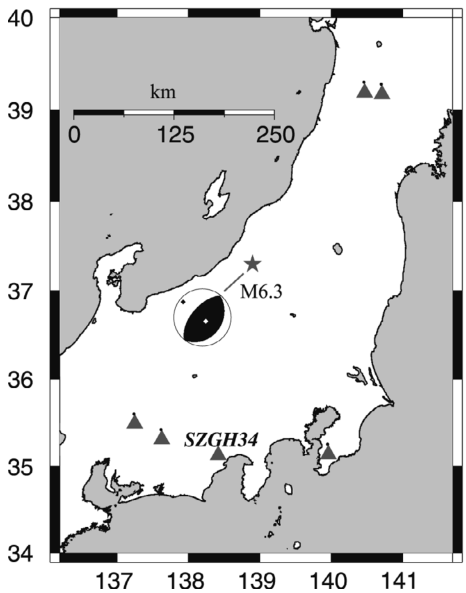

Fig. 2 Map showing locations M_W 6.3 earthquake (star) on October 23, 2004. at 09 : 34 (UTC) and stations (triangles) at distances from 246 to 258 km. Seismograms from station SZGH34 are shown in Fig. 3. The focal mechanism diagram shows a thrust northeast striking fault.

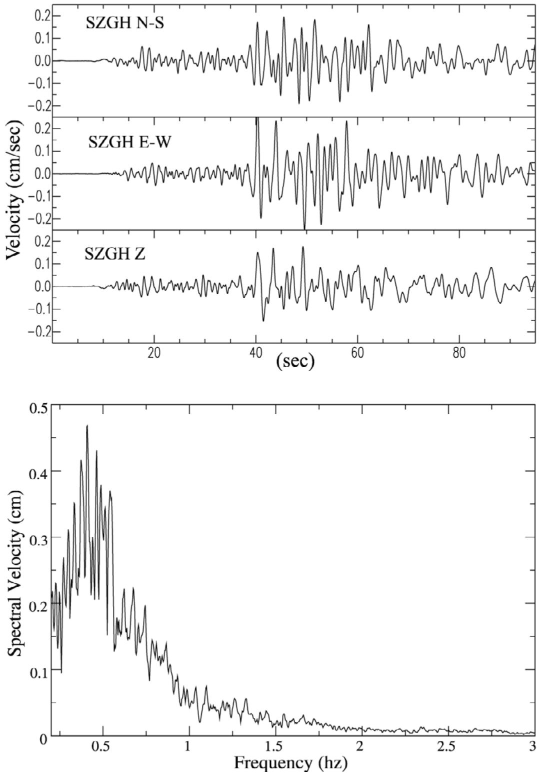

Fig. 3 Velocity seismograms (top) for a station located 248 km from a shallow M_W 6.3 earthquake recorded in Japan on October 23, 2004 at 09 : 34 (UTC). Velocity spectrum (bottom) averaged from 6 stations at distances of 246 to 258 km. All data are recorded in boreholes at depths of 100 to 200 m.

26, 2006, occurred at 22 : 53 : 58 (UTC) with a shallow (about 10 km depth) hypocenter at 7.96°S and 110.46°E, as determined by the National Earthquake Information Center of the U.S. Geological Survey. (It has been speculated that this earthquake is also associated with renewed activity at the nearby Merapi Volcano during May). The distance to LUSI is 252 km to the east (Fig. 1). The earthquake was lightly felt in Sidoarjo with Modified Mercalli Intensity level of II to III. Since there were no seismometers operating in Sidoarjo, we show a record for a similar size earthquake recorded at a similar distance in a borehole in Japan (Fig. 2). The level of shaking should be similar to the level at depth for the LUSI drill site. Fig. 3 shows seismograms for a shallow (depth 10 km) M_W 6.3 earthquake on October 23, 2004, at 09 : 34

recorded at station SZGH34, which is 246 km from the epicenter. The maximum velocity amplitudes are about 0.25 cm/s. The bottom portion of Fig. 3 shows the average spectral amplitudes for 6 different stations at epicentral distances of 246 to 258 km. Averaging the data from a number of stations will help reduce any unusual site or source effects that may dominate the data from a single station. The peak velocity amplitudes are in the frequency range from about 0.3 to 0.5 Hz. This level of ground motion is consistent with the observed Modified Mercalli Intensity II–III intensity observed in Sidoarjo from the Yogyakarta earthquake.

Without actual seismic recordings at the mud volcano site from the Yogyakarta earthquake, it is difficult to estimate precisely the level of ground shaking, however, we only want to estimate the order of magnitude of the seismic ground motions, for comparison with other triggering examples mentioned later in the paper. There are many uncertainties, as mentioned in the next paragraph, but this typical event from Japan should give the general level of shaking at a distance of about 250 km for the Yogyakarta earthquake, which has a similar size and depth.

The earthquake from Japan is recorded on a borehole stations which will minimize the effects of surface geology. Also, this estimate of seismic amplitude is consistent with the trying to infer the seismic amplitudes at depth of 1,000 to 2,000 m for the triggering process at LUSI. Difference in the earthquake source, such as focal mechanism or rupture directivity may affect the amplitudes, but these factors are all relatively small for the frequency range we are analyzing (*e.g.*, Liu and Heaton, 1984).

By most conventional thinking, such small ground motions would not be large enough to trigger magmatic eruptions, mud eruptions, or other earthquakes. For example, Manga and Brodsky (2006) compiled cases of mud volcanoes, liquefaction and other hydrological changes that were triggered by earthquakes. Their results indicate that the shaking at LUSI from the Yogyakarta earthquake is below the threshold level that would trigger a mud eruption, assuming a liquefaction mechanism. Mellors *et al.* (2007) also studied mud volcano triggering from earthquakes mainly in Azerbaijan, and found that there were induced eruptions for strong shaking levels of Modified Mercalli Intensity VI and distances less than 100 km.

On the other hand, over the last 15 years there has been a significant change in the way triggering mechanisms from earthquakes have been considered. Previously, most seismologists would probably have said that triggering of earthquakes over distances of hundreds to thousands of kilometers was not likely. Recently, however, there have been many published studies of small earthquakes occurring with the passage of seismic waves from other distance events that produce small stress changes on the level of 10^{-3} to 10^{-1} MPa (*e.g.*, Hill *et al.*, 1993; Miyazawa and Mori, 2006; Hill and Prejean, 2007; Fisher *et al.*, 2008). Most of these cases are associated with hydrothermal areas, so the role of fluids is thought to be important.

Fig. 4 shows the values of dynamic stress changes as a function of frequency, that have induced small seismic events for a number of recent examples, as compiled by Fisher *et al.* (2008). Small earthquakes have been produced by stress over a wide range of amplitudes from 10^{-3} to 1 MPa at frequencies of 0.02 to 0.5 Hz. The stress changes, σ, produced by seismic waves of the Yogyakarta earthquake in Sidoarjo are estimated using, $\sigma = v\ V_S\ \rho$ (Fisher *et al.*, 2008) where v is the observed particle velocity (0.1 to 0.2 cm/s), V_S is the S-wave velocity (2.0 km/s) and ρ is the density (2.5 g/cm^3). This gives estimates of 0.005 to 0.010 MPa for frequencies of 0.3 to 0.5 Hz. These values are in the lower portion but still within the range of amplitudes and frequencies that have been shown to have triggered small earthquakes in other regions.

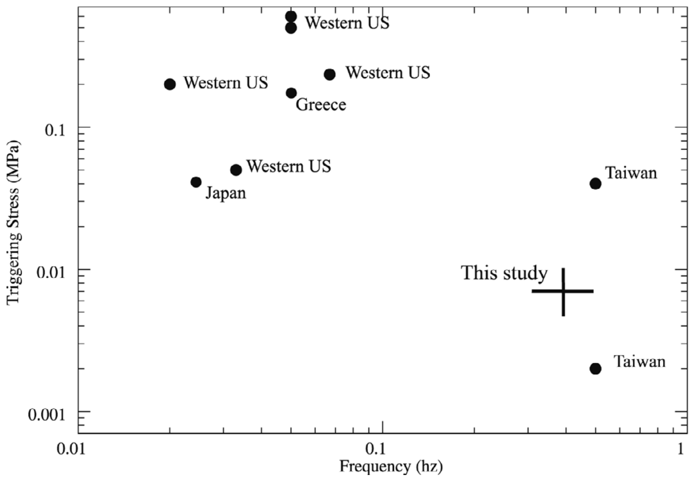

Fig. 4 Values for dynamic stress and frequency of seismic waves that have triggered small seismic events, compiled by Fisher *et al.* (2008). Cross shows the estimate for the Yogyakarta earthquake at LUSI.

2) Changes in Local Fluid Pressures due to Earthquakes

In addition to induced earthquakes, there are a number of examples of local fluid pressure changes due to seismic waves from distant earthquakes (*e.g.*, Roeloffs, 1998, Brodsky *et al.*, 2003; Kitagawa *et al.*, 2006). Pressure changes in water wells observed in California are associated with moderate and large earthquakes at distances of tens to hundreds of kilometers (Roeloffs, 1998). Also, with the passage of seismic waves, pressure changes in water wells can sometimes show large amplifications, which may be due to sudden changes in the permeability structure (Brodsky *et al.*, 2003). Such mechanisms may be especially applicable to overpressurized regions, such as at LUSI. As mentioned below, there was an apparent change in flow rate at a nearby gas well associated with the Yogyakarta earthquake.

3) Possible Response at LUSI

There was an apparent response a few minutes after the earthquake in the fluid pressure of the borehole that was being drilled at LUSI prior to the start of the mud eruption. The earthquake occurred at about 22 : 54 UTC on May 26 (05 : 54 on May 27 local time), and at about 23 : 00 the operators reported a small pressure loss in the borehole, which had reached a depth of 3,092 m. 7 hours later at 06 : 00 on May 27 there was a total loss of pressure in the well and the operators began to retrieve the drill string. At about 22 : 00 on May 27 there was an increase in pressure when the drill bit was at a depth of 1,413 m. The first signs of the mud eruption were observed at about 22 : 30 on May 28 at a location 150 m from the drill site. This surface manifestation of the mud volcano occurred about 48 hours after the earthquake. The time sequence of events for the drilling operations was presented by drillers of PT Lapindo Brantas at the International Geological Workshop on the Sidoarjo Mud Volcano, which was held February 20–21, 2007 in Jakarta.

4) Response of a Nearby Gas Well

At a gas well in Carat, which is located 4 km southwest of LUSI there was an apparent change in flow rate due to the earthquake. At that site, the flow rate is manually recorded about every hour by an operator. After the earthquake there was an apparent decrease in the flow rate of about 10 to 20 percent. So the shaking from the Yogyakarta earthquake seemed to have influenced fluid flows in the region.

III. Discussion

There are some indications that the Yogyakarta earthquake may have affected the local fluid conditions in the region. It may or may not be a coincidence that there was an observed pressure change in the well several minutes after the earthquake. Also, another nearby gas well seemed to have had a change in flow rate in association with the earthquake. Even though the stress changes caused by the earthquake are inferred to be quite small (about 0.005 to 0.01 MPa), there have been several recent studies showing that small earthquake, especially in hydrothermal regions, can be triggered by stresses of this size. An important question is then, can such small pressure escalate into a process that triggers a mud eruption?

If there is a connection between a small stress change produced by seismic waves and the triggering of a mud eruption, there needs to be a cascading type of mechanisms that amplifies the local fluid pressure changes. Changes of local pore pressure due to earthquakes have been attributed to processes such as, breakdown of the permeability structure (Brodsky *et al.*, 2003), mobilization of gas bubbles (Sturtevant *et al.*, 1996; Roeloffs, 1998) and shaking-induced dilatancy (Bower and Heaton, 1978). It is possible that these types of mechanisms could lead to a local increase in fluid pressure in the overpressurized zone. Then, hydrofractures in the overlying rock could open up pathways that lead to a surface eruption. In a cascading situation the small changes in pressure are important and might be clarified in pressure recordings from the well.

Of course, any stress changes caused by the seismic waves are very small compared to the disturbances caused by the drilling, also small compared to the conditions in the over-pressurized zone that is the source of the mud eruption. The earthquake, and possibly the drilling, can be regarded only as triggers, and certainly not the cause of the eruption. In this regard, one can raise the question, would the eruption have eventually occurred even if there had not been an earthquake, or if there had not been drilling? Geologically there is evidence on Java for large natural mud eruptions that are comparable in size or larger than LUSI (Itihara *et al.*, 1985).

A strong argument against a connection between the earthquake and mud volcano eruption, is that if such triggering occurred at such small stress levels, there should be many examples of triggered eruptions from the many earthquakes that are always occurring in the region. And, one might have expected eruptions to be triggered at other mud volcanoes in the region. However, triggering phenomena are often difficult to characterize because they may occur only a small percentage of the time. As pointed out in Mellors *et al.* (2007), there seems to be a good correlation of mud volcano eruptions with strong earthquake shaking in the Azerbaijan region, but most strong earthquakes do not trigger eruptions, and even for those earthquakes that do trigger eruptions, only a fraction of the potential mud volcanoes are triggered. So triggering appears to be a very selective process that depends strongly on the local conditions.

IV. Conclusions

Our view is that the shaking from the Yogyakarta earthquake likely perturbed the local fluid conditions of the region near LUSI. This is based on the close timing of pressure changes in the well with the earthquake occurrence, also the observation that there was a flow rate change at a nearby gas well. However, it remains an unanswered question whether this small change in fluid pressure was significant enough to actually trigger the mud volcano eruption.

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2006年ジョグジャカルタ地震は Sidoarjo 泥火山の噴出を誘発したか？

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2006年5月26日に発生したジョグジャカルタ地震による地震動が，250 km 離れたインドネシアの Sidoarjo 泥火山の噴出を誘発した可能性について検討した。この泥火山は2006年5月から噴出を続けている。泥火山の近傍で生じた流体圧変化と地震発生の時間的な一致から，地震波がこの地域の地下流体の状態に影響を与えたことが示唆される。別の同規模の地震のデータを用いて，地震波による応力変化の大きさを見積った。応力変化はごくわずか（0.005から0.010 MPa）であったが，他の地域であればこの程度の応力変化でも微小地震を誘発した場合がある。地震の数分後に流体圧変化が生じたようであり，これは地下流体が地震動に対して応答したことを示していると考えられる。2006年ジョグジャカルタ地震は，Sidoarjo 泥火山で小さな流体圧変化をひきおこした可能性があるが，これが泥火山の噴出開始に直接関係しているかどうか評価することは困難である。

キーワード： 泥火山，Sidoarjo，誘発，ジョグジャカルタ地震，地下流体圧

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