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The East Java mud volcano (2006 to present): An earthquake or drilling trigger?

Richard J. Davies [a,*], Maria Brumm [b], Michael Manga [b], Rudi Rubiandini [c], Richard Swarbrick [d], Mark Tingay [e]

[a] Centre for Research into Earth Energy Systems (CeREES), Department of Earth Sciences, University of Durham, Science Labs, Durham, DH1 3LE, UK
[b] Department Earth and Planetary Science, UC Berkeley, Berkeley CA 94720-4767, USA
[c] Petroleum Engineering, Teknik Perminyakan, Institut Teknologi Bandung, Jl. Ganesha No.10, Bandung 40132, Indonesia
[d] Geopressure Technology Ltd. Mountjoy Research Centre, Stockton Road, Durham, DH1 3UZ, UK
[e] School of Earth & Environmental Sciences, University of Adelaide, SA, 5005, Australia

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ABSTRACT

On May 29th 2006 a mud volcano, later to be named 'Lusi', started to form in East Java. It is still active and has displaced >30,000 people. The trigger mechanism for this, the world's largest and best known active mud volcano, is still the subject of debate. Trigger mechanisms considered here are (a) the May 27th 2006 Yogyakarta earthquake, (b) the drilling of the nearby Banjar Panji-1 gas exploration well (150 m away), and (c) a combination of the earthquake and drilling operations. We compare the distance and magnitude of the earthquake with the relationship between the distance and magnitude of historical earthquakes that have caused sediment liquefaction, or triggered the eruption of mud volcanoes or caused other hydrological responses. Based on this comparison, an earthquake trigger is not expected. The static stress changes caused by the rupture of the fault that created the Yogyakarta earthquake are a few tens of Pascals, much smaller than changes in stress caused by tides or variations in barometric pressure. At least 22 earthquakes (and possibly hundreds) likely caused stronger ground shaking at the site of Lusi in the past 30 years without causing an eruption. The period immediately preceding the eruption was seismically quieter than average and thus there is no evidence that Lusi was "primed" by previous earthquakes. We thus rule out an earthquake-only trigger. The day before the eruption started (May 28th 2006), as a result of pulling the drill bit and drill pipe out of the hole, there was a significant influx of formation fluid and gas. The monitored pressure after the influx, in the drill pipe and annulus showed variations typical of the leakage of drilling fluid into the surrounding sedimentary rock strata. Furthermore we calculate that the pressure at a depth of 1091 m (the shallowest depth without any protective steel casing) exceeded a critical level after the influx occurred. Fractures formed due to the excess pressure, allowing a fluid-gas-mud mix to flow to the surface. With detailed data from the exploration well, we can now identify the specific drilling induced phenomena that caused this man-made disaster.

1. Introduction

The east Java mud volcano known as 'Lusi' is over a year old, covers an area of >6.5 km^2 and has displaced >30,000 people (see Cyranoski, 2007). It was first observed as an eruption of gas, water, mud and steam in the Porong subdistrict of Sidoarjo in eastern Java on May 29th, 2006 (Davies et al., 2007; Manga, 2007; Mazzini et al., 2007; Fig. 1). Despite its unprecedented catastrophic impact on the local population and high media and scientific profile, one of the most fundamental questions about Lusi has yet to be resolved — was the eruption caused by exploration well operations (Davies et al., 2007), an earthquake (Mazzini et al., 2007), or a combination of the two phenomena? The 'liability debate' has significant socio-economic and political implications, and implications for future drilling operations, but very little has been published on the detailed scientific arguments behind each causal mechanism.

The Yogyakarta earthquake of May 27th 2006 had an epicentre 250 km from the eruption and a moment magnitude of 6.3. It is well known that earthquakes can trigger liquefaction (e.g. Ambraseys, 1988) and mud volcano eruptions (Chigira and Tanaka 1997; Panahi 2005; Manga and Brodsky, 2006; Mellors et al., 2007). By analogy, Mazzini et al. (2007) argued that the Yogyakarta earthquake triggered the Lusi eruption. Manga (2007), in contrast, showed that if an earthquake triggered the eruption it would represent an unprecedented sensitivity of the mud volcano system to seismic triggering. Manga (2007), also showed that there were larger and closer earthquakes that did not trigger an eruption. Also in contrast to Mazzini et al. (2007), Davies et al. (2007) proposed that Banjar Panji-1, a gas exploration borehole which was drilling through sedimentary rocks only 150–200 m away from where the eruption started, was the cause of the mud volcano (see Cyranoski, 2007; Normile, 2007).

* Corresponding author.
E-mail address: richard.davies@durham.ac.uk (R.J. Davies).

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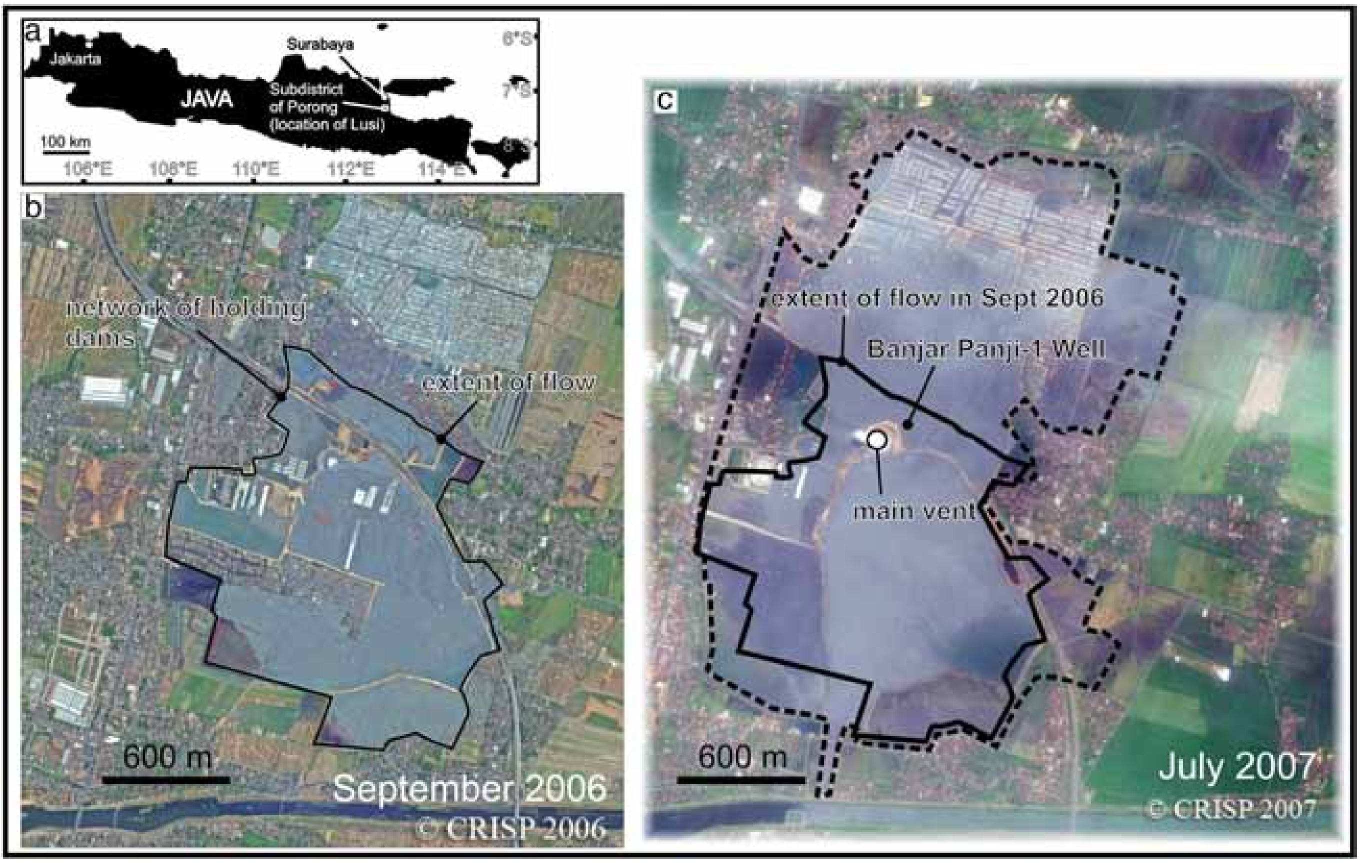

Fig. 1. a: Location of the Lusi mud volcano in East Java. b: Satellite photo from September 2006. c: Satellite photo from July 2007. Satellite photos courtesy of CRISP.

Available data can be used to resolve the conflicting hypotheses on the trigger mechanism. These data include historical records of earthquakes that have caused eruptions and the detailed records of what happened during the drilling of the Banjar Panji-1 exploration well. We show quantitatively and empirically that the trigger for the Lusi mud volcano can be identified. We first consider the possible effects of the Yogyakarta earthquake, followed by the role of drilling the Banjar Panji-1 exploration well and also the evidence for fault reactivation due to the earthquake. We then assess whether the trigger was the earthquake, a combination of the earthquake and drilling, or solely drilling operations.

1.1. Mud volcano systems

Mud volcanoes are an important means for the focussed escape of fluids and gases from sedimentary basins (Dimitrov, 2002). They are poorly understood phenomena because (a) we cannot witness most of the key processes directly, (b) little is known about the geological conditions prior to and during eruptions and (c) unlike igneous systems we know of no well exposed exhumed mud volcano systems where the rock-mud relationships can be examined. Mud volcano systems require fractures in overburden strata (Brown, 1990). These can be caused by hydraulic fracturing, when high pore fluid pressures exceed the minimum principal stress and tensile strength of the rock (Engelder, 1993). Such fractures can propagate on the order of 1000 s meters per day (Engelder, 1993). Once initiated, fractures will propagate to the surface if there is a continued source of high-pressure fluids. Subsequently, either buoyancy from gas exsolution or the excess pressure of the fluid source drives the water-mud mix to the surface (Brown, 1990).

In some mud volcano systems the source of fluid does not coexist with mud source beds. Rather, the fluid comes from deeper strata and then passes through mud strata that are susceptible to subsurface erosion (Bristow et al., 2000; Deville et al., 2003). We know little of the detailed structure of the feeder conduits (Davies and Stewart, 2005; Stewart and Davies, 2006) but they probably consist of a complex system of fractures and mud-filled dykes that feed a fluid-sediment mix to the earth's surface (e.g., Morley, 2003). The eruption of Lusi caused excitement amongst some mud volcanologists because it represents a unique scientific event: the geological conditions immediately prior to the eruption were observed in a gas exploration well, which was located 150–200 m away at the time of the eruption, and the birth and early stages of a mud volcano's evolution have not been closely observed before (Davies et al., 2007).

1.2. Geological setting

The Lusi mud volcano erupted in the East Java basin, which is an inverted extensional basin (Matthews and Bransden, 1995). It comprises a series of east-west striking half-graben that were active in extension during the Paleogene and reactivated in compression during the Early Miocene to Recent. The Oligo-Miocene to Recent basin is filled with shallow marine carbonates and marine muds, some of which are known to be overpressured (see Osborne and Swarbrick, 1997). As a result of the compressional inversion, these strata are gently folded with normal and reverse faults cutting the inversion anticline crests (see Matthews and Bransden, 1995). A section of one of these east-west trending anticlines was targeted by the Banjar Panji-1 exploration well. Several mud volcanoes have been identified before in East Java, the nearest is the Kalang Anyar mud volcano, which is 30 km from Lusi near Surabaya airport.

1.3. Background

Two days before the eruption started, on May 27th 2006, an earthquake measuring 6.3 in magnitude occurred 250 km to the east near Yogyakarta, Java. The Banjar Panji-1 exploration well had been on location in a populated part of Sidoarjo for several weeks before May 27th 2006. The well was 150–200 m from where the eruptions started, drilling toward its target, the Kujung Limestone and the drill bit was at a depth of approximately 2800 m. 6 h after the earthquake the well had reached a depth of 2834 m when there was a total 'loss of returns' — the mud that was meant to circulate down the drill pipe, through the bit, and back to the surface stopped flowing. Such mud losses occur when the mud flows into the rocks that are being drilled or into rocks already penetrated. This led to a decision to withdraw the drill-bit and drill-pipe (the steel pipe connecting the bottom hole assembly to the surface where an electric motor forces it to rotate) and this was carried out on the night of the May 27th and the early morning of the 28th May 2006.

The eruption began early on May 29th 2006. Over the following days several small edifices formed that were aligned in a NE-SW direction (Davies et al., 2007; Mazzini et al., 2007) and it has been suggested that these track along the trend of a NE-SW fault zone that was reactivated during the earthquake (Mazzini et al., 2007). As of February 2007, 0.045 km^3 of mud and water had been erupted. Mazzini et al. (2007) provides a useful overview, stating that (a) the volumes of erupted mud increased from the initial 5000 m^3 per day during early stages to 120,000 m^3 per day by August 2006, (b) temperatures as high as 97 °C have been measured adjacent to the eruption site, (c) the gases being vented are composed of methane, carbon dioxide and hydrogen sulphide, and (d) some of the fossils retrieved from the erupting mud are age-diagnostic, with first or last downhole appearances within the Plio-Pleistocene and Pleistocene and from a depth range of 1219 to 1828 m (Fig. 2).

2. The Yogyakarta earthquake

The Yogyakarta earthquake occurred on May 27th 2006 at 05:54 local time. Aftershocks of magnitude 4.8 and 4.6 occurred 4 and 5 h later, respectively. The earthquake caused almost 6,000 deaths and left more than half a million people homeless.

In this section we consider (a) the distances and magnitudes for earthquakes that triggered liquefaction or where other hydrological effects have been observed (b) expected changes in pore pressure due to changes in static stress generated by the earthquake and (c) the estimated ground motions for earthquakes that affected Sidoarjo between 1973 and 2007 that did not lead to eruptions at this site.

2.1. Comparison with earthquake-induced hydrological effects

Earthquakes are known to trigger hydrological responses including liquefaction, changes in stream flow (Montgomery and Manga, 2003), and the eruption of mud volcanoes (e.g., Manga and Brodsky, 2006; Mellors et al., 2007). Wang et al. (2006) compiled such observations and determined a relationship between the maximum distance for these responses and earthquake magnitude (Fig. 3). The solid line in Fig. 3, with its uncertainty indicated by the dashed lines, can be interpreted as a threshold distance beyond which hydrological responses have not been documented. In fact, hydrological effects are not common occurrences at distances below the line, and the solid line is thus best interpreted as the maximum distance at which such effects might be expected under optimal conditions.

Fig. 3 also shows the distance between regional earthquake hypocenters for the period 1973–2007 (magnitudes and hypocenters are from the USGS NEIC earthquake catalogue, http://neic.usgs.gov/neis/epic/epic.html) and the site of the Lusi eruption. The Yogyakarta earthquake is shown by a triangle. The distance and magnitude of this event place it well above the empirically determined threshold for the occurrence of other triggered mud volcano eruptions, liquefaction, and changes in streamflow. In other words, given its size, the Yogyakarta earthquake is further away than would ordinarily be expected for an earthquake capable of initiating an eruption, even under optimal conditions. Moreover, as noted by Manga (2007), there were two larger and closer earthquakes that did not trigger an eruption. Additionally, one other event lies below the threshold shown in Fig. 3, and did not trigger an eruption. The data set presented

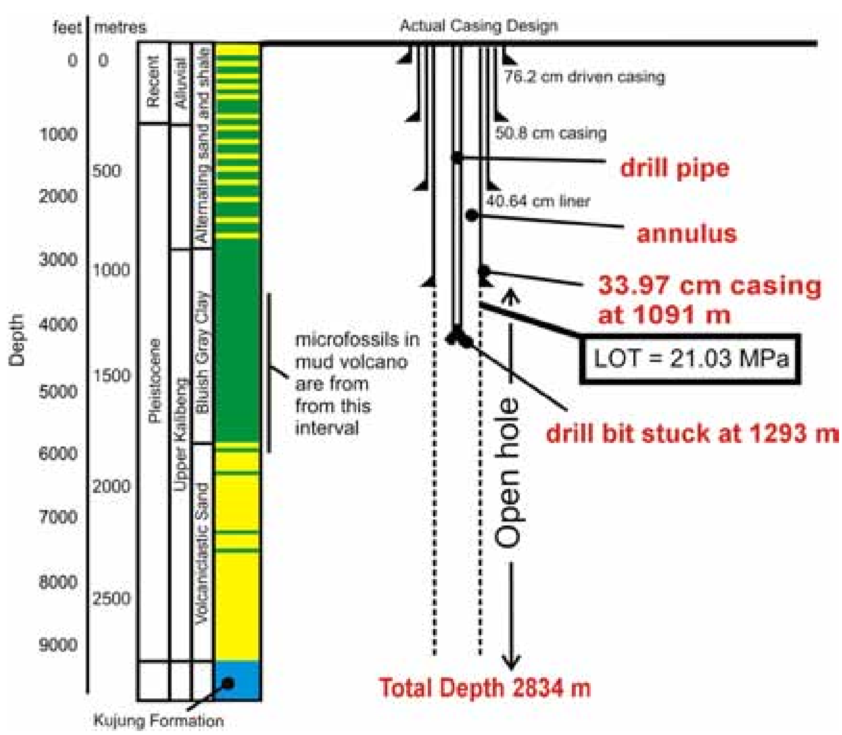

Fig. 2. Summary of the stratigraphy drilled by the Banjar Panji-1 well, and the casing design. Key depths are 1091 m which is the depth of the deepest casing shoe and 1293 m which is the depth at which the drill bit was stuck on the 29th May 2006. The lowermost 1734 m of the exploration well had no protective casing.

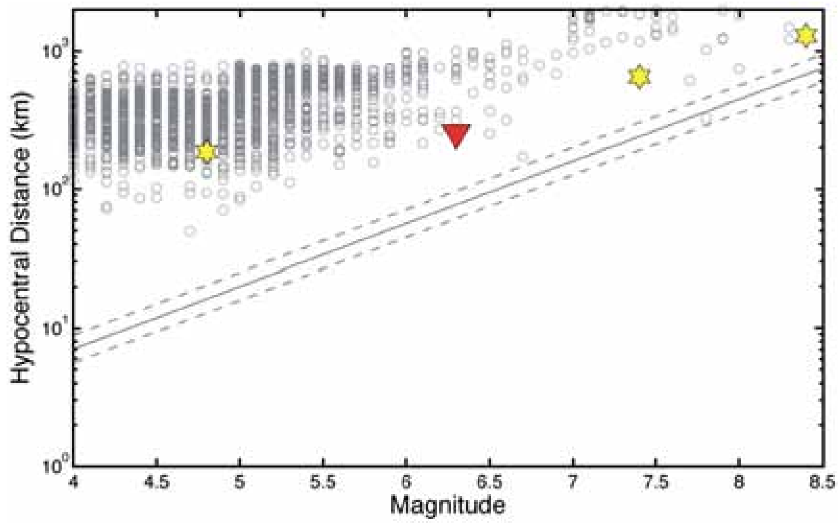

Fig. 3. Distance between historical earthquake hypocenters (1973–2007) and Lusi, as a function of earthquake magnitude. The Yogyakarta earthquake is shown as a red triangle. The August 8, 2007 Mw = 7.4 and September 12, 2007 Mw = 8.4 earthquakes, which were followed by an increase in the rate of mud eruption at Lusi (Istadi, personal comm.), are shown by yellow stars. The solid black line represents the empirical upper bound on observed hydrological responses to earthquakes as determined by Wang et al. (2006).

in Fig. 3 is slightly larger than that presented in Manga (2007), but the additional events are not near the liquefaction limit.

The threshold shown in Fig. 3 is for a specific class of hydrological responses to earthquakes: those that require permanent changes in the subsurface and that are manifested at the surface. Other hydrological responses, including fluctuations in the water level in wells (e.g., Cooper et al., 1965), (small) permanent changes in the water level in wells (e.g., Roeloffs, 1998; Brodsky et al., 2003), and changes in the eruption frequency of geysers (e.g., Husen et al., 2004) have been documented at distances above the threshold shown in Fig. 3 (see Montgomery and Manga, 2003 for a compilation). Other responses to distant earthquakes that would also fall above the line, with a possible direct or indirect hydrological connection, include non-volcanic tremor (Rubinstein et al., 2007; Miyazawa and Mori, 2006) and triggered earthquakes (e.g. Hill et al., 1993; West et al., 2005; Brodsky and Prejean, 2005). It is by analogy to these more distant responses that Mazzini et al. (2007) suggested that the earthquake could have triggered the eruption. In contrast, since it was a mud volcano that erupted, we believe that a comparison with hydrological responses that have a similar origin (i.e. other mud volcanoes, liquefaction) is more appropriate.

2.2. Change in pore pressure due to static stress changes

Earthquakes can permanently expand or contract the crust. These permanent changes in stress, referred to as static stress changes, will cause changes in pore pressure and could potentially initiate hydrofracturing. We calculated the mean stress (s_{kk}) caused by the Yogyakarta earthquake (Fig. 4) using Coulomb 3.0 (Lin and Stein, 2004; Toda et al., 2005), and the focal mechanism and slip parameters from the global CMT catalogue (www.globalcmt.org). At the site of the Lusi eruption, the increase in mean stress is ~30 Pa. For a linear poroelastic material, the change in pore pressure for undrained conditions is given by:

$$p = \frac{B}{3^{S}kk} \quad (1)$$

where B is the Skempton's coefficient (Wang, 2000). For mud, $B \sim 1$ (Wang, 2000), implying a change in pore pressure of ~10 Pa. This change in pore pressure is negligible when compared to the ~ few kPa changes in stress caused by barometric pressure variations or tides (e.g., Melchior, 1983) which have not triggered eruptions in the past.

2.3. Role of shaking

Seismic waves generated by earthquakes also create dynamic stresses, which are temporary changes in the stress level of the crust as the wave passes through. These dynamic stresses differ from static stresses in that in a perfectly elastic medium, dynamic stresses cause no net change in stress or pore pressure after the seismic waves have

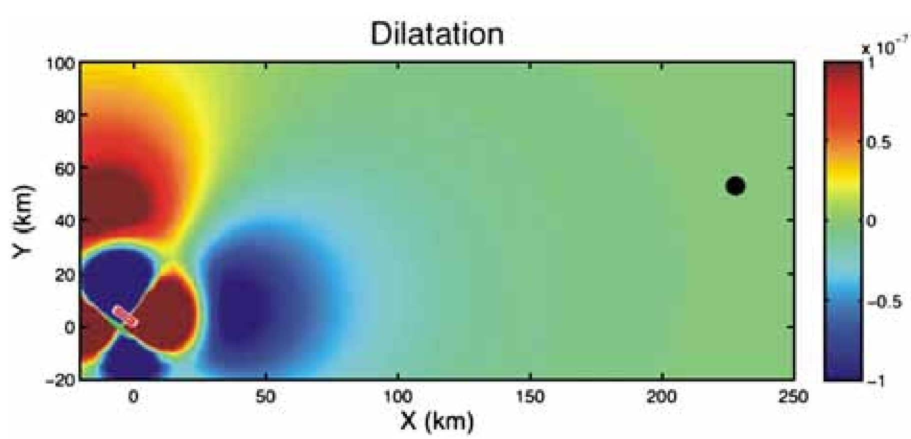

Fig. 4. Predicted volumetric strain caused by the Yogyakarta earthquake, assuming a bulk modulus of 5.3 GPa. The black dot represents the approximate location of Lusi.

Table 1
Fits of regional seismicity data to various attenuation relationships

Y	C_1	C_2	C_3	C_4	r^2
Arias intensity (m/s)	8.97	3.00	−6.92	0.00641	0.67
PGA (g)	11.2	1.50	−5.26	0.00575	0.72
PGV (m/s)	4.67	2.04	−4.53	0.00478	0.79

PGA and PGV here refer to the geometric mean of the horizontal component measurements. We also take R to be hypocentral distance in kilometres.

passed. Instead, for them to have any effect they must cause long-lasting changes in the structure of the porous material. Indeed, dynamic stresses, if sufficiently large and repeated over multiple cycles, can rearrange particles in unconsolidated or poorly-consolidated materials, leading to an increase in pore pressure. Sufficient increases in pore pressure lead to liquefaction and fluidised sediment flow (Jolly and Lonergan, 2002), conditions that can initiate mud volcanism.

At distances of more than a couple times the length of the part of the fault that ruptures, dynamic stresses will be larger than static stresses (Lay and Wallace, 1995). Lusi is approximately 30 fault lengths from the epicentre, so it is likely that passing seismic waves would play a more important role in triggering hydrological responses than static stresses.

2.3.1. Estimating ground motion

Here we compare the ground motion predicted by published seismic attenuation relationships, as well as a new attenuation relation derived specifically for East Java, to broadband seismic data. This predicted ground motion allows us to compare the shaking caused by the Yogyakarta earthquake with that of previous large earthquakes.

The precise mechanism of liquefaction or mud volcano triggering by earthquakes remains unclear, and no consensus exists about the seismic wave types or frequencies most likely to be responsible (Mellors et al., 2007). Therefore, we consider several measures of ground shaking (peak ground acceleration, PGA; peak ground velocity, PGV; Arias Intensity) that are often used to characterize liquefaction hazards. Using many attenuation relationships and ground shaking parameters allows us to make more robust predictions of the relative strengths of shaking produced by historical earthquakes, and to estimate uncertainty.

The nearest broadband seismic station to Lusi is GEOFON station UGM (http://www.gfz-potsdam.de/geofon/stat_book/UGM/ugm.html), located 245 km to the southeast (see Fig. 1). We obtained seismic data for 52 earthquakes recorded at UGM, with reported magnitudes ranging from 3.5 to 6.9 (see table in electronic supplement). For each earthquake we obtained 3-component records beginning 60 s before the first P wave arrival and lasting until 10 min after the first S wave arrival. We bandpass filtered the records between 0.01 and 5 Hz.

We made several simplifications in our analysis of the seismic data. We used the magnitude reported by the NEIC earthquake catalogue (typically moment or body-wave magnitude) as a generic magnitude and did not correct for slight differences between magnitude scales. We did not attempt to segregate earthquakes by focal mechanism or tectonic environment, but we did distinguish between deep (>70 km) and shallow earthquakes. Where existing attenuation relationships called for distance to the fault, we approximated it with the epicentral distance. These simplifications all introduce additional error to the predicted ground motions. However, these uncertainties are accounted for implicitly in the calibration with recorded ground motions, and are reflected in the error bars shown in Fig. 6.

2.3.2. Empirical attenuation relations for East Java

Attenuation relationships are frequently developed for earthquakes within a single tectonic region; they therefore reflect the stress drop characteristic of earthquakes in that region and the attenuation characteristics of local crust. However, few relationships have been specifically developed for Indonesia and Southeast Asia (exceptions include Megawati et al., 2003; Petersen et al., 2004). Here we develop an attenuation relationship specific to East Java.

The simplest common ground motion attenuation relationship for measure y is of the form:

$$\ln(y) = C_1 + C_2 M + C_3 \ln(R) + C_4 R \qquad (2)$$

where R is distance, M is magnitude, and C_1–C_4 are regression coefficients (Campbell, 2002). To find attenuation relation coefficients for PGA, PGV, and Arias Intensity, we performed a least-squares regression using the 52 earthquakes for which data was obtained from station UGM. The resulting coefficients, as well as the regression correlation coefficient, are shown in Table 1.

2.3.3. Ground motion results

Fig. 5 shows the relationship between predicted and observed peak ground acceleration and peak ground velocity at UGM for the East Java attenuation relationships from the present study. Deep-

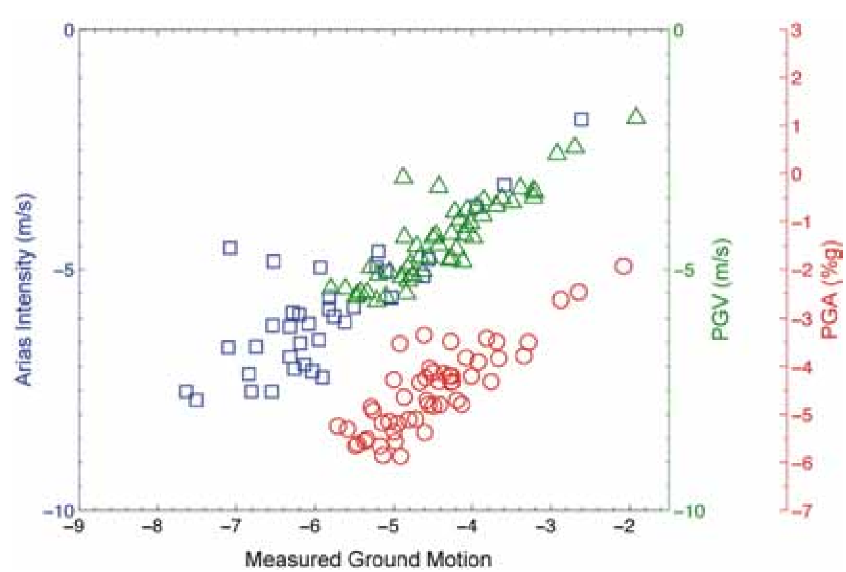

Fig. 5. Predicted vs. actual ground motions at UGM. The base-10 logs of predicted (y-axes) and actual (x-axis) Arias intensity, peak ground acceleration, and peak ground velocity are shown as squares, circles, and triangles, respectively.

Table 2
Attenuation relationship parameters

Attenuation relationship	Regional coverage	Magnitude/ distance coverage	Parameter estimated	R^2
Frankel et al. (1996)	Central and Eastern United States	M_w 4.4–8.2 10–1000 km	PGA	0.68
Toro et al. (1997)	Central and Eastern North America	R>~a few rupture lengths	PGA	0.71
Sadigh et al. (1997)	California	M_w 4–8 r<100 km [1]	PGA	0.69
Youngs et al. (1997)	Subduction zones	M_w 5 10–500 km	PGA	0.68
Petersen et al. (2004)	Subduction zones plus additional data from Singapore and Malaysia	"	PGA	0.64
Travasarou et al. (2003)	Shallow crustal earthquakes at plate margins	M_w 4.7–7.6	Arias intensity	0.69
Kanno et al. (2006)	Japan		PGA PGV	0.49 0.40
Hwang et al. (2004)	1999 Chi-Chi, Taiwan earthquake	$M_{7.7}$ 0 to ~300 km	Arias intensity	0.71
This study	East Java	M 4–6.9 R<1200 km	PGA PGV Arias intensity	0.72 0.79 0.67

focus earthquakes do not show any systematic differences from shallow earthquakes so we include all earthquakes in our analyses (Manga, 2007 omitted deep earthquakes) – Fig. 5.

Table 2 shows the quality of fit produced by applying published attenuation relations to data at UGM. Results obtained with these attenuation relations are qualitatively similar to those discussed below. Some attenuation relationships produce a (slightly) better fit to the UGM data because they use different functional forms for the attenuation relationship.

Fig. 6a shows predicted ground motions at Lusi for the period 1973–2007. Predicted ground motion for the Yogyakarta earthquake is shown by a dashed line on Fig. 6b, which shows ground motions during the period 1st June 2005–1st June 2006. For all attenuation relationships we considered, tens of previous earthquakes (and for some relationships, hundreds) had larger expected ground motions than the Yogyakarta earthquake. Many would have produced significantly larger ground motion.

The possibility that previous earthquakes could have "primed" the volcano, so that a small additional perturbation (i.e. the Yogyakarta earthquake) would initiate the eruption, has been proposed (Van Zerge report, 2007). We consider earthquakes, here, because the non-seismic processes that can cause mud volcano eruption (e.g., tectonic compression, gas or fluid migration) operate on long time scales (e.g., Kopf, 2002) — much longer than the time separating large earthquakes in Indonesia. Therefore, we find it improbable that, in the 6 months after the large 2005 earthquakes, internal processes would have moved the mud volcano from a subcritical state, in which the system was not particularly vulnerable to earthquake triggering, to a very near critical state.

Fig. 7 shows the cumulative estimated ground motion at Lusi for the period 1973–2007. Inset figures show the ground motion in the year preceding the eruption, June 1st 2005 to June 1st 2006. Steeper slopes on these figures indicate periods in which seismic energy was delivered at a higher than average rate; flatter slopes indicate periods when very little seismic energy reached the mud volcano system. If semi-permanent changes in soil structure caused by repeated shaking acted to shift the mud volcano to a near-critical state, we would expect an eruption to occur in the period following a steep upward jump on the graph. However, Fig. 7 shows that the three months preceding the eruption were seismically quieter than average.

2.4. Pore pressure change caused by dynamic stresses

We can use peak ground velocity to estimate the dynamic stress induced by an earthquake in a linear elastic material:

$$\sigma \sim \mu * (\mathrm{PGV}/\mathrm{Vs}) \tag{3}$$

where μ is the shear modulus and Vs the shear velocity of the material for which PGV was determined. In this case, we assumed a shear velocity

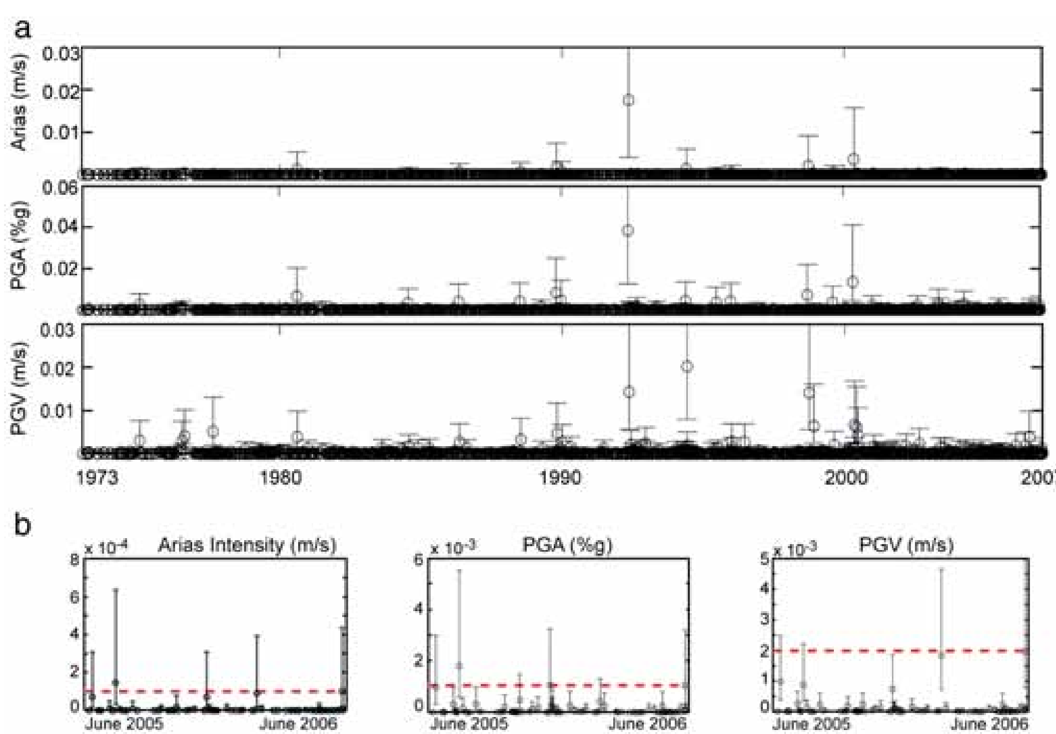

Fig. 6. a: Predicted ground motions at Lusi, 1973-2007. Ground motion was determined using the relationship derived in this paper and data from the NEIC earthquake catalogue. The strongest expected shaking is from a moderate Mb = 4.7 earthquake that occurred less than 50 km from the site of the Lusi eruption on May 14th, 1992. b: Predicted ground motions at Lusi, 1 June 2005–1 June 2006. The level of shaking expected from the Yogyakarta earthquake is shown by a dashed line.

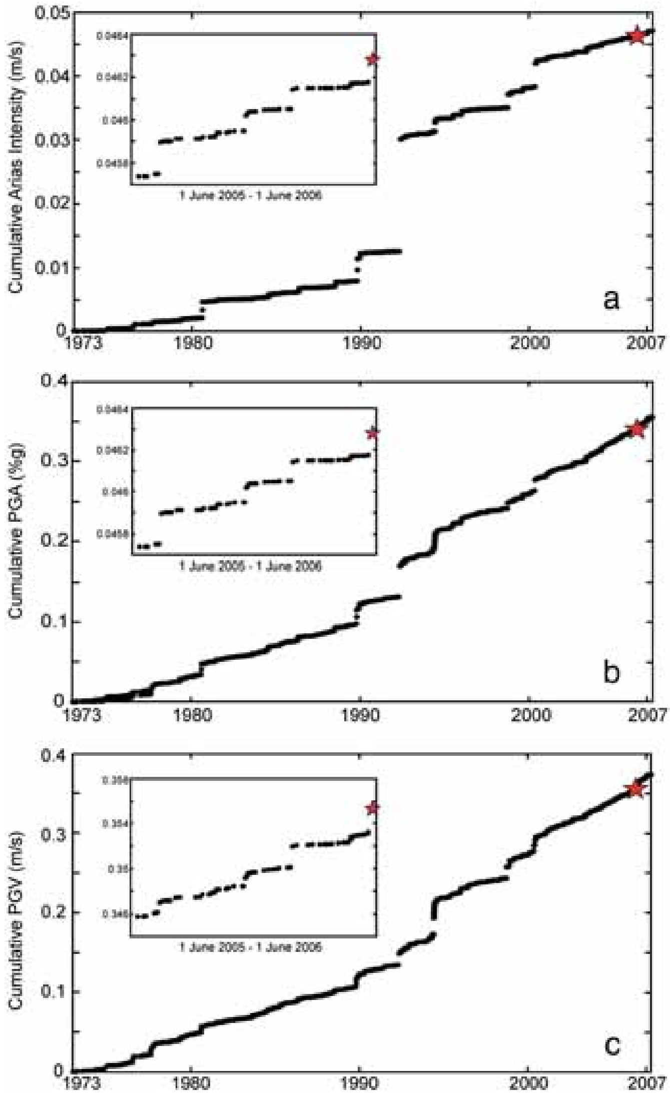

Fig. 7. Cumulative a) Arias intensity b) peak ground acceleration and c) peak ground velocity at Lusi since 1973. Inset figures show June 1st 2005–June 1st 2006. The Yogyakarta earthquake is shown by a red star.

of 2500 m/s and shear modulus of 30 GPa. From the peak ground velocity determined earlier, we find that the amplitude of the dynamic stress induced by the Yogyakarta earthquake is 21+33/−12 kPa. Transient changes in pore pressure that accompany these dynamic stresses will be less than this value.

It is possible that the region around the mud volcano is weakened by the presence of pre-existing faults. The damage zone of many faults is characterized by a 30–50% reduction in shear velocity (Ben-Zion et al., 2007). Because the shear modulus scales as the shear velocity squared, a decrease in shear velocity due to the presence of a fault would mean a decrease in the dynamic stress if PGV is held constant. However, changing site conditions typically do not produce constant wave amplitudes. Instead, a decrease in shear velocity will produce an increase in seismic wave amplitude such that the wave's energy (i.e. stress density) is conserved.

3. Banjar Panji-1 well operations

3.1. Overview

Mazzini et al. (2007) reports that the well drilled (1) alluvial sediments; (2) Pleistocene alternating sandstone and shale of the Pucangan Formation, (up to 900 m depth), (3) Pleistocene bluish gray clay of the Upper Kalibeng Formation, to 1871 m depth and (4) volcaniclastic sand at least 962 m thick (Fig. 2). Seismic correlations from the Porong-1 well, 6.5 km to the northeast, show that beneath these sediments is the Kujung Formation.

Fig. 2 shows the depths at which 76.2 cm (30"), 50.8 cm (20") casing, 40.64 cm (16") liner and 33.97 cm (13 3/8") casing were set. The 33.97 cm casing shoe was set at 1091 m and the lowermost 1734 m of the exploration well had no protective casing (Fig. 2). Since fracture strength tends to increase with depth, the weakest part of the open-hole section is located in the vicinity of the casing shoe. Fracture strength at the casing shoe is estimated using a leak off test (LOT). By increasing or decreasing the mud weight, measured in pounds per gallon (1 ppg = 1.175×10^{-3} MPa m^{-1}) it is possible to control the

Table 3
Key events in May and June 2006 (source — compiled from (a) the records kept at the wellsite (b) Lapindo Brantas, the operator of the Banjar Panji-1 well and (c) the Indonesian independent investigation team)

Key event	Time and date (2006)
Leak off test at 33.97 cm (13 3/8″) shoe recorded at 1091 m as between 19.5 MPa (equivalent to 15.3 ppg) and a maximum of 21.03 MPa (equivalent to 16.4 ppg)	May 6th 2006
Drilling new hole to next casing point	May 6th–May 27th
Yogyakarta earthquake	May 27th 05.54
While drilling with mud with a mud weight of 0.0173 MPa m^{-1} (14.7 ppg), 3.2×10^{2} L (20 barrels) of mud lost	May 27th 06:02 (less than 10 min after the earthquake)
Two major aftershocks	May 27th 11:30
Total loss of returns when drilling at 2834 m	May 27th 12:50 (less than 2 h after two major aftershocks)
Pumped 9.6×10^{2} L (60 barrels) of loss control material	Started May 27th 13:02 completed around May 27th 13:20
Losses stopped	
Start to pull out of the hole	May 27th 23:15 to May 28th 05:00
While pulling out of the hole, there was a well kick (influx of formation fluid and gas into the wellbore)	Between May 28th 05:00 and May 28th 08:00
Influx of salt water and hydrogen sulphide gas into the wellbore	
Hydrogen sulphide at surface measured as 500 ppm at the surface. Rig evacuated.	
Volume of kick is significant. Around 360 bbls of drilling mud were displaced from the welbore.	
Arround 30% of the total mud has been displaced by the influx	
Valves at surface (blow out preventors – BOP) are closed.	May 28th 07:50
Stablized well using 'Volumetric Method' by pumping 19 bbls (3.2×10^{2} L) mud weight of 0.0173 MPa m^{-1} (14.7 ppg) and bleed off annulus.	May 28th 08:00 to 12:00
Well died after 2 cycles	
The shut in pressure was reported for 140 min (Fig. 8)	
Open BOP around 10:00 h circulated fluid out. Fluid contaminated with salt water with mud weight of 8.9 ppg (0.0104 MPa m^{-1})	May 28th around 12.00 to May 29 02:00
Tried to continue pulling pipe out but apparently it was differentially stuck. Not able to move pipe, no rotation but still able to circulate through	
Drill pipe stuck with bit at 1293 m. Tried to move the string not successful	
Attempted to fish pipe by jarring	
Pumped 6.4×10^{2} L (40 barrels) of high viscosity high oil concentration mud and soak it overnight	May 28th around 12:00
Prepared for free point indicator (used to determine what depth the drill pipe can be recovered from)	May 29th at 02:00
First eruption of steam, water, mud and gas Located 150 m from wellbore	May 29th 05.00 am
Free point indicator cancelled	
Evacuate personnel to muster area	
Gas and water gushed out intermittenly with maximum height of around 8 m every 5 m	

(continued on next page)

Table 3 (*continued*)

Key event	Time and date (2006)
Pumping volumes of mud Pump mud downhole to check possible communication with broach, if any 20,670 L (130 barrels) 0.0173 MPa m^{-1} (14.7 ppg) followed by 100 bbls 14.7 ppg; 0.0188 MPa m^{-1} (16 ppg) with loss control material 31,800 L (200 barrels). Squeeze pressure high; initial pressure 8.27 MPa (900 psi) Eruption weakens from 8 m high every 5 min, reduces to 3 m high and then reduces to lowest eruption 30 cm with 30 min interval Pump cement to put a barrier between the open hole below the bit and the rig floor in order to continue fishing job safely	May 29th and May 30th
Free point indicator test and cut the drill pipe at 911 m Second eruption started	June 1st 04.00 to 18.00
Start removing rig and equipment from drill site	June 3rd 06
Pump cement plug for temporary abandonment	June 2nd to June 3rd
Dismantle the drilling rig.	June 3rd

changes in pressure that occur as the well is drilled. When drilling, the mud weight in the borehole is adjusted so that the pressure at the casing shoe is below the LOT. The extra pressure created on the borehole by mud circulation provides a tolerance to a sudden influx of fluid or gas into the wellbore known as 'a kick'.

3.2. Key operational events

A summary of events that occurred after the 33.97 cm casing had been set is provided in Table 3.

The leak off pressure at the 33.97 cm casing point has been calculated using several methods. These methods give a range of leak off pressure ranging from 19.6–21.03 MPa. Drilling from 1091 m to 2834 m occurred without setting any more casing. On 27th May at 05:54, the Yogyakarta earthquake occurred. 3.2×10^2 L of mud were lost 6–10 min after the earthquake; this is approximately 1.8% of the total mud volume in the hole, and therefore a minor loss. Drilling continued until 6 h later, at a depth of 2834 m, drilling mud stopped returning to the surface (lost circulation). Therefore, a significant volume of mud was lost by mud flowing rapidly into surrounding rock strata. Loss control material was added into the circulating mud system and successfully stemmed these losses. 17 h after the earthquake, when the borehole had stabilized, removal of the drill bit and the drill pipe began. In order to maintain the level of the mud in the hole, as the drill pipe is removed the volume it occupied has to be replaced with more drilling mud, otherwise the pressure is reduced in the borehole due to the decreased column of the mud. The drill pipe was pulled out of the hole in 27.43 m (90 ft long) sections while mud continued to circulate. Circulating mud helps maintain a slightly higher pressure below the bit, and prevents the 'swabbing in' (essentially sucking in) of fluid or gas from the surrounding formation as the bit is pulled out. Ten stands (274.3 m) were removed, at which point the bit was at a depth of 2559 m. The next 46 stands were removed without circulating mud, until the drill bit was at a depth of 1293 m.

3.3. Well kick — May 28th 2006

While pulling out of the hole significantly increased levels of saline water and hydrogen sulphide gas were noticed in the mud returning to the surface. This shows that formation fluid and gas entered the wellbore displacing the drilling mud. The volume of drilling mud displaced was between 390 and 600 barrels (62,000–95,000 L), which is approximately 30–50% of the total mud volume in the well — a significant volume. The blow out preventors at the rig site were closed to prevent more fluid and gas coming to the surface, and while these were closed the pressures in the casing and the drill pipe were measured (Fig. 8). The pressures changed significantly during this two hour period. A key measurement is the drill-pipe pressure which was initially 3.39 MPa and dropped to 2.42 MPa over a period of 25 min prior to renewed pumping (Fig. 8). 3021 L of 0.0173 MPa m^{-1} (14.7 ppg) mud were then pumped into the drill pipe from the 25th minute to the 32nd minute of the shut in. From the 40th to 75th minute, pressure in the annulus was bled off, and this was repeated from the 75th to 90th minute. Between the 90th and 135th minute the pressure in the drill pipe is seen to be declining (marked X on Fig. 8).

The mud weight prior to the influx of fluid was 0.0173 MPa m^{-1} (14.7 ppg). At the stage when the well was shut in, we can calculate the pressure exerted by the column of mud in the drill pipe above the depth of 1293 m, as $0.0173 \text{ MPa m}^{-1} \times 1293 \text{ m} = 22.37$ MPa. The pressure in the drill pipe at surface reached at least 2.42 MPa when blowout preventors were closed. The total pressure at 1293 m would have been 22.37 MPa + 2.42 MPa = 24.79 MPa. 202 m higher up in the well bore at the casing shoe (1091 m), this pressure would have been less. Using the

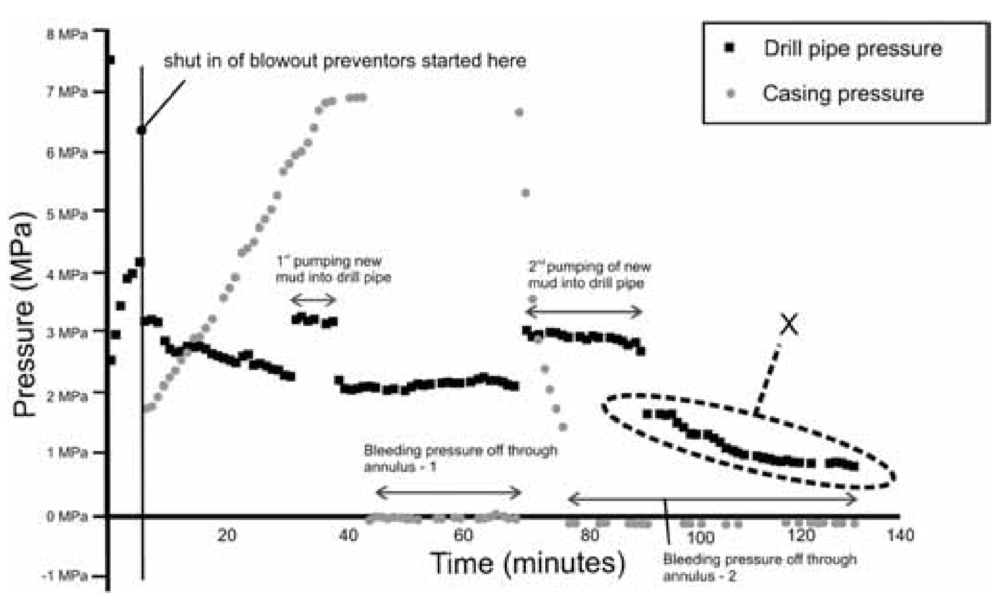

Fig. 8. Pressure measured in the drill pipe and casing for 125 min during shut in of the Banjar Panji-1 well on May 28th, 2006.

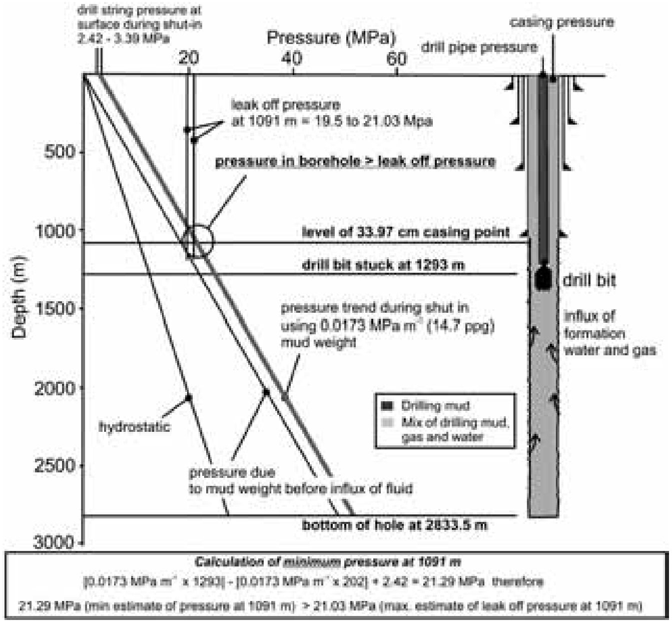

Fig. 9. Graph of hydrostatic pressure plotted against depth. The leak off test at 1091 m can be interpreted as between 19.62 MPa (equivalent to 15.9 ppg) and a maximum of 21.03 MPa (equivalent to 16.4 ppg) (vertical grey bar). The pressure in the drill pipe with depth marked by thick black line. Circled region shows that the pressure in the wellbore after the influx of formation fluids would have exceeded the LOT pressure, when the blow out preventors were shut on May 28th 2006.

same mud weight of 0.0173 MPa m^{-1}, we can calculate it would be reduced by $0.0173 \times 202 = 3.46$ MPa (Fig. 9). Therefore the minimum pressure at the 33.97 cm casing shoe at 1091 m was 21.29 MPa. This is greater than the maximum estimate of the leak off pressure (21.03 MPa) – Fig. 9. Therefore when the well was shut in, the wellbore fluid pressure was higher than the rock strength at the last casing point.

4. Fault reactivation

Mazzini et al. (2007) briefly describe a NE-SW oriented fault that they state extends from the Arjuno-Welirang volcanic complex (south west of Lusi) to the east Java coastline (their Fig. 1). If the fault exists in the position reported by Mazzini et al. (2007) then the Banjar Panji-1 well is located near to the fault trace. Satellite photographs may support the interpretation of some sort of NE-SW orientated lineament, and the eruptions that started on May 29th and the subsequent days were aligned in a NE-SW orientation (see Mazzini et al., their Fig. 4). The presence of a fault is not conclusive and seismic data show that there are numerous faults surrounding the well location, with no evidence for a single clear fault cross cutting the Banjar Panji-1 well.

If a fault is present, reactivation by the Yogyakarta earthquake is unlikely for the same reasons we don't favour an earthquake trigger: there were many large earthquakes that did not induce an eruption. Additionally, we calculated the change in Coulomb stresses on a vertical left-lateral fault with a NE-SW strike using Coulomb 3.0 (Lin and Stein, 2004; Toda et al., 2005), using the same model parameters as the calculation reported in Fig. 4. Coulomb stresses are components of stress in a direction that favours fault motion. We found that the Yogyakarta earthquake caused a total Coulomb stress decrease of only 200 Pa. This is a negligible magnitude of change, and it occurred in a direction that decreased the probability of slip on a dextral fault.

5. Discussion

Here we consider the proposed trigger scenarios (a) the earthquake as the sole trigger (b) a combination of the earthquake and drilling operations and (c) drilling operations as the sole cause.

5.1. Earthquake sole trigger

On the basis on past seismicity and previous documented responses to earthquakes, we can draw the following conclusions:

1. By comparison with previous triggered mud volcanoes, the magnitude 6.3 earthquake on May 27, 2006 was too small and too distant to trigger an eruption. Moreover, there were bigger, closer earthquakes that did not trigger an eruption.
2. The change in pore pressure due to changes in static stress caused by the earthquake is ~10 Pa, which is negligible.
3. For all attenuation relationships we considered, tens of previous earthquakes (and for some relationships, hundreds) had significantly larger expected ground motions at Lusi than the Yogyakarta earthquake. In the year leading up to the eruption, there were other earthquakes that caused more shaking (see Fig. 6b).
4. We find no evidence to support the concept that repeated shaking acted to shift the subsurface to a near-critical state, prior to the Yogyakarta earthquake.
5. The amplitude of the dynamic stress induced by the Yogyakarta earthquake is $21+33/-12$ kPa, which is negligible.

We disagree with the conclusion of Mazzini et al. (2007) that the Yogyakarta earthquake reactivated the NE-SW striking fault zone, that may to run near to the well location, causing the eruption. Coulomb stress changes from the Yogyakarta earthquake are too small and have the wrong sign to reactivate a left-lateral fault. The kink in the railway line that Mazzini et al. (2007) described as evidence for fault movement formed in several months after the eruption began, not during the Yogyakarta earthquake. The strongest argument against an earthquake trigger is that other earthquakes, which were larger, closer, and generated stronger shaking, did not initiate an eruption. The chances of the earthquake being the sole causal mechanism are small enough that we conclude this scenario can be discounted.

However, we add several caveats to this conclusion. First, the earthquake apparently triggered a number of seismic events in the vicinity of Banjar Panji-1 (Istadi, personal comm.). Second, other types of geological and hydrological phenomena (not including the eruption of mud volcanoes and liquefaction) have been documented at distances and magnitudes similar to the case of Lusi and the Yogyakarta earthquake. Third, the already-erupting Mt. Semeru, located at the same distance from the epicentre as Lusi, became more active immediately following the Yogyakarta earthquake (Harris and Ripepe, 2007). Since the eruption began, two other large earthquakes have caused changes in eruption rate: a magnitude 7.4 event on Aug 8th 2007 and a magnitude 8.4 event on September 12 2007 (shown by yellow stars on Fig. 3). Following the former earthquake, the eruption rate at Lusi increased significantly for two days (Istadi, personal comm.).

5.2. Combination of earthquake and drilling

We propose two ways in which the combined effects of drilling and the Yogyakarta earthquake could have triggered the Lusi eruption. First, that the earthquake critically weakened the surrounding rock strata, and second that it increased the pressure in the fluid in the borehole very slightly, in both cases resulting in a borehole pressure greater than the strength of the surrounding rock. Drilling records show that nothing happened in the wellbore during the earthquake. 6 h after the earthquake there were significant mud losses, but these mud losses could have been caused by drilling into naturally fractured rock or cavities in limestone such as the Kujung Formation, or because the mud weight that was too high. We also know that these losses were successfully stemmed. Therefore there is no evidence to support weakening of the wellbore during the earthquake or during subsequent aftershocks.

We calculate that dynamic stresses caused by the earthquake could have temporarily increased pore pressure by 22 kPa. The common practice in drilling is to have a mud weight that is 1.38 MPa higher than the pore pressure when the drill bit is being retrieved, a value used specifically to compensate for swab pressures while pulling the drill bit and drill pipe out. 22 kPa represents 1.6% of the extra mud weight used to prevent an influx of formation fluid during drill-pipe and drill-bit retrieval operations, and therefore the change in pressure that could have occurred due to the earthquake is insignificant. We conclude that there is very little evidence to support the trigger being the combined effect of drilling and the earthquake.

5.3. Well operations

On 28th May 2006 the drill bit and drill pipe were being taken out the hole. The drilling mud has a density which is set so that the pressure within the column of mud is higher than the pressure of the fluids in the rock strata, therefore preventing flow of formation fluid into the hole. To maintain the pressure within the hole while removing the drill pipe and drill bit, their volume has to be replaced with an equal volume of drilling mud, otherwise the level of the drilling mud in the hole will drop and the pressure exerted by the drilling mud will also fall. It was during this operation, 24 h after the Yogyakarta earthquake, that a significant influx of formation water and gas into the wellbore occurred. The evidence for this is that 30–50% of the drilling mud (62,000–95,000 L) came to the surface because it was being displaced by the flux of formation fluid. If formation fluids (e.g. saline water) and gas enter the wellbore, usually from permeable rock strata, then the mud is diluted and the density of the mud is reduced. Despite the flux of fluid from the formation into the hole, the pressure exerted by the rock formation pore fluid remains the same because this flux depletes the total volume of formation fluid by only a small fraction. The lower pressure now exerted by the column of diluted drilling mud would allow further influx to occur. The drilling mud was therefore forced out at the surface because the column has a lower density and therefore the pressure of the drilling mud at surface exceeds atmospheric pressure. The normal method of dealing with this is to close the blowout preventors (shut the well in) to stop this flow. When this was done it was possible to measure the excess pressure at the surface. The pressure in the annulus and the drill pipe were measured during the shut-in (Fig. 8). At the start of the monitoring period, pressure in the annulus increased from 1.27 MPa to 7.27 MPa showing that fluids and gas were moving from the formation into the borehole. The casing pressure reached a maximum of 7.27 MPa. Most of the other pressure changes in the drill pipe and annulus seen on the pressure curves were caused by intentional pumping of heavier mud into the hole to increase the mud again or the bleeding off pressure, but we also identify a steady decline in pressure between 90 and 135 min in the drill pipe pressure, when there was no pumping taking place (marked X on Fig. 8). This indicates that after the peak casing pressure of 7.27 MPa, rather than influx occurring there was now leakage of drilling mud into the surrounding formation. This is consistent with the development of fractures in the uncased section of the borehole or leakage through the cement located between the casing and the penetrated rock strata.

Furthermore we can also calculate the pressure at the 33.97 cm casing point at 1091 m when the well was shut in. The shut in pressure for the drill pipe was between 2.42 MPa and 3.39 MPa (Fig. 8) which, combined with the pressure due to the column of mud would have exceeded the maximum estimated leak off pressure of 21.03 MPa (the circled region of the graph in Fig. 9). The lowermost 1734 m of the exploration well had no protective casing, if the casing had been set

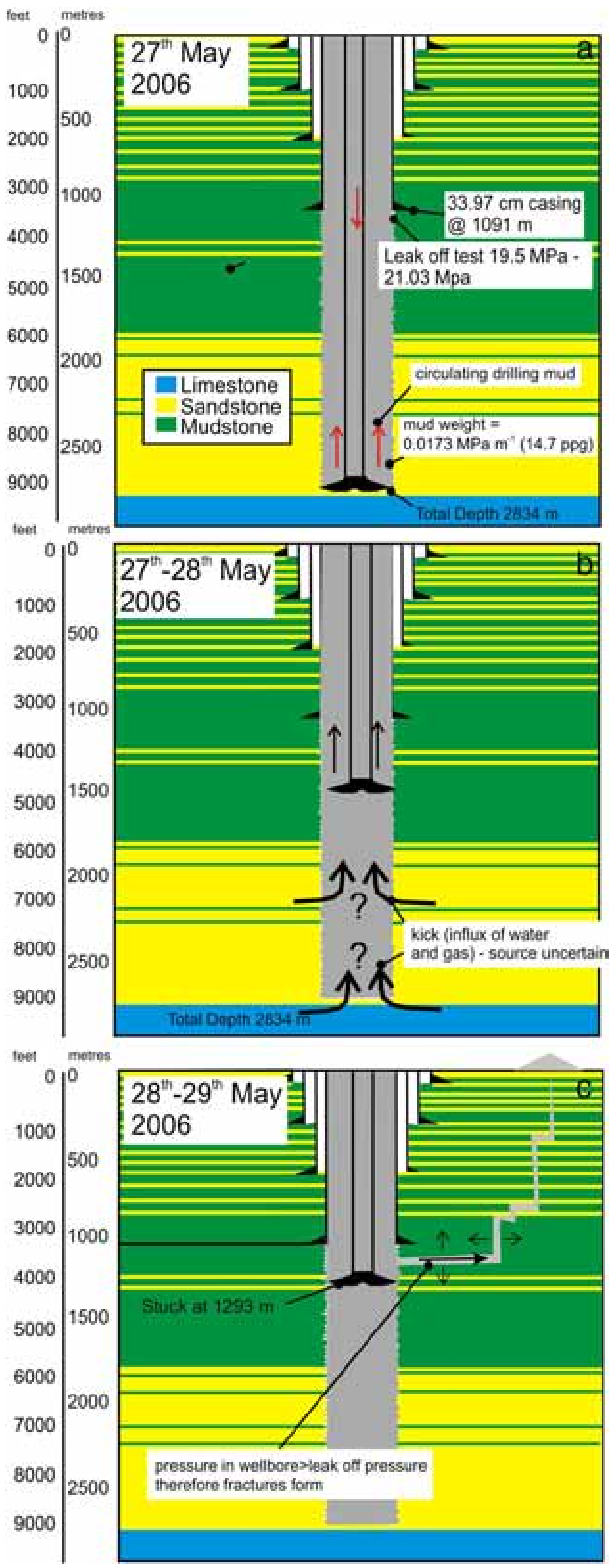

Fig. 10. Summary of key operations, mud weights and shut in drill pipe pressure between May 27th and 29th, 2006. a: During drilling of on the 27th May total loss of returns, loss control material is used to stop the losses. Decision to retrieve drill bit and drill pipe. b: During the retrieval of the bit, we interpret that fluid and/or gas was swabbed into the hole. c: when the drill bit is stuck at 1293 m there is a kick (influx of fluid or gas or both into the wellbore). The well is shut in and a pressure of between 2.42 and 3.39 MPa is measured in the drill pipe. This pressure, when added to the pressure exerted by the drilling fluid below the deepest casing point is *greater* than the leak off test carried out at 1091 m. Therefore during shut in on the 29th May 2006, fractures developed below this depth. We do not know at exactly what depth these fractures would have formed. They provided a link between the Kujung Limestone, and overpressured mud at a depth of 1323 m to 1871 m (Mazzini et al., 2007) and the surface. Mud, gas, steam and water start to erupt at the surface on 29th May 2006.

deeper in the hole as was planned prior to drilling, then the leak off pressure at the lowest casing point would have been higher than 21.03 MPa. The chances of the pressure during the shut-in exceeding the higher leak off pressure would have been much lower. In other words the well may have tolerated the shut in pressure of 2.42–3.39 MPa and not failed had the casing been set deeper in the hole.

We predict, and have direct evidence for, leakage of mud into the surrounding sedimentary strata. This leakage most likely started when the well was shut, when the pressure in the wellbore would have been highest. Leakage into the rock strata normally occurs by a process of hydraulic fracturing where the fluid pressure exceeds the minimum principle stress and tensile strength of the rock (see Jolly and Lonergan, 2002). Fractures would have propagated to surface if a constant flow of high pressure fluid could be accessed. We propose that this occurred from the morning of the 28th May 2006, to the early morning of the 29th May 2006, when the water, gas and mud mix was seen at surface. The alignment of eruptions suggests that at some level the flows utilised existing structural weaknesses and hence have a NE-SW alignment or that fractures developed orthogonal to minimum principal stress direction. The most likely mechanism for the kick is that insufficient mud was used to replace the volume of the drill pipe as it was extracted on May 27th and May 28th 2006. Insufficient mud in the well would have caused the well to become 'underbalanced' (pressure from the column of mud is less than the pore fluid pressure) and fluid and gas would have been able to enter the well from surrounding rock strata. The composition of the initial eruption material, which was described as methane and hydrogen sulphide gas, water and mud, is similar to what was reported to constitute the influx of fluid and gas into the wellbore. The key events of May 27th to May 29th 2006 are summarised in Fig. 10. The initial discharge of mud, water and gas occurred at low rates, we interpret this flow to have occurred up the wellbore (below 1091 m) and then through the hydrofractures.

6. Conclusions

The cause of the Lusi mud volcano disaster can be determined with a very high degree of confidence. On the basis of a comparison with the non-response of Lusi to previous earthquakes we rule out the Yogyakarta earthquake as the sole causative mechanism (*contra* Mazzini et al., 2007). Furthermore we present several key pieces of data which show that Lusi was triggered by drilling operations. The key event was the removal of the drill bit and drill pipe on May 27th to 28th which caused an influx of formation fluid and gas into the wellbore as this operation was conducted. As a result of shutting in the well during this kick event, the high level of excess pressure in the drill pipe on the 28th May 2006 combined with the pressure of the drilling mud would have been sufficient to cause hydraulic fracturing below the 33.97 cm casing shoe. The hydraulic fractures propagated to the surface and the eruption initiated. This mechanism is known as a subsurface blowout. The fact that the lowermost 1734 m of the exploration well had no protective casing was a contributing factor but it was the kick induced by withdrawing the drill pipe and drill bit that triggered the mud volcano.

We cannot be certain of the exact depth the failure took place nor the initial source of the gas or fluid but our preferred model is that the fluid is now coming from a porous and permeable lithology, probably the Kujung limestone (Davies et al., 2007) beyond 2833 m depth. In order to predict the duration of the eruption, which at the time of going to press is 750 days, estimating of the volume of the Kujung limestone aquifer would be fruitful.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2008.05.029.

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