Triggering of the Lusi mud eruption: Earthquake versus drilling initiation

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ABSTRACT

The Lusi mud volcano in East Java has erupted unabated for almost 2 yr, flooding an area of 7 km^2 and displacing more than 25,000 people. Despite its disastrous impact, the mechanism for triggering the Lusi eruption remains highly controversial; two distinct mechanisms have been proposed. One hypothesis suggests that the eruption was triggered by the M_w 6.3 earthquake that struck Yogyakarta (250 km from Lusi) two days before the eruption. However, an examination of static and dynamic stress changes and stress transfer mechanisms indicates that the Yogyakarta earthquake was at least an order of magnitude too small to reactivate faults and open fluid flow pathways under Lusi. An alternate theory suggests that Lusi was triggered by a blowout following drilling problems in the nearby Banjar Panji-1 well. Blowouts result from an inability to control pore fluid intakes into the borehole and typically occur when the drilling window (fracture pressure minus pore pressure) is approximately zero and when there is insufficient protective casing of the well bore. Pore and fracture pressure data from Banjar Panji-1 indicate that the well had a narrow drilling window of only 0–2.3 MPa. Furthermore, two planned casing points were skipped during drilling, resulting in 1742 m of unprotected borehole. The combination of hazardously narrow drilling window and long uncased borehole would have made drilling problems in Banjar Panji-1 difficult to control, placing the well at high risk of blowing out. Furthermore, well-bore pressures following drilling problems in Banjar Panji-1 reached magnitudes in excess of the fracture pressure and thus were sufficient to create fluid flow pathways in the subsurface. Therefore, we suggest that no viable method is known by which the Yogyakarta earthquake could have triggered the mudflow and that a blowout in the Banjar Panji-1 well was the most likely mechanism for triggering the Lusi eruption.

Keywords: mud volcano, Lusi, East Java, blowout.

INTRODUCTION

On 29 May 2006, mud and steam began to pour out of the ground near Sidoarjo, East Java. This eruption, named Lusi (Davies et al., 2007), has continued unabated for 2 yr at rates of 5000–180,000 m^3 per day (Mazzini et al., 2007). The eruption of >0.05 km^3 of mud has been an unprecedented disaster in a largely urban region, flooding an area of >7 km^2 to depths of 20 m. Lusi is a mud volcano, a common feature in sedimentary basins (Kopf, 2002). However, the mechanism of triggering this eruption is highly controversial, and two distinct mechanisms have been proposed. One hypothesis suggests Lusi was triggered by a blowout in the Banjar Panji-1 (BJP-1) gas exploration well 200 m from the eruption (Davies et al., 2007; Manga, 2007). However, others, and the company operating BJP-1, contest this theory and propose that the eruption was naturally induced by the large earthquake that struck Yogyakarta (250 km W-SW of Sidoarjo) 40 h prior to the first mud eruption (Mazzini et al., 2007), an earthquake that triggered an increase in eruption rates of the Javanese Merapi and Semaru volcanoes (Harris and Ripepe, 2007). The question of whether the mud eruption was triggered by anthropogenic or natural events is highly contentious, especially following damage estimates of U.S. $420 million (Cyranoski, 2007). Herein we conduct a quantitative analysis of the mechanics underlying the earthquake triggering theory and suggest that this hypothesis is mechanically implausible. We then examine the blowout hypothesis, in particular focusing on the drilling problems that occurred in BJP-1 and whether the well was drilled with a sufficient safety margin and adequate casing required for avoiding a blowout after problems occurred.

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SUBSURFACE STRUCTURE OF THE LUSI MUD VOLCANO

Mud volcanoes exhibit a wide variety of subsurface plumbing systems that directly reflect the mud volcano origin (Brown, 1990; Kopf, 2002). Mud volcanoes are commonly thought to be sourced from deep highly overpressured shales (e.g., diapirs), liquefaction of clays, or shallow overpressured gas, hydrate, or water-rich sequences (Brown, 1990; Galli, 2000; Kopf, 2002). However, none of these commonly considered systems is applicable to Lusi.

The mud extruded in the Lusi region is primarily a mixture of water and solids, with a solid fraction that has gradually increased from 20%–30% initially to present values of 50%–70%. The solid fraction is primarily composed of clays from the base of the upper Kalibeng formation at 1219–1828 m depth, but with significant components from deeper and shallower formations (Mazzini et al., 2007). Some clay units within the Kalibeng formation are thixotropic, and it has been considered that the erupted mud may be due to liquefaction of the Kalibeng formation. However, the temperature and chemistry of the erupted fluids indicate that the water component of the mud is primarily sourced from at least 1700 m depth from within both the Kalibeng formation and deeper units (Mazzini et al., 2007). Therefore, the mud erupted at Lusi is a combination of deep overpressured water that entrains sediments from shallower sequences during upward migration.

Migration of mud to the surface is thought to be via a vertically extensive network of NE-SW–oriented faults or tensile fractures, based on the opening of a long NE-SW–striking surface fracture on the first day of the Lusi eruption and the NE-SW dextral displacement of a nearby train line in September 2006 (Mazzini et al., 2007). The existence of a NE-SW–fractured feeder system is supported by the occurrence of more than 45 small short-lived mud and fluid eruptions within 3 km of the main Lusi crater, mostly along a NE-SW trend, and by the observation that subsidence around Lusi is occurring in a 22 km^2 NE-SW–oriented elliptical region (Mazzini et al., 2007). The combination of a fractured subsurface plumbing system and largely separate origin of solid and fluid mud fractions indicates that analysis of the Lusi eruption trigger must primarily examine mechanisms for the initiation and/or reactivation of NE-SW–oriented faults and fractures beneath the eruption site.

EARTHQUAKE TRIGGERING HYPOTHESIS

The earthquake triggering hypothesis proposes that the A.D. 2006 Yogyakarta earthquake caused dextral reactivation of an existing NE-SW–trending vertical fault underneath the Lusi eruption site (Fig. 1; Mazzini et al., 2007). It is suggested that the reactivation of this fault increased its permeability and allowed the migration of deep overpressured fluids to the surface. The initiation of mud volcanoes has historically been linked to major earthquakes (Kopf, 2002; Mellors et al., 2007). For example, the A.D. 1945 Makran earthquake, offshore Iran, triggered large mud eruptions leading to the formation of several new islands (Kopf, 2002). Furthermore, it has been well documented that distant earthquakes can cause increases in the eruption rates of existing hydrological features, such as mud volcanoes and geysers (Galli, 2000; Husen et al., 2004; Manga and Brodsky, 2006; Mellors et al., 2007).

Examination of the earthquake triggering hypothesis requires quantitative analysis of the mechanics behind remotely triggered fault reactivation. Four mechanisms have been suggested for the reactivation of faults by distant earthquakes: coseismically induced static stress changes; postseismic relaxation of static stress changes; poroelastic rebound effects; and dynamic stress changes due to seismic wave shaking. The static change in Coulomb failure stress (ΔCFS) caused by an earthquake is a well-documented mechanism for remotely triggering seismicity (King et al., 1994; Stein, 1999). The ΔCFS resulting from the Yogyakarta earthquake was calculated for vertical NE-SW–striking fault planes with dextral strike-slip motion (thought to have occurred at Lusi) using published earthquake fault plane geometries and a homogeneous elastic half-space model with optimal Poisson ratio of 0.25 and shear modulus of 40 GPa (Nakano et al., 2006). Figure 1 displays the model causing the maximum ΔCFS, which assumed a small rupture surface with a peak coseismic displacement of 1.8 m (in agreement with the released seismic energy). The Yogyakarta earthquake is calculated to cause a maximum ΔCFS of only +0.4 kPa on faults at the Lusi site (Fig. 1). This is significantly below the typical minimum value of 10 kPa required for remote earthquake triggering (King et al., 1994; Stein, 1999) and, hence, the Lusi eruption could not have been triggered by coseismic static stress changes.

Static stress changes also induce processes of poroelastic rebound, such as those observed after the A.D. 1992 Landers earthquake (Peltzer et al., 1998), and transient postseismic stress transfer due to stress relaxation (Freed and Lin, 2001). However, these are not valid triggering mechanisms for the Lusi eruption as they are only effective at distances of twice the rupture length (≤20 km) and would have no effect 250 km away. Furthermore, given the small ΔCFS, postseismic stress changes could not be diffused to the eruption site within the 40 h between the earthquake and eruption.

The only remaining earthquake triggering mechanism is dynamically induced stress changes (Brodsky et al., 2003). This scenario proposes that the seismic waves generated by the Yogyakarta earthquake caused sediment consolidation, overpressure development, and associated redistribution of fluid pressures at the eruption site (Manga, 2007), in turn directly triggering fault reactivation. This mechanism has been suggested as the trigger for the mud eruption following partial loss of drilling mud in the BJP-1 well, indicating fracturing of the well-bore wall, 10 min after the earthquake (Mazzini et al., 2007). The Yogyakarta earthquake was felt in the area around Lusi with an intensity level of II. However, the dynamically induced stress changes at the eruption site resulting from the Yogyakarta earthquake were <+33 kPa, well below the ~200 kPa changes observed to have remotely triggered other hydrological responses (Husen et al., 2004) and the minimum dynamic stress changes empirically estimated as being required for fault reactivation (Manga and Brodsky, 2006; Manga, 2007). Indeed, an extensive data set of known hydrological responses associated with remote earthquakes suggests that the Yogyakarta earthquake would have needed to have been at least one order of magnitude greater for dynamically induced stress changes to have caused fault reactivation at the Lusi site (Manga, 2007). Therefore, despite the close temporal relation between the Yogyakarta earthquake and the Lusi mud eruption, all of the known processes for remote triggering of fault reactivation and associated mud volcanism are implausible.

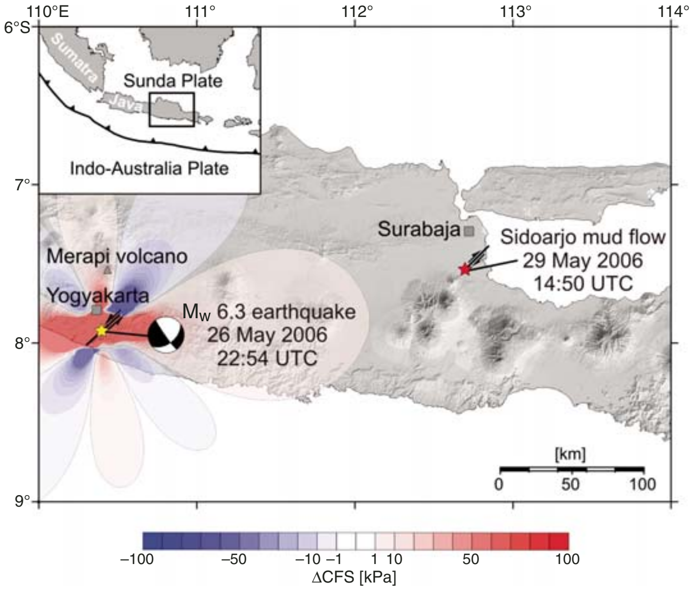

Figure 1. Change in Coulomb failure stress (ΔCFS) from the A.D. 2006 Yogyakarta earthquake on vertical NE-SW dextral faults. ΔCFS of at least +10 kPa is required to remotely trigger fault reactivation. However, Yogyakarta earthquake caused maximum ΔCFS of only +0.4 kPa at Lusi eruption site. Therefore, static stress changes from Yogyakarta earthquake could not have triggered Lusi eruption.

DRILLING-INDUCED HYPOTHESIS

The alternative hypothesis for the Lusi eruption proposes that an internal (underground) blowout occurred in the nearby BJP-1 well, allowing overpressured fluids to be transferred from deep source reservoirs, via the borehole, into shallow sequences (Fig. 2; Davies et al., 2007). This theory suggests that the blowout caused pore pressures to increase inside shallow formations, fracturing the overlying rock and allowing fluid escape to the surface. The drilling-induced theory is supported by the occurrence of several well control problems in BJP-1 immediately prior to the Lusi eruption and the formation of surface fractures from the BJP-1 well site toward the main Lusi crater on the day the mud eruption began (Mazzini et al., 2007). Furthermore, several similar examples of surface eruptions following internal blowouts have been previously documented, most notably the Champion internal blowouts offshore Brunei (Tingay et al., 2005).

The operators of BJP-1 (Lapindo Brantas) deny that a blowout occurred (Cyranoski, 2007); however, it is known that numerous well control incidents took place during the drilling of BJP-1, culminating with major problems 1–2 days before the Lusi eruption. A series of

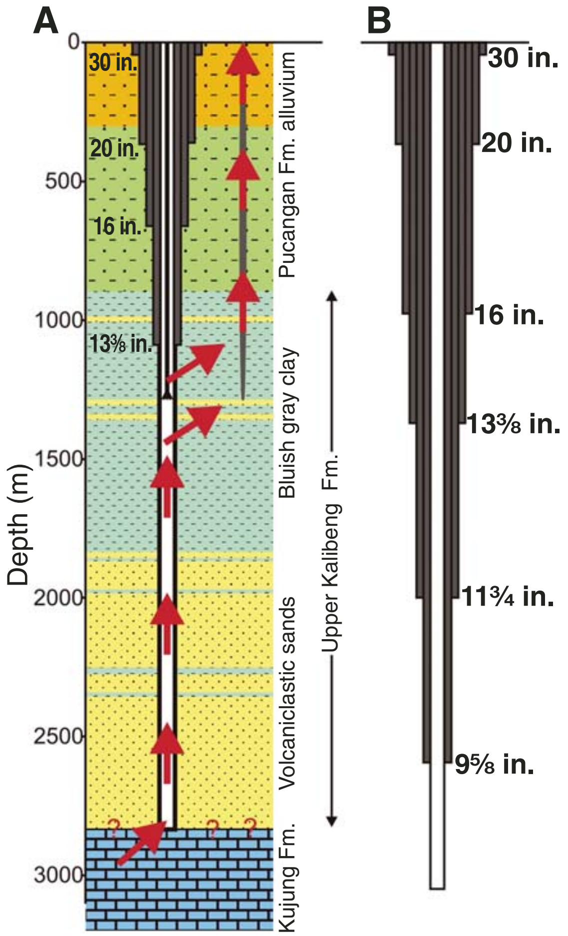

Figure 2. A: Depth of casing points and lithologies encountered in Banjar Panji-1 (BJP-1) and schematic representation of hypothesized drilling trigger for Lusi eruption (adapted from Davies et al., 2007; Mazzini et al., 2007; Sutriono, 2007). In this hypothesis, internal blowout occurs on 28 May 2006, allowing overpressured fluids from >2800 m depth (red arrows) to be transferred into shallow sequences. Increased pressure in shallow sequences fractured overlying rocks, allowing fluids to escape to surface. B: Planned depths for setting of protective casing in BJP-1. BJP-1 was designed to have uncased sections no longer than 610 m. The skipping of planned 11.75 in (~29.84 cm) and 9.675 in (~24.57 cm) casing points resulted in 1742 m of uncased section. Failure to set casing in regions of known overpressure is considered highly unsafe and makes blowout prevention difficult once kicks or losses occur.

drilling mud "losses" (typically indicating fracturing of the well bore) were reported on 27 May 2006, including total losses 6.5 h after the Yogyakarta earthquake. The complete loss of drilling mud is a serious incident and is often a precursor to a blowout. Hence, efforts were made to remove the drill string in order to cement casing and increase structural integrity of the borehole. However, early on 28 May 2006, while pulling out of the borehole, the well took partial losses followed by a major influx of formation fluids (termed a "kick"). The kick resulted in the release of 62,000–95,000 L of water, drilling mud, and gas at the well site (approximately half the hole volume) in 3 h before the surface blowout-preventer valves could be closed.

Kicks and losses are routine occurrences in hydrocarbon drilling and can usually be managed by varying the mud density inside the well bore, using mud additives and regularly setting protective casing. However, available reports of events after the kick are incomplete and often contradictory and cannot confirm whether the kick in BJP-1 developed into an internal blowout. Hence, the potential for a blowout to have occurred in BJP-1 is investigated herein by examining conditions in the borehole prior to the kick, particularly the safety aspects that critically affect the ability for kicks and losses to be controlled: the available drilling window and length of open borehole susceptible to kicks and/or losses.

BJP-1 CASING DESIGN

Steel casing is routinely cemented into the upper sections of wells to increase structural integrity and allow drilling with higher mud pressures to avoid kicks. Drilling long uncased sections and making large deviations from planned casing designs is considered hazardous, especially in overpressured zones. Casing points were designed prior to drilling BJP-1 such that open hole sections would not exceed 610 m in length (Fig. 2; Sutriono, 2007). However, minor kicks and well-bore instability forced setting of the third and fourth casing points several hundred meters shallower than planned. Two additional casing points were planned at 1981 m and 2591 m, the latter depth estimated to be just inside the target Kujung Formation (Fig. 2). However, the planned 1981 m casing point was skipped and, when the Kujung Formation was not encountered at 2591 m depth, the deep casing point was also passed over and drilling continued until the well reached 2834 m depth and complete losses occurred (Fig. 2). Hence, BJP-1 had an uncased section of 1742 m vulnerable to kicks and losses prior to the occurrence of drilling problems.

BJP-1 DRILLING WINDOW

Kicks and losses often develop into an uncontrolled blowout when the maximum pore pressure in an open hole section is close to the minimum fracture pressure (a narrow drilling window). Under such conditions, a small drop in the mud pressure within the borehole will result in a potentially uncontrollable kick, while an increase in mud pressure will result in formation fracturing and losses, making it difficult to maintain high mud pressures throughout the well and often resulting in a kick and blowout. Internal blowouts caused by a narrow drilling window may result in a subsequent surface eruption, because the transfer of even small amounts of overpressured fluids to shallower formations can exceed the fracture pressure (Tingay et al., 2005).

The fracture pressure and maximum pore pressure in BJP-1 can be estimated from drilling reports and leak-off tests. The maximum pore pressure in BJP-1 was reported as both 38 MPa at 2130 m depth (17.84 MPa/km; Davies et al., 2007) and 48 MPa at 2800 m depth (17.1 MPa/km; Mazzini et al., 2007). Neither of these values can be verified by available data, so we assume a maximum pore pressure gradient range of 17.1–17.84 MPa/km for the purposes of estimating the lower bound of the drilling window (Fig. 3). This pore pressure estimate is consistent (equal or slightly higher) with the static mud weight of 17.3 MPa/km in BJP-1.

The fracture gradient was estimated from the lower bound of leak-off tests in BJP-1 and nearby wells and suggests a fracture pressure in the uncased section of the borehole of between 18.5 and 19.3 MPa/km (Fig. 3; Breckels and van Eekelen, 1982). However, some doubt remains about the critical BJP-1 leak-off pressure at 1091 m depth, which we interpret as 17.9 MPa/km, but has also been reported as 18.5 MPa/km and 19.2 MPa/km. Thus we estimate a minimum fracture gradient (upper bound of the drilling window) of 17.9–19.2 MPa/km.

The reported maximum pore pressure gradients and minimum fracture gradients indicate that, prior to the Lusi eruption, BJP-1 was being drilled with a safety window of 0.06–2.1 MPa/km (Fig. 3), equating to a window of only 0.07–2.3 MPa at 1091 m depth (depth of casing). Furthermore, high levels of H_2S (500 ppm) released during the kick suggest that BJP-1 was in communication with the Kujung Formation, which is known to have pore pressure gradients of 18.5 MPa/km in the adjacent Porong field (Davies et al., 2007). Such pressure gradients, if encountered in BJP-1, would reduce the safe drilling window to just 0–0.7 MPa/km.

Drilling mud pressures frequently fluctuate by several megapascals due to normal mud circulation (pumping), borehole constrictions in

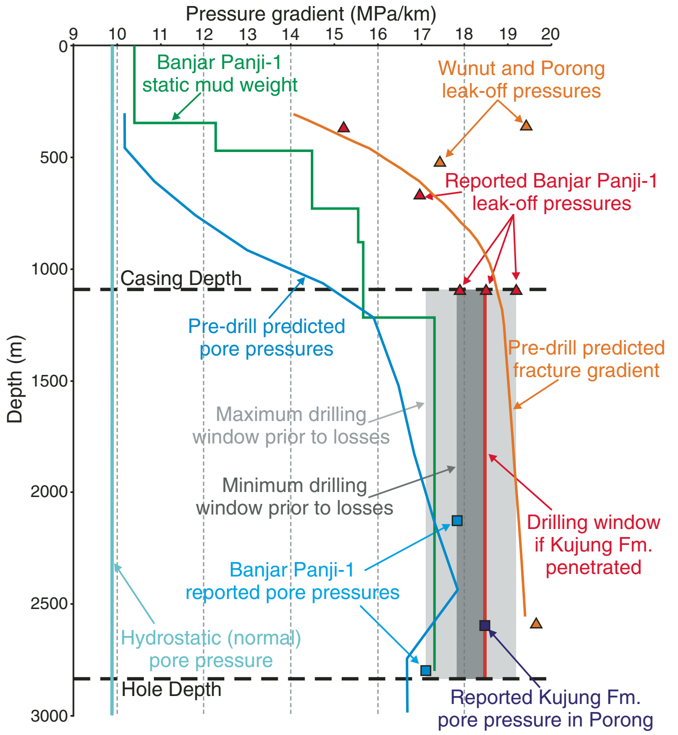

Figure 3. Reported pore pressures, leak-off pressures, and mud pressures in Banjar Panji-1 (BJP-1) and neighboring Porong and Wunut fields (compiled from Davies et al., 2007; Mazzini et al., 2007; Sutriono, 2007). Maximum pore-pressure gradients of 17.1–17.84 MPa/km are reported in BJP-1. Fracture gradient in uncased borehole section is estimated from leak-off pressures as between 17.9 and 19.2 MPa/km. BJP-1 was operating with very narrow drilling window (fracture gradient minus pore pressure; shaded gray) of at most 0.06–2.1 MPa/km prior to major kicks and losses. This drilling window would reduce to 0–0.7 MPa if Kujung Formation was penetrated (shaded red). Hence, BJP-1 was at high risk of blowing out when a major kick occurred on 28 May 2006. Furthermore, wellbore fluid pressures of over 19.5 MPa/km measured during the kick indicate that borehole pressures were well in excess of the fracture gradient and thus large enough to initiate fluid flow pathways to surface.

sequences containing swelling clays (e.g., the Kalibeng formation), and, especially, while the drill string is being pulled out of the well. Hence, the 0–2.1 MPa/km drilling window in BJP-1 was likely to be insufficient for safe control of the losses and kicks. Furthermore, fluid pressures inside the well exceeded 19.5 MPa/km shortly after the blowout preventer was closed, indicating that pressures in BJP-1 during the kick were well outside the safety window. Indeed, the wellbore pressures measured during the kick would be sufficient to exceed the fracture pressure throughout much of the open hole section and create fluid flow pathways to shallow depths or the surface.

CONCLUSIONS

Analysis of static and dynamic stress changes resulting from the Yogyakarta earthquake suggests that this earthquake was at least an order of magnitude too small to have triggered the Lusi mud eruption. However, the combination of a hazardously narrow drilling window and long uncased borehole would have made the major kick in BJP-1 difficult to control and placed the well at high risk of blowing out. Furthermore, pressures in BJP-1 during the kick event were sufficient to extensively fracture the formation and create fluid flow pathways to the surface. Therefore, we suggest that no viable mechanism is yet known by which the Yogyakarta earthquake could have triggered the mudflow and that a drilling accident in the BJP-1 well, combined with unsafe drilling practices, was the most likely triggering mechanism for the Lusi eruption.

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