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An alternative review of facts, coincidences and past and future studies of the Lusi eruption

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Abstract

The cause of the Lusi mud eruption remains controversial. The review by Miller and Mazzini (2017) firmly dismisses a role of drilling operations at the adjacent Banjarpanji-1 well and argues that the eruption was triggered by the M6.3 Yogyakarta earthquake some 254 km away. We disagree with these conclusions. We review drilling data and the daily drilling reports, which clearly confirm that the wellbore was not intact and that there was a subsurface blowout. Downhole pressure data from Lusi directly witness the birth of Lusi at the surface on the 29th of May 2006, indicating a direct connection between the well and the eruption. Furthermore, the daily drilling reports specifically state that Lusi activity was visibly altered on three separate occasions by attempts to kill the eruption by pumping dense fluid down the BJP-1 well, providing further evidence of a connection between the wellbore and Lusi. By comparison with other examples of newly initiated mud eruptions elsewhere by other earthquakes, the Yogyakarta earthquake was far away given its magnitude. The seismic energy density of the Yogyakarta earthquake was only 0.0043 J/m^3, which is less than a quarter of the minimum 0.019 J/m^3 seismic energy density that has ever been inferred to trigger other mud eruptions. We show that the Lusi area had previously experienced other shallow earthquakes with similar frequencies and stronger ground shaking that did not trigger an eruption. Finally, the data from the BJP-1 well indicates that there was no prior hydrodynamic connection between deep overpressured hydrothermal fluids and the shallow Kalibeng clays, and that there was no evidence of any liquefaction or remobilization of the Kalibeng clays induced by the earthquake. We thus strongly favor initiation by drilling and not an earthquake.

Keywords: Lusi. Mud volcano. Drilling. Earthquake

1. Introduction

Lusi has been a fascinating laboratory for studying the birth and evolution of large mud eruptions. The triggering of this unique disaster has been highly controversial, with some studies proposing that the disaster is man-made due to a drilling accident (e.g. Davies et al., 2007, Davies et al., 2008, Tingay et al., 2008), while other studies propose a natural earthquake trigger for the eruption (e.g. Mazzini et al., 2007; Sawolo et al., 2009, Lupi et al., 2013). To interpret observations made during this eruption, especially during the early stages of the eruption, we contend that it is essential to understand the processes that initiated the eruption. Ten years after the eruption began is an appropriate time to look backwards at what we have learned. In the review by Miller and Mazzini (2017), the eruption is attributed to an earthquake and the authors argue that the nearby drilling operations at the Banjarpanji-1 (BJP-1) well played no role.

It is important to highlight that, despite the claims made by Miller and Mazzini (2017), the drilling-trigger and earthquake-trigger models are very similar, and only differ on two key issues. Both hypotheses argue that something changed the effective stress (stress minus pore fluid pressure) on faults or fractures under Lusi, causing those faults or fractures to become active and permit fluid flow to the surface. The earthquake and drilling triggering mechanisms differ on two main points:

1) What caused the change in effective stress under Lusi? Drilling-trigger proponents argue that the change in effective stress was the large pressure increase in the BJP-1 borehole that occurred when the well was shut-in during a kick (an influx of fluid) on the 28th of May 2006 (resulting in a minimum effective stress decrease of 2.6 MPa; Davies et al., 2008, Sawolo et al., 2009). Earthquake trigger proponents argue that the change in effective stress was the result of gas release due to liquefaction of the Kalibeng clays, with this liquefaction being triggered by the dynamic shaking from the passage of seismic waves from the 27th May 2006 Yogyakarta event (resulting in a maximum effective stress reduction of 0.2 MPa, less than 1/13th the effective stress change caused by the kick; Lupi et al., 2013).

2) What was the primary initial source of high-pressure water driving the initial eruption, and, specifically, were the Kalibeng clays hydrodynamically connected to deep overpressured fluids prior to the Lusi eruption? Drilling-trigger proponents argue that the water that primarily drove the start of the Lusi eruption was sourced from the deep carbonates at ~2800 m depth (which are directly connected to a deep overpressured, and possibly hydrothermal, system), and that the kick in BJP-1 allowed these fluids to use the borehole to flow up into the Kalibeng clays, entraining these clays as they flowed through fractures to the surface. This model suggests no prior hydrodynamic connection between the Kalibeng clays and deeper waters (though does not specifically preclude such a connection). In contrast, the earthquake trigger proponents argue that the Kalibeng clays had been previously ‘charged’ by deep overpressured and hydrothermal fluids via the Watukosek fault, and claim that hydrothermal fluid invasion would make the Kalibeng clays susceptible to liquefaction or mobilization. Published earthquake-triggering models specifically require the Kalibeng clays to be in hydrodynamic connection prior to the Yogyakarta earthquake (Mazzini et al., 2012; Lupi et al., 2013).

These two issues are essentially the key to distinguishing between the earthquake- and drilling-trigger arguments, as summarized in Fig. 1.

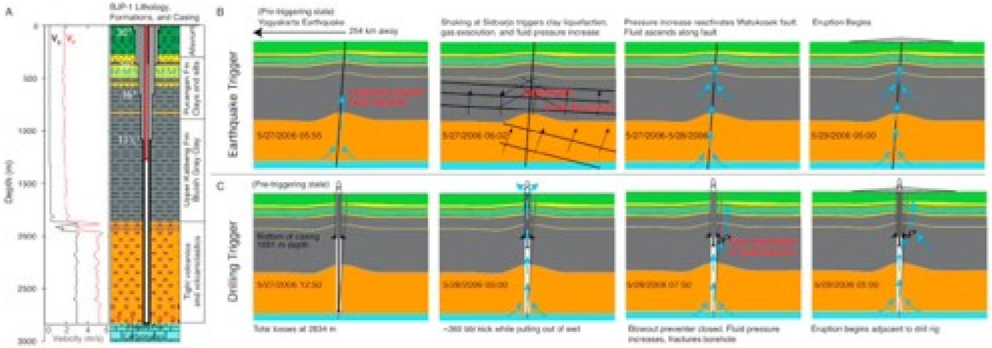


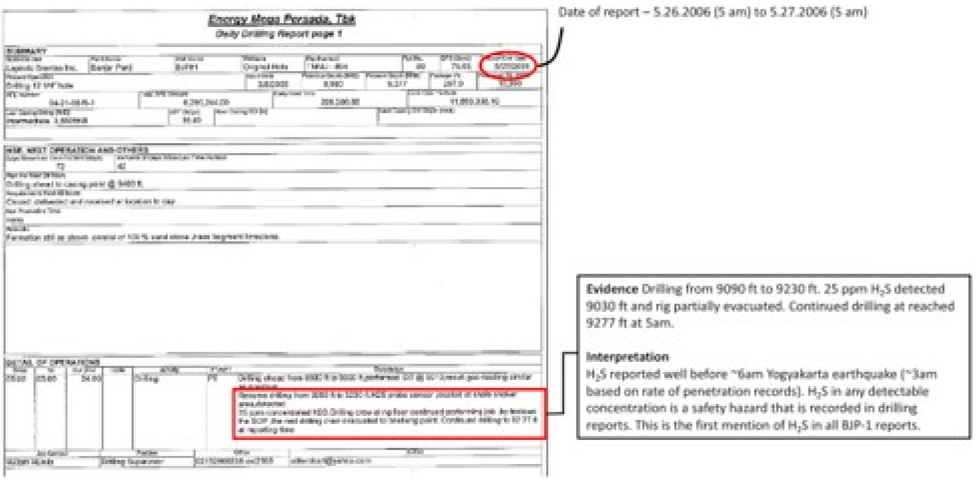
Fig. 1. Schematic illustration of the two models for the initiation of the 2006 Lusi eruption.

Here we provide a chronology and explanation of the published data from daily reports and drilling logs. We then update previous compilations of earthquake-triggered eruptions. Together these analyses allow us to critically assess all the key claims in Miller and Mazzini (2017) that an earthquake triggered the eruption. In particular, the highly detailed analysis of the original daily drilling reports and data undertaken herein highlights major pieces of evidence that have been overlooked in prior studies, such as the multiple instances in which drilling reports document a direct connection between Lusi and the BJP-1 well. We argue, instead, that the extensive evidence strongly supports the drilling-trigger model, and contradicts the earthquake-triggering model.

2. Drilling

Miller and Mazzini (2017) do not bring any new data to the argument that drilling did not create the Lusi mud volcano, and repeat the claims made by Sawolo et al., 2009, Sawolo et al., 2010, which were primarily authored by the Lapindo Brantas engineers who drilled the BJP-1 well.

All key observations related to drilling the BJP-1 well, and of the first days of the Lusi eruption, are documented in the daily drilling reports, and were published previously as online appendices to Sawolo et al. (2009). We summarize these observations and show the daily drilling reports for the 24-h periods ending at 5 a.m. on the 27th to 31st of May 2006 (Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6). These reports directly contradict most of the key statements in Miller and Mazzini (2017)and the key claims made in Sawolo et al., 2009, Sawolo et al., 2010. It is the official original drilling data and daily drilling reports, as well as other (published) data, that form the basis of the arguments made by proponents of the drilling-trigger hypothesis for Lusi (Davies et al., 2007, Davies et al., 2008, Davies et al., 2010, Tingay et al., 2008, Tingay et al., 2015).

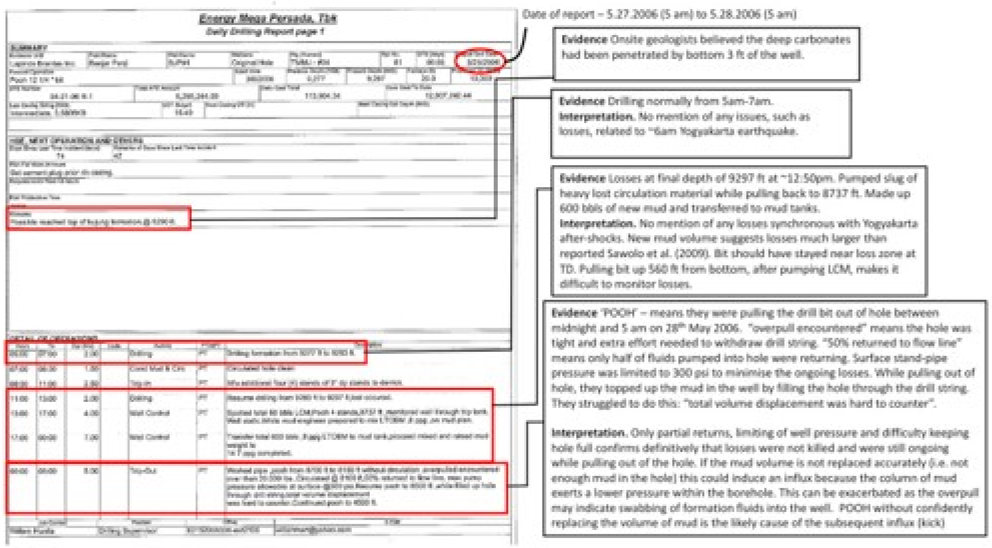


Date of report – 5.26.2006 (5 am) to 5.27.2006 (5 am)

Evidence Drilling from 9090 ft to 9230 ft. 25 ppm H_2S detected 9030 ft and rig partially evacuated. Continued drilling at reached 9277 ft at 5am.

Interpretation
H_2S reported well before ~6am Yogyakarta earthquake (~3am based on rate of penetration records). H_2S in any detectable concentration is a safety hazard that is recorded in drilling reports. This is the first mention of H_2S in all BJP-1 reports.

Fig. 2. Daily drilling report on the 27th May 2006, which spans the period from 05:00 on the 26th of May to 0:500 on the 27th of May 2006 (previously published in Sawolo et al., 2009), with annotations showing key evidence and interpretations.



Date of report – 5.27.2006 (5 am) to 5.28.2006 (5 am)

Evidence Onsite geologists believed the deep carbonates had been penetrated by bottom 3 ft of the well.

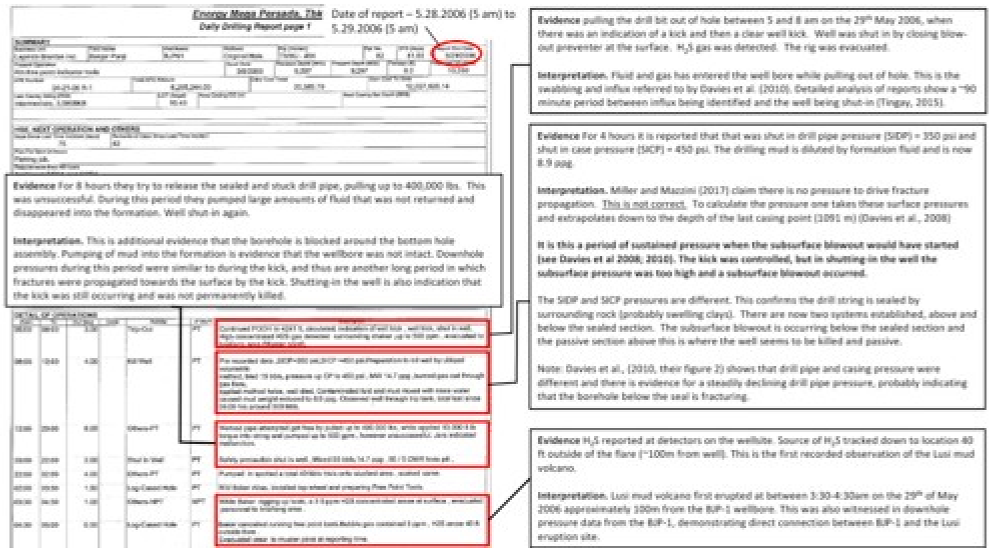
Evidence Drilling normally from 5am-7am.
Interpretation. No mention of any issues, such as losses, related to ~6am Yogyakarta earthquake.

Evidence Losses at final depth of 9297 ft at ~12:50pm. Pumped slug of heavy lost circulation material while pulling back to 8737 ft. Made up 600 bbls of new mud and transferred to mud tanks.
Interpretation. No mention of any losses synchronous with Yogyakarta after-shocks. New mud volume suggests losses much larger than reported Sawolo et al. (2009). Bit should have stayed near loss zone at TD. Pulling bit up 560 ft from bottom, after pumping LCM, makes it difficult to monitor losses.

Evidence 'POOH' – means they were pulling the drill bit out of hole between midnight and 5 am on 28th May 2006. "overpull encountered" means the hole was tight and extra effort needed to withdraw drill string. "50% returned to flow line" means only half of fluids pumped into hole were returning. Surface stand-pipe pressure was limited to 300 psi to minimise the ongoing losses. While pulling out of hole, they topped up the mud in the well by filling the hole through the drill string. They struggled to do this: "total volume displacement was hard to counter".

Interpretation. Only partial returns, limiting of well pressure and difficulty keeping hole full confirms definitively that losses were not killed and were still ongoing while pulling out of the hole. If the mud volume is not replaced accurately (i.e. not enough mud in the hole) this could induce an influx because the column of mud exerts a lower pressure within the borehole. This can be exacerbated as the overpull may indicate swabbing of formation fluids into the well. POOH without confidently replacing the volume of mud is the likely cause of the subsequent influx (kick)

Fig. 3. Daily drilling report on the 28th May 2006, which spans the period from 05:00 on the 27th of May to 0:500 on the 28th of May 2006 (previously published in Sawolo et al., 2009), with annotations showing key evidence and interpretations.



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Daily Drilling Report page 1

Date of report – 5.28.2006 (5 am) to 5.29.2006 (5 am)

Evidence For 8 hours they try to release the sealed and stuck drill pipe, pulling up to 400,000 lbs. This was unsuccessful. During this period they pumped large amounts of fluid that was not returned and disappeared into the formation. Well shut-in again.

Interpretation. This is additional evidence that the borehole is blocked around the bottom hole assembly. Pumping of mud into the formation is evidence that the wellbore was not intact. Downhole pressures during this period were similar to during the kick, and thus are another long period in which fractures were propagated towards the surface by the kick. Shutting-in the well is also indication that the kick was still occurring and was not permanently killed.

Evidence pulling the drill bit out of hole between 5 and 8 am on the 29th May 2006, when there was an indication of a kick and then a clear well kick. Well was shut in by closing blow-out preventer at the surface. H_2S gas was detected. The rig was evacuated.

Interpretation. Fluid and gas has entered the well bore while pulling out of hole. This is the swabbing and influx referred to by Davies et al. (2010). Detailed analysis of reports show a ~90 minute period between influx being identified and the well being shut-in (Tingay, 2015).

Evidence For 4 hours it is reported that that was shut in drill pipe pressure (SIDP) = 350 psi and shut in case pressure (SICP) = 450 psi. The drilling mud is diluted by formation fluid and is now 8.9 ppg.

Interpretation. Miller and Mazzini (2017) claim there is no pressure to drive fracture propagation. This is not correct. To calculate the pressure one takes these surface pressures and extrapolates down to the depth of the last casing point (1091 m) (Davies et al., 2008)

It is this a period of sustained pressure when the subsurface blowout would have started (see Davies et al 2008; 2010). The kick was controlled, but in shutting-in the well the subsurface pressure was too high and a subsurface blowout occurred.

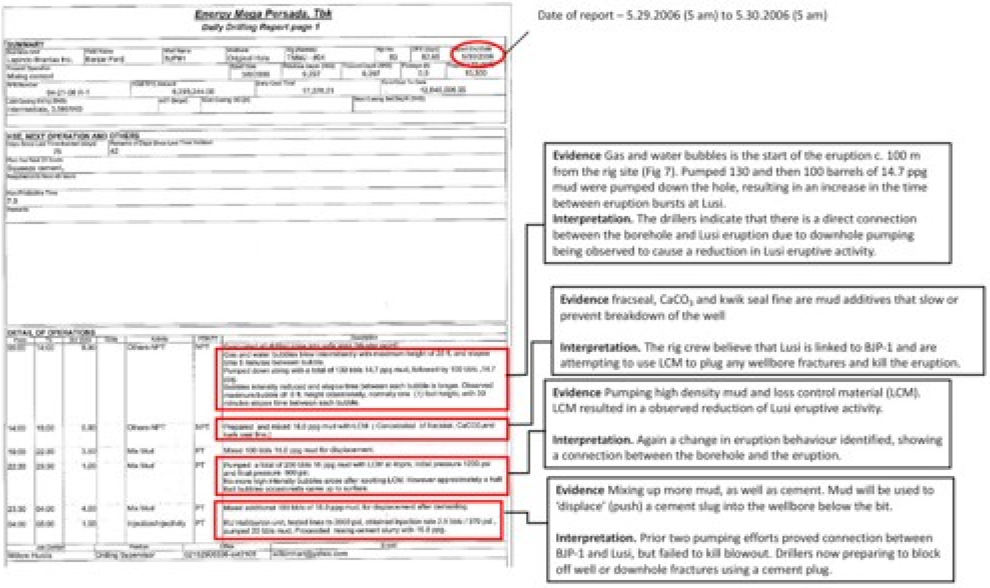
The SIDP and SICP pressures are different. This confirms the drill string is sealed by surrounding rock (probably swelling clays). There are now two systems established, above and below the sealed section. The subsurface blowout is occurring below the sealed section and the passive section above this is where the well seems to be killed and passive.

Note: Davies et al., (2010, their figure 2) shows that drill pipe and casing pressure were different and there is evidence for a steadily declining drill pipe pressure, probably indicating that the borehole below the seal is fracturing.

Evidence H_2S reported at detectors on the wellsite. Source of H_2S tracked down to location 40 ft outside of the flare (~100m from well). This is the first recorded observation of the Lusi mud volcano.

Interpretation. Lusi mud volcano first erupted at between 3:30-4:30am on the 29th of May 2006 approximately 100m from the BJP-1 wellbore. This was also witnessed in downhole pressure data from the BJP-1, demonstrating direct connection between BJP-1 and the Lusi eruption site.

Fig. 4. Daily drilling report on the 29th May 2006, which spans the period from 05:00 on the 27th of May to 0:500 on the 28th of May 2006 (previously published in Sawolo et al., 2009), with annotations showing key evidence and interpretations.



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Daily Drilling Report page 1

Date of report – 5.29.2006 (5 am) to 5.30.2006 (5 am)

Evidence Gas and water bubbles is the start of the eruption c. 100 m from the rig site (Fig 7). Pumped 130 and then 100 barrels of 14.7 ppg mud were pumped down the hole, resulting in an increase in the time between eruption bursts at Lusi.

Interpretation. The drillers indicate that there is a direct connection between the borehole and Lusi eruption due to downhole pumping being observed to cause a reduction in Lusi eruptive activity.

Evidence fracseal, $CaCO_3$ and kwik seal fine are mud additives that slow or prevent breakdown of the well

Interpretation. The rig crew believe that Lusi is linked to BJP-1 and are attempting to use LCM to plug any wellbore fractures and kill the eruption.

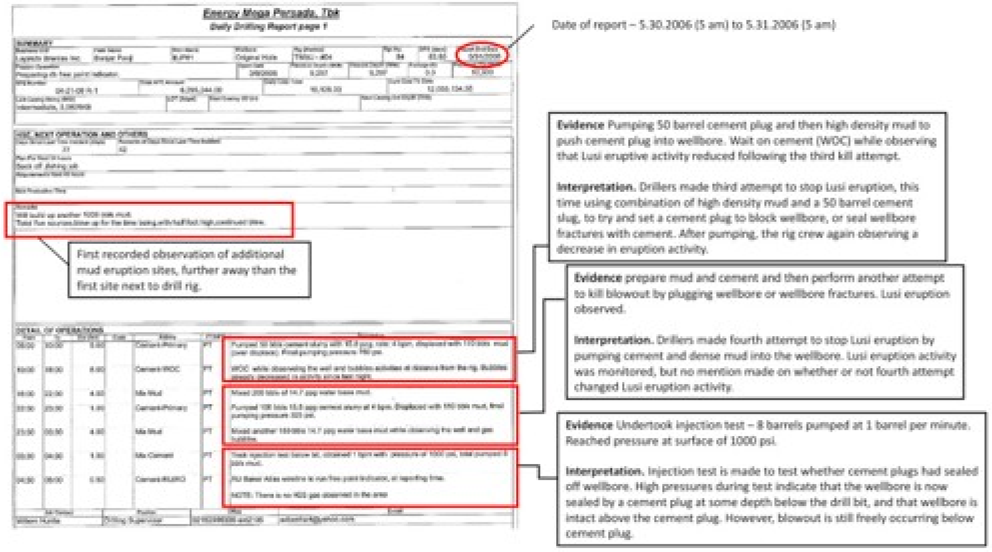
Evidence Pumping high density mud and loss control material (LCM). LCM resulted in a observed reduction of Lusi eruptive activity.

Interpretation. Again a change in eruption behaviour identified, showing a connection between the borehole and the eruption.

Evidence Mixing up more mud, as well as cement. Mud will be used to 'displace' (push) a cement slug into the wellbore below the bit.

Interpretation. Prior two pumping efforts proved connection between BJP-1 and Lusi, but failed to kill blowout. Drillers now preparing to block off well or downhole fractures using a cement plug.

Fig. 5. Daily drilling report on the 30th May 2006, which spans the period from 05:00 on the 29th of May to 0:500 on the 30th of May 2006 (previously published in Sawolo et al., 2009), with annotations showing key evidence and interpretations.



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Daily Drilling Report page 1

Date of report – 5.30.2006 (5 am) to 5.31.2006 (5 am)

First recorded observation of additional mud eruption sites, further away than the first site next to drill rig.

Evidence Pumping 50 barrel cement plug and then high density mud to push cement plug into wellbore. Wait on cement (WOC) while observing that Lusi eruptive activity reduced following the third kill attempt.

Interpretation. Drillers made third attempt to stop Lusi eruption, this time using combination of high density mud and a 50 barrel cement slug, to try and set a cement plug to block wellbore, or seal wellbore fractures with cement. After pumping, the rig crew again observing a decrease in eruption activity.

Evidence prepare mud and cement and then perform another attempt to kill blowout by plugging wellbore or wellbore fractures. Lusi eruption observed.

Interpretation. Drillers made fourth attempt to stop Lusi eruption by pumping cement and dense mud into the wellbore. Lusi eruption activity was monitored, but no mention made on whether or not fourth attempt changed Lusi eruption activity.

Evidence Undertook injection test – 8 barrels pumped at 1 barrel per minute. Reached pressure at surface of 1000 psi.

Interpretation. Injection test is made to test whether cement plugs had sealed off wellbore. High pressures during test indicate that the wellbore is now sealed by a cement plug at some depth below the drill bit, and that wellbore is intact above the cement plug. However, blowout is still freely occurring below cement plug.

Fig. 6. Daily drilling report on the 31st May 2006, which spans the period from 05:00 on the 30th of May to 0:500 on the 31st of May 2006 (previously published in Sawolo et al., 2009), with annotations showing key evidence and interpretations.

We argue that the original well report statements and raw drilling data presented herein demonstrate conclusively that the wellbore was fractured during the kick, suffered large ongoing downhole losses for long periods after the kick commenced, and that there was direct communication between the BJP-1 wellbore and Lusi eruption. These processes are described in Claims 4 and 7below, and are the key evidence supporting a drilling-trigger for the Lusi disaster. However, we also discuss all major claims made by Miller and Mazzini (2017) and Sawolo et al. (2009) and show that their claims require readers to ignore large parts of the original drilling records and reports.

We do not discuss many other claims in Miller and Mazzini (2017), such as production rate changes in nearby hydrocarbon wells and reported drops in water levels in villages, as these are anecdotal statements for which no supporting evidence has ever been published, and hence cannot be verified or quantitatively assessed. The claims below are listed in chronological order. We first summarize each claim, explain why it matters, review the evidence, and provide a conclusion about each claim.

We use a clear hierarchy of data in our assessment. We consider raw data and the BJP-1 daily reports to be the most reliable data, as these reports list observations and routine calculations made at the time of events. Furthermore, we give greater confidence to evidence, statements and observations that are confirmed in multiple sources (e.g., stated in multiple daily reports, or on both reports and raw data). It should be noted that such daily reports are generally classified as legal documents, that are confirmed and signed off for their accuracy by multiple sources, and have been included within legal proceedings related to the Lusi disaster (Novenanto, 2015). Such raw data should always be considered more robust and reliable than claims, statements or interpretations made significantly after the events at BJP-1, which have the potential to be affected by biases and, in some cases, are not supported by any verifiable data.

Claim 1

"BJP-1 well recorded partial losses of drilling mud directly after the earthquakeand followed by total loss of drilling mud directly after two strong *aftershocks* of the Yogyakarta earthquake" (Miller and Mazzini, 2017).

Why it matters: During drilling operations, mud is continuously circulated through the drill string, past the bit, and back up the annulus between the drill string and the casing (or open wellbore) where it is recaptured at the surface. The circulating mud lubricates the drill bit, flushes debris from the borehole, and in the uncased section, exerts a fluid pressure engineered to slightly exceed the formation fluid pressure, preventing exchange of formation fluid with the borehole. 'Partial losses' refers to an imbalance between the rate at which mud is pumped into the well and the rate at which it is recovered, indicating that mud is being lost from the well bore to the surrounding formations. Losses coincident with the passage of seismic waves could indicate that a distant earthquake modified subsurface conditions.

The evidence: We begin by addressing the second part of this claim. A total "loss of returns" (which means that drilling mud stopped returning to the surface) at the BJP-1 wellbore occurred at 12:50 p.m. on the 27th of May 2006. Three significant aftershocks occurred following the 05:54 a.m. Yogyakarta earthquake that day, namely a M_w4.4 at 08:07 a.m., a M_w4.8 at 10:10 a.m. and a M_w4.6 at 11:22 am. Thus, the total losses in BJP-1 occurred 88–283 minutes after any aftershocks, and the claim by Sawolo et al. (2009) and Miller and Mazzini (2017) that the losses occurred "*directly after two strong aftershocks*" is thus misleading. Indeed, the claim implies a definite connection between the total losses and the aftershocks, despite the significant delay between the aftershocks and total losses. Importantly, the drilling reports (Fig. 3) make no mention of the Yogyakarta earthquake and its aftershocks. Nor is there mention of any cessation of drilling activities being required during this period. Nevertheless, a lag might be expected if disturbances require time to propagate to the well. Regardless, normal drilling activities continued throughout the approximately eight-hour period between the Yogyakarta earthquake and the total losses in BJP-1 (and in the ~90 minutes between the final aftershock and the total loss of circulation).

The first part of this claim states that the BJP-1 well experienced partial downhole losses immediately after with the passage of earthquake waves from the main Yogyakarta earthquake. Sawolo et al. (2009) present an annotated partial copy of the mudlogger's surface mud pit volume graph (their Fig. 12), which is used to record the volume of mud in the mud pits on the surface (note that the stated volume of ~740 barrels, compared to a total volume of mud in the hole of 1273 barrels on the daily mud engineers report for the 27th May 2006, Sawolo et al. (2009) appendix G3, confirms that the chart is the surface mud pit volume and not the downhole mud volume). This graph shows an approximate 20 barrel drop in mud volume in the surface pits at 6:02 a.m., or approximately 7 minutes after the main Yogyakarta earthquake. However, there are a number of issues and irregularities that cast significant doubt on whether this volume change is due to downhole losses. First, these are surface pit volumes, and are not the charts used for downhole volumes. This chart simply shows that the surface mud pit volume reduced by ~20 barrels over a period of, presumably, some minutes (no time scale is given in the chart). There is no statement in the daily mud reports of any losses downhole at this time, nor of what this 20 barrel change in surface mud volume refers to (Sawolo et al., 2009). Surface mud pit volumes may change due to removal of mud from the pits for cleaning, and are also done routinely many times each day to top off mud in the well that is lost from gradual downhole seepage and from spillage associated with actions of the shale shakers. There is no evidence to confirm that this minor change refers to sudden downhole losses.

There are also doubts over the timing of this drop in surface mud tank volume, as discussed in detail in Tingay (2015). Fig. 12 of Sawolo et al. (2009) is partial and unclear. The figure is annotated in blue with the time 06:00, but the actual time stamps (in black) are unclear, due to image quality, with one looking like 05:00 and another 06:00. Most tellingly, what is clearly written on the left of the chart is the depth they are drilling when the 20 barrel change occurred, which occurred while the well was drilled between the depths of 9274.2 and 9275.2 feet. The daily drilling reports for BJP-1 clearly state the depth of the well at 5 a.m. on the 27th of May 2006 as being 9277 feet (which is confirmed as the 5 a.m. depth in the Daily Geological Reports and Daily Mud Reports; Sawolo et al., 2009 and Fig. 2). This is a clear discrepancy in the claim made by Sawolo et al. (2009) – how could BJP-1 be drilling from 9274.2 to 9275.2 feet depth at 06:00 a.m. when they had already drilled several feet past this depth at 05:00 am. The available published evidence implies that the 20 barrel change in surface pit volume possibly occurred before the earthquake.

Conclusion: The Miller and Mazzini (2017), and Sawolo et al. (2009), claim of total losses being “directly after” major aftershocks is incorrect or at least highly misleading. There is no reliable evidence to support their stated definitive linkage between earthquakes near Yogykarta and losses in BJP-1. A link between any aftershocks and the total losses in BJP-1 is not expected given the >90 minute time delay, and the magnitude of these aftershocks being significantly lower (by approximately two orders of magnitude) than the main earthquake. Indeed, the seismic energy density of the aftershocks is well below that which has ever triggered a remote hydrological response (see section 4 herein). Importantly, none of the published drilling reports make any mention of losses occurring “directly after” either the Yogyakarta earthquake or any of the smaller aftershocks. There is no reliable evidence to support the claim of downhole losses coincident with the arrival of seismic waves at approximately 06:02 a.m. on the 27th of May 2006. The only provided evidence shows 20 barrels of change in surface mud pits, with no supporting data to determine whether this relates to downhole losses. Furthermore, there is a clear discrepancy in the reported timing of this event, with the original time stamps being ambiguous, and the reported depth of these losses corresponding with the drilling depth shortly prior to 05:00am. Hence, the claim of subsurface losses coincident with the earthquake must be considered as unverified, with the provided supporting data being contradictory, or at least ambiguous, to the claim.

Claim 2

Following the key event in which the well experienced “total loss of circulation and 130 bbls (21670 l) mud loss at 12:50pm on the 27th May 2006, the losses were cured and “well static for 7 h without any further loss or kick”.

Why it matters: Total loss of circulation indicates that all mud added to the well is lost to the surrounding formations. Significant and ongoing losses can lead to insufficient mud weight, which can cause a kick.

The evidence: The daily mud engineer report states that a total of 607 barrels of mud were lost in the 24 hour period covering the total losses, including 142 barrels lost during the subsequent pull-out-of-hole (POOH) operations (Sawolo et al., 2009). The daily reports do not state the mud amount during the total loss event, but the mud engineer's report suggests that the losses at terminal or total depth (TD) were up to 465 barrels (Sawolo et al., 2009). The daily drilling report also states that 600 barrels of new mud were made and transferred to the surface mud tanks after the losses, and prior to POOH, which further suggests that losses were significantly greater than the 130 bbls claimed by Sawolo et al. (2009).

Most significantly, the claim that these losses were cured, and no further losses occurred, is directly contradicted by the daily reports. When the losses occurred, the drillers “*spotted 60 barrels of LCM* (Lost Circulation Material)” while pulling out of hole to 8737 feet, and then monitored the well as being static (Fig. 2). However, pumping a slug of concentrated LCM may only temporarily slow losses, and pulling back the drill-bit away from the loss zone can make losses harder to detect. As stated previously, the mud engineer report states “*Total mud loss along POOH* (pull out of hole) *= 142 bbls* (barrels)” between 22:00 on the 27th of May and 05:00 on the 28th of May (meaning that losses continued while pulling out of hole). Furthermore, the reports state that, while pulling out of hole, “*total volume displacement hard to counter*” (unable to keep the hole full of mud) and “*circulated at 8100 feet with 50% returns*” (meaning that half of the mud being pumped into the hole was being lost into the formation). Both statements, and the mud engineers report, clearly demonstrate that losses were ongoing while pulling out of hole, and that the losses at TD were likely not fully cured (Sawolo et al., 2009, Adams, 2006).

Conclusion: The claim is partially correct, but the data and statements in reports directly contradict the claim that the losses were fully stopped, and rather suggest the losses were only temporarily stopped or slowed. Indeed, the daily drilling and mud engineer reports clearly state that losses were ongoing while pulling out of hole (Fig. 3). Furthermore, data in the drilling reports suggest that the loss was more significant than claimed in Sawolo et al. (2009).

Claim 3

Sawolo et al. (2009)*and*Miller and Mazzini (2017)*claim that the kick was quickly controlled and completely killed by 8:05am on the 28th of May 2006. Direct quotes include "Well kicked, shut in and kill well" at 07:30, and also at 07:50 "well kicked" and "Shut BOP to stop further influx". "Well dead" at 08:05am.*

Why it matters: If the kick was quickly and fully controlled, then it is less likely that Lusi was triggered by drilling activities. However, if the kick was not completely controlled, then a subsurface blowout could occur. Closing the blowout preventer simply stops overpressured fluids from escaping at the wellhead. High-pressure fluids will continue to flow into the wellbore when the BOP is closed, but these fluids will increase the pressure inside the wellbore until pressures in the wellbore reach equilibrium with the 'kicking' formation. However, a subsurface blowout can occur if the increase in fluid pressure in the wellbore causes fluids to flow into shallow low-pressure zones, or if the high wellbore pressures cause initiation or reactivation of shear or tensile fractures in the formation. Subsurface blowouts are hard to control, because the wellbore is no longer a 'closed system'. Furthermore, underground blowouts that trigger fracturing can result in the fracture propagating to the surface, and lead to a surface blowout at some distance from the wellbore (as proposed by the drilling-trigger model for Lusi; Fig. 1).

The evidence: There are contradictory reports of the timing of the kick. The chronology provided by Sawolo et al. (2009) suggests that two kicks occurred, one at 7:30 a.m. and one at 7:50 a.m., with the blow out preventers (BOP) shut-in and killed both times. Yet, daily reports only report one kick. The kick was first reported as "*well flowing*" at ~06:25 a.m., the "*well kicked*" at ~07:30am when fluids erupted at the surface at the wellsite, and the BOP was shut-in at ~07:53 a.m. (Sawolo et al., 2009, Adams, 2006). No statements are made about why almost 90 minutes passed between the kick being first detected and the BOP being shut-in, when all well control procedures state that the annular BOP should be shut-in immediately upon confirmation of any influx (Baker, 1998). Regardless, the key claim is that the kick had been killed by ~08:50 am. This is supported by the data in Sawolo et al. (2009) showing that the BOP was open and the well could be circulated between ~12:30 p.m. and 14:20 on the 28th of May 2006. Again, however, this evidence is incomplete, and the drilling reports and data contradict the claim that the kick was fully killed, and instead suggest that the kick was only temporarily controlled.

Sawolo et al. (2009) present key data for casing and drill pipe pressures, active flow, and trip tank volume in their Fig. 9. Sawolo et al. (2009)Fig. 9 presents two pressure-time plots, a short zoomed in chart (time from -20 to 200 minutes) in which the 'time zero' starts when the BOP is shut-in at ~07:53, and an extended time chart (0-1500 minutes) in which the 'time zero' is ~50 minutes before the BOP is closed and thus shows wellbore pressures from ~07:00am on the 28th of May to 09:00am on the 29th of May 2006. This is the essential data for analyzing the subsurface conditions during the kick and afterwards. The casing pressure is the fluid pressure in the annulus measured at the surface. The drill pipe pressure is the pressure measured in the drill string at the surface (which is in communication with the wellbore via the drill-bit). Both pressure gauges show changes in fluid pressure in the wellbore, and are particularly important in periods when the BOPs are closed. The wellbore is isolated when the BOP is closed, and thus changes in the drill-pipe or casing pressure are caused by fluid entering (pressure increases) or leaving (pressure reductions) the wellbore. When the BOP is closed, fluids can enter the wellbore (pressures increase) by either being deliberately pumped into the wellbore from the surface (via the drill-pipe or via kill lines in the BOP), or by high-pressure subsurface fluids entering the wellbore as a kick. Fluids can leave the wellbore (pressure drops) by either the pressures being bled off through the surface well control equipment (specifically the choke lines and manifold system), or by fluids exiting the wellbore into the formation via losses into faults, fractures or subsurface permeable zones. Hence, the data in Fig. 9 in Sawolo et al. (2009) can be carefully analyzed, and changes in subsurface pressures can be checked to see whether they indicate well control activities on the surface (pumping or bleeding off of pressures) or whether the changes in pressure indicate subsurface fluids flowing into or out of the wellbore.

Fig. 7. Photo of the TMMJ drill rig and BJP-1 location and the first documented Lusi eruption site approximately 100 m from the well (“40ft SW of flare pit”). Exact time of the photograph is not documented, but is within the first 3 days of the Lusi eruption, as the drill pipe is clearly still visible in the racks on the rig tower, and daily drilling reports note that this was removed before sunrise on the 2nd of June. Photo from Guslan Gumilang/Jawa Pos, with permission.

Fig. 8. The 1997 Dieng-24 blowout in the Dieng geothermal field in Central Java. The eruption of mud and steam occurs at a location away from the well location (photos taken from close to the well-site location), and shows several similarities with the Lusi eruption. This is one of many analogous examples of mud eruptions triggered by drilling blowouts, including several instances from Indonesia, and demonstrates that there is extensive precedence for the drilling-trigger model for Lusi. Photo from Elliot Yearsley, with permission.

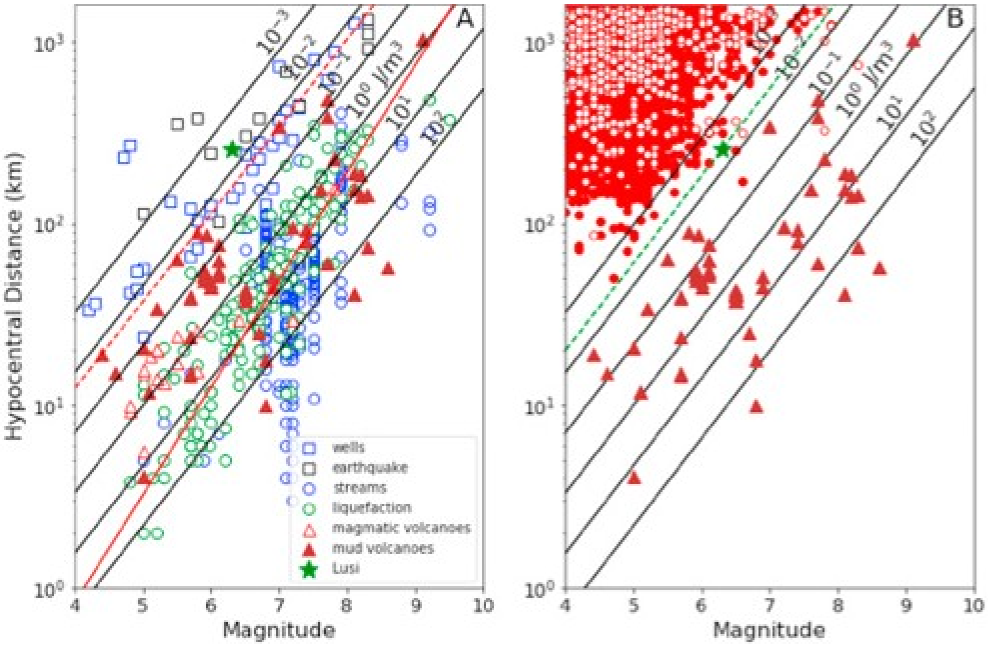

Fig. 9. (A) Response of various subsurface hydrological or magmatic systems to earthquakes. The category of mud volcanoes only includes new eruptions rather than modulation of already-ongoing eruptions (such as the events reported in Rudolph and Manga, 2012); the magmatic volcanoes only includes large eruptions in catalogs, not remote-sensing based changes in already-active systems. Sources for mud eruptions are listed in Table 1 and sources for other data are from Manga and Wang (2015). Sloping lines are lines of constant seismic energy density; the dotted line has an energy density of 0.0185 J/m^3; the red line shows one fault length. We do not include two events mentioned in Miller and Mazzini (2017) because we could not verify their occurrence; the eruption of the Napag mud volcano in Iran was attributed to heavy rain in the news article, and for the eruption in Taiwan is was unclear whether it was a response to an earthquake and to which earthquake it might have responded. (B) Historic seismicity within 1500 km of Lusi (red), including shallow (<30 km, open circles) and deeper events (filled circles). Time period is 1 January 1976 to 28 May 2006. Since we were unable to reproduce some of the points shown in Fig. 8 of Miller and Mazzini (2017) we include plotted mud eruption data in Table 1 and a script for generating this figure at https://github.com/maxrudolph/mv_triggering.

The casing and drill-pipe pressure data show a period during which the drill pipe pressure increases for 40-60 minutes after shut-in (~08:30-08:50 a.m.). This is a period when there is no pumping, and thus the pressure increase can only occur if the kick is ongoing. The BOP was shut in again at ~14:20 p.m. as a “safety measure”, when the ability to circulate the well ceased. However, immediately after shutting in the well at 14:20 p.m., there is a period of approximately an hour when the drill pipe pressure gradually increases, from ~450 to ~510 minutes in Fig. 9 of Sawolo et al. (2009), during a period with no pumping (zero flow into well), which demonstrates that an influx (kick) is occurring. Indeed, the data also show that fluid is flowing out of the well at ~200 gallons per minute over this time period, despite there being no fluid pumped into the well and pressures increasing inside the borehole – indicating that subsurface fluids are still flowing into the well from a kick, and were being removed from the well via the choke and manifold. In addition, there are short pressure anomalies reported at ~16:30 p.m. and ~18:00 p.m. on the 28th of May, as well as ~03:00 a.m. on the 29th of May. These multiple sharp increases in downhole pressure, when the well was shut-in and there was no pumping, are clear evidence that the kick was still ongoing throughout the 28th of May and into the 29th of May. Furthermore, the final downhole pressure increase, from approximately 02:30-04:00 a.m. on the 29th of May, was associated with detection of H_2S from somewhere outside the well area (Fig. 4), and, according to the daily drilling reports, appears to be the time at which the Lusi eruption commenced at the surface just "*40 ft SW of the flare*" pit at the well site (though the eruption was not visually confirmed and reported until sunrise approximately 1 hour later; Sawolo et al., 2009). It should also be noted that the drill pipe pressure registered non-zero values throughout most of the period after circulation ceased at ~14:30 p.m., including periods after the drill string pressures had been bled back to zero. The drill pipe pressure should record values of zero continuously if the well was dead – the positive values and increases in pressure without pumping are conclusive evidence that the kick was never fully stopped.

There is a third series of observations from BJP-1 that further confirm that the kick was not killed, and likely also explain why the influx temporarily ceased on the 28th of May 2006. The daily drilling reports repeatedly indicate that there were large amounts of debris in the wellbore, which is common during kicks and blowouts as fragments of the wellbore wall break away and become entrained due to the flow of high pressure fluids. For example, the drill string became stuck, due to the accumulation subsurface debris around the bottom-hole assembly, at approximately noon on the 28th of May (Sawolo et al., 2009). The drillers then lost the ability to circulate fluids at approximately 14:30 on the 28th of May, which suggests that the wellbore annulus above the drill-bit had become completely packed-off by low-permeability (presumably clay-rich) debris (Sawolo et al., 2009). The continued packing-off of debris around the bottom-hole assembly during the morning of the 28th of May is further evidence that deep pressures were continuing to push material up the wellbore and that the kick had not been killed as claimed. Finally, a 'free-point indicator tool' was run on the 31st of May, and observed that debris had been pushed up the wellbore to at least 285-495m above the drill bit in the days after the kick (Sawolo et al., 2009). Indeed, a zone of 100% blockage from debris was found at 2600 feet, which is inside the steel13-3/8" casing (Sawolo et al., 2009, Tingay, 2015). This confirms that debris had been continuously pushed up the wellbore, and even pushed up by over 100 m inside the casing, in the days after the kick began.

The observations of large amounts of debris in the wellbore, and the recorded build-up and movement of this debris over time, are additional clear evidence that the kick could not have been killed on the morning of the 28th of May. Furthermore, this offers a likely explanation for why the kick has been incorrectly claimed to have been killed on the morning of the 28th of May, and why the well could be partially circulated and BOPs opened for a brief period on the 28th of May. The movement of large amounts of debris in the wellbore is common during kicks and blowouts, and often causes what are termed ‘bridges’, in which debris builds up and forms temporary or permanent blockages in the wellbore. Indeed, it is not uncommon for blowouts to be naturally temporarily or permanently killed through ‘self-bridging’, such as the occurrences of temporary bridging, and then final complete bridging, observed in the Alborz-5 blowout in Iran (Mostofi and Gansser, 1957, Gretener, 1982). Given the amount of debris observed in the BJP-1 wellbore, it is entirely plausible that a temporary bridging of the BJP-1 well occurred at some depth below the drill bit in BJP-1 during the kick on the 28th of May. Such a bridge would give the appearance that the kick had ceased or significantly reduced at the drill-bit, but the kick would still be ongoing below the blockage. However, such an apparent ‘well dead’ situation will only last until the blockage breaks-up and the debris gets pushed further up the wellbore.

Conclusion: The claim that the kick was killed by 08:50 a.m. is not supported by the data in Sawolo et al. (2009). There is evidence to suggest that the kick temporarily ceased, and it is correct that the well could be (partially) circulated for a brief period from ~12:30 to 14:20 p.m. on the 28th of May. However, these short-term observations were likely the result of temporary blockage in the well due to muddy debris, which were pushed up the wellbore, and even into the casing, during the kick and in subsequent days. The drill-pipe and casing pressure and wellbore flow data conclusively demonstrate that downhole pressures continued to increase during several subsequent periods in which the well was closed off and there was no pumping (and also when all circulation had ceased due to well blockage around the bottom-hole assembly). Furthermore, there are clear extended periods when fluids are flowing rapidly out of the well, despite there being no pumping of mud into the well, which can only happen if a kick is still ongoing. These downhole pressure increases are conclusive evidence that the kick was still occurring underground until at least the morning of the 29th of May, with the pressure variations in the well ceasing exactly when Lusi first erupted at the surface. These periods of influx are separated by periods of downhole losses, discussed in the next claim, and suggest repeated cycles of kick followed by fracturing and fracture propagation in the well. Furthermore, the increase, and then sudden drop to zero, in wellbore pressure early on the 29th of May 2006 (which coincided with a surface release of H_2S and the birth of Lusi at the surface), indicates that the well directly witnessed the birth of Lusi at the surface and that the well was in communication with Lusi (see Claim 7).

Claim 4

“The well was intact” and was not fractured during the kick, and “a sustained pressure to propagate a fracture” did not exist (Miller and Mazzini, 2017).

Why it matters: In a subsurface blowout, overpressures in the wellbore drive the propagation of fractures from the uncased region of the wellbore to the surface. If the integrity of the well had been compromised and elevated pressures were maintained, a mechanism existed for fractures to propagate to the surface.

The evidence: There are two arguments claiming that the BJP-1 wellbore was not fractured during the kick, which would indicate that drilling was not responsible for triggering Lusi. The first argument is the claim by Sawolo et al. (2009) that pressures during the kick did not exceed the leak-off pressure at the 13-3/8” casing shoe, and is the focus of discussion in this claim. The second argument is the claim in Sawolo et al. (2009) and Miller and Mazzini (2017) that there was no observed connection between pumping in BJP-1 and the Lusi eruption. The evidence for direct connection between the BJP-1 wellbore and Lusi eruption is discussed in Claim 7 below.

The debate about whether the BJP-1 wellbore was intact during and after the kick has previously centered on whether or not the pressures within the borehole during the kick exceeded the leak-off test pressure at the 13-3/8” casing shoe (Davies et al., 2008, Davies et al., 2010, Tingay et al., 2008, Sawolo et al., 2009). The debate highlights the uncertainty that can exist in calculating kick pressures via different methods and on differing interpretations of the leak-off test data. Furthermore, this earlier debate examined only whether tensile fracturing occurred during the kick, whereas most drilling-triggering interpretations since 2009 have proposed that shear fracturing occurred, which better agrees with other evidence and is more geomechanically likely (Tingay, 2010, Tingay, 2016). Indeed, geomechanical modeling indicates that the pressures in the BJP-1 wellbore during the kick were sufficient to trigger failure at any point between 1090m (the casing shoe) and ~1740m depth, with failure most likely occurring somewhere between 1090m and 1470m depth (Tingay, 2016). However, this specific and initial debate, on whether pressures did or did not exceed the fracture gradient, is essentially rendered moot by the statements and observations made in the drilling reports and the data presented in Sawolo et al. (2009). These statements and data clearly show that large underground losses occurred in BJP-1 at numerous times during and after the kick, demonstrating that the well was fractured, and thus supersede prior arguments based on model calculations.

The daily drilling report at noon on the 28th of May states “*Observed well through trip tank, total lost since 05:00 hrs around 300 bbls*” (Fig. 4), which indicates that 300 barrels of drilling mud were lost underground in the period during which the kick occurred (Sawolo et al., 2009). The daily mud engineer report states that only 20 barrels of mud were lost underground during the pull out of hole operations from 5 a.m. until the kick (Sawolo et al., 2009). Thus the reports clearly state that 280 barrels of drilling mud were lost underground from the wellbore during the kick, and wellbore integrity was breached. There are further losses reported downhole, with the daily mud report stating “*loss during circulated*(sic) *to release stuck: 287 bbls* (which took place from noon to 20:00 on the 28th May)*, Loss during Spot Hivis: 102 bbls*” (which occurred between 22:00 on the 28th May to 02:00 on the 29th of May). These statements confirm that losses occurred underground in BJP-1 both during the initial kick and at periods for almost an entire day after the well was claimed by Sawolo et al. (2009) to be “dead”.

Periods of underground losses, and thus loss of wellbore integrity, are also visible in the pressure and flow data presented in Fig. 9 of Sawolo et al. (2009). As discussed in Claim 3, the wellbore was open and could be circulated from ~12:30 p.m. and 14:20 p.m. on the 28th of May 2006. However, the flow data in Sawolo et al. (2009)Fig. 9 demonstrate that this was partial circulation, with only between 40 and 60% of the fluid being pumped down the well actually returning to the surface, and thus suggesting 40-60% loss of fluids underground. During the kick, there is a period from ~09:15 to 10:00 a.m. on the 28th of May during which the drill pipe pressure decreases, despite the kick being ongoing at this time and the wellbore being sealed. Such a loss of pressure from a sealed system can only indicate that fluids are being lost underground. Similar events are observed after other influx events highlighted in Claim 3 above. Pressures gradually reduce from ~15:30 to 16:30 p.m. (510-570 minutes in the graph) after the pressure increase during the influx that occurred from ~14:30-15:10 pm. Drill pipe pressures also gradually reduce between ~16:30 and ~21:30 p.m. on the 28th of May. During both periods, it is again clear that the pressure in the well is reducing slowly, despite the well being sealed, which demonstrates, and further confirms the drilling report statements, that ongoing underground losses occurred both during the kick and for a long period afterwards. Hence, all evidence demonstrates that significant losses occurred in the ~19 hours from when the kick commenced and Lusi first erupted, implying that well integrity was breached.

The long period of high, but gradually reducing, drill pipe pressure from ~16:30 to ~21:30 on the 28th of May is also important, as it directly refutes the claim made in Miller and Mazzini (2017) that there was no pressure underground to propagate a fracture, and that fracture propagation would be arrested as fluid pressure was reduced by increasing fracture volume. However, over this entire 5 hour period, the drill pipe pressure (measured at the surface) is 500–600 psi, and indicates that the wellbore was exposed to approximately the equivalent pressure observed during the initial kick event, which was sufficient to exceed the fracture pressure as evidenced by the daily drilling report's stated losses during the kick. Furthermore, the drill pipe pressure downhole is gradually decreasing, indicating that losses are occurring. This pressure-time pattern is consistent with observations during large-scale hydraulic fracture tests, when large volumes of fluid are pumped into a well and drive fracture growth (Warpinski and Smith, 1989, Zoback, 2007). Hydraulic fracture stimulation involves a period of ‘fracture propagation’, in which a high, but slowly reducing, pressure is maintained, with the gradual pressure drop related to the increase in fracture volume (Cornet et al., 2007). Hence, the data in Sawolo et al. (2009) indicate that there were long periods, including one of over 5 hours in length, in which sustained pressures existed in the well that were sufficient to fracture the rocks, and record gradual pressure drops that are consistent with losses and fracture propagation. Miller and Mazzini (2017) claim that the drill pipe pressures should read zero if the well integrity was breached, yet this claim is completely inconsistent with observations in wells that are undergoing kicks or being fracture stimulated (Baker, 1998, Cornet et al., 2007). Indeed, the drill pipe pressures would only ever be expected to return to zero if they are manually bled off at the surface, or if a fracture is propagated to the surface, which is what was observed in the drill pipe pressures early on the morning of the 29th of May 2006, when Lusi first erupted next to the drilling lease (see Claim 6).

Conclusion: The claim that the well was intact and not fractured during the kick contradicts the drilling reports. These clearly state that large losses occurred underground during the initial kick and at multiple times afterwards, which can only occur if wellbore integrity has been lost. These statements in the drilling reports are directly confirmed by the pressure and flow data presented by Sawolo et al. (2009). Early debates, which only focused on differing interpretations and model calculations of the subsurface kick and leak-off pressures, are largely irrelevant, because the drilling reports state, and the well data directly confirm, that substantial losses occurred underground during and after the kick. Furthermore, there is a repeated pattern of periods of kick followed by periods of losses, which is consistent with fracturing and fracture propagation.

Claim 5

“*No Lusi mud exited the borehole, and no oil-based drilling mud was observed (and would have been easily detected) mixing with the Lusi mud. This demonstrates two isolated systems”* (Miller and Mazzini, 2017).

Why it matters: The direct detection of Lusi mud in the borehole or the eruption of oil-based drilling mud would be a clear indication of a pathway between the borehole and the eruption during its initial stage.

The evidence: The statement by Miller and Mazzini (2017) suggests that no fluid erupted from the BJP-1 well. However, reports clearly confirm that >360 barrels of contaminated mud and water erupted from the wellsite. The mud that erupted from Lusi is composed of water and clay, and the fluids erupted from BJP-1 were also almost entirely comprised of saline water mixed with clay. Indeed, the erupted water during the kick has the same density (which reflects clay content and water salinity) as the samples of initial mud erupted from Lusi (Sawolo et al., 2009), suggesting they have the same source. Miller and Mazzini (2017) make the misleading statement that ‘mud’ did not erupt from BJP-1. Yet, the drilling trigger model does not require mud to erupt from BJP-1, as it proposes that the deep water primarily becomes entrained with clays (and turns into mud) as it passes through faults/fractures en-route to the surface. The low permeability of the Kalibeng clays means that the kick waters would only be expected to entrain small amounts of clay as they flow up the wellbore, and thus predicts that water, with small amounts of clay, would erupt from BJP-1. The >360 barrels of muddy formation waters that erupted from BJP-1 during the kick are entirely consistent with the drilling-trigger model. The claim by Miller and Mazzini (2017) also ignores the H_2S observations in both the initial erupted fluids and kick fluids, covered in Claim 11 below, that indicate a common source of the kick fluids and Lusi's initial erupting (Sawolo et al., 2009, Tingay et al., 2015).

The total amount of oil-based drilling mud required to fill the BJP-1 annulus, and subsequently pumped into BJP-1 during well control, is only ~150 m^3, with this volume lost in multiple periods over ~48 hours following the kick. Only 6 samples of Lusi mud, collected between 66 and 72 hours after Lusi commenced erupting, were analyzed in this period (Sawolo et al., 2009). These samples were collected significantly after any drilling mud from BJP-1 would be expected to have erupted from Lusi. Furthermore, an estimated 137,500-150,000 m^3 of mud had erupted from Lusi by the time these Lusi mud samples were collected based on estimated initial discharge rate of 50,000 m^3/day (Istadi et al., 2009). Hence, it is expected that drilling mud would constitute <0.1% of the total volume erupted by Lusi at the times the samples were collected. Given the extremely low relative proportion of drilling mud to erupted mud, and the timing at which Lusi mud samples were collected, it is hardly surprising that traces of drilling mud were not observed.

Conclusion: The claim by Sawolo et al. (2009) and Miller and Mazzini (2017) is erroneous and/or misleading. The absence of a detection of drilling mud in the initial erupted products cannot be interpreted as a strong evidence of a lack of connection between BJP-1 and the nascent eruption, as drilling mud would constitute only a negligible amount of the erupted fluids at the time of sampling. Subsurface fluids did erupt at the BJP-1 wellsite during the kick, and these fluids have properties and descriptions consistent with the initial waters erupted from Lusi. The detection of H_2S in both the kick fluids and initial eruption (and absence of large amounts of H_2S in any of the formations encountered when drilling the known mud source region, the Kalibeng muds), is a strong indication of a common origin of these fluids (see Claim 11 below).

Claim 6

“The mud first appeared about 700 m from the borehole, and the second appearance was also about 700 m from the borehole and about 350 m west of the first sighting. The third appearance was about 100 m from the borehole, while no mud was observed exiting the open borehole. Finally, mud appeared another 150 m, then 300 m from the borehole.”

Why it matters: Miller and Mazzini (2017) argue that the initial eruption began further from BJP-1, and that the eruption close to BJP-1 was just a later coincidence. Miller and Mazzini (2017) also imply that a more distant eruption makes the drilling-trigger hypothesis more likely (which is addressed in more detail in claim 9). Furthermore, the initial location of the eruption may provide important insight into the cause of the eruption, and thus it is important to verify, or reduce uncertainty on, key events that occurred in the initial days of the Lusi eruption (Fig. 7).

The evidence: There is no evidence to support this unreferenced and unsubstantiated claim in Miller and Mazzini (2017). The most reliable published source of information on initial vent locations is the daily drilling reports and raw data in Sawolo et al. (2009). The first indication of Lusi occurs between approximately 03:00–04:00 a.m. (during the night) on the 29th of May, when there is a sharp drill pipe pressure spike and then drop in the BJP-1 wellbore, coincident with 35 ppm H_2S being detected at the surface. The source of H_2S was tracked down and located between 4:30-05:00 a.m. (approximately day-break), with the first recorded observation of the Lusi eruption, which is stated in the daily drilling reports as erupting 5 ppm H_2S bubbles located just “40 ft outside flare” (or approximately 100m from the BJP-1 well) (Fig. 4). This is further confirmed in the mud logger's report for the 24-h period ending at 5 a.m. on May 30, which states “Got craters at outside of rig site (H_2S 700 ppm) & flood on wet rice field” (Sawolo et al., 2009). The daily drilling reports do not note the initiation of additional, further away, eruptions until the 31st of May, where the report states “*Total of five sources, blew up for the time being, with half foot high, continued blew*” (Fig. 6). The drilling report for the 2nd of June then states “*Cracker channel still blew up contaminated fluid and mud volcano, caused flow over road. Have six additional sources point blew up mud vulcanic (sic), located 500 ft approximately, west direction, over highway*”, confirming that additional eruptions at a distance from BJP-1 occurred after the first eruption adjacent to BJP-1. While there are no clear or verifiable reports of the timing of additional eruptions, it is evident from the daily drilling reports that the Lusi vent, only ~100m from the well, was the first detected eruption (at 03:00-04:00 a.m.) and then visually observed at ~04:30-05:00 a.m. on the 29th of May. As such, the statement that the first Lusi eruptions were 700 m from the well is inconsistent with published observations on the day. Indeed, Miller and Mazzini (2017) offer no references or evidence to support their claim that other eruptions occurred first.

Conclusion: All available evidence suggests that the initial eruption of fluids, including H_2S, occurred much closer to the drill rig (~100 m away from BJP-1) at between 03:00-05:00 a.m. on the 29th of May 2006 (Fig. 4). Miller and Mazzini (2017) offer no evidence to support their claim that the first two eruptions of Lusi occurred ~700 m from Lusi, nor that the eruption 100 m from Lusi was the third eruption site. We suggest that the first documented observations of Lusi in the BJP-1 daily drilling reports be considered to mark the time and place of Lusi's birth.

Claim 7

"High injection test pressures on the well confirmed that the shoe was intact and there were no channels formed between the well and the eruption." (Sawolo et al., 2009) *and "Three high pressure injection tests performed after a reported kick showed sustained pressures (up to 8 MPa), demonstrated conclusively that the borehole was intact and the well had been successfully killed"* (Miller and Mazzini, 2017).

Why it matters: If the wellbore was still intact while the eruption was ongoing, this could be an indication that the well and the eruption were unconnected and unrelated, as claimed by Miller and Mazzini (2017). However, evidence of a direct connection between the wellbore and Lusi eruption would strongly support the drilling trigger argument.

The evidence: This claim is directly contradicted by the daily drilling reports. These reports document that a direct connection between the BJP-1 well and Lusi eruption was observed in association with three separate periods of pumping into the BJP-1 well. The drillers on BJP-1 made three attempts to pump high density fluid into BJP-1 in an attempt to kill the Lusi eruption. The first such test was at ~06:30 a.m. on the 29th of May, in which 130 barrels of mud, followed by a second batch of 100 barrels, with a density of 14.7 ppg (1.76 sg) were pumped down the drill pipe. The daily drilling report states that before pumping the Lusi vent was erupting as follows: "*Gas and water bubbles blew intermittently with maximum height of 25 ft, and elapse time 5 minutes between bubble*" (Sawolo et al., 2009, Fig. 5). However, while pumping, the drilling report states that "*Bubbles intensity reduced and elapse time between each bubble is longer. Observed maximum bubble of 8 ft height occasionally, normally one (1) foot height, with 30 minutes elapse time between each bubble"* (Fig. 5). Hence, the drilling report clearly states that Lusi eruption activity was reduced by this first period of pumping into BJP-1.

Similar observations were made during the second injection test, which occurred between 22:30 p.m. and 23:30 p.m. on the 29th of May, and involved pumping 200 barrels of 16.0 ppg (1.91 sg) drilling mud with concentrated loss circulation material at a rate of 4 barrels per minute. The daily drilling report states that immediately after this test "*No more high intensity bubbles arose after spotting LCM. However approximately half foot bubbles occasionally came to the surface*" (Fig. 5). Hence, Lusi activity is specifically stated to have been reduced by the second period of pumping into BJP-1. It should also be noted that all of this pumped drilling mud was lost downhole, further confirming that the wellbore had lost integrity (see Claim 4).

The third period of pumping commenced at 05:00 a.m. on the 30th of May and was designed to try and plug off the BJP-1 wellbore below the drill-bit. This third period of pumping involved first pumping a 20 barrel slug of cement (15.8 ppg; 1.89 sg) into the wellbore, followed by 150 barrels of mud (16.0 ppg; 1.91 sg) at four barrels per minute to displace (push) the cement slug down into the wellbore below the drill bit (pumping would normally push cement up the annulus above the drill bit, but the hole was completely packed off around the bottom hole assembly at this time, thus forcing fluid and the cement plug downwards). After pumping the cement plug and high-density displacement mud, the daily drilling report states “*WOC (wait on cement) while observing the well and bubbles activity at distance from the rig. Bubbles already decreased in activity since last night*” (Fig. 6), which again clearly reports that pumping into the BJP-1 well resulted in an observable reduction in the Lusi eruption.

The well reports clearly show three instances when injection of high-density mud and, finally, cement into BJP-1 was observed to cause a temporary reduction in flow rate at the Lusi vent. It should be noted that Sawolo et al. (2009) dismiss these three statements of reported connection between BJP-1 and Lusi as being purely “coincidental”, but provide no evidence to support that claim. The daily drilling reports were signed off as being accurate by the authors of those reports, and by other drilling personnel. Hence, statements in the daily drilling reports can only be dismissed with direct evidence. Instead, rather than examine these first tests, Sawolo et al. (2009) and Miller and Mazzini (2017) focus on only one later injection test, which was conducted after the wellbore around the drill-bit was plugged with cement.

An additional 100 barrel cement plug (with 110 barrels of displacement mud) was pumped at ~22:30 p.m. on the 30th of May 2006 (Lusi vent activity is not stated following this test, and thus it is not known whether or not this test had any effect on the Lusi eruption). The injection test focused on by Sawolo et al. (2009) and Miller and Mazzini (2017) was then subsequently made, in which just 8 barrels of mud were pumped at 1 barrel per minute. However, this injection test was specifically conducted to test whether the prior two cement plugs had sealed off the well below the drill bit. The stated observation of high pressure build up during this brief injection test simply confirms that the cement plugs placed previously had set, and had effectively sealed off the drill-bit (at ~1275 m depth) from the long open hole section underneath (which extends to ~2833 m, and in which the blowout was free to continue). As such, the injection test does not provide any evidence to support or refute the connection between the wellbore and BJP-1, as the wellbore had been plugged by cement at some depth below the drill bit. Although, Miller and Mazzini (2017) claim that the setting of these cement plugs is a “physical impossibility”, the successful injection test results demonstrate conclusively that this plug was set (which was the first of several cement plugs set before BJP-1 was abandoned).

Conclusion: The claims of no observed connection between the Lusi eruption and pumping in BJP-1 are completely contradictory to the statements in Lapindo Brantas drilling reports. There were three periods of pumping of high-density fluid and cement, and the daily drilling reports specifically state that flow rates and eruption activity at the Lusi vent were noticeably reduced by each of these first three pumping stages. The documented direct connection between the wellbore and the Lusi eruption only ceased after cement plugs were placed in the well immediately below the drill bit, isolating the drill bit from the kick that was still occurring below the cement plug. The direct connection between Lusi and BJP-1 documented in the daily drilling reports is further confirmed by the observation of pressure spikes and drops in the BJP-1 well at ~03:00-04:00am on the 29th of May, which coincided with the first eruption of Lusi at the surface (see Claim 3above).

The unambiguous statements by Miller and Mazzini (2017) and Sawolo et al. (2009) that there were no observed connections between the BJP-1 well and Lusi vent conflict directly with three such instances specifically reported in the daily reports. These statements in the daily drilling reports possibly constitute the most clear and direct evidence that the kick in BJP-1 was responsible for the Lusi eruption – yet Sawolo et al. (2009) and Miller and Mazzini (2017) not only ignore these statements, but make specific claims that are the exact opposite of what the daily drilling reports observed. Furthermore, these three instances of observed direct connection between the wellbore and Lusi eruption contradict and refute all arguments made by Miller and Mazzini (2017) that the wellbore was too insignificant to affect the eruption.

Claim 8

Miller and Mazzini (2017)*state that "A great deal of effort has been expended on the minutiae of borehole observations, but at the scale of*Fig. 6A *the borehole sampled less than 0.02 percent of the affected region. That is, 99.98% of the affected region was not sampled, so concluding anything about the regional scale from borehole observations is certainly not warranted."*

Why it matters: On the basis of scale alone, Miller and Mazzini (2017) appear to be claiming that data from the BJP-1 wellbore are not relevant to understanding the Lusi system. This claim also suggests that BJP-1 must be inconsequential because Lusi eruptions occurred in a number of locations (up to 700m from BJP-1), despite there being many examples of drilling blowouts triggering eruptions at greater distances.

The evidence: The diameter of the wellbore compared to the surface area covered by the mudflow is irrelevant. The BJP-1 wellbore represents the only reliable in-situ subsurface data collected for Lusi, and also the only data in the immediate vicinity and depth ranges that were collected prior to the disaster. The borehole was located ~100 m from the first Lusi eruption and was in the optimal position to provide baseline information, and also to witness any subsurface effects both before the surface eruption and in the days after (Fig. 4). Indeed, as highlighted in prior claims, the pressure data in the BJP-1 borehole appear to have witnessed the birth of Lusi on the morning of the 29th of May 2006, and also document direct connection between Lusi and pumping in BJP-1 (Claim 7).

Conclusion: We recognize that the geochemical and other sampling, as well as fieldwork, collected by all researchers studying Lusi are valuable and important. Also important is the unique dataset provided by the BJP-1 well (and other wells in close proximity to Lusi) as it represents a significant proportion of the proximal data available prior to Lusi erupting and was the closest source of subsurface data, especially in the initial days of the Lusi eruption. All data, records, and observations of the Lusi eruption need to be considered when studying this disaster, and we recommend that no data be dismissed without valid scientific justification.

Claim 9

“If drilling were the trigger, Lusi would represent the only example in geological history of a tectonically driven system conceived from a 30 cm diameter borehole” and “We recognize that blowouts sometimes occur and breach the surface away from the drill hole, such as occurred Brunei in 1974 and 1979 …. the Brunei example is not relevant to Lusi”.

Why it matters: Lessons learned from analogue systems provide insight and perspectives. If nothing like Lusi has ever been caused by drilling accidents then other blowout-induced surface eruptions may not be applicable. The drilling-trigger argument may seem less plausible if there are no precedents.

The evidence: Surface eruptions resulting from underground blowouts have been documented on numerous occasions, with some instances of eruptions occurring several kilometers from the drilling location, as well as blowouts and eruptions being long-lived. Famous examples include the Frade blowout offshore Brazil in 2011 and the Platform A blowout offshore Santa Barbara, California in 1969 (Clarke and Hemphill, 2002). Miller and Mazzini (2017) propose that the documented Champion-41 and Champion-141 blowouts offshore Brunei, often considered to be analogous to Lusi, should not be considered relevant on the basis of an argument that these blowouts occurred in an oil, not gas, field.

The location of the Champion blowouts within an oil field is completely irrelevant. The Champion blowouts were primarily water blowouts (not oil or gas) that lasted 20 years, and are thus directly analogous to Lusi. Indeed, the first detailed publication on these blowouts (made prior to the Lusi eruption) specifically documents how these blowouts are highly analogous to mud volcano systems (Tingay et al., 2003). There are numerous parallels between Lusi and the Champion blowouts, as both events occurred while drilling through highly overpressured and competent rocks when a water kick occurred (Tingay et al., 2003, Tingay, 2015). Both wells suffered a series of losses followed by a major kick. The Lusi eruption and Champion blowouts occurred at a distance from where the well was located, and resulted in a long, linearly-aligned series of eruptions (Tingay et al., 2005). Finally, both the Lusi eruption and Champion underground blowouts have been long lived, with the Champion blowouts lasting 20 years (Tingay et al., 2003).

It makes little sense to dismiss any blowout incident purely due to the well being located within an area of oil production or exploration. Mud volcanoes are commonly observed in oil fields, and are often linked to hydrocarbon systems (Planke et al., 2003, Stewart and Davies, 2006, Roberts et al., 2011). Indeed, hydrocarbons have also flowed from Lusi. Furthermore, the Lusi eruption is within 5 km of the producing Wunut and Tanggulangin hydrocarbon fields. Finally, blowout-related eruptions have been observed numerous times, and so there is clear precedent for the drilling trigger model for Lusi. Indeed, there are four other known mud eruptions triggered by drilling in Indonesia alone, namely the 1997 Dieng-24 (Fig. 8) and 2008 Gresik mud eruptions in Java,[1] a December 2015 mud eruption from geothermal drilling in Sulawesi[2], and a mud volcano in Samarinda Ulu in East Kalimantan.[3] According to media reports in January 2016, this East Kalimantan mud volcano continues to show activity >20 years after it began erupting.[4]

Conclusion: There is no basis to Miller and Mazzini's (2017) claim that long-lived mud eruptions have never been triggered by drilling activities. Miller and Mazzini (2017) used invalid and incorrect assumptions to dismiss the many blowouts that are analogous to Lusi, particularly the Champion blowouts. There is extensive precedence to support the drilling-trigger model for Lusi.

Claim 10

Miller and Mazzini (2017)*state "The arguments for, and support of, a drilling-trigger follows a familiar pattern. The authors make a statement in a publication, without clear supporting evidence, and then in all subsequent publications cite this previous work (also without evidence) as established proof. By the fourth publication, the original unsubstantiated statement becomes a "laundered" and indisputable fact."*

Why it matters: This claim is extremely serious because of the implied scientific misconduct. Science must always be based on evidence and data, and thus it is a very serious allegation to claim that proponents of the drilling-trigger hypothesis make key claims without any evidentiary basis.

The evidence: Miller and Mazzini (2017) use two specific examples to attempt to demonstrate this claim. The first example is the reported 20 barrels of losses being synchronous with the Yogyakarta earthquake, and how this is disputed in Tingay (2015). In Claim 1, it is explained that it is uncertain whether these losses occurred underground, and that there is also a critical discrepancy between when the losses are claimed to have occurred and the data shown on the chart, especially the depth at which the losses occurred (a depth that had been drilled over an hour prior to when the losses are claimed to have occurred). The arguments, evidence and sources summarized in Claim 1 are directly repeated from the detailed arguments and evidence presented in Tingay (2015). Yet, Miller and Mazzini (2017) inexplicably state that there is no evidentiary basis or explanation for this claim.

The second example of what Miller and Mazzini (2017) claim is a "laundered" statement is the observation of 25 ppm of H_2S in the BJP-1 well several hours prior to the earthquake. Miller and Mazzini (2017) suggest that this observation never happened, and claim that the only record of this 25 ppm H_2S is from an unpublished report (Adams, 2006). Again, this is entirely false. The 25 ppm H_2S is clearly reported in the Lapindo Daily Drilling Reports for the 27th of May 2006 (Sawolo et al., 2009), and is simply confirmed in the detailed time line of events provided in Adams (2006). The published daily drilling reports state that while drilling at 9230 ft "*the H_2S probe sensor, located at shale shaker area, detected 25 ppm, concentrated H_2S. Drilling crew at rig floor continued to perform job, by foolows* (sic) *SOP, the rest drilling crew evacuated to briefieng* (sic) *point*" (Fig. 2). There is no obvious basis for Miller and Mazzini (2017) to dispute this observation, nor to claim that it is from an unreliable source.

Miller and Mazzini (2017) further attempt to discredit the H_2S observation by casting doubt on when the observation occurred. Specifically, Miller and Mazzini state:

> "there is no mention in the Adams (2006) report about what time this reading was actually taken. Three hours before the earthquake was 3 a.m. (local time), but there is no document yet produced that corroborates the time that this H_2S reading was taken. With no documentation, the readers are left with an act of faith in the authors, or must assume that there are additional undisclosed sources that document and support this claim".

We contend that the drilling reports (reproduced in Fig. 3) are fully disclosed and reliable sources of information that have been publicly available since the publication of Sawolo et al. (2009).

The sources of the H_2S observation data are the BJP-1 daily drilling reports published by Sawolo et al. (2009) and fully confirm statements in Adams (2006). Miller and Mazzini (2017) are correct that the daily drilling report does not specifically state the time of the H_2S measurements. However, it is clearly stated in the daily drilling reports that the H_2S was observed prior to 5 a.m., and thus definitively prior to the earthquake (Fig. 3). Furthermore, it is a relatively simple and routine procedure to calculate the time of drilling events using the depth at which they occurred, provided the timing of other proximal drilling depths is known. In this instance, the daily drilling report states that the well was drilling at 9277′ at the 05:00 a.m. reporting time on the 27th of May 2006. The time at which the H_2S observation at 9230' can then be calculated using the drilling rate of penetration information that is available in the daily drilling reports and, more accurately, in the rate of penetration log (both published in Sawolo et al., 2009). This routine and simple calculation provides the "~02:00 a.m." timing for this H_2S observation stated in Tingay (2015), and is expected to be accurate to within ±15 minutes. Indeed, one of the main reasons why Tingay (2015) is so quoted by drilling trigger proponents is that this study includes the most detailed published and peer-reviewed timeline of drilling events in the BJP-1 well. This timeline was the result of an extensive and careful forensic review of all available drilling reports and raw data, in which every listed drilling observation was carefully checked, cross-referenced and confirmed (Tingay, 2015). Furthermore, the drilling events timeline in Tingay (2015) is significantly more detailed than the similar timeline provided in Sawolo et al. (2009), as the timeline by Sawolo et al. (2009)omitted a large number of significant observations and statements from the BJP-1 daily drilling reports.

Conclusion: The Miller and Mazzini (2017) statement about laundered facts can be shown to be incorrect by following the refereed scientific literature. The evidence that H_2S was observed in the BJP-1 borehole prior to the Yogyakarta earthquake is based on specific statements in the published daily drilling reports (e.g., Fig. 3).

Claim 11

Miller and Mazzini (2017)*repeated claims that the H_2S observations from BJP-1 and the Lusi eruption are not relevant to the triggering argument*.

Why it matters: H_2S was not measured in the Kalibeng clays, but is present in deeper fluids. Detection of H_2S would support inferences that the borehole created a new fluid pathway from deep sources to the Kalibeng clays and then to the surface. Furthermore, observations of H_2S can be used to test whether the Kalibeng clays were made susceptible to liquefaction by the invasion of hydrothermal fluids prior to the Lusi eruption, which is an essential requirement of the earthquake-triggering argument.

The evidence: In addition to questioning the occurrence and timing of the 25 ppm H_2S observed in BJP-1 prior to the Yogyakarta earthquake (see Claim 10 above), Miller and Mazzini (2017) argue that this observation should be dismissed as being just a negligible amount and entirely coincidental. Miller and Mazzini (2017)make the statements "*whatTingay et al. (2015)also fail to acknowledge clearly is that volcanic environments are where H_2*S is typically present and can be found in such minor amounts in any *sedimentary basin* worldwide" and "*why would anyone be surprised to detect 25ppm of H_2S in a volcanic basin as drilling approached the basement? It would probably be strange not to detect any H_2S*." In summary, Miller and Mazzini (2017) dismiss the H_2S observations from BJP-1 because l they claim that the concentration of H_2S is low and observations of H_2S in, thus they argue that these H_2S observations in BJP-1 are entirely coincidental, and not related to the triggering of Lusi.

Miller and Mazzini (2017) are correct that H_2S is often observed in sedimentary basins and volcanic environments, and H_2S is a known common hazard in the East Java Basin, especially in the deep carbonates (e.g. Darmawan et al., 2011). However, the claims of Miller and Mazzini (2017) do not agree with the observations during drilling of the BJP-1 well, in which H_2S is only reported on three very specific occasions. Furthermore, the concentrations of H_2S are irrelevant, as the key issue highlighted in Tingay et al. (2015) is the observed temporal and stratigraphic distribution of H_2S observations in BJP-1.

Before highlighting the key significance of H_2S observations in testing the drilling and earthquake triggering hypotheses, it is important to note that H_2S (which is both flammable and poisonous) is regarded as a significant hazard in drilling operations. As evidenced from the quoted daily drilling report in claim 11, even 25 ppm of H_2S, an apparently “minor amount” according to Miller and Mazzini (2017), was sufficient to trigger the temporary evacuation of most of the rig personnel, as per the rig's standard operating procedures (SOPs; Fig. 2). Indeed, it is standard safety procedure during drilling that personnel are evacuated whenever any amount of H_2S is detected and, because of the associated expensive loss of productive time, such H_2S observations are always documented on daily drilling reports. The specific make and model of the H_2S detectors used at BJP-1 are unknown, but such sensors on drilling rigs are typically capable of detecting any H_2S concentrations of >1 ppm. Hence, it should be readily apparent that the observation of any H_2S during drilling operations is regarded as a highly significant safety hazard, resulting in evacuation of personnel as per SOPs, and is duly recorded in drilling reports. Thus, it is unlikely that H_2S would be detected and not reported, and the absence of any reported H_2S observations in daily drilling reports can therefore be considered as strong evidence that no H_2S was detected during that reporting period.

It is therefore significant that there are no other mentions of H_2S being observed during the drilling of BJP-1 at any time between when the well was spudded on the 8th of March 2006 and the observation of 25 ppm H_2S early in the morning of the 27th of May 2006 (Adams, 2006, Tingay et al., 2015). Sawolo et al. (2009)only contains the daily drilling reports from the 26th of May 2006. We have been provided with the full daily drilling reports for BJP-1 by Lapindo Brantas, but do not have permission to publish these herein and we suggest other researchers request these reports directly from Lapindo Brantas. However, the daily drilling reports simply verify the detailed summary of well activities that is publicly documented in Adams (2006). Neither Adams (2006) nor the daily drilling reports make any mention of H_2S in the entire 80 days of well operations prior to the 27th of May 2006. Hence, H_2S was not frequently observed while drilling, despite the claim by Miller and Mazzini (2017) that H_2S should be common. In particular, Tingay et al.

(2015) highlight that no H_2S was ever reported while drilling the Kalibeng clays, despite >60 m^3 of crushed up Kalibeng clay drill cuttings being run past the H_2S detectors at the shale shakers. This indicates that no detectable H_2S was present in the Kalibeng clays prior to the Lusi eruption.

Mazzini et al. (2012), Lupi et al. (2013) and Miller and Mazzini (2017) suggested that large volumes of hydrothermal fluids had invaded the Kalibeng clays prior to the Yogyakarta earthquake. This requirement is fundamental and essential to the entire earthquake-triggering hypothesis, as it is the only means by which this model can explain the occurrence of H_2S in the initial days of the Lusi eruption (and geochemistry of Lusi muds sampled subsequently that indicate deep hydrothermal input), and in order for the Kalibeng clays to be susceptible for liquefaction (Mazzini et al., 2012). Furthermore, the earthquake-triggering model requires Kalibeng clay liquefaction to commence immediately after the Yogyakarta earthquake, as the liquefaction would be needed to generate the high fluid pressures (via gas exsolution and bubble formation) that the hypothesis claims caused fault reactivation at the Lusi location (Mazzini et al., 2012; Lupi et al., 2013). Hence, the earthquake-triggering model can be directly tested in two ways, namely by looking for any evidence of:

1) a pre-eruption hydrodynamic connection between the Kalibeng clays and deeper hydrothermal fluid reservoirs, and;

2) liquefaction and associated gas exsolution from the Kalbeng clays after the earthquake.

As is documented in detail in Tingay et al. (2015), the BJP-1 borehole was perfectly located, and collected appropriate data, to examine both of these tests of the earthquake-trigger hypothesis.

The first test of the earthquake-triggering hypothesis can be made by looking at specific fluid chemistry distributions in BJP-1, such as the distribution of reported H_2S. If there was significant and widespread pre-eruption invasion of hydrothermal fluids into the Kalibeng clays, then there should be detectable levels of H_2S in the Kalibeng clays. H_2S is first reported just 20 m above the final depth of BJP-1. H_2S was also reported both during the kick in BJP-1 on the 28th of May, and was directly measured as being released from the Lusi eruption vent on the 29th of May (these are the only three specific observations of H_2S in the drilling reports). The occurrence of H_2S from Lusi, combined with the absence of H_2S in formations above 2813 m depth, strongly indicates that:

1) at least some, if not most, of the initial Lusi eruption fluids were sourced from a depth of at least 2813 m, and;

2) there is no evidence of any significant pre-eruption hydrodynamic connection between the Kalibeng clays and this deep H_2S-bearing reservoir.

The lack of any pre-eruption hydrothermal input into the Kalibeng clays is also supported by Raman spectroscopic carbonaceous material thermometry (RSCM) and chlorite geothermometry of erupted clasts from Lusi, which show no evidence of any pre-eruption hydrothermal heating or alteration of the Kalibeng clays (Malvoisin et al., 2016).

The distribution of H_2S observations, combined with other data, highlights that there is no evidence to support the critical requirement of hydrothermal invasion into the Kalibeng clays, but also suggests that the Kalibeng clays were previously isolated from the deep H_2S-bearing reservoir. Indeed, the Kalibeng clays are underlain by an ~1000 m thick sequence of low porosity and low permeability volcanic and volcaniclastic rocks (Tingay, 2015). Given the lack of prior hydrodynamic communication, the earthquake triggering model therefore requires that large volumes of deep overpressured H_2S-bearing fluids suddenly managed to find a new pathway to the surface, through both ~1000 m of sealing volcanics and a further ~1300 m of low permeability clays in just the 2 days between the Yogyakarta earthquake and the Lusi mud eruption. The earthquake-triggering proponents suggest that it is simply mere coincidence that the BJP-1 borehole (which forms a direct fluid flow pathway through the sealing volcanics) encountered deep H_2S-bearing fluids just ~24 hours before a H_2S-bearing fluid kick and ~2 days before H_2S-bearing fluids erupted at Lusi (Miller and Mazzini, 2017).

Tingay et al. (2015) also test the requirement of the earthquake-triggering model for earthquake-induced liquefaction of the Kalibeng clays. Lupi et al. (2013)highlight that liquefaction is associated with widespread gas exsolution, and claim that it is the release of large volumes of gas (particularly CO_2) that would generate the high fluid overpressures sufficient to induce fault reactivation under Lusi. However, as documented in Tingay et al. (2015), and from the drilling reports in Sawolo et al. (2009), the drilling mud gas records from BJP-1 show no increase in gas concentrations (including CO_2) coming from the BJP-1 well in the entire 24-hour period between the Yogyakarta earthquake and the kick in BJP-1. Indeed, the gas records from BJP-1 show a slight, but negligible, decrease in all subsurface gas concentrations (including CO_2) in the 24-hour period following the earthquake (compared to the preceding days). This lack of any post-earthquake gas release in BJP-1 confirms that there is no evidence for earthquake-induced liquefaction at the Lusi location. Furthermore, the daily drilling reports document abundant evidence for remobilization of the Kalibeng clays (e.g., gas release, clay debris, fluid influxes and losses) witnessed by the BJP-1 borehole, but these were all only observed during and subsequent to the kick on the 28th of May 2006.

Conclusion: Miller and Mazzini (2017) argue that only “minor amounts” of H_2S were observed in BJP-1 and that such amounts are simply coincidental, as H_2S should be extremely common in the geological environment. However, this argument, and its underlying assumptions, is not supported by drilling records (Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6), which show no observations of H_2S in the BJP-1 well in the 80 days of drilling operations prior to reaching 2830 m on the 27th of May 2006. Furthermore, the distribution of H_2S in BJP-1 shows that there is no evidence of pre-eruption invasion of hydrothermal fluids into the Kalibeng clays. In addition, the gas records from BJP-1 show no evidence of any liquefaction of the Kalibeng clays in the 24 hours following the earthquake. This data represents the only currently known method for directly testing the earthquake-triggering model, and do not support the fundamental arguments and claims underlying the entire earthquake-triggering hypothesis. Indeed, these observations essentially refute the entire earthquake triggering hypothesis for Lusi. However, the observations of H_2S in BJP-1 and at the Lusi eruption site, combined with the drilling data from BJP-1, are fully consistent with the drilling-trigger model for Lusi.

3. Conceptual model for the initiation and subsequent behavior of Lusi

Conceptual models, and their mathematical representations, are important because they can be used to make predictions and to develop testable hypotheses and hence to guide further studies. Miller and Mazzini (2017) suggest that because Lusi has a deep plumbing system, the mathematical models of Davies et al. (2011) and Rudolph et al. (2011) are “irrelevant”. We disagree for two reasons. First, surface deformation confirms that the much of the erupted materials come from the shallow (1.4–1.8 km deep) Kalibeng clays (Shirzaei et al., 2015), though erupted materials are indeed diluted by a deeper source of fluids (see claim 11). Second, these two models (Davies et al., 2011, Rudolph et al., 2011), as do all models in which material erupts from a source of finite dimensions, have similar mathematical behaviors, with both discharge and deformation decreasing approximately exponentially with time for long times, consistent with data through 2011 (Rudolph et al., 2013). In fact, Rudolph et al. (2013) use this data (and model) to make the testable forecast “that discharge at Lusi will decrease by an order of magnitude to $< 10^3$ m^3/day by 2017±1 year”. In this light, both the geysering behavior (e.g., Vanderkluysen et al., 2014), and the new discharge values cited by Miller and Mazzini (2017) that greatly exceed those in 2011 can be interpreted as evidence for some combination of changes in behavior in recent years and/or missing features from the models of Davies et al. (2011) and Rudolph et al. (2011) – confirming the value of models to interpret observations. Given the importance of discharge for testing models and anticipating the future of Lusi, we look forwards to documentation of how and when the new discharge measurements were obtained and the uncertainty in the measurements. Discharge measurements are critical for assessing models and forecasting eruptions (National Academies, 2017).

4. Response of hydrothermal systems to distant earthquakes

It has long been established that earthquakes induce a variety of hydrological and volcanic responses (e.g., Pliny, 1st century AD as reported in Pliny, 1855). A comparison of the Lusi eruption -Yogjakarta earthquake pair with other examples of triggered phenomena provides a basis for assessing whether this particular possible example is expected or unusual. Key is defining what types of triggered phenomena are appropriate for comparison. Miller and Mazzini (2017) conclude that it is “necessary to include Lusi with other triggered volcanic/hydrothermal systems”.

Since Lusi was a new eruption, we contend instead that a comparison with new eruptions is appropriate – already erupting systems as noted by Miller and Mazzini (2017) and also documented quantitatively by others (e.g., Manga et al., 2009, Avouris et al., 2017, Menapace et al., 2017) are more sensitive to earthquakes. Fig. 9 is a compilation of mud eruptions triggered within days of earthquakes, and details and references are provided in Table 1. We include only cases for which we could verify that the reference directly tied the eruption and earthquake. We also do not include examples where local seismicity and eruptions may both be triggered by a common underlying process (e.g., Pitt and Hutchinson, 1982). For comparison, we also plot lines of constant seismic energy density, a measure of ground motion. If this is a reasonable proxy for the propensity for triggering (Wang and Manga, 2010), the energy density at Lusi from the Yogyakarta earthquake was 0.0043 J/m^3, smaller than the smallest value of 0.019 J/m^3 for any of the other events shown in Fig. 9.

Table 1. Mud volcano eruptions triggered within days of earthquakes (data plotted in Fig. 9).

Earthquake date	Name	Magnitude	Distance (km)	Reference
March 4, 1977	Beciu, Romania	7.4	92	Mellors et al. (2007)
December 26, 2004	Baratang, Andaman Islands	9.1	1030	Manga and Brodsky (2006), distance updated in Bonini et al. (2016)
December 10, 2003	Luoshang, Taiwan	6.8	10	Bonini et al. (2016)
December 10, 2003	Leikunghuo, Taiwan	6.8	18	Bonini et al. (2016)
September 24, 2013	Makran Coast, Pakistan	7.7	383	Bonini et al. (2016)
May 20, 2012	Torre, Italy	6.1	77	Bonini et al. (2016)
May 20, 2012	Regnano, Italy	6.1	63	Manga and Bonini (2012)

Earthquake date	Name	Magnitude	Distance (km)	Reference
May 29, 2012	Regnano, Italy	5.9	52	Manga and Bonini (2012)
May 20, 2012	Casola-Querzola, Italy	6.1	63	Bonini et al. (2016)
May 29, 2012	Casola-Querzola, Italy	5.9	52	Bonini et al. (2016)
May 20, 2012	Nirano, Italy	6.1	52	Manga and Bonini (2012)
May 20, 2012	Puianello, Italy	6.1	55	Manga and Bonini (2012)
May 29, 2012	Ospitaletto, Italy	5.9	49	Bonini et al. (2016)
March 4, 1952	Niikappu	8.6	58	Chigira and Tanaka (1997)
May 16, 1968	Niikappu	8.2	186	Chigira and Tanaka (1997)
March 21, 1982	Niikappu	6.7	25	Chigira and Tanaka (1997)
January 15, 1993	Niikappu	7.6	153	Chigira and Tanaka (1997)
December 28, 1994	Niikappu	7.8	226	Chigira and Tanaka (1997)
September 25, 2003	Niikappu	8.3	145	Manga and Brodsky (2006)
91 BC	Nirano, Italy	5.7	15	Bonini (2009)
91 BC	Montegibbio	5.7	15	Bonini (2009)
Aprril 5, 1781	Montegibbio	5.94	87	Bonini (2009)
May 16, 1873	Montegibbio	5.09	12	Bonini et al. (2016)
February 27, 2015	South Semau	7	340	Documented in email from Mark Tingay
January 28, 1872	Kalamaddyn, AZ	5.7	24	Mellors et al. (2007)

Earthquake date	Name	Magnitude	Distance (km)	Reference
Jnauary 28, 1872	Shikhzairli, AZ	5.7	40	Mellors et al. (2007)
February 13, 1902	Shikhzairli, AZ	6.9	45	Mellors et al. (2007)
February 13, 1902	Bozakhtarma, AZ	6.9	51	Mellors et al. (2007)
November 28, 1945	Ormara, Makran	8.1	41	Delisle (2005)
November 28, 1945	Hingol, Makran	8.1	189	Delisle (2005)
November 28, 1945	Gwadar, Makran	8.1	155	Delisle (2005)
May 30, 1935	Thok, Baluchistan	7.7	61	Snead (1964)
July 8, 1895	Livanoca, South Caspaun	8.2	141	Mellors et al. (2007)
September 24, 1848	Marazy, AZ	4.6	15	Mellors et al. (2007)
December 4, 1957	Gobi Altay, Mongolia	8.3	75	Rukavickova and Hanzl (2008)
June 15, 2006	Gobi Altay, Mongolia	5.8	90	Rukavickova and Hanzl (2008)
January 26, 2001	Kandewari, Pakistan	7.7	482	Manga et al. (2009)
October 11, 1915	Regnano, Italy	5	21	Martinelli et al. (1989)
September 4, 1895	Portico di Romagna, Italy	5	4	Bonini (2009)
December 13, 1990	Paterno, Italy	5.7	39	Bonini (2009)
October 4, 1978	Paterno, Italy	5.2	34	Bonini (2009)
March 5, 1828	Caltanizetta, Italy	5.9	56	Bonini (2009)
September 5,	Kumano Knoll #5,	7.4	80	Tsunogai et al. (2012)

Earthquake date	Name	Magnitude	Distance (km)	Reference
2004	Japan			
August 24, 2016	S.Maria in Paganico, Italy	6	48	Maestrelli et al. (2017)
August 25, 2016	La Croce, Italy	6	45	Maestrelli et al. (2017)
August 26, 2016	Case tedeschi 2 bis, Italy	6	45	Maestrelli et al. (2017)
October 30, 2016	S. Maria in Paganico, Italy	6.5	43	Maestrelli et al. (2017)
October 31, 2016	Valle Corvone, Italy	6.5	41	Maestrelli et al. (2017)
November 1, 2016	La Croce, Italy	6.5	41	Maestrelli et al. (2017)
November 2, 2016	Case Tedeschi 1, Italy	6.5	41	Maestrelli et al. (2017)
November 3, 2016	Case Tedeschi 3, Italy	6.5	41	Maestrelli et al. (2017)
November 4, 2016	Monteleone 1, Italy	6.5	41	Maestrelli et al. (2017)
November 5, 2016	Monteleone 2, Italy	6.5	41	Maestrelli et al. (2017)
November 6, 2016	Monteleone 3, Italy	6.5	41	Maestrelli et al. (2017)
November 7, 2016	Contrada S. Salvatore 1, Italy	6.5	38	Maestrelli et al. (2017)
November 8, 2016	Contrada S. Salvatore 2, Italy	6.5	38	Maestrelli et al. (2017)
November 9, 2016	Contrada S. Salvatore 3, Italy	6.5	38	Maestrelli et al. (2017)
January 18, 2017	S.Maria in Paganico, Italy	5.5	64	Maestrelli et al. (2017)

To highlight how much more sensitive other Earth systems are to earthquakes, we include a compilation of observations of responses in wells, magmatic volcanoes, triggered earthquakes, geysers, and streams based on the data compilation in Manga and Wang (2015). It is these types of events that Miller and Mazzini (2017) use to argue that Lusi was not unusual. We contend that initiating a new eruption of aqueous fluids and solids is different from triggering seismicity or changing the behavior of a geyser. Once Lusi began erupting we fully agree with Miller and Mazzini (2017) that a comparison with other already-active systems, including geysers, is appropriate.

We emphasize that Fig. 9 only captures two aspects of the earthquake: its magnitude and distance. It neglects directivity effects in the rupture direction, which can enhance ground motion and may be important for volcano triggering (Delle Donne et al., 2010); the 2013 Gwadar triggered eruption may be an example of a mud eruption enabled by directivity (e.g., Bonini et al., 2016). Lusi, however, was not at an azimuth where directivity would amplify ground motion (Walter et al., 2008, Tingay et al., 2008). The type of compilation in Fig. 9 and the model for seismic energy density also do not account for regional variations in attenuation, though Davies et al. (2008) did develop an attenuation model for east Java and did not find evidence for weak attenuation. Last, the frequency content of deformation may matter, with suggestions based on observations that long period waves may be more effective than short period waves of the same amplitude (e.g., Beresnev, 2006, Manga et al., 2009, Rudolph and Manga, 2012) – if so, the energy density needed to trigger eruptions would decrease with increasing earthquake magnitude, making Lusi even less likely to have been triggered (assuming Fig. 9 is relevant). Nevertheless, that Lusi may have been more sensitive to earthquakes than other documented examples of new eruptions is *not* a definitive argument against an earthquake trigger – there must always be a most-sensitive example in any collection of observations.

A stronger argument against an earthquake trigger, made in some of the earliest papers published shortly after the eruption, is that other earthquakes produced greater ground motions without triggering an eruption (Manga, 2007, Davies et al., 2008). Table 2 lists 9 earthquakes that had greater seismic energy density at Lusi than the Yogyakarta earthquake. Energy density is only one measure of ground motion, but one whose magnitude may be best correlated with responses to earthquakes (Wang and Manga, 2010). Other measures of ground motion, including peak ground velocity and peak acceleration, calculated using the attenuation relationships for East Java developed in Davies et al. (2008), are also listed in Table 2; if these measures are adopted, then more, possibly many more, events had stronger ground motion (Davies et al., 2008). Data in this table were retrieved on July 10, 2017 from the USGS earthquake catalog.

Table 2. Ground motion for earthquakes that have greater seismic energy density at the Lusi site than the Yogyakarta event (first line).

Time (UTC)	Magnitude	Depth (km)	Epicenter distance (km)	Hypocenter distance (km)	Latitude	Longitude	Energy density (J/m^3)	PGA (m/s^2)	PGV (m/s)
2006-05-26 22:53:58.920	6.3	12.5	254.45	254.75	−7.961	110.446	4.27e-03	8.87e-04	1.73e-03
2000-06-04 16:28:26.170	7.9	33.0	1216.07	1216.52	−4.721	102.087	7.94e-03	6.62e-04	3.78e-03
1998-09-28 13:34:30.490	6.6	151.6	80.82	171.80	−8.194	112.413	3.84e-02	6.86e-03	1.28e-02
1996-06-17 11:22:18.540	7.9	587.3	1091.49	1239.47	−7.137	122.589	7.50e-03	6.84e-04	3.87e-03
1996-01-01 08:05:10	7.9	24.0	1214.88	1215.12	0.729	119.931	7.96e-03	6.60e-04	3.77e-03

Time (UTC)	Magnitude	Depth (km)	Epicenter distance (km)	Hypocenter distance (km)	Latitude	Longitude	Energy density (J/m^3)	PGA (m/s^2)	PGV (m/s)
.830									
1994-06-03 21:06:59.880	6.6	25.9	314.24	315.31	−10.362	112.892	6.10e-03	6.42e-04	1.62e-03
1994-06-02 18:17:34.020	7.8	18.4	326.62	327.14	−10.477	112.835	3.04e-01	3.43e-03	1.68e-02
1992-12-12 05:29:26.350	7.8	27.7	1018.01	1018.38	−8.48	121.896	9.73e-03	4.64e-04	2.67e-03
1977-08-19 06:08:55.200	7.9	33.0	744.47	745.20	−11.085	118.464	3.50e-02	5.80e-04	3.65e-03
1976-07-14 07:13:24	6.5	40.0	250.40	253.57	−8.17	114.888	8.45e-03	1.22e-03	2.65e-03

Time (UTC)	Magnitude	Depth (km)	Epicenter distance (km)	Hypocenter distance (km)	Latitude	Longitude	Energy density (J/m^3)	PGA (m/s^2)	PGV (m/s)
.000									

We agree with Miller and Mazzini (2017) that the Yogyakarta event remains unique among the events in Table 2 as a strike-slip event. However, we disagree with the claim by Miller and Mazzini (2017) that only earthquakes with high frequency ground motions affect Lusi because Lusi is not sensitive to surface waves. This claim is based on numerical simulations of wave propagation at Lusi that erroneously included a non-existent very high velocity layer ($V_p > 6000$ m/s, which represented the velocities of the steel wellbore casing) above the mud source (Lupi et al., 2013). The revised V_s structure used in the corrigendum to Lupi et al. (2013) (Lupi et al., 2014) also contains a higher-impedance layer above the Kalibeng clays, which focuses seismic energy into the underlying region.
This impedance contrast was attributed to changes in fluid overpressure. A revised velocity structure constrained by borehole geophysical logs, check-shot data, geological observations and pore pressure measurements at BJP-1 and offset wells (Tingay, 2015) shows no evidence for the impedance contrast used in Lupi et al. (2014) and disfavors significant variations in effective stress(overburden minus pore pressure) in this depth interval (see also Fig. 1). Models of wave propagation carried out with a revised velocity structure show no such extreme focusing of vertically-incident energy (Rudolph et al., 2015). Hence, the sensitivity of Lusi to other types of seismic waves remains unresolved.

The other magnitude 6 events in Table 2 should have had similar frequency contents but larger amplitudes relative to the Yogyakarta event. We note that long period waves may favor triggering of earthquakes in geothermal settings (e.g., Brodsky and Prejean, 2005), non-volcanic tremor (Guilhem et al., 2010), and initiating liquefaction (e.g., Holzer and Youd, 2007). Indeed, the study by West et al. (2005) showed that (long period) Rayleigh waves trigger earthquakes when they maximize local failure stresses. Nevertheless, a review of frequency dependence did conclude that data supporting this conclusion remain sparse (Manga et al., 2012).

We agree that accurate measures of ground motion will benefit from improved seismic velocity models and simulations of 3D wave propagation through more realistic structures. This includes both P and S velocity models. Better predictions and measurements of ground motion will make comparisons with other settings more meaningful and also provide insights that will be valuable elsewhere.

5. Summary

Daily drilling reports document that a kick occurred while drilling, that the kick was not controlled, and that wellbore integrity was lost, all leading to a subsurface blowout. Pressure data document fracture propagation and also appear to have directly witnessed the birth of the first Lusi eruption at the surface on the 29th of May 2006. Gas data confirm that fluids from a deep (>2800m) source erupted during the initiation of Lusi, and show no evidence for either pre-eruption hydrothermal invasion of the Kalibeng clays, nor of any earthquake-induced liquefaction. Daily drilling reports (Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6) clearly state that Lusi eruption behavior was modified during attempts to kill the mudflow on three occasions, confirming the direct connection between BJP-1 and Lusi that is also witnessed in the drill-pipe pressure data. All of these official observations and reports contradict the key claims and arguments made against the drilling trigger by Miller and Mazzini (2017).

Analogous events are relevant for understanding how drilling and earthquakestrigger eruptions. Drilling has initiated similar eruptions elsewhere. We contend that the most appropriate comparisons for earthquake-triggering are new eruptions, or quiescent mud volcanoes, triggered by earthquakes. A compilation of 58 documented examples of triggered mud eruptions shows that Lusi would need to be the most sensitive system yet documented if it erupted in response to the Yogyakarta earthquake. Moreover, other earthquakes caused greater shaking at Lusi and did not initiate an eruption, which is in full agreement with the drilling records that indicate no earthquake-induced liquefaction, nor any reliable or reported hydrodynamic response to seismicity, at the Lusi location.

Lusi remains a great testbed for models and ideas about what initiates eruptions and how large, deeply sourced eruptions evolve. Drilling reports and data collected prior to, during, and after the eruption provide key insights into the sequence of events and allow hypotheses to be tested. We maintain that these primary reports and data support a trigger by drilling and provide direct evidence against the earthquake-triggering hypothesis.

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References

Adams, 2006

N. Adams**Causation Factors for the Banjar Panji No. 1 Blowout. Report and Data. Rep**

(2006), p. 63

Avouris et al., 2017

D.M. Avouris, S.A. Carn, G.P. Waite**Triggering of volcanic degassing by large earthquakes**

Geology, 45 (2017), pp. 715-718

G39074–1

Baker, 1998

R. Baker

Practical Well Control (fourth ed.), University of Texas at
Austin, Austin (1998), p. 352

ISBN 0-88698-183-2

Beresnev, 2006

I.A. Beresnev**Theory of vibratory mobilization on nonwetting fluids entrapped in pore constrictions**

Geophysics, 71 (6) (2006), pp. N47-N56

Bonini et al., 2016

M. Bonini, M.L. Rudolph, M. Manga**Long-and short-term triggering and modulation of mud volcano eruptions by earthquakes**

Tectonophysics, 672 (2016), pp. 190-211

Bonini, 2009

M. Bonini**Mud volcano eruptions and earthquakes in the Northern Apennines and Sicily, Italy**

Tectonophysics, 474 (3) (2009), pp. 723-735

Brodsky and Prejean, 2005

E.E. Brodsky, S.G. Prejean**New constraints on mechanisms of remotely triggered seismicity at Long Valley Caldera**

J. Geophys. Res.: Solid Earth, 110 (B4) (2005)

Chigira and Tanaka, 1997

M. Chigira, K. Tanaka**Structural features and the history of mud volcanoes in southern Hokkaido, northern Japan**

J. Geol. Soc. Jpn., 103 (1997), pp. 781-791

Clarke and Hemphill, 2002

K.C. Clarke, J.J. Hemphill

Darrick Danta (Ed.), The Santa Barbabra Oil Spill, a Retrospective. Yearbook of the Association of Pacific Coast Geographers, 64, University of Hawai'i Press (2002), pp. 157-162

Cornet et al., 2007

F.H. Cornet, Th Berard, S. Bourouis**How close to failure is a granite rock mass at 5km depth?**

Int. J. Rock Mech. Min. Sci. (2007), pp. 47-66

v. 44

Darmawan et al., 2011

G.R. Darmawan, N. Buntu Sangka, S. Djoko Susilo, J.T. Shaun, S.W. Nas, A. Eka Prasetia, S. Sisworo**Integrated Downhole Isolation Valve and Managed Pressure Drilling to Facilitate Development of Sour Fractured-Limestone Gas Reservoir in East Java, Indonesia. 2011 SPE/IADC Drilling Conference and Exhibition, SPE-140267-MS**

(2011), 10.2118/140267-MS

Davies et al., 2007

R.J. Davies, R.E. Swarbrick, R.J. Evans, M. Huuse**Birth of a Mud volcano: east Java, 29 may 2006**

GSA Today, 17 (2) (2007), p. 4

Davies et al., 2008

R.J. Davies, M. Brumm, M. Manga, R. Rubiandini, R. Swarbrick, M. Tingay**The East Java mud volcano (2006 to present): an earthquake or drilling trigger?**

Earth Planet Sci. Lett., 272 (3) (2008), pp. 627-638

Davies et al., 2010

R. Davies, M. Manga, M. Tingay, S. Lusianga, R. Swarbrick**Discussion: Sawolo et al. (2009) the Lusi mud volcano controversy: was it caused by drilling?**

Mar. Petrol. Geol., 27 (2010), pp. 1651-1657

Davies et al., 2011

R.J. Davies, S.A. Mathias, R.E. Swarbrick, M.J. Tingay**Probabilistic longevity estimate for the LUSI mud volcano, East Java**

J. Geol. Soc., 168 (2) (2011), pp. 517-523

Delisle, 2005

G. Delisle**Mud volcanoes of Pakistan—An overview**

Mud Volcanoes, Geodynamics and Seismicity, Springer, Netherlands (2005), pp. 159-169

Delle Donne et al., 2010

D. Delle Donne, A.J. Harris, M. Ripepe, R. Wright**Earthquake-induced thermal anomalies at active volcanoes**

Geology, 38 (9) (2010), pp. 771-774

Gretener, 1982

P.E. Gretener**Another look at Alborz Nr. 5 in Central Iran**

Bull. Ver. Schweiz. Pet. -Geologen -Ingenieu (114) (1982), pp. 1-8

v. 48

Guilhem et al., 2010

A. Guilhem, Z. Peng, R.M. Nadeau**High-frequency identification of non-volcanic tremor triggered by regional earthquakes**

Geophys. Res. Lett., 37 (16) (2010)

Holzer and Youd, 2007

T.L. Holzer, T.L. Youd**Liquefaction, ground oscillation, and soil deformation at the Wildlife Array, California**

Bull. Seismol. Soc. Am., 97 (3) (2007), pp. 961-976

Istadi et al., 2009

B. Istadi, G. Pramono, P. Sumintadireja**Modeling study of growth and potential geohazard for LUSI mud volcano: east Java, Indonesia**

Mar. Petrol. Geol., 26 (2009), pp. 1724-1739

Lupi et al., 2013

M. Lupi, E.H. Saenger, F. Fuchs, S.A. Miller**Lusi mud eruption triggered by geometric focusing of seismic waves**

Nat. Geosci., 6 (8) (2013), p. 642

Lupi et al., 2014

M. Lupi, E.H. Saenger, F. Fuchs, S.A. Miller**Corrigendum: Lusi mud eruption triggered by geometric focusing of seismic waves**

Nat. Geosci., 7 (9) (2014), p. 687

Maestrelli et al., 2017

D. Maestrelli, M. Bonini, D. Delle Donne, M. Manga, L. Piccardi, F. Sani**Dynamic triggering of mud volcano eruptions during the 2016–2017 Central Italy seismic sequence**

J. Geophys. Res.: Solid Earth (2017), 10.1002/2017JB014777

Malvoisin et al., 2016

B. Malvoisin, A. Mazzini, S. Miller**Constraining the thermal structure beneath Lusi: insights from temperature record in erupted clasts**

Geophys. Res. Abstr., 18 (2016)

EGU2016–16421, 2016 EGU General Assembly

Manga, 2007

M. Manga**Did an earthquake trigger the May 2006 eruption of the Lusi mud volcano?**

Eos, Transactions American Geophysical Union, 88 (18) (2007)

201–201

Manga and Bonini, 2012

M. Manga, M. Bonini**Large historical eruptions at subaerial mud volcanoes**

Italy. Natural Hazards and Earth System Sciences, 12 (11) (2012), p. 3377

Manga and Brodsky, 2006

M. Manga, E. Brodsky**Seismic triggering of eruptions in the far field: volcanoes and geysers**

Annu. Rev. Earth Planet Sci., 34 (2006), pp. 263-291

Manga et al., 2009

M. Manga, M. Brumm, M.L. Rudolph**Earthquake triggering of mud volcanoes**

Mar. Petrol. Geol., 26 (9) (2009), pp. 1785-1798

Manga et al., 2012

M. Manga, I. Beresnev, E.E. Brodsky, J.E. Elkhoury, D. Elsworth, S.E.Ingebritsen, C.Y. Wang**Changes in permeability caused by transient stresses: field observations, experiments, and mechanisms**

Rev. Geophys., 50 (2) (2012)

Manga and Wang, 2015

M. Manga, C.Y. Wang**4.12. Earthquake Hydrology. Treatise on Geophysics**

(second ed.), Elsevier, Oxford (2015), pp. 305-328

Martinelli et al., 1989

G. Martinelli, A. Bassignani, G. Ferrari, P.B. Finazzi**Predicting earthquakes in Northern Appenines: recent developments in monitoring of Radon 222**

Proceedings of the 4th International Symposium on the Analysis of Seismicity and Seismic Risk, Bechyne Castle, Czechoslovakia, 4–9 Sept. 1989 (1989), pp. 192-208

Mazzini et al., 2007

A. Mazzini, H. Svensen, G.G. Akhmanov, G. Aloisi, S. Planke, A. Malthe-Sørenssen, B. Istadi**Triggering and dynamic evolution of the LUSI mud volcano, Indonesia**

Earth Planet. Sci. Lett., 261 (3) (2007), pp. 375-388

Mazzini et al., 2012

A. Mazzini, G. Etiope, H. Svensen**A new hydrothermal scenario for the 2006 Lusi eruption, Indonesia. Insights from gas geochemistry**

Earth Planet. Sci. Lett., 317 (2012), pp. 305-318

Mellors et al., 2007

R. Mellors, D. Kilb, A. Aliyev, A. Gasanov, G. Yetirmishli**Correlations between earthquakes and large mud volcano eruptions**

J. Geophys. Res.: Solid Earth, 112 (B4) (2007)

Menapace et al., 2017

W. Menapace, D. Völker, H. Sahling, C. Zoellner, C. dos Santos Ferreira, G.Bohrmann, A. Kopf**Long-term in situ observations at the Athina mud volcano, Eastern Mediterranean: taking the pulse of mud volcanism**

Tectonophysics, 721 (2017), pp. 12-27

Miller and Mazzini, 2017

S.A. Miller, A. Mazzini**More than ten years of Lusi: a review of facts, coincidences, and past and future studies**

Mar. Petrol. Geol. (2017)

(in press)

https://doi.org/10.1016/j.marpetgeo.2017.06.019

Mostofi and Gansser, 1957

B. Mostofi, A. Gansser**The story behind the 5 Alborz**

Oil Gas J. (3) (1957), pp. 78-84

v. 55

National Academies, 2017

National Academies of Sciences, Engineering, and Medicine**Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing. Washington, DC**

The National Academies Press (2017)

https://doi.org/10.17226/24650

Novenanto, 2015

A. Novenanto**Discoursing Disaster: Power and Actor of the Lapindo Case in Indonesia**

PhD Thesis at

Heidelberg University, Germany (2015), p. 310

Pitt and Hutchinson, 1982

A.M. Pitt, R.A. Hutchinson**Hydrothermal changes related to earthquake activity at mud volcano, Yellowstone National Park, Wyoming**

J. Geophys. Res.: Solid Earth, 87 (B4) (1982), pp. 2762-2766

Planke et al., 2003

S. Planke, H. Svensen, M. Hovland, A. Banks, B. Jamtveit**Mud and fluid migration in active mud volcanoes in Azerbaijan**

Geophys. Res. Lett., 23 (2003), pp. 258-268

Pliny, 1855

Pliny the Elder**The Natural History of Pliny**

(1855)

translated from Green by J.Bostock and H.T. Riley, H.G. Bohn, London

Roberts et al., 2011

K. Roberts, R.J. Davies, S. Stewart, M. Tingay**Structural controls on mud volcano vent distributions: examples from Azerbaijan and Lusi, East Java**

J. Geol. Soc. Lond, 168 (2011), pp. 1013-1030

Rudolph et al., 2011

M.L. Rudolph, L. Karlstrom, M. Manga**A prediction of the longevity of the Lusi mud eruption, Indonesia**

Earth Planet Sci. Lett., 308 (1) (2011), pp. 124-130

Rudolph and Manga, 2012

M.L. Rudolph, M. Manga**Frequency dependence of mud volcano response to earthquakes**

Geophys. Res. Lett., 39 (14) (2012)

Rudolph et al., 2015

M.L. Rudolph, M. Manga, M. Tingay, R.J. Davies**Influence of seismicity on the Lusi mud eruption**

Geophys. Res. Lett., 42 (18) (2015), pp. 7436-7443

Rudolph et al., 2013

M.L. Rudolph, M. Shirzaei, M. Manga, Y. Fukushima**Evolution and future of the Lusi mud eruption inferred from ground deformation**

Geophys. Res. Lett., 40 (6) (2013), pp. 1089-1092

Rukavickova and Hanzl, 2008

L. Rukavickova, P. Hanzl**Mud volcanoes in the Khar Argalantyn Nuruu, NW Gobi Altay, Mongolia as manifestation of recent seismic activity**

J. Geosci., 53 (2) (2008), p. 181

Sawolo et al., 2009

N. Sawolo, E. Sutriono, B.P. Istadi, A.B. Darmoyo**The LUSI mud volcano triggering controversy: was it caused by drilling?**

Mar. Petrol. Geol., 26 (2009), pp. 1766-1784

Sawolo et al., 2010

N. Sawolo, E. Sutriono, B.P. Istadi, A.B. Darmoyo**Was LUSI caused by drilling? – Authors reply to discussion**

Mar. Petrol. Geol., 27 (2010), pp. 1658-1675

Shirzaei et al., 2015

M. Shirzaei, M.L. Rudolph, M. Manga**Deep and shallow sources for the Lusi mud eruption revealed by surface deformation**

Geophys. Res. Lett., 42 (13) (2015), pp. 5274-5281

Snead, 1964

R.E. Snead**Active mud volcanoes of Baluchistan, west Pakistan**

Geogr. Rev., 54 (4) (1964), pp. 546-560

Stewart and Davies, 2006

S.A. Stewart, R.J. Davies**Structure and emplacement of mud volcano systems in the South Caspian Basin**

AAPG Bull., 90 (5) (2006), pp. 771-786

Tingay, 2010

M. Tingay**Anatomy of the ‘Lusi’ mud eruption, East Java**

Aust. Soc. Explor. Geophys. Extended Abstracts, 2010 (2010), pp. 1-6, 10.1071/ASEG2010ab241

Tingay, 2015

M. Tingay**Initial pore pressures under the Lusi mud volcano, Indonesia**

Interpretation, 3 (1) (2015), pp. SE33-SE49

Tingay et al., 2003

M. Tingay, R. Hillis, C. Morley, R. Swarbrick, E. Okpere**Pore pressure/stress coupling in Brunei Darussalam – implications for shale injection**

P. Van Rensbergen, R.R. Hillis, A.J. Maltman, C.K. Morley (Eds.), Subsurface Sediment Mobilization, 216, Geological Society of London Special Publication, London (2003), pp. 369-379

Tingay et al., 2005

M. Tingay, R.R. Hillis, C.K. Morley, R.E. Swarbrick, S.J. Drake**Present-day stress orientation in Brunei: a snapshot of 'prograding tectonics' in a Tertiary delta**

J. Geol. Soc. Lond, 162 (2005), pp. 39-49

Tingay et al., 2008

M. Tingay, O. Heidbach, R. Davies, R. Swarbrick**Triggering of the Lusi mud eruption: earthquake versus drilling initiation**

Geology, 36 (8) (2008), pp. 639-642

Tingay, 2016

M. Tingay**What Caused the Lusi Mudflow Disaster in Indonesia?**

(2016)

American Association of Petroleum Geologists Search and Discovery Article #41791

http://www.searchanddiscovery.com/pdfz/documents/2016/41791tingay/ndx_tingay.pdf.html

Tingay et al., 2015

M.R.P. Tingay, M.L. Rudolph, M. Manga, R.J. Davies, C.Y. Wang**Initiation of the Lusi mudflow disaster**

Nat. Geosci., 8 (7) (2015), pp. 493-494

Tsunogai et al., 2012

U. Tsunogai, K. Maegawa, S. Sato, D.D. Komatsu, F. Nakagawa, T. Toki, J.Ashi **Coseimic massive methane release from a submarine mud volcano**

Earth Planet. Sci. Lett., 341 (2012), pp. 79-85

Vanderkluysen et al., 2014

L. Vanderkluysen, M.R. Burton, A.B. Clarke, H.E. Hartnett, J.F.Smekens**Composition and flux of explosive gas release at LUSI mud volcano (East Java, Indonesia)**

Geochem. Geophys. Geosyst., 15 (7) (2014), pp. 2932-2946

Wang and Manga, 2010

C.Y. Wang, M. Manga**Hydrologic responses to earthquakes and a general metric**

Geofluids, 10 (1–2) (2010), pp. 206-216

Walter et al., 2008

T.R. Walter, R. Wang, B.G. Luehr, J. Wassermann, Y. Behr, S. Parolai, A.Anggraini, E. Günther, M. Sobiesiak, H. Grosser, H.U. Wetzel**The 26 May 2006 magnitude 6.4 Yogyakarta earthquake south of Mt. Merapi volcano:**

did lahar deposits amplify ground shaking and thus lead to the disaster?

Geochem. Geophys. Geosyst., 9 (5) (2008)

Warpinski and Smith, 1989

N.R. Warpinski, M.B. Smith**Rock mechanics and fracture geometry**

Recent Advances in Hydraulic Fracturing, vol. 12 (1989), pp. 57-80

West et al., 2005

M. West, J.J. Sánchez, S.R. McNutt**Periodically triggered seismicity at mount Wrangell, Alaska, after the Sumatra earthquake**

Science, 308 (5725) (2005), pp. 1144-1146

Zoback, 2007

M.D. Zoback**Reservoir Geomechanics**

Cambridge University Press (2007)

464 pages

[1] https://www.scientificamerican.com/article/indonesian-mud-volcano-also-spewed-oil/.

[2] http://www.thejakartapost.com/news/2009/01/02/caution-urged-gresik-drilling.html?1.

[3] http://banjarmasin.tribunnews.com/2015/12/21/lumpur-panas-tiba-tiba-menyembur-warga-takut-seperti-lapindo.

[4] http://kaltim.tribunnews.com/2016/01/19/mud-vulcano-samarinda-kembali-menyembur-setelah-20-tahun-tak-aktif?page=3.