Manuscript Number: JMPG-D-09-00142

Title: DISCUSSION: Sawolo et al., (2009) The LUSI mud volcano controversy: Was it caused by drilling?'

Article Type: Discussion

Keywords:

Corresponding Author: Prof Richard Davies,

Corresponding Author's Institution:

First Author: Richard Davies

Order of Authors: Richard Davies; Richard J Davies; Michael Manga; Mark Tingay; Susila Lusiaga; Richard Swarbrick

Abstract: there is no abstract - this is a discussion

DISCUSSION: Sawolo et al., (2009) The LUSI mud volcano controversy: Was it caused by drilling?'

Richard J. Davies[a], Michael Manga[b], Mark Tingay[c], Susila Lusianga[d] and Richard Swarbrick[e]

[a]Centre for Research into Earth Energy Systems (CeREES), Department of Earth Sciences, University of Durham, Science Labs, Durham, DH1 3LE, UK (email: richard.davies@durham.ac.uk)
[b]Department of Earth and Planetary Science, UC Berkeley, Berkeley CA 94720-4767, USA.
[c]Department of Applied Geology, Curtin University, Perth, 6845, Australia
[d]Taman Kebon Jeruk F1/41, Jakarta Barat, Indonesia
[e]Geopressure Technology Ltd. Science Labs, Durham, DH1 3LE, UK.

Introduction

The Lusi mud volcano in Sidoarjo, East Java, was first noticed by local villagers at 5 am on the 29th May 2006. It started to erupt 150 m from the Banjar Panji-1 gas exploration well (Fig. 1) two days after the Yogyakarta Earthquake (5:54 am 27th May 2006), has displaced 13,000 families and led to 13 fatalities. The trigger for the mud volcano has been the subject of significant debate (Davies et al., 2007; Manga 2007; Mazzini et al., 2007; Davies et al., 2008; Tingay et al., 2008).

The Sawolo et al., (2009) paper assesses and then dismisses the possibility that there was a subsurface blowout (breakdown of the structural integrity of the well) caused by a kick in the well (an influx of water or gas from surrounding formations) which occurred on the 27th and 28th May 2006. For the subsurface blowout to have occurred, the pressure of the fluid (drilling mud, water, gas) in the unprotected section of the well has to exceed the maximum pressure the well can tolerate, which is estimated by a pressure test known as a leak off test (LOT). To reach this conclusion Sawolo et al. (2009) estimate what we deem to be an unrealistically high leak off pressure (LOP) and unrealistically low pressure within the borehole during the kick.

Here we counter the main arguments made by Sawolo et al., (2009), pointing out inaccuracies, incorrect interpretations and deviations from the daily drilling report (the factual account of daily operations). We also take this opportunity to describe for the first time direct evidence that the well was the cause of the mud volcano. Lastly we show that their claim of an earthquake trigger is not supported by the mud log data they present.

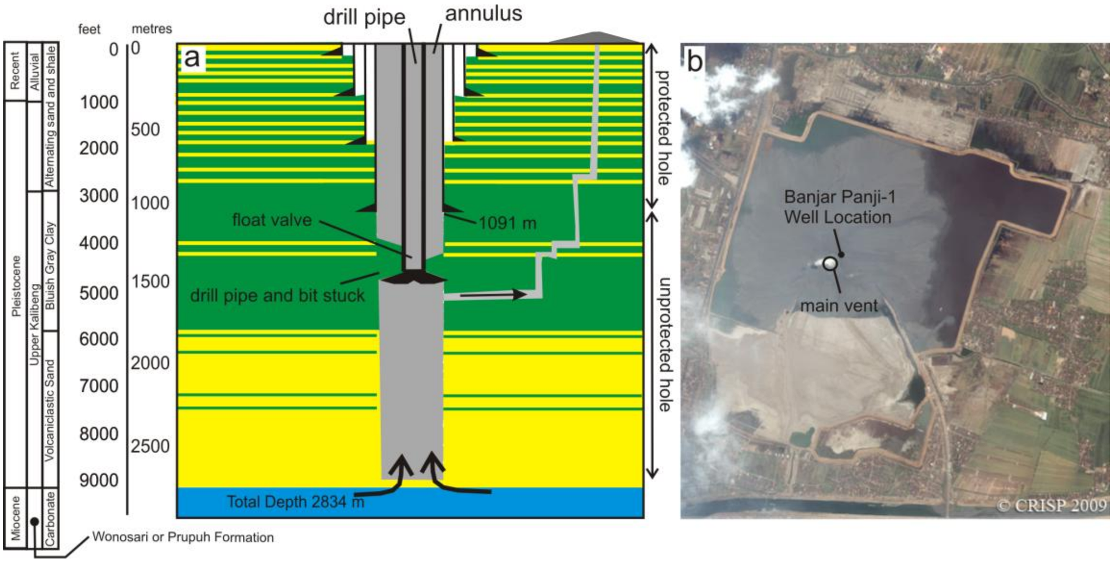

Figure 1 a: Banjar Panji-1 well after the kick on 28th May 2006 with postulated flow path for fluids initially erupted by the Lusi mud volcano (after Davies et al., 2008) b: Satellite photo of Lusi (August 2009).

What pressure could the well tolerate?

The estimated LOP proposed by Sawolo et al., (2009) is 16.4 ppg (19.27 MPa/km) measured at 1091 m (1 ppg = 1.175 MPa/km). In determining the leak off pressure (LOP), industry accepted practice is to take the inflexion point on a pressure build-up curve (Bell, 1996; Enever et al., 1996; Addis et al., 1998; Jørgensen & Fejerskov, 1998; Økland et al., 2002; Raaen et al., 2006; van Oort & Vargo, 2008). Based upon the pressure versus time plot (their figure 11), using this method the leak off was 15.8 ppg (18.57 MPa/km). The rationale stated by Sawolo et al., (2009) for not interpreting the LOP by the conventional method is that interpreting leak-off pressure is less reliable when using oil-based muds and they suggest that the ‘fracture closure pressure’ was used instead.

The fracture closure pressure (FCP) is generally considered to be equal to the minimum principal stress magnitude and thus equal to the pressure required to open any pre-existing fractures. Hence, the FCP can be an accurate value to use as formation strength. However, the 16.4 ppg (19.27 MPa/km) value suggested by Sawolo et al., (2009) as the ‘fracture closure pressure’ is in contravention of all techniques for estimating FCP. FCP is determined by carefully monitoring the pressure decay in the well after the pumps are turned off (Enever et al., 1996; Jørgensen and Fejerskov, 1998; Raaen et al., 2006). The FCP can then be estimated from the pressure decay curve by a variety of methods, with the double tangent or root time methods most commonly used (Enever et al., 1993; Raaen et al., 2006). These techniques all require the pressure decay to be monitored for a long duration after the pumps are shut-in (generally >10 minutes; Enever et al., 1996; Jørgensen & Fejerskov, 1998; Raaen et al., 2006). Furthermore, FCP is also almost universally observed to be less than or equal to the LOP, as the leak-off pressure involves fracture initiation and thus must overcome both the minimum principal stress and the rock’s tensile strength (Breckels and van Eekelen, 1982; Gaarenstroom et al., 1993; Tingay et al., 2009). However, in stark contrast to all industry conventions, Sawolo et al. (2009) have selected their ‘fracture closure pressure’ as the pressure at which the leak-off test stabilized *before* the pumps were turned off and a value that is much greater than the 15.8 ppg (18.57 MPa/km) LOP. Furthermore, the leak-off test only recorded pressures for three minutes after the pumps were switched off, and it is impossible to reliably measure FCP in such a brief period. Indeed, the 16.4 ppg (19.27 MPa/km) pressure reported by Sawolo et al., (2009) as ‘fracture closure pressure’ most likely represents the fracture propagation pressure (FPP) and is not a value used to estimate formation strength by any industry standards (Jørgensen & Fejerskov, 1998; Økland et al., 2002; Raaen et al., 2006; van Oort & Vargo, 2008).

As FCP cannot be determined from the leak-off test data available, the only value for fracture strength than can be utilized from the data in figure 11 of Sawolo et al., (2009) is the 15.8 ppg (18.57 MPa/km) leak-off pressure determined from the inflexion point (or break in linearity) in the pressure increase. However, Sawolo et al.

(2009) argue that this value is unreliable when using oil-based muds due to their compressibility. Using oil-based muds does indeed affect the reliability of leak-off tests, but it does not just affect the estimate of LOP alone. The compressibility of oil-based muds, in addition to their thermal expansion and gel strength, can cause a change in the mud density with depth, meaning that pressures obtained by summing surface gauge values and the static mud density may vary from the true pressure at the test depth (van Oort & Vargo, 2008), thus making any pressure reading (LOP, FCP, FPP, etc) potentially unreliable. Note that the use of oil-based muds does not change the way we pick the point of leak-off or fracture closure on the pressure-time plot, but simply affects the static mud column pressure used in calculating these pressures (van Oort & Vargo, 2008). However, the influence of depth and temperature on leak-off tests with oil-based muds can be determined, and it is known that surface gauge derived leak-off pressures conducted at shallow depths in regions of high geothermal gradient, such as in Banjar Panji-1, are likely to be *overestimates* of the true formation strength (van Oort & Vargo, 2008).

In summary, the 16.4 ppg (19.27 MPa/km) value of formation strength derived by Sawolo et al., (2009) is incorrectly reported as the ‘fracture closure pressure’. The 16.4 ppg (19.27 MPa/km) pressure is actually the fracture propagation pressure and is not a value that should be used for formation strength. Indeed, the fracture closure pressure cannot be determined from the LOT data, leaving the LOP of 15.8 ppg (18.57 MPa/km) as the only potential formation strength value that can be determined from the data provided by Sawolo et al. (2009). Furthermore, this value is likely to be an *overestimate* of the formation strength due to the influence of mud compressibility, mud thermal expansion. In addition, Sawolo et al. (2009) have not provided LOT pressures from the other two surface gauges, in particular from the casing pressure gauge, which typically reveal the common overestimate of drill-pipe pressure based LOPs due to pumping pressure surges. Thus, the 16.4 ppg (19.27 MPa/km) value used by Sawolo et al., (2009) is an erroneous value to use, is contrary to all industry practices and is an extensive overestimation of formation strength. Lastly, it should be noted that formation strength is determined principally for essential drilling safety as a value that should never be exceeded. Hence, when given the option of multiple possible values for formation strength, the safest procedure is always to pick the *lowest* possible value for leak-off pressure. Sawolo et al., (2009) did the opposite; they picked the maximum possible value reached during the leak-off test.

Did the pressure in the well exceed the pressure the well could tolerate?

If one were to disregard all the reasons provided above accept their value of 16.4 ppg (19.27 MPa/km) as the pressure the well could tolerate, was this overestimate of the pressure that the well could tolerate exceeded? There are several methods for estimating the pressure in the unprotected section of the wellbore (from 1091 m to 2834 m). It is generally accepted that after a kick has occurred the most accurate method for calculating the pressure at the last casing shoe is to use the density of the mud in the drill-pipe, because there is a float valve at the base of the drill pipe (see their figure 7) which prevents any contamination of the drilling mud and therefore its density is not changed. Mud was pumped through the drill pipe during the initial casing pressure build-up ensuring the opening of the drill pipe float valve and accurate pressure measurement. Also the valve has within it a small hole allowing pressure communication. If one uses this method then the ***minimum*** pressure at the last casing point (1091 m) was estimated by Davies et al., (2008) to be 21.29 MPa. This is higher than what we propose is the ***overestimated*** pressure the well could tolerate 16.4 ppg (19.27 MPa/km) which at the depth of 1091 m was 21.03 MPa (Davies et al., 2008).

In order to conclude that the pressure in the well did not exceed the pressure the well could tolerate, Sawolo et al., (2009) had to make two incorrect assumptions, firstly they used the ‘fill-up method’ for estimating the pressure at the bottom of the hole and secondly they assumed the mud density had not changed as a result of the kick. The fill up method uses the level of the mud column after losses have occurred at the bottom of the hole as an indication of the pressure at the bottom of the hole. This is estimated to be 12.8 ppg (15.04 MPa/km). This estimated pressure is less than the 14.7 ppg (17.27 MPa/km) mud weight that the well was using when it took the kick (influx). This in itself suggests that the 12.8 ppg (15.04 MPa/km) is a significant underestimate of the maximum pore pressure of the hole (a kick requires the pore pressure to be higher than the pressure of the mud in the well). The fill-up method is normally accurate, but the normal practice is to top fill the annulus with light weight fluid, which can produce reasonably accurate estimates of the mud level and hence the fracture gradient of the loss zone. But in this case filling up was occurring *while* mud was being lost from the hole into the surrounding strata. There could have not been any differentiation between mud volume lost, mud volume used to fill the hole or the volume of any formation fluid influx. No information is gained on pore pressure, fracture gradient or whether formation fluid influx has occurred using this method when losses are taking place. Therefore their method for estimating the pore pressure is not appropriate. Furthermore they then assume that density of the fluid in the wellbore has not been affected by the kick 14.7 ppg (17.27 MPa/km) – their figure 8. *Only* by making these two convenient assumptions could they reach the conclusion they have. The result is misleading and essentially contrived.

Is it worth also adding that other techniques noted for estimating pore pressure, such as the influx tests and D-exponent used by Sawalo et al., (2009) are also not relevant in this case, primarily due to the lithology being that of low porosity volcanics (and not the sands often reported). Influx tests are only applicable in permeable formations – yet a low porosity volcanic rock with less than 5% porosity is hardly likely to be permeable. The D-exponent was designed for shales and looks for changes in drilling rate due to changes in pressure – but again this is unlikely to be relevant in low porosity volcanic rocks.

There can be no doubt that the well pressures exceeded what the well could tolerate. This is evident because there were static mud losses (mud lost when there was no movement of the drill pipe or pumping). Sawolo et al., (2009) state that there were surface indications that the well was ‘static’ but there was no verification that the well was ‘static’ with a 14.7 ppg (17.27 MPa/km) mud column or that the well was static downhole.

Was the well controlled?

At 11:00 am on 28th May 2006 the blow out preventors were opened and there was no flow of drilling mud, water or gas (Table 1). However they also record that by 14:30 on the same day that ‘Jar stop functioning’ and that the ‘well appeared to have caved in’, this caving in of the hole explains why they could open the blow out preventors without any surface flow taking place. Opening the blowout preventors and witnessing no flow does *not* demonstrate the well was under control. Insufficient mud had been pumped into the well during volumetric well control to establish a 14.7 ppg (17.27 MPa/km) mud column down to the level of the bit, never mind the bottom of the hole. A well that required 14.7 ppg (17.27 MPa/km) to control the gas levels during drilling can never be under control until a 14.7 ppg (17.27 MPa/km) mud column is established from surface to bottom of the hole.

We propose that the lack of flow up the well and the inability to circulate mud on the 28th of May was because a bridge or pack-off formed a complete pressure seal in the annulus above the bit (illustrated in Fig. 1a). The first casing pressure bleed off with no associated decline in drill pipe pressure would indicate that annulus plugging was a factor that may have influenced surface pressure readings (marked 1 in Fig. 2). This is confirmed by the lack of any surface annulus pressure, even when the blow out preventor was closed. Hence the drill pipe pressure was a valid monitor of the pressure on the formation below the annulus pack-off. If this were the case then the slow leak off of drill pipe pressure (marked 2 in Fig. 2) is leakage of mud through fractures (i.e. direct evidence for the failure of the well).

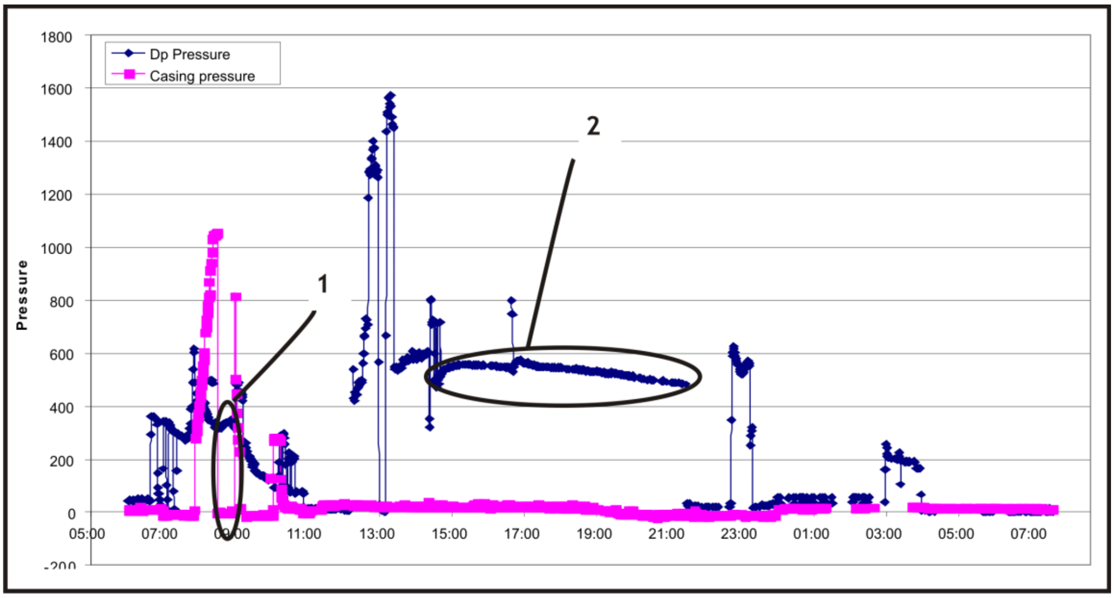

Figure 2 Pressure plot of the drill pipe and casing during shut in. Region marked 1 is a period when mud was being pumped into the drill pipe so the drill pipe pressure is high, but there is no change in pressure in the casing. This shows that there was a blockage between the base of drill pipe and casing (termed packing off). The region

marked 2 marks a period when there was no activity at the rig, but pressure was declining. This indicates fluids were leaking from the open-hole section.

Other arguments against the blowout hypothesis

Sawolo et al., (2009) propose several other lines of argument to suggest that the Lusi mud volcano is not the result of a blowout. They present shallow sonan and temperature logs collected when the Banjar Panji-1 well was re-entered approximately 7 weeks after Lusi began to erupt. These logs indicate that no fluid was flowing up the inside or close against the outside of the borehole. However, they fail to point out that Banjar Panji-1 was plugged with cement which would prevent fluids coming up the well above the plugs. Furthermore, fluids will only flow up the outside of the well if there is poor cementing of the casing and no other pathways for the fluids to go. Hence, lack of fluids flowing up or on the outside of the wellbore two months after the eruption started does not indicate that an underground blowout did not occur.

The re-entry of the Banjar Panji-1 well also indicated that the drill bit was still stuck in the original depth. Sawolo et al., (2009) argue that the bit should have fallen into the well and thus there is no blowout occurring. However, the drill bit can remain stuck in position during blowouts, particularly in zones of highly swelling clays and in wells that have had large volumes of cement pumped into them. Hence, the bit being stuck in its original location again does not prove an underground blowout was not ongoing.

Sawolo et al. (2009) argue that the Kujung carbonates, suggested to be a possible source of water erupting from Lusi (Davies et al., 2007), cannot produce the high rates of water erupting from Lusi. However, a common mistake made by Sawolo et al. (2009) and others is to assume that the carbonate formation targeted by Banjar Panji-1 is the Kujung carbonates. Strontium 86-87 analysis from the Porong-1 well, which targeted the same deep carbonates just 7 km away, revealed that these carbonates are 16 million years old and thus cannot be the 30-35 Ma Kujung carbonates (Kusumastuti et al., 2002). Hence, it is not relevant to use data from the Kujung Formation as evidence against a blowout. Indeed, the use of the Kujung formation by Sawolo et al., (2009) highlights one of the strangest aspects of the drilling of Banjar Panji-1: prediction of pore pressure and casing points using offset wells far offshore that target the Kujung Formation. It seems quite unusual that such distant offset wells were used for well planning instead of data and evidence from Lapindo's adjacent Porong-1 well.

Direct evidence for well failure

On the 30th May 2006, a day after the eruption had started, while the drill rig was still on site the daily drilling reports states:

'05:00 to 14:00 Evacuated all drilling crew into safe area (Muster point). Gas and water bubbles blew intermittently with maximum height of 25 ft, and elapse time 5 minutes between bubble. Pump down string with a total of 130 bbls 14.7 ppg mud, followed by 100 bbls 14.7 ppg. Bubbles intensity reduced and elapse time between each bubbles is longer'.

The pumping the 130 barrels and then 100 barrels of 14.7 ppg (17.27 MPa/km) mud caused a reduction in the rate of flow to the surface. The reason for pumping the mud was to stop the flow by increasing the pressure exerted by the mud column in the well and slowing the rate of flux of fluid from surrounding formations. The observation that pumping mud into the hole caused a reduction in eruption rate indicates a direct link between the wellbore and the eruption.

The Yogyakarta earthquake

Sawolo et al., (2009) imply in their abstract, table 1 summarizing the drilling operations, and their conclusion, that the magnitude 6.3 Yogyakarta earthquake located 250 km away led to the loss of mud from the well and initiated a set of processes that culminated in the eruption. Here we critically analyze their inference that the mud loss was triggered by the earthquake. We rely on the observations Sawolo et al., (2009) summarize in their table 1 and their data in their figure 12.

The arguments proposed in some studies for an earthquake trigger to the Lusi eruption have focussed solely on the timing relationship with the Yogyakarta earthquake (Mazzini et al., 2007; Sawolo et al., 2009). These studies note that Lusi started erupting approximately 48 hours after the Yogyakarta earthquake and that partial losses were observed in Banjar Panji-1 seven minutes after the earthquake and use this as the sole basis for suggesting that Lusi was triggered by the earthquake. However, in previous work (Manga, 2007; Davies et al., 2008; Tingay et al., 2008), we have argued that an earthquake trigger can be ruled out because the earthquake was too small given its distance and that the stresses produced by the earthquake were minute (smaller than those created by tides and weather). However, there are in fact hydrological responses that are more sensitive to seismic shaking than the initiation of mud volcano eruptions. Examples include changes in the eruption behaviour of already-erupting systems such as geysers (e.g., Husen et al., 2004), mud volcanoes (Manga et al., 2009), and changes in the water level in wells (e.g., Roeloffs, 1998; Wang and Chia, 2008). Based on a global compilation of > 500 observations of changes in water level in wells, the Yogyakarta earthquake lies right at the threshold distance where changes in water levels in wells (changes in pore pressure) might be possible under optimal conditions (Wang and Manga, 2009) (Fig. 3).

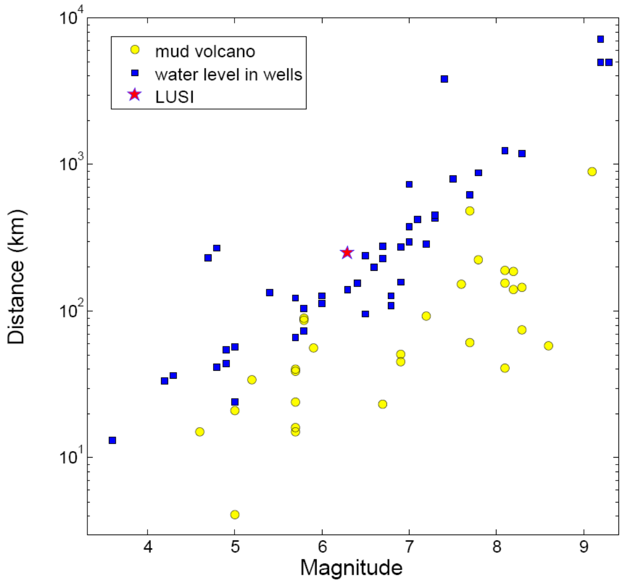

Figure 3 Global compilation of responses to earthquakes: blue squares show permanent changes of the water level in wells (data sources provided in Wang and Manga, 2009), yellow circles indicate triggered eruptions of mud volcanoes (data

tabulated in Manga et al., 2009). The red star indicate the location and magnitude of the Yogyakarta earthquake.

The seismic energy density, a measure of the energy in the seismic waves available to cause a response, at this threshold distance is 4 orders of magnitude smaller than that needed to cause liquefaction (Green and Mitchell, 2004; Wang, 2007) and two orders of magnitude smaller than that needed to initiate undrained consolidation (Ishihara, 1996). Any possible response of the Lusi mud volcano is thus unlikely to caused by consolidation or liquefaction. More plausible are changes in permeability in which the dynamic strains or induced oscillations in fluid flow remove blockages in fractures or other pore space leading to an increase in permeabilty and thus permits a redistrbution of pore pressure. This mechanism is commonly invoked for a range hydrologic responses at such large distances from earthquakes (e.g., Mogi et al., 1989; Rojstaczer et al., 1995; Brodsky et al., 2003; Wang et al., 2004; Elkhoury et al., 2006), and would seem to be the most likely way in which the Yogyakarta earthquake could have influenced the subsurface in the Sidoarjo area. We now evaluate this possibility.

Sawolo et al., (2009) claim a causal connection between the earthquake and mud loss, as recorded by mud logging data that show a loss of 20 barrels 7 minutes after the earthquake (their figure 12). A time lag between earthquake shaking and hydrological responses is not unexpected if the response occurs at some distance from the well. Indeed, peak hydrological responses to earthquake often occur days after the earthquake, though changes typically do begin coseismically. Examples include changes in the water level in wells (e.g., Roeloffs, 1998; Brodsky et al., 2003; Manga and Wang, 2007) and changes in streamflow (e.g., Manga et al., 2003). Thus a lag of 7 minutes is not in principle unreasonable. Can the occurrence of these changes be verified?

The response of the well to subsequent earthquakes – the aftershocks of the Yogyakarta earthquake – provide an opportunity to test the hypothesis that the main shock triggered permeability increases. If the permeability increased, then subsequent responses should be sensed with even shorter time lags at the well because hydraulic diffusivities will have increased. Instead, Sawolo et al., (2009) report in table 1 and show in their figure 12 that the losses occurred 2 hours after these aftershocks. It is possible that the aftershocks caused changes at greater distances from the well resulting in longer time lags, but given that the aftershocks were smaller than the main shock, they should not be able to change hydrogeological properties where a larger earthquake could not. Consequently, we disagree with the claim that "that losses that happened after the earthquake showed a compelling argument that a temporal connection exists between the earthquake and Banjarpanji well" (quotation from caption of figure 12). A quantitative consideration of the data presented in their figure 12, specifically the timing of the hypothesized responses to Yogyakarta earthquake and its aftershocks, does not support the claim in Sawolo et al., (2009).

We certainly agree with Sawolo et al., (2009) that the Lusi eruption occurred "in an area prone to mud volcanism". The presence of other mud volcanoes in the region, and the right geological setting for mud volcanism, are clear. However, despite the Sawolo et al., (2009) implying a link between earthquakes and Lusi simply on the basis of similar timing, the 2006 Yogyakarta earthquake was not the trigger. We must reiterate two key conclusions from previous studies: first, by comparison with every other documented example of triggered eruptions, the earthquake was too small given its distance to initiate an eruption (Manga, 2007); second, dozens to hundreds of other earthquakes caused more shaking at the eruption site without initiating an eruption (Davies et al., 2008). These two constraints remain the strongest arguments against an earthquake trigger.

So what went wrong?

On the 27th May 2006 the well lost circulation (Davies et al., 2008; Sawolo et al., 2009). The decision was then made to pull the drill bit out of the hole but crucially *without verifying that a stable mud column was in place and it was done while very severe circulating mud losses were in progress*. It was this procedure that caused the kick. Because there was a significant open hole section the ability to tolerate the kick ('kick tolerance' or 'drilling window') was small (0-2.3 MPa; Tingay et al., 2008). The ability to tolerate a kick was further depleted as evidenced by the continuing severe mud loss. The kick probably occurred by sucking water and gas into the borehole while pulling the drill bit and pipe out of the hole (termed swabbing).

Severe swabbing is reported in their paper while pulling drill pipe and at the same time severe mud loss is reported while pumping during the trip.

This is a critical part of their paper Sawolo et al., (2009) have deviated from the record of the daily drilling reports. In the paper Sawolo et al., (2009) report ‘no apparent drag. Unlikely to swab’ (line 21 in Table 1), but in the daily drilling reports it states ‘worked pipe, pooh [pull out of hole] from 8700 ft to 8100 ft without circulation, overpull encountered over 30000 lbs’. Despite their statement ‘no apparent drag. Unlikely to swab’ the data from the well are perfectly clear, there was severe swabbing while the drill bit was being pulled out of the hole, which brought large quantities of formation fluids into the wellbore until the mud pressure in the well reduced sufficiently to allow a substantial ingress. The kick was inevitable as a result of a failure to identify the swabbing. A failure to react to the well flow resulted in the well being allowed to flow for 1.5 hours reaching a reported flow rate of 8,720 m^3/day before the well was shut-in and the flow from the well stopped. The resulting magnitude of the kick had an influx volume of around 119 m^3, including swabbed volume, (around 58% of hole volume). It can be of little surprise that the integrity of this excessively long, fragile open hole section was breached.

Conclusions

The main issues we contest are tabulated (Table 1).

Issue	**Sawolo et al., (2009) interpretation**	**Our interpretation**	**Our reasoning**
Leak off pressure at last casing point (1091 m)	Leak off 16.4 ppg (19.29 MPa/km)	Leak off 15.4 ppg (18.1 MPa/km)	The inflexion point on the pressure build-up curve is the most appropriate measure of LOP.
Estimation	Use fill-up method	Use the mud in	Their fill-up

of pressure in open-hole section (their figure 8B)	to derive 12.8 ppg (15.04 MPa/km) mud weight at base of hole	the drill pipe to the bottom of the drill pipe	method was incorrectly executed, as mud losses were taking place at the same time as filling up. Their method also relies on assuming that no influx came into the drill hole. Also it’s a physical impossibility to have a significant kick when there is a pore pressure of 12.8 ppg (15.04 MPa/km) and the mud weight is 14.7 ppg (19.27 MPa/km)
Sonic log to estimate pore pressure	Advocated	Not advocated	Only appropriate for porous and permeable successions, and not tight welded volcanics as observed in the lower sections of the well.
D-exponent to estimate pore pressure	Advocated	Not advocated	Only appropriate for mudstone successions, and not tight welded

			volcanics as observed in the lower sections of the well.
Log resistivity to estimate pore pressure	Advocated	Not advocated	Only appropriate for mudstone sequences and not tight welded volcanics as observed in the lower sections of the well.
Well Design	Their figure 8A shows ‘DESIGN PLOT –BASE CASE’. Inferring that that this was the original well design	This casing design was a significant deviation from the original plan and resulted in a significant open hole section.	Original well design is in the public domain and illustrated in Tingay et al., 2008.
Earthquake caused mud losses	Proposed that 20 barrels lost 7 minutes after earthquake caused by earthquake	Earthquake had no effect	Changes following aftershocks have a longer time delay than changes after the Yogyakarta earthquake. Earthquake was too small and too far away.
Swabbing	Report ‘no apparent drag. Unlikely to swab’	Propose that swabbing caused the kick	Daily drilling report states ‘‘worked pipe, pooh [pull out of

			hole] from 8700 ft to 8100 ft without circulation, overpull encountered over 30000 lbs’. In addition Table 2 reports very large swabbed volumes during the trip.
Pressure plots show well killed	Advocate that well killed within 3 hours (28th May 2006)	Advocate well not killed and that underground blowout occurring on 28th and 29th May 2006	Evidence for pumping without any increase in annulus pressure and evidence for declining pressure in the drill-pipe indicative of leakage
Sonan and temperature logs taken on re-entering the hole	Show that the well was killed and no fluid movement behind casing	Do not show that the well was killed.	Banjar Panji-1 was plugged with cement which would prevent fluids coming up the well above the plugs. Furthermore, fluids will only flow up the outside of the well if there is poor cementing of the casing and no other pathways for the

			fluids to go.
Re-entry of well showed drill bit still stuck	Indicates well in tact and no blowout occurring	Does not indicates well in tact and that blowout was not occurring	The drill bit can remain stuck in position during blowouts, particularly in zones of highly swelling clays and in wells that have had large volumes of cement pumped into them

Table 1. Key data and interpretation that we dispute.

We applaud the publication of some of the geological and drilling data from the Banjar Panji-1 well but disagree with the conclusion that drilling was not the cause of the Lusi mud volcano. This ecological and humanitarian disaster was caused by pulling the drill string and drill bit out of the hole on the 27th and 28th May 2006, while there were losses and swabbing in the well, which triggered a very large kick that could not be controlled. We can now be very specific about the critical errors which were a) having such a significant open hole section with no protective casing, b) overestimating the pressure the well could tolerate, c) after complete loss of returns, the decision to pull the drill string out of an extremely unstable hole d) pulling the bit out of the hole while losses were occurring and e) not identifying the kick more rapidly.

Acknowledgements

We are very grateful to Eric Low and Rudi Rubiandini for discussing the drilling data and operations.

References

Addis, M.A., Hanssen, T.H., Yassir, N., Willoughby, D.R., and Enever, J., 1998. A comparison of leak-off test and extended leak-off test data for stress estimation: Eurock 98 Rock Mechanics In Petroleum Engineering, p. 131-140.

Bell, J.S., 1996. Petro Geoscience 1. In situ stresses in sedimentary rocks (part 1): measurement techniques: Geoscience Canada, 23, p. 85-100.

Breckels, I. M., and van Eekelen, H.A.M., 1982. Relationship between horizontal stress and depth in sedimentary basins: Journal of Petroleum Technology, 34, 2191-2198.

Brodsky, E.E., Roeloffs, E., Woodcock, D., Gall, I., Manga, M., 2003. A mechanism for sustained groundwater pressure changes induced by distant earthquakes. Journal of Geophysical Research, 108, 2390, doi: 10.1029/2002JB002321.

Davies, R.J., Swarbrick, R.E., Evans, R.J. and Huuse, M., 2007. Birth of a mud volcano: East Java, 29 May 2006. GSA Today, 17, 4-9.

Davies, R.J., Brumm, M., Manga, M., Rubiandini, R., Swarbrick, R., Tingay, M., 2008. The East Java mud volcano (2006-present): An earthquake or drilling trigger? Earth and Planetary Science Letters, 272, 627-638.

Elkhoury, J.E., Brodsky, E.E., Agnew, D.C., 2006. Seismic waves increase permeability. Nature, 411, 1135-1138.

Enever, J.R., 1993. Case studies of hydraulic fracture stress measurement in Australia, in J. A. Hudson, ed., Comprehensive Rock Engineering, p. 497-532.

Enever, J.R., Yassir, N., Willoughby, D.R., and Addis, M.A., 1996. Recent experience with extended leak-off tests for in-situ stress measurement in Australia: Australian Petroleum Production and Exploration Association Journal, 528-535.

Gaarenstroom, L., Tromp, R.A.J., de Jong, M.C., Brandenburg, A.M., 1993. Overpressures in the Central North Sea: implications for trap integrity and drilling safety: Petroleum Geology of Northwest Europe. Proceedings of the 4th Conference, 1305-1313.

Green, RA., Mitchell, JK., 2004. Energy-based evaluation and remediation of liquefiable soils, in Geotechnical Engineering for Transportation Projects, eds: M Yegian and E Kavazanjian, ASCE Geotechnical Special Publication, No. 126, 2, 1961-1970.

Husen, S., Taylor R., Smith RB., Healser H., 2004. Changes in geyser eruption behavior and remotely triggered seismicity in Yellowstone National Park produced by the 2002 M7.9 Denali Fault earthquake, Alaska. Geology, 32, 537--540.

Ishihara, K., 1996. Soil Behavior in Earthquake Geotechnics, Clarendon Press, Oxford 350 pp.

Jørgensen, T., Fejerskov, M., 1998. Leakoff tests: How to extract important in-situ stress information from a test originally designed for another purpose: SPE/ISRM Eurock '98.

Manga M (2007) Did an earthquake trigger the May 2006 eruption of the Lusi mud volcano? EOS, 88, 201.

Kusumastuti, A., van Rensbergen, P., Warren, J.K., 2002. Seismic sequence analysis and reservoir potential of drowned Miocene carbonate platforms in the Madura Strait, East Java, Indonesia, AAPG Bulletin, 86, 213-232.

Manga, M., Wang, C-Y., 2007. Earthquake hydrology. In: Kanamori, H. (Ed.), Earthquake Seismology. Vol. 4 of Treatise on Geophysics. Elsevier, Amsterdam, Ch. 4.10, 293-320.

Manga, M., Brodsky, E.E, Boone, M., 2003. Response of streamflow to multiple earthquakes and implications for the origin of postseismic discharge changes, Geophysical Research Letters, 30, doi:10.1029/2002GL016618.

Manga, M., Brumm, M., Rudolph, M.L., 2009. Earthquake triggering of mud volcanoes. Marine and Petroleum Geology, doi:10.1016/j.marpetgeo.2009.01.019

Mogi, K., Mochizuki, H., Kurokawa, Y., 1989. Temperature changes in an artesian spring at Usami in the Izu Peninsula (Japan) and their relation to earthquakes. Tectonophysics, 159, 95-108.

Økland, D., Gabrielsen, G.K., Gjerde, J., Sinke, K., Williams, E.L., 2002. The importance of extended leak-off test data for combatting lost circulation. SPE/ISRM Paper 78219, 9p.

Raaen, A.M., Horsrud, P., Kjørholt, H., Økland, D., 2006. Improved routine estimation of the minimum horizontal stress component from extended leak-off tests. International Journal of Rock Mechanics and Mining Sciences, 43, 37-48.

Roeloffs, E.A., 1998. Persistent water level changes in a well near Parkfield, California, due to localand distant earthquakes. Journal of Geophysical Research, 103, 869-889.

Rojstaczer, S., Wolf, S., and Michel, R., 1995. Permeability enhancement in the shallow crust as a cause of earthquake-induced hydrological changes. Nature, 373, 237-239.

Tingay, M.R.P., Heidbach, O., Davies, R., Swarbrick, R.E., 2008. Triggering of the Lusi mud eruption: earthquake versus drilling initiation. Geology, 36, 639-642.

Tingay, M.R.P., Hillis, R.R., Morley, C.K., King, R.C., Swarbrick, R.E., Damit, A.R., 2009. Present-day stress and neotectonics of Brunei: implications for petroleum exploration and production. American Association of Petroleum Geologists Bulletin, 93, 75-100.

van Oort, E., Vargo, R., 2008. Improving formation-strength tests and their interpretation. SPE Drilling and Completions, paper 105193, 284-294.

Wang, C-Y., 2007. Liquefaction beyond the near field. Seismological Research Letters, 78, 512-517.

Wang, C-Y., Chia, Y., 2008. Mechanism of water level changes during earthquakes: Near field versus intermediate field. Geophysical Research Letters, 35, L12402, doi:10.1029/2008GL034227.

Wang, C-Y., Manga, M., 2009. *Earthquakes and water*, Springer-Verlag, in press.

Wang, C-Y., Wang, C-H., Manga, M., 2004. Coseismic release of water from mountains: Evidence from the 1999 (Mw = 7.5) Chi-Chi, Taiwan, earthquake. Geology, 32, 769-772.