Sawolo et al. (2009) the Lusi mud volcano controversy: Was it caused by drilling?

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1. 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, 2008; Manga, 2007; Mazzini et al., 2007; 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.

2. 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 and Fejerskov, 1998; Økland et al., 2002; Raaen et al., 2006; van Oort and 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’ should be 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; Økland et al., 2002; Raen et al., 2006; van Oort and 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’ should be used instead.

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oil-based muds does indeed affect the reliability of leak-off tests, but it does not
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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
in addition to their thermal expansion and gel
strength, can cause a change in the mud density with depth,
mean 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 and 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 and 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
and 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
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
saferest 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.

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

If one were to disregard all the reasons provided above and
accept their value of 16.4 ppg (19.27 MPa/km) as the pressure the
well could tolerate, was this pressure 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 \textit{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 \textit{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 the 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 Sawolo 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 volcaniclastic 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.

4. Was the well controlled?

At 11:00 am on 28th May 2006 the blowout 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 blowout 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 blowout 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).

5. 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 sonar 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.

6. 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:
<table>
<thead>
<tr>
<th>Issue</th>
<th>Sawolo et al. (2009) interpretation</th>
<th>Our interpretation</th>
<th>Our reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leak-off pressure at last casing point (1091 m) Estimation of pressure in open-hole section (their figure 8B)</td>
<td>Leak off 16.4 ppg (19.29 MPa/km) Use fill-up method to derive 12.8 ppg (15.04 MPa/km) mud weight at base of hole</td>
<td>Leak off 15.4 ppg (18.1 MPa/km). Use the mud in the drill pipe to the bottom of the drill pipe.</td>
<td>The inflexion point on the pressure build-up curve is the most appropriate measure of LOP. Their fill-up 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).</td>
</tr>
<tr>
<td>Sonic log to estimate pore pressure</td>
<td>Advocated</td>
<td>Not advocated.</td>
<td>Only appropriate for porous and permeable successions, and not tight welded volcanics as observed in the lower sections of the well.</td>
</tr>
<tr>
<td>D-exponent to estimate pore pressure</td>
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</tr>
<tr>
<td>Log resistivity to estimate pore pressure</td>
<td>Advocated</td>
<td>Not advocated.</td>
<td>Only appropriate for mudstone sequences and not tight welded volcanics as observed in the lower sections of the well.</td>
</tr>
<tr>
<td>Well design</td>
<td>Their figure 8A shows ‘DESIGN PLOT – BASE CASE’. Inferring that this was the original well design</td>
<td>This casing design was a significant deviation from the original plan and resulted in a significant open-hole section.</td>
<td>Original well design is in the public domain and illustrated in Tingay et al. (2008).</td>
</tr>
<tr>
<td>Earthquake caused mud losses</td>
<td>Proposed that 20 barrels lost 7 min after earthquake caused by earthquake</td>
<td>Earthquake had no effect.</td>
<td>Changes following aftershocks have a longer time delay than changes after the Yogyakarta earthquake. Earthquake was too small and too far away. Daily drilling report states ‘worked pipe, pooh [pull out of hole] from 8700 ft to 8100 ft without circulation, overpull encountered over 30,000 lbs’. In addition their table 2 reports very large swabbed volumes during the trip. Evidence for pumping without any increase in annulus pressure and evidence for declining pressure in the drill-pipe indicative of leakage.</td>
</tr>
<tr>
<td>Swabbing</td>
<td>Report ‘no apparent drag. Unlikely to swab’</td>
<td>Propose that swabbing caused the kick.</td>
<td></td>
</tr>
<tr>
<td>Pressure plots show well killed</td>
<td>Advocate that well killed within 3 h (28th May 2006)</td>
<td>Advocate well not killed and that underground blowout occurring on 28th and 29th May 2006.</td>
<td></td>
</tr>
<tr>
<td>Sonan and temperature logs taken on re-entering the hole</td>
<td>Show that the well was killed and no fluid movement behind casing</td>
<td>Do not show that the well was killed.</td>
<td>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.</td>
</tr>
<tr>
<td>Re-entry of well showed drill bit still stuck</td>
<td>Indicates well in tact and no blowout occurring</td>
<td>Does not indicates well in tact and that blowout was not occurring.</td>
<td>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.</td>
</tr>
</tbody>
</table>
'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 min 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 of 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.

7. 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 h after the Yogyakarta earthquake and that partial losses were observed in Banjar Panji-1 7 min 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, 2010) (Fig. 3).

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
8. 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 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 and evidence for swabbing fluids into the hole would be very significant in identifying the reason for the kick – but it is here that 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’ (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 30,000 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 h reaching a reported flow rate of 8720 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.

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9. Conclusions

The main issues we contest are tabulated in Table 1.

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

Michael Manga is supported by NSF EAR 0909701. We are very grateful to Eric Low and Rudi Rubiandini for discussing the drilling data and operations. We thank CRISP for permission to use their satellite photos in this and earlier research papers.