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# The LUSI mud volcano triggering controversy: Was it caused by drilling?

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ABSTRACT

Following the Yogyakarta earthquake on May 27th, 2006, the subsequent eruption of a mud volcano has been closely observed and analyzed by the geological community. The mud volcano, known as LUSI, began erupting near the Banjarpanji-1 exploration well in Sidoarjo, East Java, Indonesia. LUSI offers a unique opportunity to study the genesis and development of a mud volcano.

For the first time, this paper presents all raw and interpreted drilling data, so any interested party can perform their own assessment. Our study suggests that LUSI mud volcano was a naturally occurring mud volcano in an area prone for its mud volcanism. Pressure analysis done on the Banjarpanji well shows that the pressure exerted at the well is lower than the fracture pressure at the last casing shoe, and suggests that the well was intact and did not suffer an underground blowout. This is further supported by evidence and observation made during drilling (such as circulation was done on an open BOP) and subsequent relief wells (Sonan and temperature log runs).

This study offers a different alternative to earlier hypothesis that events at the Banjarpanji well were the trigger for the LUSI mud volcano. More work is needed by the scientific community to study the sequence of events in order to explain and clarify the real trigger of LUSI.


## 1. Introduction

On May 29th, 2006 at around 05:00 h an intermittent eruption of hot water and steam was observed some 200 m from the Banjarpanji-1 well. The location map of Banjarpanji is shown in Fig. 1. The eruptive bursts of hot water and steam were dramatic with a distinct geyser-like cycle of active and passive periods. This marked the birth of a new mud volcano known as LUSI in East Java, Indonesia, shown in Fig. 2 (Cyranoski, 2007; Satyana, 2007).

The cause of LUSI is controversial. The essence of the controversy is whether the mudflow i) Originates from the wellbore, thus an underground blowout (Davies et al., 2007, 2008; Tingay et al., 2008) or ii) Originates from an eruption of overpressured shale through reactivated faults as conduits (Mazzini et al., 2007a,b), or iii) Originates from geothermal activity, where superheated hydrothermal fluids at high temperature and pressure were released through a fault zone or fracture network as the conduit (Sudarman and Hendrasto, 2007).

Only the first hypothesis, the underground blowout hypothesis, will be discussed in this paper. Hypothesis based on fault reactivation and geothermal activities is beyond the scope of this paper and will not be discussed. This paper lays out the drilling engineering data and analysis on the Banjarpanji well. It analyzes the bottom hole pressure and rock strength data to test if the pressure induced by the kick was sufficient to fracture the shoe and caused an underground blowout. It also examines the evidence surrounding the well and during the re-entry program after the mud eruption. The analysis results suggest that the well remained intact and did not suffer any underground blowout.

This paper also presents relevant data from 8750 ft to 9297 ft (2667 m–2834 m) while drilling to look for the top of the Kujung formation. This includes the daily drilling report, daily geological report and daily mud loggers report. Real time data plot for the critical period between the times when the BOP was closed to the time that the mud eruption was reported is also attached for critical analysis by interested parties.

## 2. Regional geology of East Java

The Eocene and Early Oligocene Sequence of East Java back arc basin is associated with rifting where clastic deposition and carbonate buildup of the Ngimbang Formation took place. The Late Oligocene and Miocene sequence is separated from the underlying sequence by an unconformity which served as the foundation of ENE-WSW oriented carbonate trends. This platform development, which is known as the Kujung limestone, occurred in the late Oligocene while the Prupuh and Tuban reefal development took

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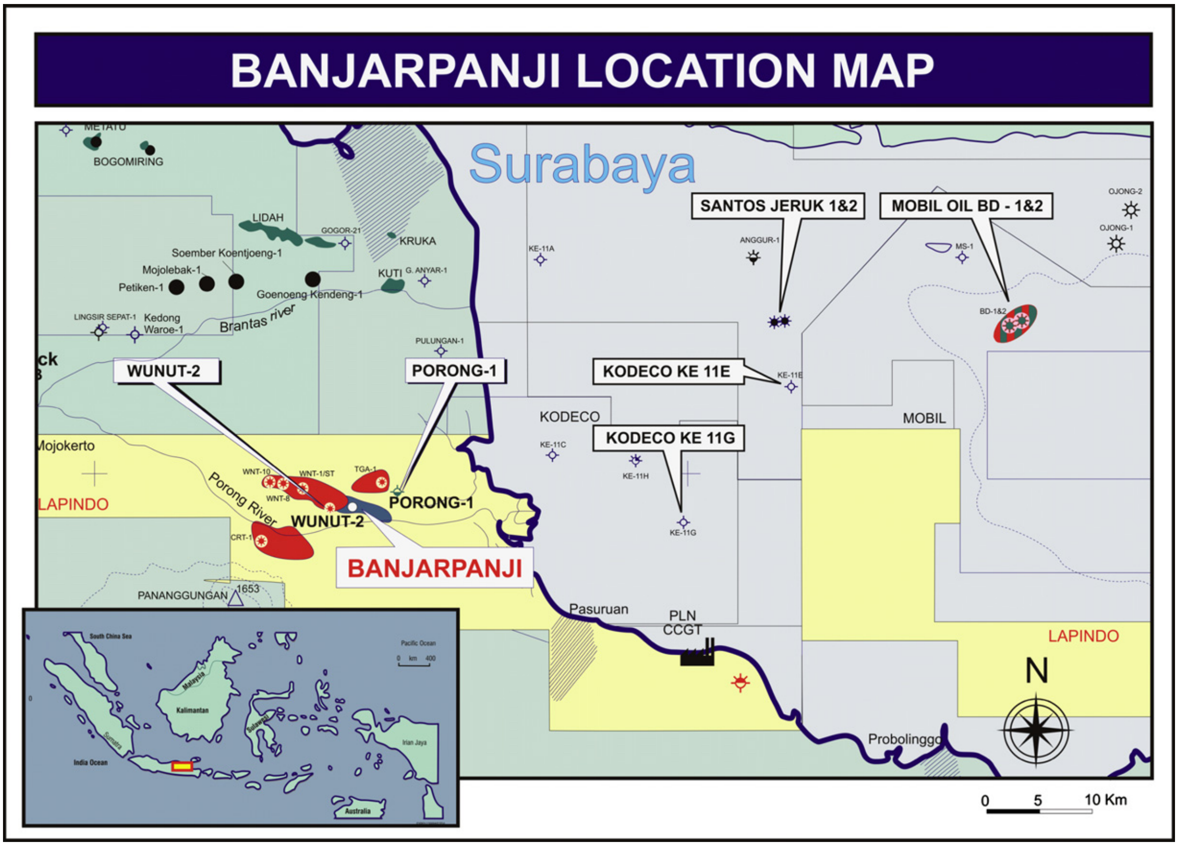


**Fig. 1.** Banjarpanji-1 location and its offset wells. Banjarpanji-1 is located 30 km south of Surabaya, in the island of Java, Indonesia. Banjarpanji offset wells, both onshore and offshore, provided good drilling information and lessons learned to help design the well. These include the setting of casing shoe in the carbonate formation to anticipate a pressure regression in Kujung carbonate and the use of oil base mud to mitigate the overlying highly reactive shale.

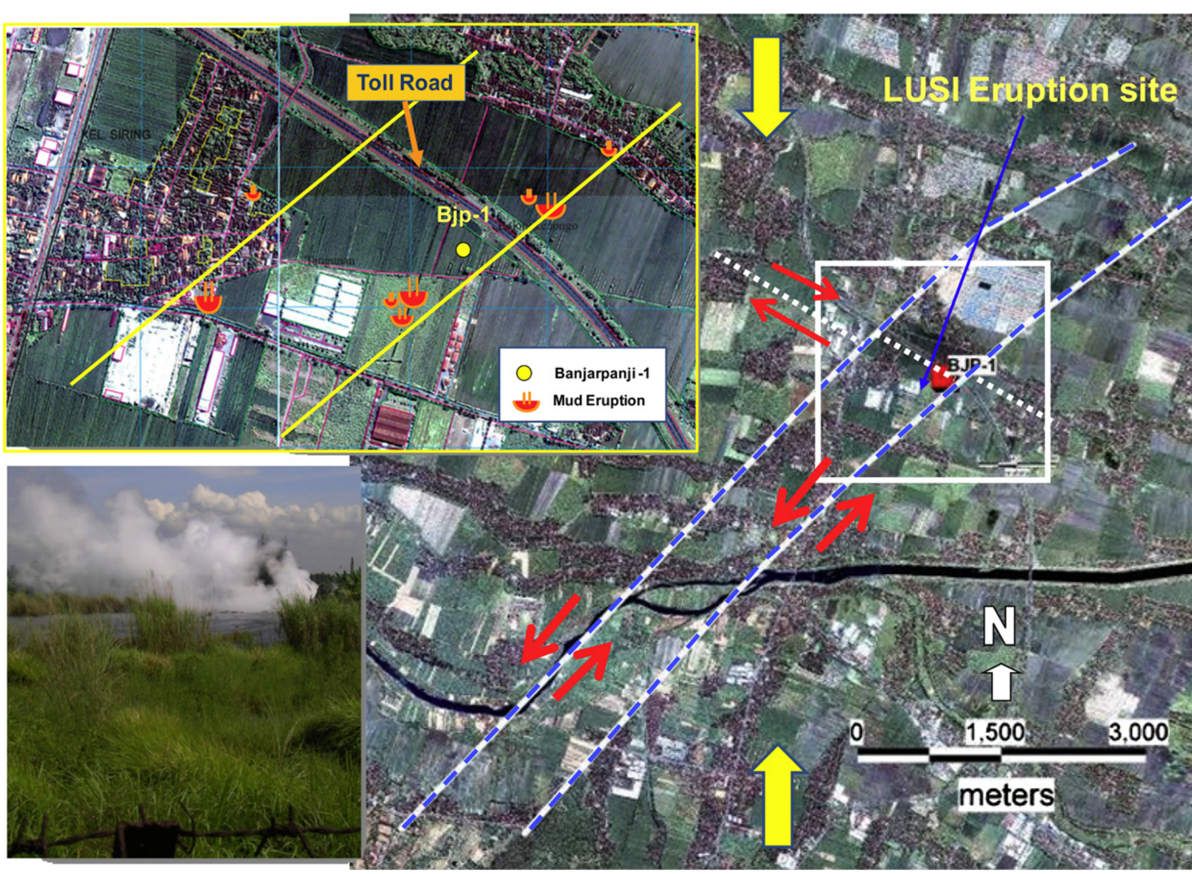


**Fig. 2.** Initial LUSI eruptions at five different locations aligned along Watukosek fault lines. River bends and escarpment aligned with the Watukosek Fault System. (photo inset) taken on 29th May 2006, 9 am four hours after mud eruption was reported showing the geyser-like mud eruption approximately 200 m away from the Banjarpanji 1 well location.

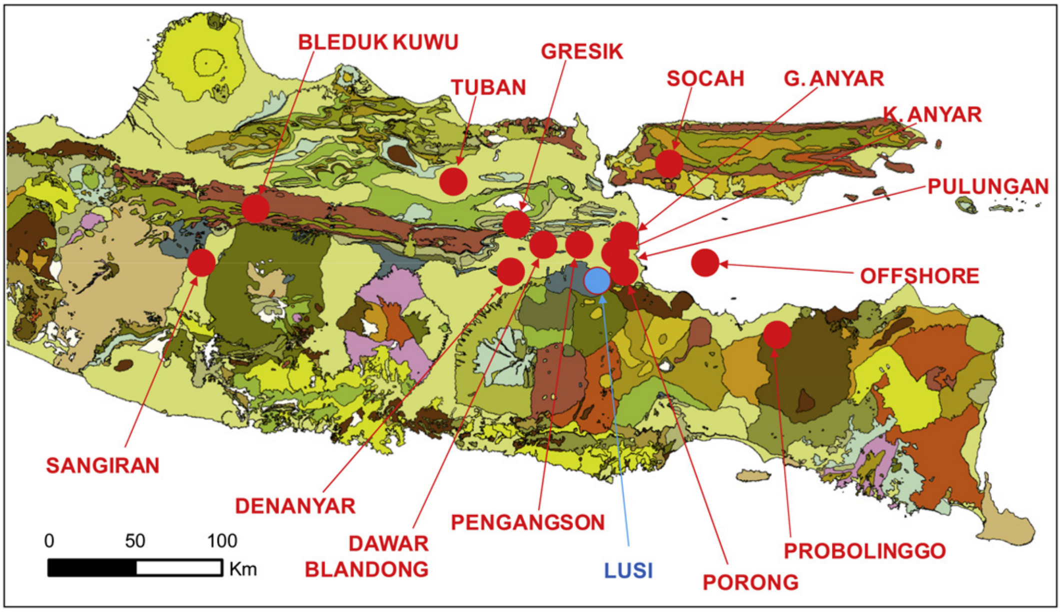


**Fig. 3.** Mud volcanoes in Eastern Java. Map of Eastern half of Java showing locations of mud volcanoes. In particular, there are at least five mud volcanoes near the Watukosek fault on the north eastern part of the island.

place in the Early to Middle Miocene. Such reefs have been the target for several exploratory wells including the offset Porong-1 well. The Plio-Pleistocene sequence overlies an unconformity. In some places this unconformity removed the entire Middle and Late Miocene section such as in Porong and the KE-11-C area. Subsequent Pliocene and Pleistocene sedimentation consisted of an eastward-prograding mudstone-dominated volcaniclastic wedge of Kalibeng and Pucangan Formation, with thickness of 8000 to 10,000 feet (2438–3048 m). The volcaniclastic materials derived from the Java volcanic arc south of the Sidoarjo area. The mudstone of the Kalibeng Formation is overpressured in most parts of the basin where rapid pressure transition occurs.

Several tectonic models have been proposed to explain the complexity of East Java Basin, and the understanding of the tectonic and basin development of the area is still subject to ongoing debate. A continental fragment model is favored, a continental fragment where possibly detached from the Gondwana super-continent which collided with the eastern margin of the Sunda Microplate and uplifted a mélange complex in Central Java. This tectonic model was proposed by Hamilton, 1979, and has been followed by every

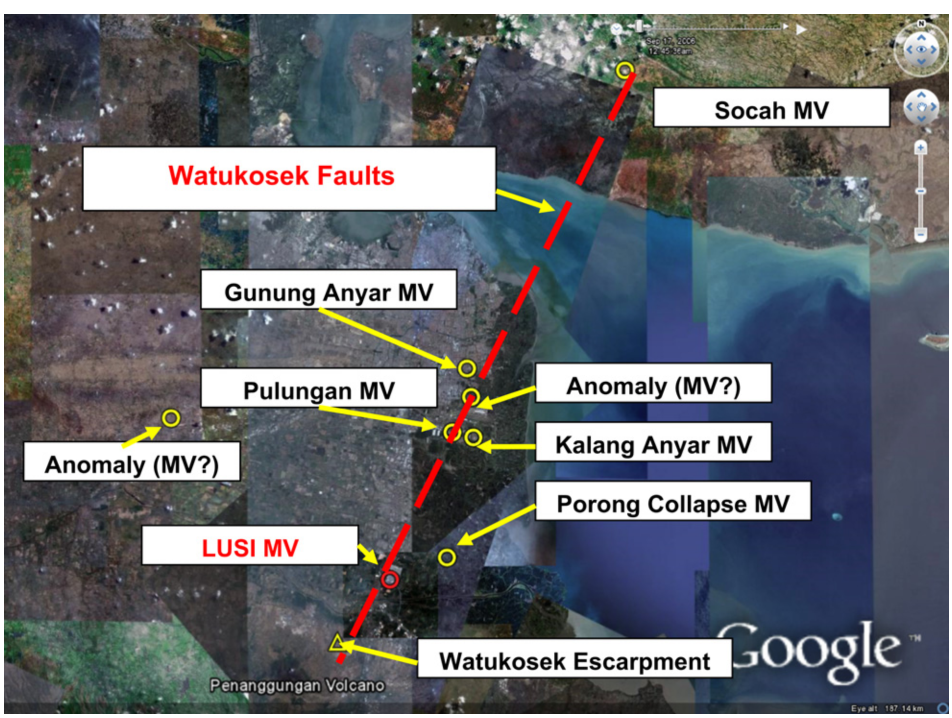


**Fig. 4.** Mud Volcanoes along Watukosek faults. LUSI and five other known mud volcanoes are located along the Watukosek fault zone. The concentration of mud volcanoes near Watukosek fault confirms that weak zones adjacent to the fault are conducive and prone to mud volcanism.

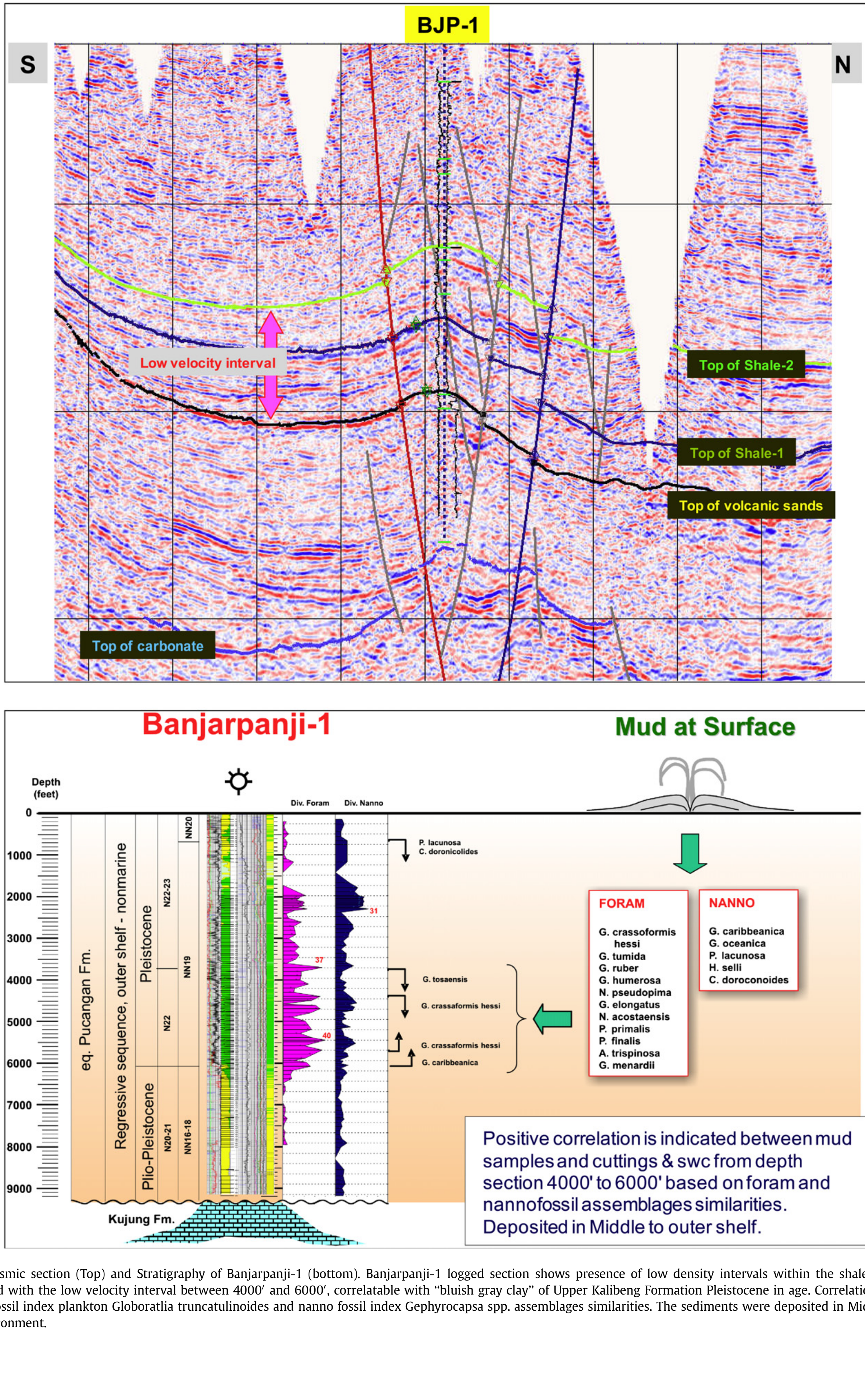


**Fig. 5.** Seismic section (Top) and Stratigraphy of Banjarpanji-1 (bottom). Banjarpanji-1 logged section shows presence of low density intervals within the shale unit which correspond with the low velocity interval between 4000′ and 6000′, correlatable with "bluish gray clay" of Upper Kalibeng Formation Pleistocene in age. Correlation based on: i) foram fossil index plankton Globoratlia truncatulinoides and nanno fossil index Gephyrocapsa spp. assemblages similarities. The sediments were deposited in Middle to outer shelf environment.

worker since e.g. Daly et al. (1987), Hall (2001), Longley (1997), Sribudiyani et al. (2003). The model was finally proven by Smyth et al., 2005, 2007. The grain of the continental basement influenced basin trends. The dominant basement grain is E–W, in eastern part of East Java Basin, and at the collision zone NE–SW direction, parallel to the direction of the collisional suture. Prasetyadi et al., 2006, continue this line of thought and propose a micro-continent as the core of southeast Java ("East Java Micro Plate").

The complex geology and presence of overpressure sediments results in the many mud volcanoes in the area (Fig. 3).

**Table 1**
Drilling Operations.

| Key event | Date (2006) and Time |
|---|---|
| Performed Leak Off Test at 13-3/8″ casing shoe. LOT at 3580 ft (1091 m) was 16.4 ppg (19.29 MPa/km) | May 6th |
| Drill 12-1/4″ (31.1 cm) hole section to 8750 ft (2667 m) | May 6th–May 23rd |
| Prognosis of the top of carbonate was at 8500 ft (2591 m) Drill to 8750 ft (2667 m) without encountering any carbonate section. Log the well to better determine the carbonate top. | |
| Log well. | May 23rd–May 25th |
| Result of VSP log suggested that the expected depth of carbonate section can be as deep as 9600 ft (2926 m). | |
| At 10 bbls and 0.5 ppg (1590 l and 0.59 MPa/km) pre-determined kick tolerance, the deepest that it was safe to drill was 9400 ft (2865 m). Decided to continue drilling to top of carbonate or 9400 ft (2865 m) maximum depth. | |
| Continue to drill 12-1/4″ (31.1 cm) hole to 9297 ft (2834 m) | May 25th–May 27th |
| Yogyakarta earthquake | May 27th 05:55 |
| Well recorded a 20 bbls (3180 l) mud loss 7 minutes after main earthquake | May 27th 06:02 |
| Well recorded a total loss of circulation and 130 bbls (21670 l) mud loss less than 2 h after two major aftershocks (Fig.12). The proximity of the times suggest that the earthquake had an impact down hole in the well. | May 27th 12:50 |
| Pumped 60 bbls (9540 l) of Loss Control Material to stop losses. Losses cured. Well static for 7 h without any further loss or kick, and is deemed to be safe to start pulling out of hole. Decided this will be the casing point. | May 27th 13:00–22:00 |
| Pulling out of hole | May 27th 22:00 |
| After sufficient new mud is made and well static, start pulling out of hole. Pulling rate ~5 min per stand, pumping mud every 4–7 stands, no apparent drag. Unlikely to swab. | |
| Well kicked, shut in and kill well | May 28th 07:30 |
| Well kicked, $H_2S$ content 500 ppm. Shut BOP (Blow out preventer) to stop further influx. ISIDP 450 psi (3.10 MPa) and ISICP 350 psi (2.41 MPa) volume of influx ~360 bbls. (57240 l). ISIDP, ISICP and influx are reading from Real Time Chart. | May 28th 07:50 |
| Kill well by using volumetric method, applied twice and well dead. Maximum SICP 1054 psi (7.27 MPa). Attempted but not able to burn influx. Circulated out the kick and found influx to be saline water of 8.9 ppg. (10.47 MPa/km) density | |
| Open BOP but found drill string stuck | May 28th 11:00 |
| Drill string stuck, but still able to circulate, BHA appeared to be differentially stuck. Stretch calculation suggests it was stuck at 4182 ft (1275 m) | May 28th 11:00–14:20 |
| Fish stuck drill string while circulating at high rate, unsuccessful. Ability to circulate stopped at around 14:30; the well appeared to have caved in. Jar stop functioning. Wait for fishing tool while circulating through trip tank. | May 28th 14:20–21:30 |
| Released trapped pressure. Pumped 40 bbls (6380 l) soaking fluid to try to dehydrate mud cake, pumping with no return. Shut in to let soaking fluid to work. | May 28th 21:30–23:00 |
| Rig up free point indicator (FPI) to cut the drill string. Bleed off trapped pressure in the drill pipe. While rigging up tool, 35 ppm $H_2S$ gas detected at the rig floor. Evacuate personnel and abandon FPI. | May 29th 02:00–04:00 |
| Mud eruption started | May 29th 05:00 |
| Villagers reported a hot water flow in their field ~200 m from the well. | |
| Hot water and steam blew intermittently to around 25 ft (8 m) height geyser like with 5 min intervals between bursts. | |
| Checking for any connection or channel between the well and the mud eruption | May 29th 10:00–23:30 |
| Pumped first batch of mud 185 bbls of 14.7 ppg (29415 l of 17.29 MPa/km) down hole with a pressure of 700 psi (4.83 MPa) | |
| Second batch of mud 200 bbls of 16 ppg (31800 l of 18.82 MPa/km) with Loss Circulating Material with a pressure of 900 psi (6.21 MPa) | |
| Initially suspected that injection reduced the eruption intensity. But high pressure indicated the absence of any channel between the well and the eruption. This absence of channel and connection to the eruption was interpreted as safe to continue fishing job. | |
| Continue to fish stuck drill string | May 29th–June 2nd |
| As an added safety measure while fishing, a barrier of cement will be laid below the fish to isolate it from the open hole below. | |
| Perform injection test, with 2.5 bpm rate at 370 psi (398 l/m at 2.55 MPa) This third injection test again showed a high pressure injection above the LOT pressure meaning the absence of any channels. | May 30th 04:00–05:00 |
| Pump two batches of cement to isolate the fish from the open hole below. Injection test after laying cement plugs showed 1000 psi suggesting that the cement plugs were in place. | May 30th 05:00–June 1st 04:30 |
| Ran free point indicator and found that the stuck point has moved upward from 4182 ft (1275 m), the original stretch measurement, to 3200 ft or 2600 ft (between 980 m and 790 m) | |
| Ran string shot and finally the drill string was backed off at 2989 ft (911 m). Pull out of hole with the drill string. | |
| Temporarily abandon well and move out rig | June 2nd–4th |
| Condition at the rig was critical with mud starting to enter location, more eruptions and developing new cracks at the rig site. | |
| To safe lives and properties, decided to Temporary Abandon the well and move the rig out. This will give time to assess situation and plan intervention program | |
| Rig released | June 4th 00:00 |

The overpressure is due to high sedimentation rates in a rapid subsidence and burial basin (Willumsen and Schiller, 1994; Schiller et al., 1994) and maturation of the organic materials. The East Java geosyncline has thick Tertiary sediments of more than 6000 m (Koesoemadinata, 1980) with an estimated sedimentation rate of 2480 m/ma in the vicinity of LUSI (Kadar, 1986). Mud volcanism is known to be associated with highly under compacted over-pressured shales and there is a clear relationship between mud volcanoes breaching the surface and tectonic movement along faults as evidenced in the mud volcanoes aligned along the Watukosek fault zone (Fig. 4).

## 3. Geology of LUSI mud volcano

LUSI mud volcano adds to the many mud volcanoes existing in the area, such as the Porong collapse structure (NE of LUSI), Kalang Anyar & Pulungan (Sedati, Sidoarjo), Gunung Anyar (UPN campus, Surabaya), Bleduk Kuwu & Keradenan (Purwodadi), Wringin Anom/Pengangson (Gresik), Semolowaru (Unitomo campus, Surabaya), Dawar Blandong (Mojokerto), Sangiran (Central Java), Socah (Bangkalan, Madura) and others.

All of these mud volcanoes occurred naturally; some of which are still active and still erupting mud. The existence of mud volcanoes in East Java have been mapped as early as 1936. (Duyfjes, 1936, 1938). In the eastern part of Java, in the East Kendeng zone, a number of these mud volcanoes exhibited a pattern that follows the Watukosek fault. This major fault started from the Arjuno – Welirang volcano complex along the SSW/NNE direction. LUSI and other mud volcanoes that lie along this trend are shown on Fig. 4.

LUSI mud volcano is unique, as scientists can observe the evolving geological processes from its birth. The solid matter in LUSI's mud is "bluish gray clay" from the Upper Kalibeng Formation, which is Pleistocene in age, as confirmed from mud samples, cuttings and side-wall cores taken from the Banjarpanji-1 well from a depth section of 4000–6100 feet (1219–1859 m). Specifically, i) Foraminifera index plankton *Globorotalia truncatulinoides* and nannofossil index *Geohyrocapsa* spp. assemblages similarity. The sediments were deposited in a Middle to outer shelf environment (Kadar et al., 2007) as shown in Fig. 5; ii) Kerogen composition is correlatable with side-wall cores taken at a depth of 5600 feet (1707 m); iii) Thermal maturity profile shows positive vitrinite reflectance correlation with cuttings & side-wall cores taken at depths from 5100 to 6300 feet (1554–1920 m). The presence of overpressured shale is evident from the logs and was identified as drilling hazard in the well prognosis.

The source of fluid, however, is still debated. Mazzini et al. (2007a,b) used geochemical data to suggest that the overpressured fluids are primarily sourced from clay diagenetic dehydration within the Upper Kalibeng Formation. Davies et al. (2007) suggest that the fluids are primarily sourced from the Kujung carbonate formation. Whereas Sudarman and Hendrasto (2007) suggest a deeper fluid source, where geothermal activity induced the mud eruption by the release of superheated hydrothermal fluids at high temperature and pressure through fault zone or fracture network as the conduit.

In the early stages, the eruption consist of hot water, steam followed by erratic and intermittent explosions of mud. The mud consists of clay and salt water in slurry state at temperatures between 80° and 100 °C. The gas bubbles consist primarily of methane, $N_2$, $CO_2$ and small percentage of higher hydrocarbons indicating the presence of thermogenic oil. The gas composition indicates similarities with gas from the adjacent Wunut Field deep horizons.

## 4. Operational summary of Banjarpanji #1 well

The drilling operation of Banjarpanji was done by PT Tiga Musim Mas Jaya, a reputable drilling company in Indonesia. The key services (the mud chemical services, the electric logging and the cementing services) were provided by M-I, Baker Atlas and Halliburton, all in the top five of their respective fields. Other ancillary services are provided by PT Elnusa (mud logging), Weatherford (equipment rentals) and Sperry-Sun (for any directional drilling and correction purposes). Apart from mud pumps equipment problems, there were no major operational issues and the team performed their specific duties as good as, or better than, expected.

In the upper hole sections, the well lithology is not significantly different from that prognosed. The only difference is in the well pressure where the depth of the transition zone to the over pressure was found to be shallower than planned requiring the upper casing shoes to be set accordingly. The end result is such that subsurface drilling problems in the upper hole section of the Banjarpanji well were almost non existent (Sutriono, 2007).

Once the 13-3/8″ (34.0 cm) casing was set, the operation in the 12-1/4″ (31.1 cm) hole section did not go according to plan and drilling parameters were adjusted accordingly. Lithology and drilling parameters are different from the deep offset Porong well. The bottom most ∼3000 ft (910 m) of the well was a solid deposit of laharic sandstone section instead of shale. The pressure and the mud weight used to drill this section is lower, 14.7 ppg (17.29 MPa/km) compared to 15.5 ppg (18.23 MPa/km), at the same depth in offset Porong well. The Leak Off Test, on the other hand was found to be higher than prognosed (16.4 ppg vs. 16.0 ppg). The stronger shoe and lower pore pressure are the key reasons why the 9-5/8″ (24.4 cm) casing shoe was able be set deeper, thus a longer open hole section was able to be drilled with the same safety factor.

Drilling operations of the 12-1/4″ (31.1 cm) hole section until the mud eruption is summarized in Table 1.

## 5. Was LUSI caused by drilling?

LUSI gives the unique opportunity for the geoscientists to study the birth of a mud volcano. At the same time the drilling community was also interested in the birth of LUSI, but from a different perspective, namely what triggered LUSI. Was it caused by drilling or simply another mud volcano that occurred naturally?

### 5.1. Underground blowout hypothesis

Initially, the complete Banjarpanji-1 drilling data set was not publicly available. Early technical papers (Davies et al., 2007, 2008; Rubiandini et al., 2008; Tingay et al., 2008) were published based on limited data and concluded that an underground blowout was the cause of LUSI.

These papers proposed a classic underground blowout resulting from an unsafe act (swabbing while pulling out of hole) combined with an insufficient safety factor (kick tolerance) during the drilling of the well. Their conclusion was that the resulting shut in pressure after the kick fractured the deepest casing shoe and caused an underground blowout, which eventually reached the surface and caused the LUSI mud volcano.

At the time, this underground blowout hypothesis was the only explanation for the LUSI mud volcano. As a result the public understood that an underground blowout in the Banjarpanji well was the root cause of the mud eruption. However, as more data from the field became available and analyzed, it became clear that the analysis and field observations do not support the underground blowout hypothesis (Table 2 and Fig. 8A). The following chapters explain why

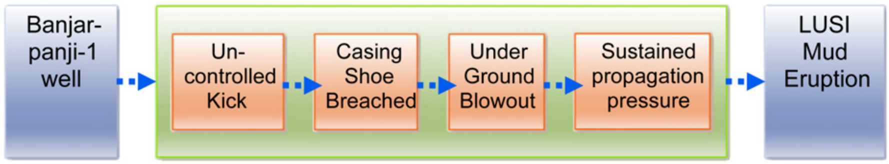


**Fig. 6.** Four key events that must take place if the mud eruption was triggered by the well. These four key events are i) Occurrence of an uncontrolled kick, ii) Pressure sufficiently high to fracture the weakest formation, typically the casing shoe, iii) An underground blowout occurred, iv) Sustained fracture propagation pressure to extend the fracture to the surface.

an underground blowout did not occur and suggest an alternative explanation whereby LUSI was triggered by natural causes.

### *5.2. Casing shoe was intact and not breached*

Pressure analysis shows the level of pressure that the well is subjected to, and compares it to the formation strength to indicate if the formation is fractured and the well-bore integrity compromised. Mostly, the analysis is done at the deepest casing shoe since it is typically, but not always, the weakest portion of the well and the point where the fracture pressure is known.

Early papers claimed that the casing shoe was subjected to a pressure higher than its Leak Off Test and failed. This was based on the pressure analysis that was done on the 'drill pipe side'. Pressure analysis on the drill pipe side is commonly done and perfectly legitimate provided that the well behaves as a perfect U-tube (Section 5.4.1, Field Evidence, Real Time Data). One must ensure that the well bore pressure can be read without any restriction on the drill pipe side. In practice this is done by slowly pumping through the drill pipe, thus ensuring that the float valve (Fig. 7) is kept in the open position. Unfortunately, this slow pumping was never performed in Banjarpanji, therefore the float valve is likely to be in a closed position and correct well pressure cannot be accessed from the drill pipe side.

Performing pressure analysis in the annulus side is more direct but it is more complex. In this particular case, the annulus is the

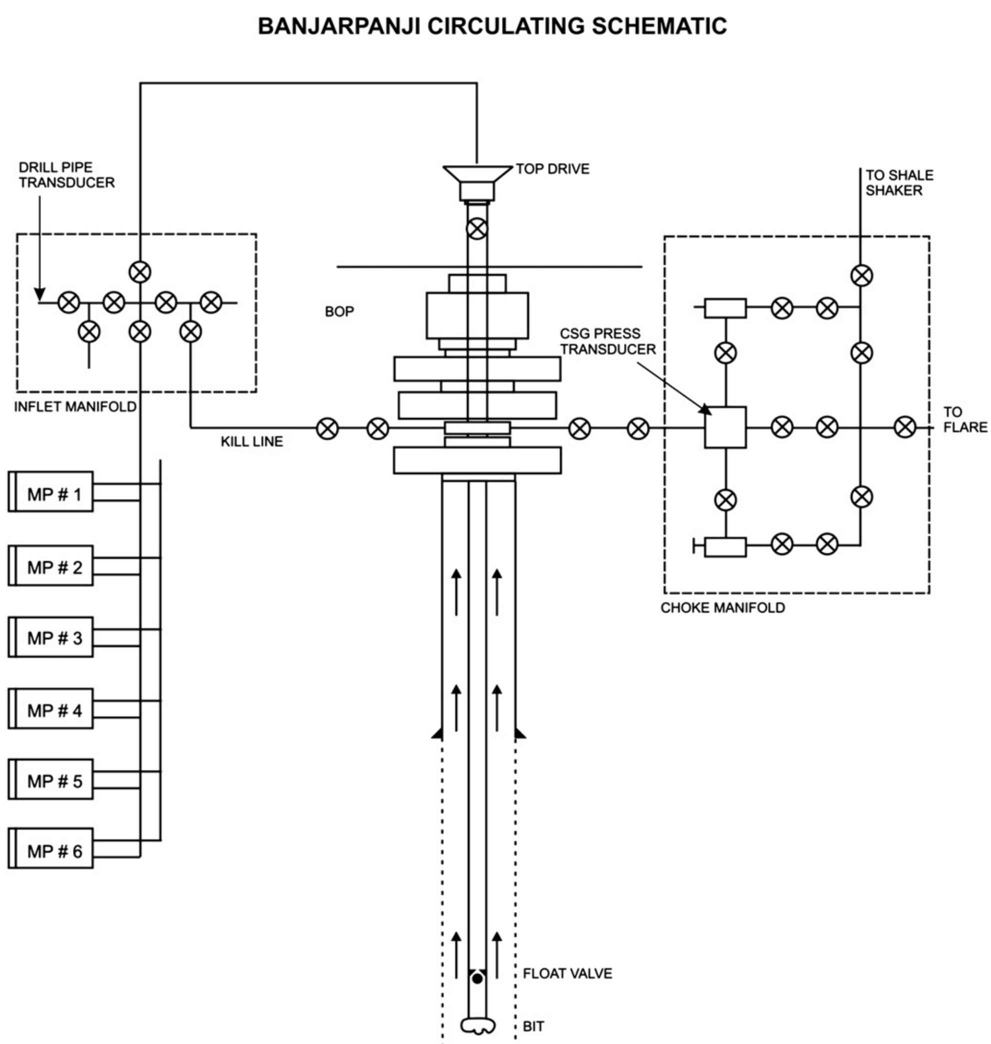


**Fig. 7.** Mud circulation system showing float valve at bottom of drill string. The use of non-ported float valve in the drill string is standard in Lapindo-Brantas, Inc. This float valve restricts pressure communication between the annulus and drill pipe unless it is kept open by slowly circulating through.

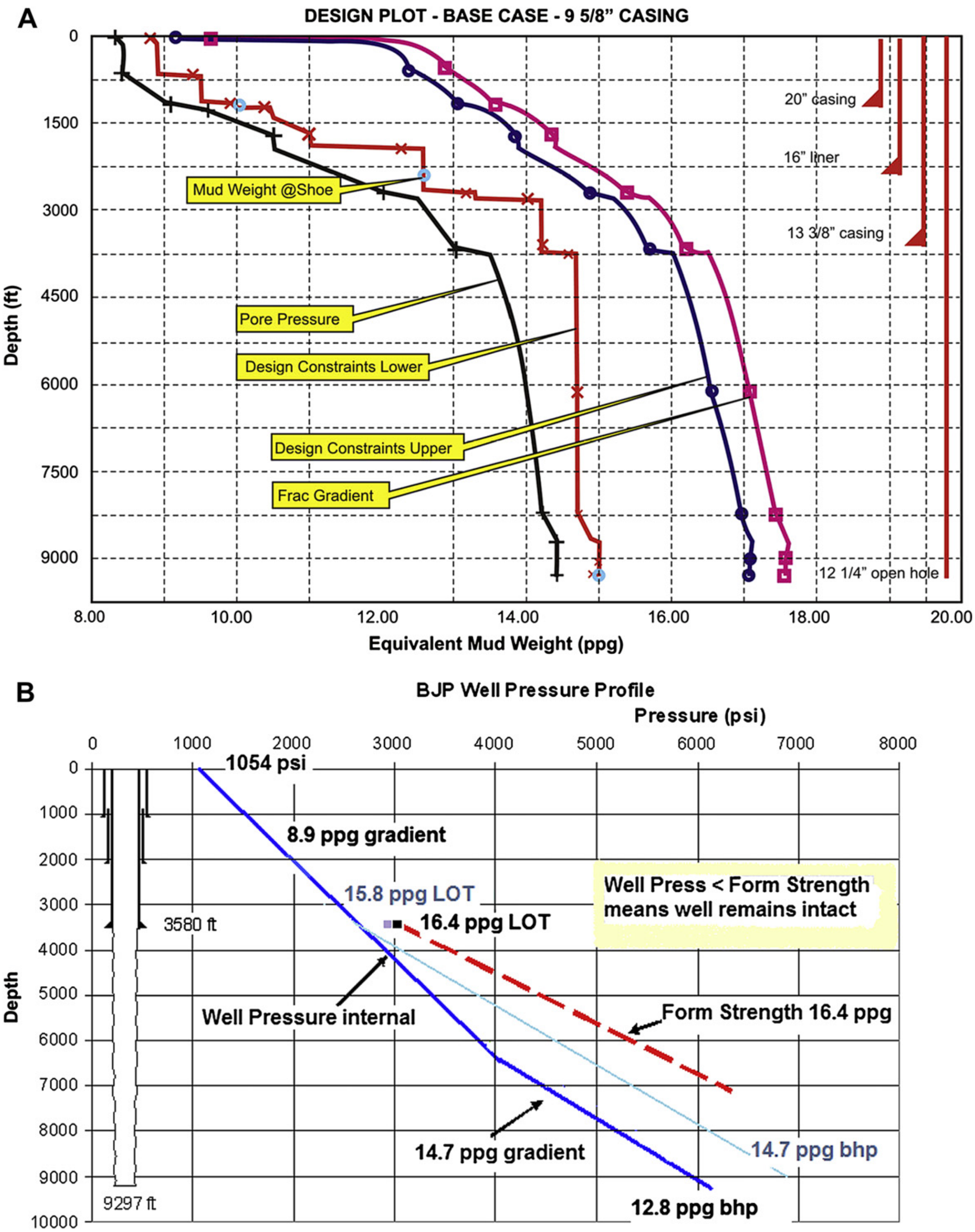


**Fig. 8.** Casing setting depth check (top). Actual casing setting depth is checked using a leading commercially available casing design software with a kick tolerance of 10 bbls and 0.5 ppg gas influx and found to be safe including a planned 9-5/8″ casing at 9300 ft TD. (Bottom) Pressure profile in wellbore and sensitivity analysis. The pressure data are plotted that shows that the well is safe. Sensitivity analysis is done with a bottom hole pressure of 14.7 ppg, and a LOT of 15.8 ppg. Even at such extreme, the wellbore pressure at any depth is always below the minimum formation strength meaning that the wellbore is always intact.

preferred leg to perform any pressure analysis as the well was not completely packed off and the fluid density and Bottom hole pressure of the well were measured. The annulus pressure is the better representation of the well-bore pressure.

The data to perform this analysis is:

i. Maximum casing pressure = 1054 psi (7.27 MPa)
ii. Fluid in the upper part of the hole (influx fluid) = 8.9 ppg (10.47 MPa/km)
iii. Fluid in the bottom part of the hole (mud) = 14.7 ppg (17.29 MPa/km)
iv. Bottom hole pressure (BHP) = 12.8 ppg (15.06 MPa/km)
v. Leak off test (LOT) at the casing shoe (3580 ft or 1091m) = 16.4 ppg (19.29 MPa/km)

Appendices C and D show how these data were obtained.

The graphical pressure analysis at the casing shoe is described in Appendix E, and the graph is shown in Fig. 8B.

The resulting pressure that is acting at the shoe is 2710 psi (18.68 MPa) whereas the formation strength at the casing shoe is 3053 psi (21.05 MPa). It shows that the formation strength is higher than the fluid pressure in the well that it was subjected to; therefore, the casing shoe is likely to remain intact.

Sensitivity runs were performed around the softer data, using a LOT of 15.8 ppg (18.58 MPa/km) and a Bottom hole pressure of

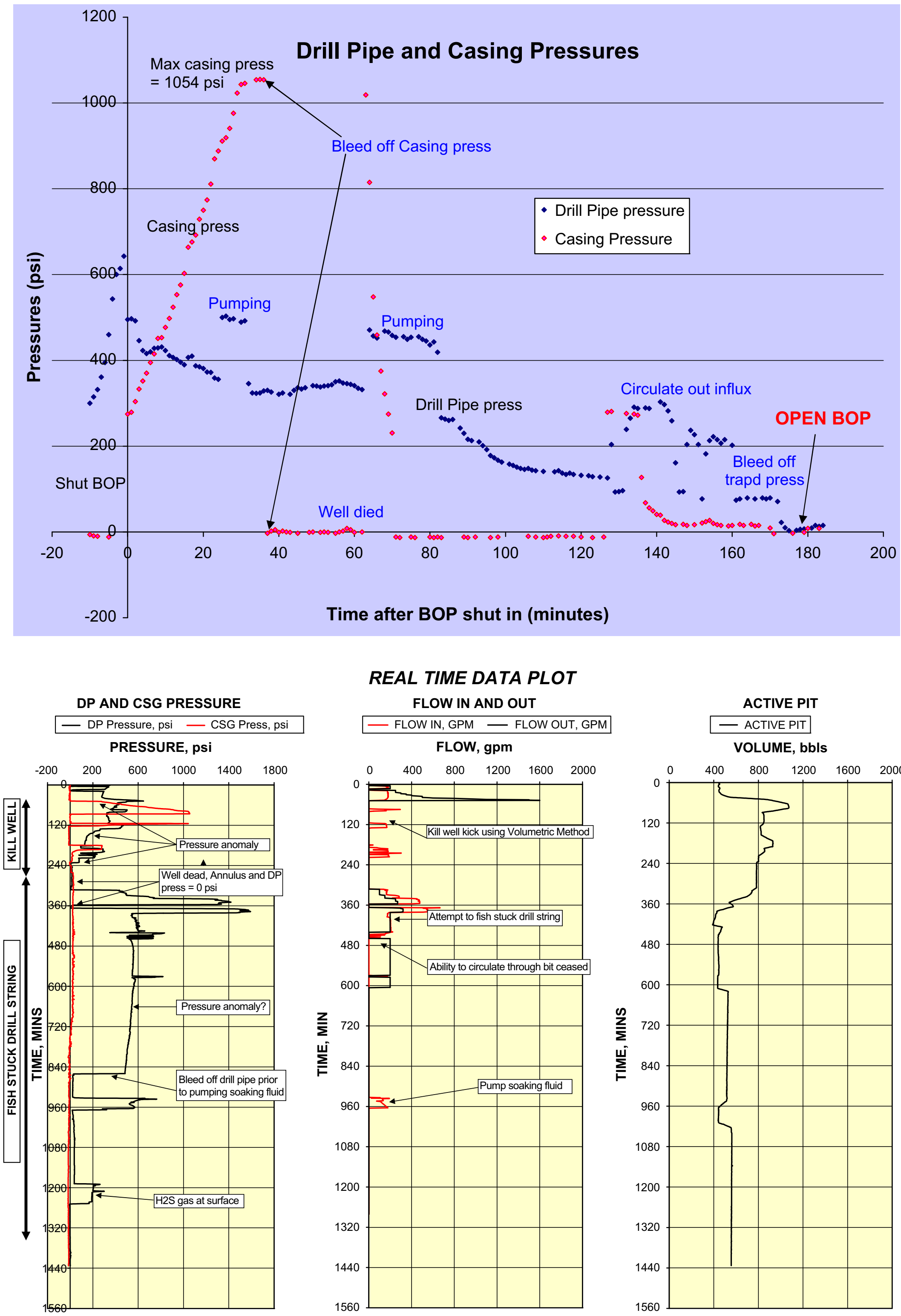


**Fig. 9.** Banjarpanji-1 Real time data dated May 28th to 29th, 2006. The top graph shows the pressure in both Drill Pipe and Casing during the shut in period. It shows that the kick was successfully killed in less than three hours. The bottom graph shows the RTD data after the well was killed until the time that the mud eruption was reported. Apart of a brief pressure increase, the fluid volume stays constant suggesting that there is no hydraulic connection with the eruption.

**Table 2**
Trip sheet data. Pulling out of hole trip sheet from the Real Time Data, showing the time, number of pipe stands pulled, its displacement and the amount of mud pumped. Pulling out was done slow, around five minutes per stand, and excessive fluid was pumped in the hole exceeding drill pipe steel displacement that negates the possibility of swabbing.

| Time | Activity | PVT | Change | Disp. | Pumped | Cum PVT |
|---|---|---|---|---|---|---|
| 23:15 | Start POH | 551 | | | | |
| 23:17 | POH 1 Stands | 551 | | | | 0 |
| 23:58 | POH 4 Stands | 556 | 5 | 2.8 | | 7.8 |
| 0:53 | Pump out 4 stands | 483 | −73 | 2.8 | 107.2 | −102.2 |
| 1:12 | Pull 2 stands | 486 | 3 | 1.4 | | −97.8 |
| 1:17 | Pump | 470 | −16 | | 15 | −113.8 |
| 1:42 | Pull 3 stands | 473 | 3 | 2.1 | | −108.7 |
| 1:56 | Pump | 439 | −34 | | 28.6 | −142.7 |
| 2:47 | Pull 7 stands | 444 | 6 | 4.9 | | −131.8 |
| 3:00 | Pump | 418 | −26 | | 32.9 | −157.8 |
| 3:40 | Pull 5 stands | 447 | 29 | 3.5 | | −148.3 |
| 3:58 | Pump | 408 | −39 | | 33.8 | −187.3 |
| 4:32 | Pull 5 stands | 411 | 3 | 3.5 | | −180.8 |
| 4:44 | Pump | 372 | −39 | | 33.8 | −219.8 |
| 5:23 | Pull 6 stands | 378 | 6 | 4.2 | | −209.6 |
| 5:40 | Pump | 339 | −39 | | 33.9 | −248.6 |
| 6:17 | Pull 7 stands | 344 | 5 | 4.9 | | −238.7 |
| 6:25 | Pull 2 stands, well flowing | 377 | 34 | 1.4 | | −203.3 |
| 6:56 | Pump, Pull 1 stand | 469 | 92 | 0.7 | 42.3 | −110.6 |
| 7:03 | Pump, Pull 1 stand | 450 | −19 | 0.7 | 25 | −128.9 |
| 7:19 | Call Co Man | 453 | 3 | | 34.2 | −125.9 |
| 7:53 | Shut In Well | 819 | 366 | | 124.5 | 240.1 |
| 8:14 | Final PVT reading | 1074 | 255 | | | 495.1 |
| | Bleed of Gas | | | | | |
| 8:17 | Pump Mud | 1045 | 29 | | 25.4 | |
| 8:24 | Bleed off Gas, Transfer mud | 851 | | | | |
| 8:59 | Pump Mud | 817 | 33 | | 52.5 | |
| | Bleed off Press, Well Dead | 929 | | | | |
| 9:13 | Circulate | 800 | | | 93 | |

14.7 ppg (17.29 MPa/km) and found to be safe. These showed that the casing shoe remained intact and not compromised even if ‘worst case’ inputs were used.

### 5.3. Four key events

For an underground blowout to occur and breach to the surface, four key events must take place (Fig. 6). If any of this sequence of events did not occur, an underground blowout that breach to the surface is very unlikely to occur. These are:

i. Occurrence of an uncontrolled kick. In Banjarpanji, there was no uncontrolled kick and the well was dead a day before the mud started to erupt.
- The kick was controlled three hours after shut in at 11:00 h (Fig. 9). Both the casing and drill pipe pressures were bled off to zero pressure.
- The BOP was opened at 11:00 h (Drilling morning report of May 29th, 2006), the well was dead and operations were underway to fish the stuck drill string by circulating and jarring up. No such operation is possible during a kick.

ii. Kick pressure that fractures the weakest part of the well, typically the casing shoe. This did not happen, as:
- The pressure exerted by the kick was too low to fracture the casing shoe. The maximum pressure at the casing shoe is 2710 psi (18.68 MPa), which is much less than the formation strength of 3053 psi (21.05 MPa) (Appendix E).
- After the mud erupted, the high pressure obtained during injection tests (Section 5.4.2, Field Evidence, High Injection Tests) showed the wellbore was totally isolated from the mud eruption, meaning that the casing shoe was not fractured and was still intact.

iii. Sufficient pressure and drive to cause an underground blowout. Observations in the field did not support this underground blowout claims.
- Circulation in the well was recorded in the RTD until May 28th, 2006 at 13:00 h (Fig. 9). In an underground blowout situation, no circulation is possible since it will be sucked by the cross-flow
- With the BOP opened starting at 11:00 h May 28th, 2006, there was no pressure in the well bore. With the well dead one cannot have an underground blowout situation.
- With the BOP opened, the path of least resistance is up through the well-head not through the formation. Nothing flowed from the well-head while a major eruption was blowing nearby.

iv. Sustained Propagation pressure to extend any fracture to the surface. No sustained pressure existed in the well bore, since:
- With the well dead and BOP opened starting at 11:00 h May 28th, 2006, there was no pressure in the wellbore able to propagate any fractures to the surface.

**Table 3**
Laboratory analysis of mud properties taken randomly from different sites near the mud eruption. Data analyzed by on site MI Mud Engineer at BJP – 1, 1/06/2006 report.

| Date | 31 May 2006 | 31 May 2006 | 31 May 2006 | 31 May 2006 | 1 June 2006 | 1 June 2006 |
|---|---|---|---|---|---|---|
| Time | 23:45 | 23:45 | 23:50 | 24:00 | 05:00 | 05:30 |
| Weight | 10.5 ppg | 8.7 ppg | 10.6 ppg | 10.0 ppg | 10.7 ppg | 11.0 ppg |
| pH | 7 | 7 | 7 | 7 | 7 | 7 |
| $Cl^-$ | 15.500 mg/l | 14.500 mg/l | 13.500 mg/l | 14.700 mg/l | 14.400 mg/l | 14.600 mg/l |
| Water | 100% | 100% | 100% | 100% | 100% | 100% |
| Oil | Nil | Nil | Nil | Nil | Nil | Nil |

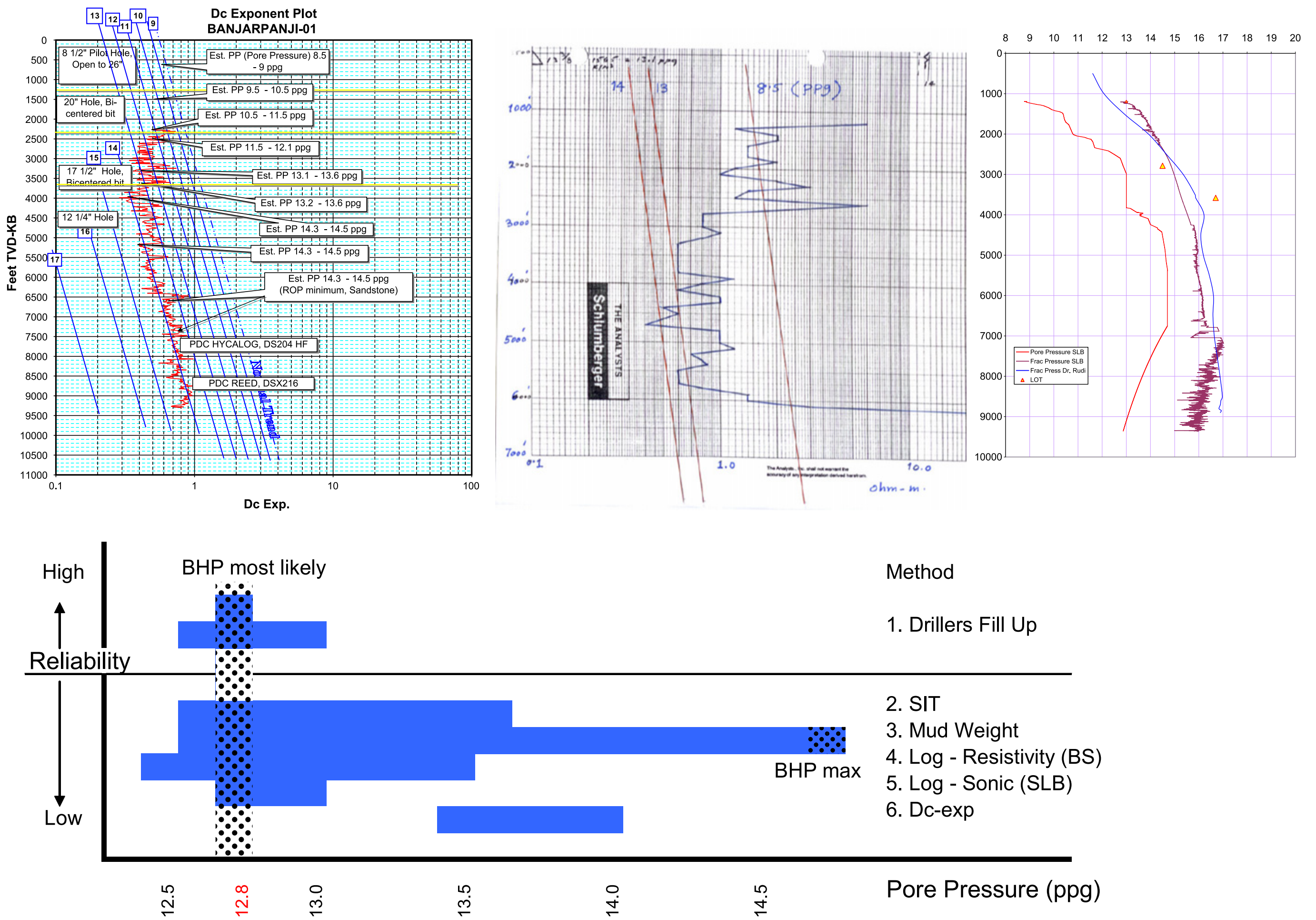


**Fig. 10.** Banjarpanji Bottom Hole Pressure (BHP) estimation. The bottom hole pressure (BHP) is estimated based on a number of methods with differing reliabilities. The most likely BHP is around 12.8 ppg and the maximum BHP of 14.7 ppg (for sensitivity analysis purpose).

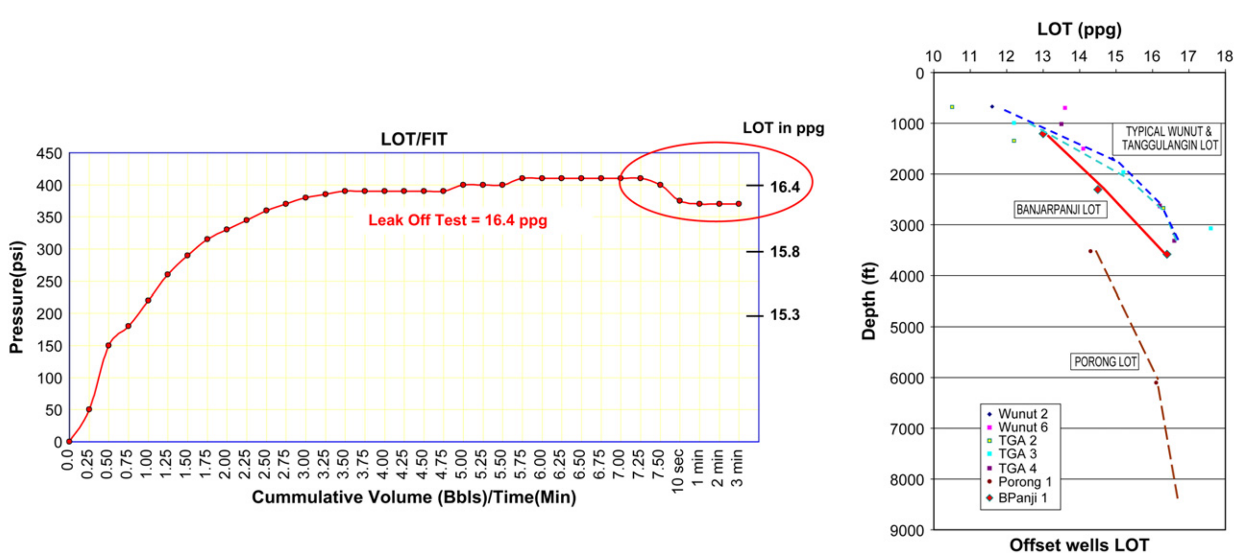


**Fig. 11.** Leak Off Test (LOT) Banjarpanji well at 3580 ft. (1091 m) depth. The LOT result was 16.4 ppg (19.29 MPa/km) (Left). The shape of the curve is typical of LOT done using oil based mud due to a higher compressibility factor compared to a water based mud system. The resulting LOT is compared to other nearby wells (Right). The formation pressure and the LOT in the shallow section of Banjarpanji resembles Wunut wells, since it is within the same closure.

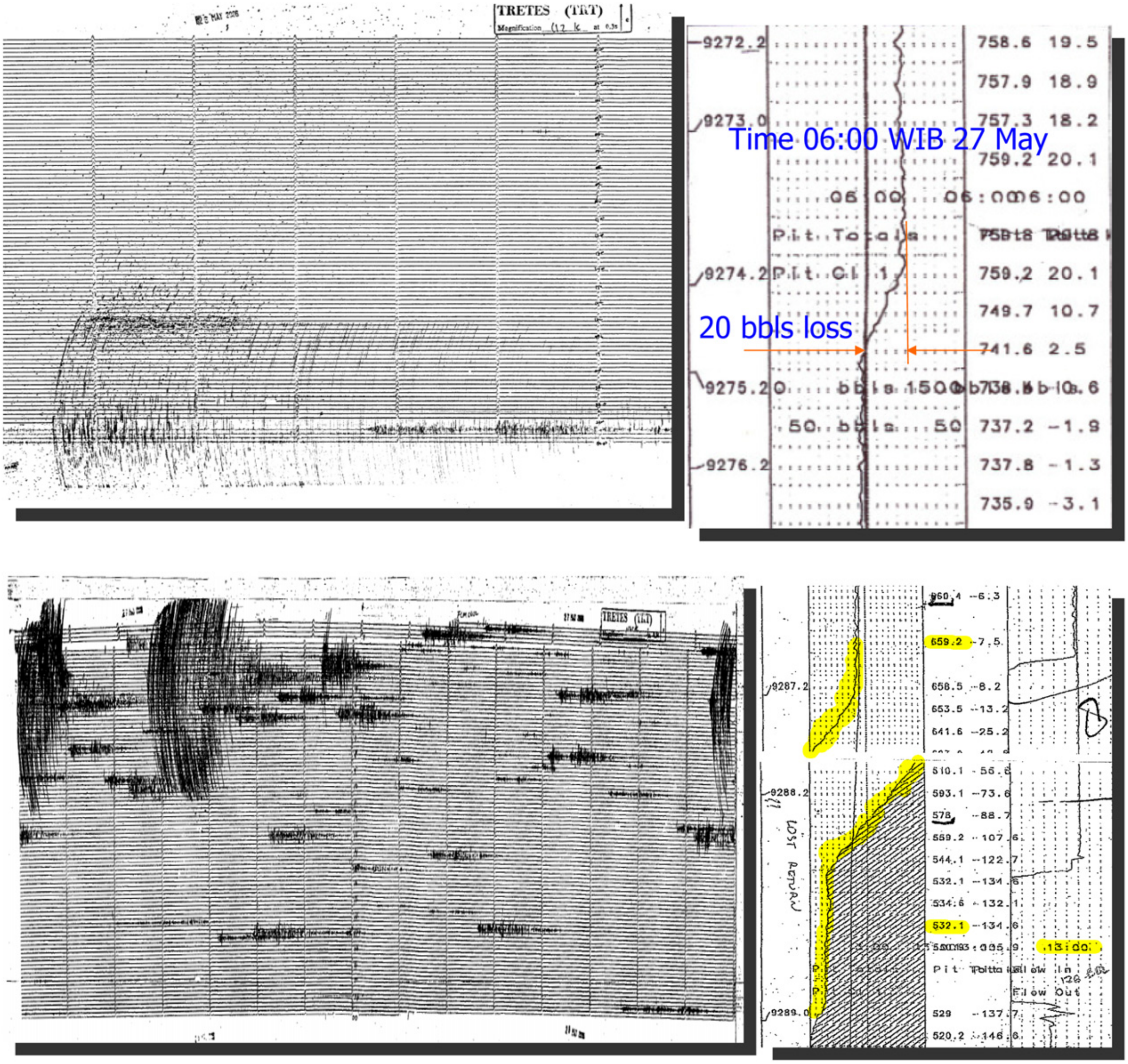


**Fig. 12.** A 20 bbls loss of mud after the main earthquake (top).The left portion showed the seismograph reading of the Yogyakarta earthquake ~ 06:00 WIB 27 May 06 at Tretes BMG station about 15 km away. The top right picture showed the 20 bbls loss from the mud logger's real time data that happenned seven minutes after the main earthquake. The bottom right shows 130 bbls complete loss of circulation from the wellbore that happenned two hours after two aftershocks. These losses that happenned after the earthquake showed a compelling argument that a temporal connection exists between the earthquake and Banjarpanji well.

- Samples of mud collected at the eruption site were analyzed without any traces of synthetic oil based mud. Results of the mud analysis are shown in Table 3. Had it been from the well, the drilling mud used will distinctly show its oil based mud signature.

### 5.4. Field evidence

Facts and evidence were collected during final days of drilling and subsequent relief well project. This evidence do not support the underground blowout claims. These include:

#### 5.4.1. Real time data

The most important piece of data to confirm the status of the well is the Mud logger's real time data (RTD) that include the pressure data, mud volume data, pumping data, gas data and the drilling parameter information. Analysis of this data helps explain the status of the well, whether it is breached or stays intact.

*5.4.1.1. During the well control incident (while the BOP was shut in).* With the drill bit off bottom when the kick was taken, the preferred well control method was the Volumetric Method (Abel et al., 1994). This method involves lubricating a volume of drilling mud (not necessarily a heavy kill mud) and bleeding off a certain amount of gas. This method is not intended to kill the kick, but simply to lower the shut-in pressure sufficiently to allow snubbing the pipe back down to bottom where the well can then be killed conventionally. But instead of the expected gradual lowering of the shut-in pressure, the well died after two cycles of lubrication.

After circulating the influx out and ensuring that the fluid in both drill pipe and annulus are full of 14.7 ppg. (17.29 MPa/km) mud, the drill pipe pressure remained at around 75 psi (0.52 MPa) while the annulus was 0 psi. The trapped pressure at the drill pipe

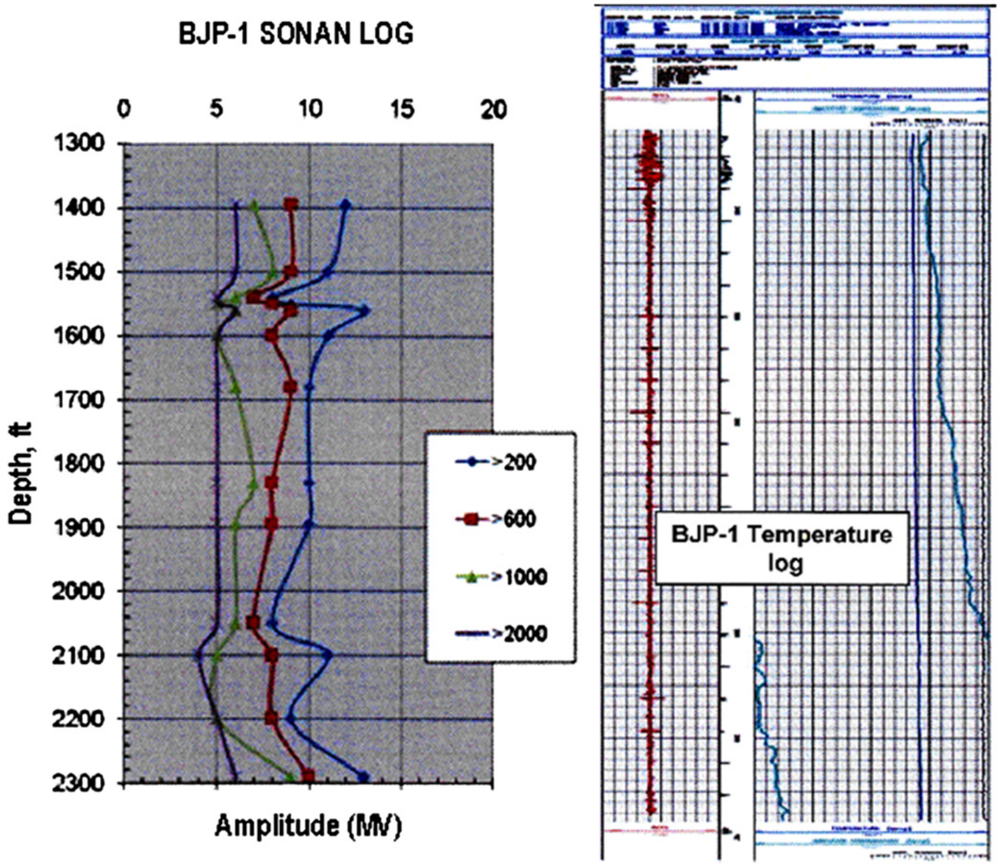


**Fig. 13.** Sonan (left) and Temperature (right) logs taken during re-entry operations, 2 months after eruption did not show any anomaly. The absence of anomalies suggests that there is no flow close to the casing. If the flow originates from the well, erratic noise or distinct temperature changes would be registered in the log. This suggests that flow may not originate from the well.

was bled off and the BOP was opened. The well was confirmed dead at 11:00 h. This is shown in Fig. 9A that plots the pressure data, both drill pipe and annulus, during shut in from the RTD. The most pertinent data for pressure analysis is the annulus shut in pressure. The annulus pressure continued to rise after shut in and reached a plateau at 1054 psi (7.26 MPa). This pressure is used as the input data in the Pressure Analysis section.

The second is the anomalies at the drill pipe leg of the well. These are:

i. At the time of the shut in, drill pipe pressure was higher than annulus pressure. The drill pipe pressure was around 500 psi (3.45 MPa) and the annulus pressure was 280 psi (1.93 MPa).
ii. After the first bleed off period, the annulus pressure remained at 0 psi whereas the drill pipe pressure stayed at a higher pressure.

The operation just before the BOP was shut in was pumping mud down hole. Therefore, the drill string was full of 14.7 ppg (17.29 MPa/km) mud whereas the annulus fluid was of unknown composition at the time of killing. However, this is in direct contrast to the pressure readings at shut in where the drill pipe pressure was higher than the annulus. The plausible explanation on why the pressure of the drill pipe can be higher than the annulus is the float valve that isolates the drill pipe pressure reading from the open formation (Fig. 7). This suggests a 'pressure trap' phenomenon or, in drilling engineering, 'the well does not behave as a perfect U-tube'. The consequence is that any accurate pressure analysis cannot be done based on the drill pipe pressure, and must be performed on the annulus side that is in direct contact to the open formation and the shoe.

*5.4.1.2. After the BOP was opened until the mud erupted (Fig. 9B).* The second piece of information from RTD is shown on Fig. 9B. It shows the operation on the well from the time that the well had died and the fishing of the drill string until the mud eruption. The critical information here are:

i. Pumping through the bit was still possible until ∼15:00 h on May 29th, 2006, despite the fact that the drill-string was stuck. The drill-string appeared to be differentially stuck but not completely packed off at the time.
ii. The 'pressure trap' phenomenon in the drill pipe prevails, which showed that the Drill Pipe pressure around 480–550 psi when there were no pumping (15:00 through to 21:00 h). This pressure trap was finally bled off just prior to spotting the soaking fluid to unseat the fish at 21:30 h.
iii. After the pressure was bled off, there was no sustained pressure in the well.

*5.4.1.3. The information from the mud logger's RTD can be summarized as follows.*

- The maximum pressure in the annulus during the well control was 1054 psi (7.27 MPa). This pressure reading is valid since the well was still able to be circulated through and not packed off.

- Float valve in the drill string appears to create a trapped pressure in the drill pipe. This trapped pressure made readings in the drill pipe invalid unless it is removed beforehand by circulating slowly that kept the float valve open.

### 5.4.2. High injection tests

On the first day of the eruption, the first operational priority was to ascertain if there was any connection between the well and the mud eruption and attempt to kill it. Three injection (pumping) connectivity tests were therefore carried out:

i. First injection test with 185 bbls (29,415 l) of 14.7 ppg (17.29 MPa/km) mud. The injection pressure was at 700 psi (4.83 MPa). (M-I Swaco report date May 29th, 2006).
ii. Second injection test with 200 bbls (31,800 l) of 16.0 ppg (18.82 MPa/km) mud loaded with LCM material. The initial injection pressure was 1200 psi (8.27 MPa) with a final pressure of 900 psi (6.21 MPa)) (Drilling morning report May 30th, 2006).

These two tests were done with a high pumping rate as the intent was to kill the eruption if possible. The initial report after the injection tests suggested that the eruption intensity decreased but further observation showed that this may not be the case; the continued erratic and intermittent nature of the eruption afterward suggests this was coincidental.

The high injection pressure, higher than the Leak Off Test, confirmed that there were no channel formed between the well and the mud eruption. It was then decided to continue to fish the stuck drill string, and as an added safety measure, cement plugs would be set in the open hole below the fish.

iii. Third injection test before cementing; the injection rate was 2.5 bpm (397.5 l/m) at 370 psi (2.55 MPa). (Daily drilling report May 30th, 2006)

These high injection pressures confirmed that the shoe was not fractured and there was no channel formed between the well and the mud flow. If such a channel existed, the injection pressures would have been lower than the leak off test pressures.

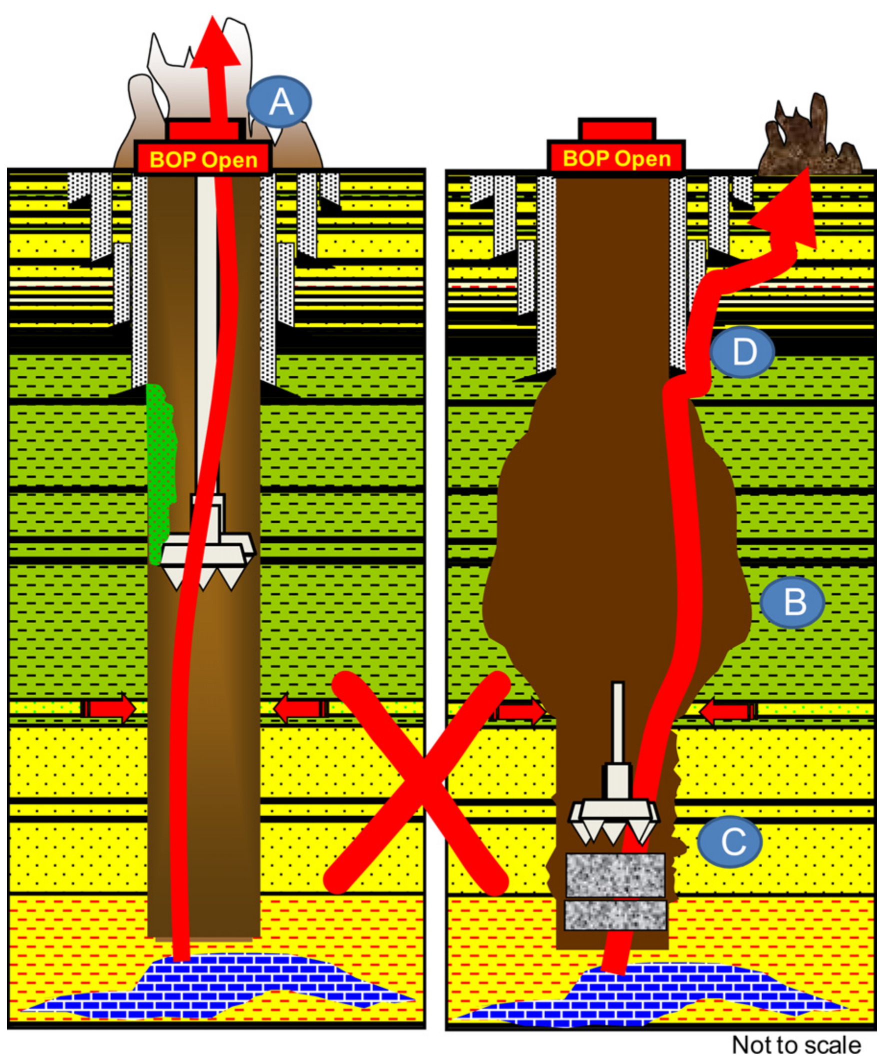


**Fig. 14.** With BOP open, well cannot be in an underground blowout situation. If BOP is opened, the path of least resistance is through the wellbore instead of fracturing the formation and breaching to the surface. Yet nothing came out of the well (A). In the Underground Blowout Hypothesis several scenario would happen: the hole would enlarged (B); the fish Fall to the bottom of the well (C); the very high flow rate, the flow behind casing would be easily detected (D). None of the above happened. The fish was found in its original abandoned depth.

### 5.4.3. Other field evidence against underground blowout claims

i. The drilling assembly stuck in the open-hole part of the well did not fall deeper into the well. If an underground blowout had occurred, the high mud flow rates would erode and enlarge the well-bore, causing the drilling assembly to fall to the bottom of the well (Fig. 14). However, it was confirmed that the fish was still at its original position during the re-entry project.
ii. LUSI has been spewing mud for more than 2 years at impressive rates; initially around 50,000 $m^3$/day of mud, increasing to around 156,000 $m^3$/day, and currently around 80,000 $m^3$/day. Speculations that the fluid is coming from the Kujung Formation are inconsistent with the known reservoir properties and water chemistry of the Kujung Formation. The productivity of LUSI is in the order of at least 150 times that of Kujung reservoir (Nawangsidi, 2007).
iii. Temperature and Sonan logging was carried out during the relief well campaign to look for evidence of an underground blowout. These logs were run on 20th of July 2006 (over 50 days after the first mud flow) to the top of fish (2984 feet or 910 m) in the re-entered Banjarpanji-1 well. The Sonan log was 'very quiet' which indicated the absence of fluid flow behind casing (Fig. 13A. The temperature logs showed 60 °C, and did not record any abnormal shift or anomaly within the Banjarpanji-1 well (Fig. 13B). If LUSI originated and was flowing near the well, the temperature would show a marked increase given the high temperature of the erupting mud (95 °C). Both the Sonan and Temperature logs did not suggest any near well bore fluid flow.

### 5.5. Well reports

Key operational data and daily reports are attached in the Appendix G to enable interested readers to perform their own assessment on the events in the rig during the critical period. These are actual operational data from a real life complex drilling operation. Some of these operational data are incomplete and often conflicting with each other and can be interpreted differently depending on how much effort and drilling experience the individual reader possesses.

The critical data include:

- Daily drilling reports
- Daily geological reports
- Daily mud loggers reports
- Real time data plot (Fig. 9)

## 6. Conclusion

LUSI is a new mud volcano in a region prone to mud volcanism. Along the vicinity of the Watukosek fault, where LUSI is situated, there are at least five other known mud volcanoes.

The Banjarpanji-1 well was planned and drilled according to standard industry practice for high pressure exploration wells. Key learnings from offset wells were incorporated into the design of the well. The safety factor applied was consistent with accepted exploration well standards, and in fact was higher than offset wells targeting the same Kujung carbonate formation, that have longer open hole sections. Drilling operations were performed by a qualified drilling contractor and supported by quality service companies. The result was minimal down-hole drilling problems right until the time of the Yogyakarta earthquake, where a serious loss of mud problem occurred.

Analysis and its sensitivity test presented in this paper shows that the weakest point in the well, the deepest casing shoe, remained intact and was not breached. Evidence further suggests that:

- The kick was killed within three hours and the well was dead. The well no longer had any pressure to support an underground blowout process.
- The well was circulated on an opened BOP; this is not possible in an underground blowout situation.
- With the BOP opened the path of least resistance is up through the well head and not through the formation. Nothing flowed from the well head while a major eruption was blowing nearby.
- 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.
- The well remained full and did not sustain any drilling mud losses throughout the eruption. Chemical analysis from the erupted mud did not contain any drilling mud particles. It indicates that the mud eruption did not originate from the well.
- The mud eruption rate was at least an order higher than the reservoir ability to flow into and up through the well bore. At this flow rate, the flow is more likely to pass through a fault plane instead of a well.
- Temperature and Sonan logs result showed the absence of a near casing fluid flow that is characteristic of an underground blowout.

Operational data are now opened to the public and scientific community and presented for the first time in this paper. Our data leads to the conclusion that LUSI was not triggered by an underground blowout. The authors welcome future studies based on this data that will help improve our understanding on the origin of mud volcanoes.

## Acknowledgements

The authors express appreciation to the management of BPMIGAS, Lapindo-Brantas Inc. and its partners for their support and permission to publish the paper. Numerous constructive discussions and inputs from drilling engineers and geoscientists are also appreciated.

## Appendix A: Banjarpanji-1 well design

The Banjarpanji-1 well was drilled as an exploration well with the Miocene Kujung or Prupuh to Tuban carbonates as its primary objective. These carbonate reservoirs are proven and prolific oil and gas reservoirs and the target of most deep exploration wells throughout East Java. A seismic section through Banjarpanji-1 is shown in Fig. 5.

Banjarpanji-1 was recognized as a High Temperature and High Pressure (HTHP) well early in the planning phase, and this necessitated an increased focus on offset geological and operational benchmark data to ensure a safe and efficient design and operation. For Banjarpanji-1 well planning, the key offset wells were:

- Huffco Porong-1, 6 km away. Porong-1 provided the most relevant drilling information and geological data in the deep portion of the well. The well experienced fluid kicks in the overpressure zones and losses while penetrating the deeper carbonate section.
- Huffco Wunut-2, 1.5 km away. Wunut −2 supplemented information on the shallow section, as it is the closest well to

Banjarpanji-1 and both wells are within the Wunut anticline structural closure. Lessons from this well were applied to combat the highly reactive overpressured shale.
- Mobil Oil BD-1 and BD-2, over 50 km away. The BD-1 and BD-2 are twin wells with two completely different results; one full of drilling problems and the other trouble free. The main design difference is that in the second well, the 9-5/8″ casing was set inside the carbonate section. These two wells provided much insight into how deep carbonate wells in East Java should be planned and executed.
- Kodeco KE-11E and KE-11G, 30 km away. The KE-11E well successfully drilled the Kujung carbonate by setting the 9-5/8″ casing at the top of the carbonate section. The KE-11G was drilled to over 15,500 ft (4730 m) but did not find the objective. These wells are good examples of how deep wells should be drilled.
- Santos Jeruk-1 and Jeruk-2, 28 km away. Jeruk-1 encountered kick and loss problems and provided good lessons for design and drilling of later wells. Jeruk-2 was drilled successfully by having its 9-5/8″ casing set inside the top of the Kujung Formation, and provides further benchmark data on a successful drilling strategy.

Operational insights from the offset wells were incorporated into the design, operational procedures and risk mitigation plans for Banjarpanji-1. The two key learnings incorporated in the well design were:

- The importance of setting the 9-5/8″ casing inside the top of the Kujung Formation, and
- The use of synthetic oil based mud to drill the highly reactive and overpressured shale sequence.

## Appendix B: length of the open hole section

The length of the open hole in a well is typically dictated by three constraints, which are:

1. Kick Tolerance limit (safety consideration)
2. Geological constraints
3. Other drilling constraints

Kick tolerance is the amount of volume and pressure of gas influx at bottom-hole conditions that can be safely taken, shut-in and circulated out of the well without fracturing the weakest point, generally at the casing shoe. The volume (measured in bbls) of the kick refers to the amount of gas influx that is allowed to be taken into the well-bore. The intensity (measured in ppg) of the kick tolerance refers to the increase in mud weight required to balance the formation pressure. There are no industry standards for Kick Tolerance as it is very much case specific. Companies set their own standards based on their experience of drilling in the area (Unocal Operating Guideline, 1998). In Banjarpanji well, the operator and its partners agreed to use a kick tolerance of around 10 bbl (1590 l) and 0.5 ppg (0.59 MPa/km) gas kick, while nearby, a company with more drilling experience drilling the Kujung formation, used kick tolerances as low as 0 bbls and 0 ppg (0 L and 0 MPa/km).

In Banjarpanji well, there was no constraint due to Kick Tolerance since the LOT was high (16.4 ppg or 19.3 MPa/km) and the Mud Weight was lower than expected (14.7 ppg or 17.3 MPa/km). Therefore, with the agreed pre-defined Kick Tolerance limit it was deemed safe to drill to around 9400 ft (2865 m) total depth provided there were no increases in mud weight. In this particular case, the need to increase mud weight with depth was unlikely since the formation drilled were permeable sandstones.

The Geological constraint is the carbonate formation. As per agreed well plan and lessons learned from offset wells, the shoe was to be set 10–20 feet (3–6 m) into the tight hard pan on the top of the carbonate. The top of the carbonate section is generally found to be tight with a thickness of around 50 ft ($\sim$15 m) where no fluid loss is expected. Below this cap, a pore pressure reversal is observed in offset wells where loss circulation is likely to be encountered. This setting of 9-5/8″ casing inside the carbonate cap allows the over pressured zone overlying the Kujung Formation to be isolated such that drilling could then continue into the lower pressured carbonate formation using a lower mud weight.

This carbonate section was not found at the prognosed depth at 8500 ft (2591 m), but based on predictive electric log result, the top of Kujung formation and hence the setting depth of the 9-5/8″ casing shoe could be as deep as 9600 ft (2926 m). Setting the casing at the very top of the Kujung Formation was an important part of well plan and accordingly frequent bottoms up circulations of cuttings were carried out to check if the carbonate formation had been penetrated.

There were no other drilling constraints in this well. The hole was in an excellent shape as evidenced by several trips (three bit trips and six short trips in the hole section) made without any drag or fill. The mud weight was sufficient to contain the formation pressure as there was no unduly high formation gas and connection gas observed from the well. The Static Influx Test conducted at 9010 ft (2746 m) confirmed that the mud weight used was above the formation pressure.

All systems were set to drill to the top of the Kujung carbonate or 9400 ft (2865 m) whichever was encountered first. However, the loss of circulation at 9297 feet (2834 m) signaled that the well condition had changed substantially and that a casing string must be set at this depth once the loss problem had been stabilized. The safety of this deeper than proposed casing setting depth was later verified using commercially available casing-design software, and found to be acceptable, as shown in Fig. 8.

The physical length of open hole itself is not an issue provided that the above three criteria are met. As an example two recent offset wells drilled by other operator nearby to the same objective have a longer open hole section (up to 6700 ft or 2042 m) compared to 5717 ft (1743 m) of this well.

In summary, the operating procedure and well plan followed in this well is fairly standard and in line with that followed by other operators in the area is proven by the number of offset wells. It is therefore believed that factors other than drilling mechanics caused the mud eruption.

## Appendix C: bottom hole pressure estimation

In Banjarpanji, direct methods from the well were used to estimate the bottom hole pressure. These methods have a high degree of reliability since the factors involved are directly measured or observed from the well. The result from these methods are compared with values from calculated methods such as Electric logs and Drilling Dc-exponent (Bourgoyne et al., 1984) to get a better estimate of the bottom hole pressure.

### *Engineer's fill up*

This method is based on a physical phenomenon that during a loss circulation event, the fluid level in the well will fall to a level that represents the pressure of the well. When pumping is resumed, the amount of mud pumped in the well until the first sign of fluid return is a good estimate of the volume necessary to fill the 'void'. Knowing the capacity of the drill pipe and the annulus, one can estimate the height of the fluid column in the pipe. The weight of the remaining mud column is inferred as the formation pore pressure. This method of calculating the bottom hole pressure is widely used by field engineers as a quick and reliable bottom hole pressure measurement.

Using this procedure, the volume pumped when the first sign of fluid return was observed was 2342 pump strokes or 220 bbls (23980 l). The empty column height is therefore 1571 ft (489 m). Assuming a fill up efficiency of 75%, the estimated pore pressure is 12.8 ppg (15.06 MPa/km). As a sensitivity test, with a fill up efficiency of 70% and 80%, the estimated pore pressure is 13.0 and 12.7 ppg (15.30 and 14.94 MPa/km) respectively.

*Static influx test*

This method is used with good success by a number of companies to estimate the upper limit of the formation pressure. In the new literature, this is referred to this as "micro-influx" method.

The mechanism of the method is by simulating a swabbing condition. Drilling process is halted; the drill pipe is then pulled to generate swabbing conditions that lower down-hole pressure. A lowering of pressure by 0.5–1.0 ppg (0.59–1.18 MPa/km) is expected as a result of this induced swabbing. If the mud weight in the well-bore was in close balance with the formation pressure, then an under-balance condition will develop that induce an influx of hydrocarbon in the well-bore. The well is then circulated to observe the characteristics of the fluid at bottoms out. Unusually high gas content would indicate a close balance between the pore pressure and the mud weight, and would provide a good estimate of the formation pressure.

In Banjarpanji-1, the shut-in test was conducted several times with the deepest at 9010 ft (2746 m), all with negative results (no influx observed). Since the mud weight in the wellbore was 14.7 ppg (17.29 MPa/km), it was inferred that the formation pore pressure is of the order of 13.7 ppg (16.12 MPa/km) or lower.

*Mud weight*

The mud weight used to drill to total depth was 14.7 ppg (17.29 MPa/km). At total depth, the well suffered a loss, which means the pore pressure of the well must be lower than and cannot be any higher than the mud weight. If the pore pressure is higher than the mud weight, the well would have suffered a kick instead of a loss. Therefore 14.7 ppg (17.29 MPa/km) is the absolute upper end of the pore pressure.

*Indirect methods*

The bottom hole pressure estimation using these methods are shown in Fig. 10 (upper picture). These are the result from other sources, with the following 'most likely' pore pressure at the bottom of the hole:

a. Dc exponent (source Elnusa) = 13.5–14.0 ppg (15.88–16.48 MPa/km)
b. Resistivity log (source Singh and Dusseault) = 12.5–13.5 ppg (14.71–15.88 MPa/km)
c. Sonic log (source Schlumberger) = 12.8–13.0 ppg (15.06–15.30 MPa/km).

*Summary of bottom hole pressure estimation*

The results of these pressure estimation methods, is shown in Fig. 10 (bottom picture). These results suggest the following:

1. The best estimate of the bottom hole pressure is around 12.8 ppg (15.06 MPa/km).
2. The bottom hole pressure is unlikely to be over 13.7 ppg (16.12 MPa/km), with the highest possible bottom hole pressure of 14.7 ppg (17.29 MPa/km)

In the Pressure Analysis section, the bottom hole pressure used is 12.8 ppg (15.06 MPa/km). The sensitivity test is performed with a maximum bottom hole pressure of 14.7 ppg (17.29 MPa/km).

## Appendix D: other pressure data

*Shut in Casing Pressure*

The maximum Casing Pressure of 1054 psi (7.27 MPa) is based on the mud logger's real time data (RTD) of May 28th, 2006. This casing pressure is considered reliable, as it is stable around 36 min after shut in, and remained constant until it was bled off as part of the well control procedure, as shown in Fig. 9 (upper picture).

The (lower) pressures recorded at the choke and obtained minutes after the well was shut-in are not considered valid indications of well bore pressure. For example, the Initial Shut In Casing Pressure (ISICP) reading of 350 psi (2.41 MPa) was not stable and tended to increase. This increasing trend is believed to be due to the migration of influx fluid up the wellbore replacing the drilling mud.

*Fluid density of the influx*

The well took a fluid influx of around 360 bbls. (57,240 l), which represents approximately 30% of the hole volume. Accurate measure of the total influx is difficult to estimate because a number of operation that was ongoing at the time.

This influx fluid migrated to the upper section of the well because of its lighter density. When the annulus pressure reached its stable period, it is likely that the whole volume of influx has reached the surface and that the exchange of mud and influx is now completed.

During the kill process, this influx was circulated out and the well was bled off. The influx fluid was found to be saline water with a density of 8.9 ppg (10.47 MPa/km), as shown in the well's IADC report and the drilling morning report dated May 29th, 2006.

*13-3/8″ casing shoe Leak Off Test*

A casing shoe leak off test (LOT) measures the strength of the formation at the casing shoe, which is the ability of the open-hole well-bore to resist fracturing. To calculate the LOT, the data needed is the casing shoe depth, the mud weight and the surface pressure.

Traditionally, a LOT involves injecting mud into the formation until it 'leaks'. The pressure when the formation starts to leak is called the 'Leak Off' pressure. However, when compressible oil-based mud is used, this traditional method is less reliable as repeatability is poor and choosing the leak-off pressure is subjective.

To have a better reliability, The LOT is done is by injecting mud into the formation until the injection pressure stabilize, stop the pump, and measure the 'closing pressure'. This 'closing pressure' is equal to the 'opening pressure' of the formation and thus the Leak Off Test pressure (Unocal Operating Guideline, 1998). This technique has better repeatability and reduces any subjectivity in picking the leak off point. This LOT technique, however, may present a safety issue in the hard rock country since the fracture caused may be difficult to heal.

In Banjarpanji well, at the 13-3/8″ casing shoe the 'closing pressure' was 400 psi (2.76 MPa) (Drilling morning report May 6, 2006). With the casing shoe depth of 3580 feet (1091 m) and the mud weight of 14.2 ppg (16.71 MPa/km), the LOT is 16.4 ppg (19.29 MPa/km) (Fig. 11, left picture). The quality of this data is high since it was measured at the cementing pump and witnessed by the drilling supervisor who had access to both pressure and volume readings.

This value is consistent with LOT results from nearby Wunut wells (NW, approximately 1.5 km away) and Tanggulangin wells (NE, approximately 3 km away). This was expected, as the shallow section of Banjarpanji-1 lies within the Wunut anticlinal structure. This value is however, significantly higher than the shallow section of Porong well (NE, approximately 6 km away). Leak Off Test results of these fields including Banjarpanji well are shown in Fig. 11 (right picture).

## Appendix E: pressure analysis – graphical method

The data to perform this pressure analysis is obtained from Appendices C and D, as follows:

a. Maximum casing pressure = 1054 psi (7.27 MPa)
b. Fluid in the upper part of the hole (influx fluid) = 8.9 ppg (10.47 MPa/km)
c. Fluid in the bottom part of the hole (mud) = 14.7 ppg (17.29 MPa/km)
d. Bottom hole pressure (BHP) = 12.8 ppg (15.06 MPa/km)
e. Leak off test (LOT) at the casing shoe (3580 ft or 1091m) = 16.4 ppg (19.29 MPa/km)

Fig. 8B graphically plots the various pressures and gradients by:

i. Plotting the maximum annulus surface pressure of 1054 psi (7.27 MPa) at the surface.
ii. Drawing a line down from the 1054 psi (7.27 MPa) surface pressure, using the 8.9 ppg (10.47 MPa/km) influx fluid gradient.
iii. Plotting the BHP of 12.8 ppg (15.06 MPa/km) at 9297 feet (2834 m) (bottom of well).
iv. Drawing a line up from the BHP, using the 14.7 ppg (17.29 MPa/km) oil-based mud gradient.
v. These two lines intersect at around 6000 feet (1829 m). This depth is consistent with the large amount of water influx taken into the well.
vi. Graphically, the pressure at the casing shoe depth is found to be 2710 psi (18.68 MPa).

Mathematically, the wellbore pressure at the casing shoe is as follows:

$$\text{Pressure at casing shoe} = \text{Maximum casing pressure} + \text{hydrostatic pressure of fluid}$$

$$P_{@3580} = 1054 + (0.052 \times 8.9 \times 3580) = 2710\ \text{psi}(18.68\ \text{MPa})$$

This is equivalent to a fluid hydrostatic pressure of 14.6 ppg (17.1 MPa/km), much lower than the LOT pressure (16.4 ppg or 19.29 MPa/km). Therefore the shoe was still intact and unlikely to have been compromised.

## Appendix F: observation

### *Timing of Earthquake and Drilling Mud Losses*

The Banjarpanji-1 well suffered two mud losses which coincided with the time of the main earthquake and its after-shocks.

At 9277 feet (2828 m), the first mud loss of 20 bbls (3180 l) was recorded at 06:02 h on May 27th, 2006, some seven minutes after the 6.3 Richter Scale magnitude Yogyakarta earthquake, (Fig. 12A). The tremors from the earthquake were felt at the rig site. The mud losses healed, and drilling continued. Cutting samples circulated from bottom at this depth showed the gas readings, lithology and biota were unchanged, and the calcimetry was constant at 4.4% carbonate.

At 9297 ft (2834 m), the second mud loss was recorded at 12:50 h on May 27th, 2006 (Fig. 12B), less than two hours after two major aftershocks that followed the main earthquake. The well experienced a total loss of circulation.

The timing of the earthquake and two mud loss events suggests that despite the 260 km distance to the earthquake epicenter, the earthquake had an impact down hole in the Banjarpanji-1 well.

### *Not a typical carbonate mud loss event*

The second mud loss was a complete loss of return, with a total loss of mud of approximately 130 bbls (20,670 l). In order to cure the loss, a pill of 60 bbls (9540 l) of loss circulation material (LCM) was pumped, and the losses cured. The bit was pulled four stands off bottom (to 8737 feet or 2663 m) and the mud was circulated while monitoring the condition of the well.

After the well suffered a complete loss of returns, the rig crew anticipated and was ready for a kick that typically follows such a major loss of mud. However, a kick did not eventuate even after eight hours of close observation. This was not a usual loss-and-kick sequence that typically occurs in carbonate formations such as that recorded at Porong-1

The other unusual characteristic of the major loss event was that it was easily cured; simply by pumping 60 bbls (9540 l) of loss circulation material (LCM). If this major loss had occurred in a permeable formation such as a fractured carbonate, then curing it would typically require much more time and involve multiple pills and different types of treatments including cement plugs. For example, in the offset Porong-1 well, curing the loss of circulation required multiple pills of LCM and finally a bentonite squeeze was used.

This suggests that the loss may not be to a carbonate formation but due to other causes, such as to a suddenly reactivated fault system creating an isolated fracture through the Banjapanji-1 wellbore. If the earthquakes created a fracture in this well, then it is very likely that they created many other fractures and opened existing fractures/faults in the area. Such re-activation of regional faults may have triggered the LUSI mud volcano.

### *Pulling out drill string and kick*

The trip out was done slowly, on an average of 5 min per stand, and no over-pull was recorded. This lack of over-pull is consistent with a good hole penetrating hard volcanoclastic sandstones and shale drilled with a synthetic oil base mud. Similarly, multiple trips in and out of this hole section had not reported any drag or fill. Electric logs run at 8750 feet (2,667 m) had shown 'gun barrel' hole conditions. The trip details extracted from the real time data are summarized in Table 2.

The pumping of mud to compensate for drill pipe displacement, the slow five minutes per stand pulling speed, the absence of any over-pull and the excellent condition of the wellbore, make it very unlikely that the pulling out of hole operation provoked an influx (swabbing).

*Unconventional influx*

During the pulling out of hole operation, a large water influx entered the wellbore. The combination of high influx rate and late BOP shut in resulted in a high influx volume of around 360 bbls (57,240 l) that was taken into the wellbore. Accurate measure of the total influx is difficult to estimate because a number of operations were ongoing simultaneously. Despite all this, this kick was easily killed.

The real time data showed that the kick was killed and the well died within three hours after the BOP was shut in (Fig. 9). This behavior was in stark contrast to the Kujung Formation loss and kick incident in Porong-1, which took six days to kill. This again suggests that the influx may not be from a carbonate formation but similar to one that caused the losses of drilling mud a day earlier.

## Appendix G. Supplementary data

Drilling data during the critical times from May 25th to June 4th, 2006 include 1. Daily drilling morning reports, 2. Daily geological reports and 3. Daily mud logger's reports which can be found in the online version, at doi:10.1016/j.marpetgeo.2009.04.002.

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