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ABSTRACT

The Lusi mud volcano of East Java, Indonesia, remains one of the most unusual geological disasters of modern times. Since its sudden birth in 2006, Lusi has erupted continuously, expelling over 90 million cubic meters of mud that has displaced ~40000 people. This study undertakes the first detailed analysis of the pore pressures immediately prior to the Lusi mud volcano eruption by compiling data from the adjacent (150 m away) Banjar Panji-1 wellbore and undertaking pore pressure prediction from carefully compiled petrophysical data. Wellbore fluid influxes indicate that sequences under Lusi are overpressured from only 350 meters depth and follow an approximately lithostat-parallel pore pressure increase through Pleistocene clastic sequences (to 1870 meters depth) with pore pressure gradients up to 17.2 MPa/km. Most unusually, fluid influxes, a major kick, connection gases, elevated background gases and offset well data confirm that high magnitude overpressures also exist in the Plio-Pleistocene volcanic sequences (1870 to ~2833 meters depth) and Miocene (Tuban Formation) carbonates, with pore pressure gradients of 17.2-18.4 MPa/km.

The varying geology under the Lusi mud volcano poses a number of challenges for determining overpressure origin and undertaking pore pressure prediction. Overpressures in the fine-grained and rapidly deposited Pleistocene clastics have a petrophysical signature typical of disequilibrium compaction, and can be reliably predicted from sonic, resistivity and drilling exponent data. However, it is difficult to establish the overpressure origin in the low porosity volcanic sequences and Miocene carbonates. Similarly, the volcanics do not have any clear porosity anomaly, and thus pore pressures in these sequences are greatly underestimated by standard prediction methods. The analysis of pre-eruption pore pressures underneath the Lusi mud volcano is important for understanding the mechanics, triggering and longevity of the eruption, as well as providing a valuable example of the unknowns and challenges associated with overpressures in non-clastic rocks.

INTRODUCTION

Early in the morning of the 29th of May 2006, hot mud started erupting from a rice paddy in the densely populated Porong District of Sidoarjo, East Java (Davies et al., 2007). At flow rates of up to 170000 m^3/day, the mud quickly inundated the city (Mazzini et al., 2007). Over eight years later and 'Lusi' (a conjunction of Lumpur Sidoarjo, or Sidoarjo mud) is still erupting, having expelled over 90 million m^3 of mud at an average rate of approximately 30000 m^3/day, with current rates of approximately 10000 m^3/day (Rudolph et al., 2013). The mud flow has covered 10 km^2 of the city to depths of over 30 meters, engulfing a dozen villages and displacing approximately 40000 people (Tingay, 2010). Lusi is predicted to continue at rates of over 1000 m^3/day until approximately 2018 (Rudolph et al., 2013).

Mud volcanoes are a relatively common feature in sedimentary basins that have been rapidly deposited or are in tectonically active areas (Kopf, 2002). However, this is the first recorded instance of the birth of a mud volcano in a major urban area. Furthermore, the Lusi mud volcano has been surrounded in controversy over how the disaster was triggered. Some scientists argue that the eruption was triggered by the magnitude 6.4 Yogyakarta earthquake that occurred on the 27th of May 2006 (Mazzini et al., 2007; Lupi et al., 2013). However, other researchers propose that the earthquake was too small to trigger the disaster and instead argue that the mud eruption resulted from a blowout in the nearby Banjar Panji-1 (BJP-1) exploration well (Manga, 2007; Tingay et al., 2008; Davies et al., 2008).

This study focuses on undertaking the first direct analysis of the pore pressures observed at the Lusi mud volcano location immediately prior to its eruption. A detailed understanding of the pre-eruption pore pressures has direct implications for understanding the initiation and mechanics of the Lusi mud volcano, and for prediction of eruption longevity (Davies et al., 2011a). Yet, despite these important implications, current pore pressure information for the region only comprises of unverified pre-drill pore pressure predictions, post-drill estimates based on undisclosed methods and different interpretations of bottom-hole kick pressures in the BJP-1 borehole (Davies et al., 2008; Tingay et al., 2008; Sawolo et al., 2009; Davies et al., 2010). In addition, Tanikawa et al. (2010) used porosity and permeability estimates to model an extremely wide range of possible pore pressures in the region, though these results have since been debated owing to inaccuracies in assumed subsurface geology (Davies et al., 2011b) and, more recently, errors in the log data used in porosity determination (Lupi et al., 2014). In contrast, this study focuses on analysis of petroleum industry data collected in nearby boreholes, particularly the Banjar Panji-1 (BJP-1) well located just 150m from Lusi, to establish the initial pore pressures under the Lusi mud volcano location and show that moderate to hard overpressures (greater than 13.0 MPa/km or 11.1 ppg) occur in all sequences below 500m depth and that the onset of overpressure is very shallow (~350 meters). Furthermore, this study discusses the possible origin of overpressures in the region and conducts post-drill pore pressure prediction from a carefully processed and compiled petrophysical log dataset. Petrophysical data and modelled pore pressures indicate that disequilibrium compaction overpressures occur, and can be reliably predicted, in shallow Pleistocene clastic sequences, but that determination of the overpressure origin and prediction of pore pressures is problematic in the deeper volcanic, volcaniclastic and carbonate formations.

The Lusi mud volcano remains the only known example of major damage caused by a mud volcano. Furthermore, it is also a likely extreme example of the devastation that can be caused by a wellbore blowout. Hence, the analysis herein is aimed to be an aid for safe drilling of wells in the onshore East Java Basin, and also represents a fascinating case-study of the difficulties in pre-drill prediction and maintenance of well control in regions of high magnitude overpressure, particularly overpressured non-clastic rocks.

GEOLOGICAL AND GEOCHEMICAL SUMMARY OF THE LUSI MUD VOLCANO

The Lusi mud volcano (7° 31’ 37.8”S, 112° 42’ 42.4”E) is located in the city of Sidoarjo, ~25 km south of Surabaya, the largest city in Eastern Java, Indonesia. Lusi is in the East Java Basin, an east-west trending inverted back-arc basin that underwent extension during the Paleogene and was reactivated during the early Miocene-Recent (Kusumastuti et al., 2000; Kusumastuti et al., 2002; Shara et al., 2005). The Miocene-Recent sequences of the East Java Basin in the region around Lusi are composed of shallow marine clastics and carbonates, marine muds, volcaniclastic sediments and volcanic units from the nearby Penanggungan volcanic complex (located 15 kilometres to the south-west of Lusi). However, despite the many geological studies of the Lusi mud volcano (for example, Davies et al., 2007; Mazzini et al., 2007; Istadi et al., 2009; Tingay et al., 2010), there remain numerous variations and uncertainties with regards to the subsurface geology. Herein, I use existing published results, as well as detailed analysis of mud log data, to describe the lithologies encountered by the BJP-1 borehole, including highlighting common errors in reported lithologies and formations.

The youngest units in the subsurface geology under the Lusi mud volcano consist of clastic rocks in the following sequence (as penetrated by the BJP-1 borehole; Figure 1; Lapindo and Schlumberger, 2006; Davies et al., 2007; Mazzini et al., 2007; Tingay, 2010).

(i) Holocene alluvium composed of alternating sands, shales and volcaniclastics (0-290m, <0.6 Ma).

(ii) Pleistocene-Holocene Pucangan Formation composed of alternating sands, silts and shales from 290 to ~520m and then shales with rare thin sands from 520-900m (0.6-1.1 Ma).

(iii) Pleistocene Upper Kalibeng smectite-illite blue clays (900-1870m) with rare thin siltstones and dolomitic siltstones (1.1-1.7 Ma).

With regards to overpressure generation and analysis, it is particularly important to note that the clastic sequences are overall predominately fine grained (almost exclusively clays below 520m depth) and were rapidly deposited (averaging 1100 m/Ma). Furthermore, high gas readings were observed throughout this sequence, with total background gas readings typically 2-12% total gas; 20000-110000 ppm methane; 3000-14000 ppm ethane; 1000-3000 ppm propane; 200-1000 ppm for both iso-butane and N-butane; 80-200 ppm pentane and 0 ppm H_2S (Lapindo and Schlumberger, 2006; Adams, 2006). This unit also often contained strong oil cuts and trace oil shows (Lapindo and Schlumberger, 2006).

The Pleistocene-Holocene clastic sequences in BJP-1 are underlain by a unit commonly reported as being Upper Kalibeng “volcaniclastic sands” that extends from 1870m to ~2830m depth (Lapindo and Schlumberger, 2006; Davies et al., 2007; Mazzini et al., 2007; Tanikawa et al., 2010). It is interesting to note that this sequence has not been previously reported in any offset wells, with the Upper Kalibeng clays in the nearby Porong-1 well (7 km ENE of Lusi) extending right down to the underlying carbonates (with minor siltstones, sands and volcaniclastics; Kusumastuti et al., 2002). This unit was initially interpreted as “volcaniclastic sands” by the on-site mud logger, and then repeated in most publications examining the Lusi disaster. This unit is extremely hard (5-20 feet/hour drilling penetration rates), has high density (2.55-2.65 g/cm^3), fast sonic velocity (DT = 60-65 μs/ft), high deep resistivity (~20 Ohm-m) and is suggested as being very low porosity (1-10%; Figure 1; Istadi et al., 2009; Sawolo et al., 2009; Tanikawa et al., 2010; Tingay, 2010). However, detailed reanalysis of sidewall cores and drill cuttings reveals that this unit is actually predominately composed of extrusive igneous rocks (primarily andesites, dacites and welded tuffs) that were ground into mostly sand-sized fragments by the drilling process and, thus, mistakenly interpreted as volcaniclastic sands by the mud logger (Tingay, 2010). In addition, there are some interpreted volcaniclastics, possibly due to lahar deposits, as well as minor layers of thin clays, siltstones and carbonates. Indeed, the unit becomes increasingly calcareous from approximately 2600m depth, and the bottom 220m of the unit are interpreted as calcareous volcaniclastics (Lapindo and Schlumberger, 2006). Hence, this unit is now interpreted to be rapidly-formed (approximately 1.7-3.0 Ma) low porosity Pliocene-Early Pleistocene volcanics and volcaniclastics.

The volcanic and volcaniclastic sequences encountered in the BJP-1 borehole also observed strong oil cuts and trace-poor oil shows, as well as significant total gas readings, despite low porosities and general absence of organic material (Lapindo and Schlumberger, 2006). Total background gas readings were typically 1-6%, with generally 25-50% lower overall amounts of gas than is observed in the Kalibeng clays (10000-80000 ppm methane; 500-5000 ppm ethane; 190-2100 ppm propane; 50-300 ppm butane; 10-80 ppm pentane; minor

H_2S near total depth). Furthermore, it is interesting to note that the volcanic sequences observed under Lusi are not obviously different in seismic character (on low quality 2D seismic; Figure 2) to the equivalent shales and silts observed under Porong-1, despite the anomalously high densities and fast velocities (Kusumastuti et al., 2002; Lapindo and Schlumberger, 2006; Mazzini et al., 2007).

The target reservoirs for the BJP-1 well were reefal carbonates, originally (and often since) reported as the Oligocene Kujung carbonates (Davies et al., 2006; Mazzini et al., 2007; Istadi et al., 2009; Tanikawa et al., 2010). The Kujung carbonates are the common reservoir units in the prolific offshore East Java Basin, and are typically not overpressured (Kusumastuti et al., 2002; Sharaf et al., 2005; Ramdhan et al., 2013). However, the carbonates under Lusi are one of a linked series of reefal carbonate build-ups, along a ENE-WSW trend, that have previously been penetrated by the Porong-1, Kedeco-11C, Kedeco-11E and BD wells (Kusumastuti et al., 2002). A red algal fragment from carbonates at the top of the nearby, and stratigraphically equivalent, carbonate build up in the Porong-1 well was dated by strontium isotope ratios as being formed at ~16 Ma (Kusumastuti et al., 2002). Hence, the carbonates underneath Lusi can not be the Oligocene Kujung formation, but are most likely the Middle Miocene Tuban Formation, and possibly equivalents of the Rancak limestone (22-15 Ma; Kusumastuti et al., 2002; Sharaf et al., 2005; Tingay, 2010). The carbonates encountered in the bottom 54m of Porong-1 well were dolomitized limestone (with minor mudstone and packstone), light grey in colour, consisting of bioclasts in a grey matrix (Kusumastuti et al., 2002). Porosity ranged up to 25%, but averaged 15%, and was occasionally vuggy to moldic (Kusumastuti et al., 2002). The carbonates in Porong-1 have fast compressional velocities (~70 μs/ft) and high resistivity (typically >5 Ohm-m; Figure 1). The limestones encountered in Porong-1 contained 50% residual oil saturations, whilst the Miocene carbonates in the Kedeco wells, and presumably BJP-1 (due to no evidence of significant hydrocarbons from Lusi), were fully water saturated (Kusumastuti et al., 2002; Mazzini et al., 2007).

It is not known whether the Miocene carbonates were penetrated by the BJP-1 well. The drillers were intending to penetrate these limestones prior to running casing (Sawolo et al., 2009). However, the well had a total loss of circulation at 2833m, and no cuttings were returned in the bottom four meters of the well following a bottoms-up circulation at 2829m (Davies et al., 2007; Sawolo et al., 2009). Some authors interpret the sudden loss of returns as being indicative of the carbonates being encountered (Davies et al., 2007), while others argue that carbonates were yet at some deeper depth (Istadi et al., 2009). Daily drilling reports note that 25 ppm H_2S was observed when drilling at 2813m depth early on the 27th May 2006, which was followed by 500 ppm H_2S during the kick on the 28th of May (Table 1; Adams, 2006). As the carbonates are the only known source of significant H_2S concentrations in the East Java Basin (Courteney, 1988; Davies et al., 2007), this early H_2S release, and subsequent large amounts of H_2S during the kick, likely indicates that the base of the well was very close to the carbonates, if not inside them. Regardless, there is general agreement that the BJP-1 well either penetrated, or was very close to the Miocene carbonates when total loss of circulation occurred at 2833m depth. Hence, in this study, I assume the Miocene carbonates to be located at ~2833m depth (terminal depth of the

BJP-1 well). Seismic data suggests these carbonates extend to approximately 3500m depth (Figure 2; Tingay, 2010).

The anatomy of the Lusi mud volcano has been extensively studied, but several key uncertainties remain (Mazzini et al., 2007; Istadi et al., 2009; Mazzini et al., 2009; Tingay, 2010). The extruded mud is primarily a simple mixture of clays and water, with ratios that have varied over time (initially 20-40% clay, but thickening over time to be 50-70% clay in 2010; Tingay, 2010). The clays have been accurately identified from foraminifera as being from the upper Kalibeng formation. However, the key uncertainty is the origin of the erupted waters (Tingay, 2010). Several models for the Lusi eruption argue that the erupted waters are also primarily (or at least initially) sourced from the Upper Kalibeng clays that have undergone extensive liquifaction (Mazzini et al., 2007; Tanikawa et al., 2010; Lupi et al., 2013). However, others argue that the mud volume and flow rate is too great to be fully sourced from the Kalibeng clays (Davies et al., 2007; Davies et al., 2008; Tingay et al., 2008; Davies et al., 2011a; Rudolph et al., 2011). Recent geochemical analysis of erupted gases suggests that there is a significant contribution of erupted material from depths greater than the Kalibeng clays, indicating that the waters primarily come from the Miocene carbonates, and possibly even a deeper hydrothermal source (Mazzini et al., 2012). Hence, the model favoured herein for the current anatomy of the Lusi mud volcano is that erupted waters are primarily sourced from the Miocene carbonates, and reach the surface via a network of fractures associated with reactivation of a nearby fault zone (the Watukosek fault zone; Mazzini et al., 2009), and possibly open sections of the BJP-1 wellbore. The waters entrain the highly thixotropic Kalibeng clays en-route to the surface (entraining both clay and formation water).

PETROPHYSICAL LOG DATA FOR THE LUSI REGION

A detailed study of the overpressures under the Lusi mud volcano requires a reliable, high quality and consistently processed petrophysical log dataset. Unfortunately, available log data for the BJP-1 well contains numerous errors and artifacts that have propagated into many other studies (Istadi et al., 2009; Tanikawa et al., 2010; Istadi et al., 2012; Lupi et al., 2013; Lupi et al., 2014). Hence, a key component of this study is the careful compilation of the first ever properly processed and quality controlled petrophysical log dataset for BJP-1, free of major artifacts and consistent with drilling records, lithologies, mud log records and nearby wells drilled through the same formations (Figure 1). This dataset is designed to also be a validated, robust and easily available petrophysical dataset, so that basic and obvious mistakes do not continue to be propagated into future studies into the Lusi mud volcano.

Petrophysical logs are extremely prone to errors during both acquisition and processing (Tittman, 1986; Schlumberger, 1989; Rider, 1996; Asquith and Krygowski, 2004), and thus require careful processing, analysis and vigilance before being used. It is a general rule in the petroleum industry that petrophysical log data should not be simply trusted or used without careful checking of the data and without a solid understanding of the potential errors in the data. Many common acquisition artifacts are the result of borehole enlargement, such as washout, breakout and rugose hole (Tittman, 1986;

Schlumberger, 1989; Rider, 1996; Asquith and Krygowski, 2004), all of which are visible in the caliper logs of BJP-1 (Figure 1 and Figure 3). Furthermore, errors and artifacts are also extremely common near casing points, where log data can be strongly affected by the steel and cement casing, as well as by the highly irregular, and often poorly cleaned out, rathole underneath the casing shoe (Tittman, 1986; Schlumberger, 1989; Figure 3). Artifacts and errors can also result through processing methods (Tittmann, 1986). For example, logs are often initially rapidly processed at the rig-site, in order to confirm that sufficient data was obtained, to make urgent real-time analysis for determining formation tops, or whether to case the hole or drill deeper. However, rig-site processing typically utilizes automatic routines, without any manual quality control, resulting in spurious and unreliable data for detailed analysis. For example, automatic sonic log processing routines are prone to picking false first p-wave and shear-wave arrivals, resulting in spurious velocities (Tittman, 1986; Schlumberger, 1989; Rider, 1996; Asquith and Krygowski, 2004). Automatic processing routines, or subsequent processing that does not adequately compensate for borehole enlargements, does not use correct time-gates and careful manual checking of arrivals. This will commonly misinterpret echoes, mud arrivals, body waves, or signals from prior or later pulses as first arrivals, resulting in either erroneously fast or spuriously slow estimated compressional and shear velocities (Tittman, 1986; Schlumberger, 1989). For these reasons, it is standard industry practice for log data provided by service companies, even after several processing efforts, to be regarded as unreliable and require extensive in-house correction prior to use.

Rugose hole also strongly affects density, neutron porosity and, to a lesser affect gamma ray logs (Tittman, 1986; Schlumberger, 1989; Rider, 1996; Asquith and Krygowski, 2004). Density and neutron porosity logging tools are required to be pressed hard against the wellbore wall, otherwise they measure the density or hydrogen index of drilling mud and filter cake, rather than just the formation properties, typically yielding erroneously low density and high porosity values (Tittman, 1986; Schlumberger, 1989). Gamma ray values need to be carefully corrected for borehole size, as less signal received by the tool in enlarged borehole, resulting in erroneously low gamma ray values (Schlumberger, 1989; Rider, 1996).

The BJP-1 wellbore is extensively enlarged and irregular for almost the entire clastic sequence, but particularly in clays between 520-1800m depth (Figure 3). This is confirmed by observations of wellbore instability during the drilling of BJP-1, which resulted in setting the 16” casing shoe shallower than planned (Table 1), and also by observations of washout and borehole breakout, visible on image logs, through the same sequences in the neighboring Wunut Field (Tingay et al., 2010). Artifacts related to borehole enlargements are extremely prevalent in petrophysical log data in the BJP-1. For example, the sonic velocity data presented in Istadi et al. (2009) and Lupi et al. (2013) contains a high velocity zone between 890-1270m depth that is a result of measured velocity of the steel and cement 13.375” casing, as well as spuriously high velocities due to borehole enlargement in the 14.5” rathole below the 13.375” casing. These errors are obvious, and the velocities are impossibly fast for Pleistocene overpressured clays, yet were assumed as correct and used to calculate porosities in Istadi et al.

(2009) and Istadi et al. (2012), for porosity, pressure and permeability models in Tanikawa et al. (2010), and seismic models in Lupi et al. (2013). A significantly improved petrophysical dataset is available that is derived from Lapindo and Schlumberger (2006), and published partially in Istadi et al., 2012 and fully in Lupi et al., 2014. However, this dataset also contains numerous obvious and uncorrected acquisition and processing errors (Figure 3). For example, compressional velocities between 300-1000m depth are strongly affected by borehole breakout and enlargements in the 17.5" and 14.5" borehole, and artifacts in the rathole below the 16" casing shoe. These generate non-existent fast and slow zones and data spikes, such as the approximate water (drilling mud) velocities at 650-700m depth (impossibly slow for sediments), to velocity spikes and artifacts between 800-900m depth (too high, plus some too slow spikes).

Detailed analysis of available log data demonstrates that all previously available petrophysical datasets for BJP-1 (Lapindo and Schlumberger, 2006; Istadi et al., 2009; Istadi et al., 2012), and particularly sonic and density log data in the clastic sequences, contain extensive errors and artifacts and can only be regarded as unreliable. As such, they should not be used for analysis into any aspects of the Lusi mud volcano. In order to rectify this, and provide reliable data to be used for pore pressure or other analysis, careful reprocessing, and correction of log data was undertaken for this study. The creation of the petrophysical dataset herein was undertaken through:

- exhaustive and detailed examination of all available BJP-1 data;
- compilation and comparison with nearby offset wells;

- reprocessing of original log data where possible;
- applying industry-standard filters for correcting or removing common artifacts and errors;
- normal corrections to appropriate lithologies (e.g. correction neutron density from its typical limestone reading);
- comparison, estimations and correlations with related data (e.g. checkshot velocity data compared to compressional sonic, resistivity and density data compared to sonic velocities), and;
- receiving collaboration, advice, assistance and valuable discussions with petroleum industry petrophysics experts.

All of these approaches are standard practice for the development of reliable log data used routinely for a variety of petroleum applications (Tittman, 1986; Schlumberger, 1989; Rider, 1996; Asquith and Krygowski, 2004). This has resulted in the final comprehensive, quality-checked, verified petrophysical dataset presented herein (Figure 1). This dataset thus represents the first reliable petrophysical dataset for the Lusi region, free of the numerous significant errors observed in previously published and utilized studies.

DRILLING EXPERIENCES ON BANJAR PANJI-1

Several studies have examined the events that occurred during the drilling of the BJP-1 well (Adams, 2006; Tingay et al., 2008; Davies et al., 2008; Sawolo et al., 2009; Davies et al., 2010). However, there are numerous inconsistencies and interpretations of some key events (Sawolo et al., 2009; Davies et al., 2010). Furthermore, careful analysis of raw data presented in Sawolo et al. (2009) indicates a number of potentially significant errors in interpretations of observations during the kick event, losses and well control efforts (Adams, 2006). For example, Sawolo et al. (2009) state that 20 barrels of losses occurred at approximately 6:02am on the 27th of May 2006, ~8 minutes after the Yogyakarta earthquake. These were minor losses, not even noticed during drilling, which continued as normal, but are argued to possibly indicate a connection between the earthquake and losses in BJP-1. However, the actual raw data presented in figure 12 of Sawolo et al. (2009) has both 6:00am and 5:00am printed on it. Most significantly, the losses are clearly indicated to have occurred when drilling at ~2827m depth. Yet, the daily drilling report (DDR) notes that the 05:00 drilling depth was 2827.5m, while the drilling depth at the time of the earthquake was 2829m (Sawolo et al., 2010). Given average drilling rates in the volcanics are 2-6 m/hr, the raw data strongly indicates that these minor losses occurred prior to the earthquake, and not slightly afterwards.

Because of the many multiple drilling data interpretations, as well as some clear interpretation errors (Sawolo et al., 2009; Davies et al., 2010), this study has made significant efforts to carefully compile the most detailed summary of key events that occurred during the drilling of BJP-1 and the different interpretations and significance of these events (Table 1).

PORE PRESSURE OBSERVATIONS FROM WELLS NEAR LUSI

No direct pore pressure measurements, such as wireline formation interval tests or drill stem tests, are available for the BJP-1 well. However, reliable indications of the pore pressure are available from mud weight used to drill the well, in combination with observations of the well flowing, connection gases, elevated levels of background gas and the shut-in stabilization pressure during the major kick. Such data has not previously been used to estimate initial pore pressures under the Lusi mud volcano, with all prior estimates coming from the pre-drill prediction and post-drill sonic and drilling-exponent estimates, all of which used undisclosed methodologies (Tingay et al., 2008; Sawolo et al., 2009; Figure 4). Sawolo et al. (2009) also present a resistivity based post-drill pore pressure prediction, but this is deemed too unreliable to use owing to a lack of useful pore pressure scale, inclusion of erroneous resistivity data and uncertainty about figure data depths.

Mud weight is often assumed to be a proxy for pore pressure, as mud weight is generally kept only slightly above pore pressure to prevent kicks, while not significantly reducing rate of penetration (Mouchet and Mitchell, 1989). However, mud weight on its own is not an ideal pore pressure indicator, because it may be significantly elevated above pore pressure due to several reasons, such as to improve borehole stability, or ahead of expected high pore pressures (Mouchet and Mitchell, 1989). Mud weight can also be below pore pressure, without taking a kick, if drilling through very low permeability sequences (Mouchet and Mitchell, 1989). However, mud weight can be considered a good indicator of the pore pressure when it is combined with observations of formation fluids entering the wellbore, such as significantly elevated gas readings during drill string connections (connection gases), during drilling (elevated background gas) and minor formation influxes (Mouchet and Mitchell, 1989; Sagala and Tingay, 2012). Minor influxes of formation fluids during connections will only occur if the pore pressure is above the static mud pressure, yet these influxes are not observed during mud circulation, and thus also indicate pore pressure is below the equivalent circulating density (ECD). ECD is typically 0.2-0.6 MPa/km above static mud weight in 12.25” holes, but varies due to hole size, pump rate, hole cleaning, bottom hole assembly (BHA) make up, and mud properties. Connection gases can also be generated if swabbing occurs during connections, resulting in minor gas influx at pore pressures slightly below static mud weight. However, there is no record of back-reaming or hole wiping during connections, and thus significant swabbing during drilling connections is unlikely (Adams, 2006; Sawolo et al., 2010). Elevated gas readings (significantly above typical background gas levels) during drilling often indicate that pore pressure may be close to the ECD, while minor fluid influxes can indicate pore pressures slightly greater than static mud weight or ECD, depending on when they occur (e.g. during drilling, tripping, running casing; Mouchet and Mitchell, 1989). Hence, connection gases, elevated background gases and minor fluid influxes indicate that the formation pore pressure is approximately equal to or only slightly above the static mud weight (Sagala and Tingay, 2012). Herein, all of these events are assumed to indicate pore pressure that is approximately equal to static mud weight, as limited details on these events are available and accurate ECD is unknown (approximate ECD available only for 25-27th June 2006; Sawolo et al., 2009).

The ‘BJP-1 Data Montage’ (Lapindo and Schlumberger, 2006) contains a total of six events reported as “gas flows”, with the shallowest at only 460m depth. These ‘gas flows’ were usually in association with a static influx test confirming that a minor influx was occurring, and are interpreted herein as minor kicks (Figure 4).

In addition, high connection gases were reported 40 times, while elevated background gas levels, typically several hundred units or more above typical levels, were reported 13 times (Figure 4; Lapindo and Schlumberger, 2006). Finally, a major kick event commenced whilst pulling out of hole on the 28th of May 2006, during which shut-in drill pipe pressure reached 620 psi, and stabilized at 375 psi (Table 1; Sawolo et al., 2009; Davies et al., 2010). These suggest a stabilized kick pressure gradient of 18.11 MPa/km at the bottom of the hole (Davies et al., 2010), which is assumed herein to be the approximate terminal depth pore fluid pressure, and possibly indicates pore pressures in the Miocene carbonates. Indeed, the BJP-1 kick pressure is consistent with pore pressures measured by kicks and wireline formation interval tests (WFIT) in the carbonates in the nearby Porong-1 well (7 km away; Figure 4; Kusumastuti et al., 2002; Davies et al., 2007).

The pore pressures estimated herein from influxes, connection gases, mud weight and a major kick reveal a pore pressure profile that is largely sub-parallel to the lithostatic trend from a top of overpressure at approximately 350m depth right down to a depth of 2800m (Figure 4; lithostatic gradient calculation described in detail in the pore pressure prediction section). This pore pressure profile is quite consistent with, though slightly higher than, predicted pre-drill pore pressures (Tingay et al., 2008; Sawolo et al., 2009), as well as post-drill pore pressure estimates based on drilling exponent and sonic data (Figure 4; Sawolo et al., 2009). Furthermore, the pore pressure data for BJP-1 presented herein is also consistent with reported WFIT pore pressures from the shallow Wunut Field that overlies the BJP-1 location (Kusumastuti et al., 2000). The only major deviation from the lithostatic parallel trend occurs at the bottom of the hole, where the calculated high kick pressures of 18.11 MPa/km are observed, and likely indicate higher magnitude overpressures in the Miocene carbonates.

The overpressures observed in BJP-1, Wunut and Porong are quite consistent with observations of pore pressure in other wells of the East Java Basin (Ramdhan et al., 2013). Onshore and offshore wells show significant overpressures from quite shallow depths (~750m) and of over 16.0 MPa/km magnitude (Ramdhan et al., 2013). Overpressures are typically observed in the Miocene or younger fine grained sequences, such as Tuban Fm shales. Oligocene Kujung carbonates typically have no or minor overpressures, further suggesting that the overpressured carbonates near Lusi are not the Kujung formation. Overpressures in the East Java Basin are also associated with large porosity anomalies and constant vertical effective stress profiles with depth, suggesting overpressure generation by disequilbrium compaction (Ramdhan et al., 2013). The shallower onset of overpressure, and higher pore pressure magnitudes, observed in BJP-1 are most likely due to the locally faster deposition rates and higher heat flows associated with being more proximal to the Penanggungan volcanic complex than the wells examined by Ramdhan et al. (2013). This is further supported by indications that pore pressures are slightly lower in the more distal Porong-1 well than in BJP-1 and Wunut (Figure 4).

DISCUSSION ON OVERPRESSURE ORIGIN

Pore pressure data compiled herein provide some insights, as well as several challenging questions, regarding the origin of overpressure that is primarily driving the Lusi mud volcano. Overpressures in the shallower Pucangan and Kalibeng clastic sequences appear to have a classic disequilibrium compaction profile, in which overpressures are generated by the rapid loading of effectively sealed sequences (Osborne and Swarbrick, 1997). Such lithostatic-parallel pore pressures (constant vertical effective stress with depth) and shallow (~350m) overpressure onset (and likely similar fluid isolation or fluid retention depth) is highly consistent with the Pleistocene to present-day regional geology of extremely rapid burial of primarily fine-grained sediments. Swarbrick (2012) models that an ~350m fluid retention depth would be expected in clay-rich sequences deposited at 1100m/Ma rates, such as observed in the Lusi area. Furthermore, these sequences are characterized by almost constant compressional slowness values of between 150-180 μs/ft for almost the entire ~1870m of clastic sequences, as well as approximately constant density, resistivity, neutron porosity and shear wave velocity from 1090-1870m depth (13-3/8” casing shoe depth to top of volcanics; Figure 1). The consistent petrophysical log values suggest that there is very little porosity change with depth (Figure 1) in the clastic sequences, and further supports the hypothesis of disequilibrium compaction overpressures.

The numerous connection gases and gas influxes in the volcanics, as well as the major kick suggested to come from the Miocene carbonates, all demonstrate that the volcanic and carbonate sequences are also highly overpressured (~17.2 MPa/km and ~18.1 MPa/km respectively). Yet, the lithology of these sequences, as well as other observations from the BJP-1 borehole, make it difficult to establish the overpressure origin. The volcanics have extremely fast p-wave velocities of between 4700-5100 m/s and densities of 2.58-2.65 g/cm3, all of which suggest very low porosity rocks (1-10%; Figure 1). Disequilibrium compaction is most typically associated with undercompaction, and thus the occurrence of such tightly compacted rocks is in stark contrast with disequilibrium compaction overpressures. Furthermore, volcanic and carbonate sequences often have 'stress insensitive' matrix frameworks that do not compact in the same way as clastic rocks with increasing vertical stress (Lubanzadio et al., 2002; Mallon and Swarbrick, 2002). The only other mechanism that has been suggested to be able to generate such high magnitude overpressures is kerogen to gas maturation (Osborne and Swarbrick, 1997; Tingay et al., 2013). Yet, this is only applicable for rocks containing large amounts of mature source rock material, and neither the clastic, volcanic nor carbonate sequences contain any significant amounts of gas-prone source rock, despite the observation of elevated drill gas readings throughout the BJP-1 well.

Whilst the low porosity volcanic rocks are expected to have extremely stiff frameworks, and likely low matrix permeability, it is possible that they are significantly fractured and have zones of relatively high permeability. Rocks with higher matrix stiffness tend to be more prone to fracturing, especially in the high stress environments such as the East Java Basin (Tingay et al., 2010). Resistivity logs show numerous zones in which shallow resistivity is significantly higher than deep resistivity (Figure 1), indicating extensive invasion of resistive oil based drilling mud into the formation, and thus providing strong evidence of permeable zones in the volcanics. Furthermore, the proximity of these rocks to the Watukosek fault zone, as well as the occurrence of gas influxes and some minor loss events, all support, to some degree, the hypothesis of zones of fracture dominated permeability in the volcanics. It is interesting to note that observed pressure gradients in the volcanics are essentially the same as the lower parts of the Kalibeng clays. This suggests that overpressures in the volcanics may be the result of downwards vertical or lateral transfer, that may be tapped into the Kalibeng clays via faults and fractures (Tingay et al., 2007), or via upwards vertical or lateral transfer from the underlying carbonates (suggested by Mazzini et al., 2012). Note that no direct pressure observations are available from the bottom 100m of BJP-1, and thus it remains uncertain whether pressures deep in the volcanics may be related to those in the deep carbonates, although H_2S observations near final depth strongly indicate some communication with the carbonates. Another possibility is that the generation of overpressures in the volcanic sequences are the result of disequilibrium compaction, via load transfer, due to the inability of fracture porosity to become compacted (Ramdhan and Goulty, 2010; Lahann and Swarbrick, 2011).

Overpressures in the deep carbonates are difficult to examine, as no petrophysical data is available for the bottom section of BJP-1, but log data is available for the similarly overpressured carbonates in Porong-1 (Figure 1). It interesting to note that the pore pressure gradients in the deep carbonates lie upon an approximately lithostatic-parallel trend (Figure 4), which may indicate that these overpressures are primarily generated by disequilibrium compaction, with a possible additional influence of lateral transfer.

In summary, it is suggested herein that overpressures in the Pleistocene clastic sequences are generated by disequilibrium compaction overpressures resulting from the rapid burial of primarily fine-grained sediments. The existence of high magnitude overpressures in volcanic and carbonate sequences is highly unusual, as these sequences appear to be stiff and largely insensitive to burial-driven compaction, but do have indications of permeable zones, most likely due to fractures in the volcanics and matrix or fracture permeability in the carbonates (Figure 1). Whilst it is hypothesized that these sequences may be overpressured through an unusual process, such as vertical transfer, load transfer or disequilibrium compaction of fractures, the origin of these overpressures is, as yet, unknown.

IMPLICATIONS FOR PORE PRESSURE PREDICTION

Post-drill pore pressure prediction has been attempted herein based on compressional sonic, shear sonic, resistivity and corrected drilling exponent (D_{xc}) data compiled in this study. Pore pressure prediction was undertaken using the standard Eaton (1972) methods and exponents (Figure 5). Whilst this prediction yields a good fit to pore pressure observations in the shallow clastic sequences (<1870 m depth), the primary purpose of this prediction is not simply to accurately replicate the observed pore pressures, but rather to highlight the challenges in predicting pore pressures in the highly overpressured volcanic and carbonate sequences.

Vertical stress magnitude has been obtained from integrated measured and estimated density information via the standard petroleum industry method

(Figure 1; Figure 4; Tingay et al., 2003). Density log data was obtained for the 12.25" borehole section and has been corrected for borehole effects herein (Figure 1). Shallow density data at the BJP-1 location has been estimated herein from available density data in the overlying Wunut Field and from estimating density from BJP-1, Porong and Wunut sonic log and checkshot velocity data via the standard Gardner (1979) relationship (Figure 1; Figure 4). The Gardner (1979) velocity-density relationship provides an excellent fit when tested in all shallow and deep zones where both sonic and density data are available in BJP-1 and nearby Wunut wells (Figure 1).

A Bowers-type shale normal compaction trend (NCT) for the compressional slowness and shear slowness data (Bowers, 1994) and semi-log shale NCT for resistivity and corrected drilling exponent data (D_{xc}; Mouchet and Mitchell, 1989) have been estimated assuming a departure from the NCT at the approximate top of overpressure (350 m; Figure 5). The NCT is based on shale compaction, and thus is only applicable for the clay-rich clastic sequences, but appears consistent with offset well data (Figure 1). Little information is available regarding likely NCTs for volcanics or the Miocene carbonates, and it is doubtful that NCTs would be relevant for pore pressure prediction in these lithologies. However, thin shales also exist in the volcanics, particularly near the top of the unit. Thus, all shale NCTs have been extrapolated into the upper parts of the volcanics to see if these thin shales might be used for pore pressure prediction, and also to highlight the problems that arise in trying to predict pore pressure in overpressured non-clastic rocks.

The results of the simple compressional and shear sonic, resistivity and D_{xc} based pore pressure prediction are presented in Figure 5. Pore pressures are predicted accurately in the clastic sequences, as may be expected given the 'classic' undercompaction signature of these disequilibrium compaction overpressures. Pore pressure estimated from Dxc seems to provide a reasonable match to observed values for the entire well, possibly because Dxc was less influenced by the volcanics than petrophysical log data (Figure 5). All petrophysical logs slightly under-predict pore pressure in two thin shales, located near the top of the volcanics (between 1900 and 1950m), (Figure 5). However, pore pressures predictions using petrophysical data significantly underestimate pore pressure in the low porosity volcanic sequences if a shale NCT is used (Figure 5). Indeed, it is extremely difficult to predict pore pressures using typical petroleum industry methods in these volcanic sequences unless an unrealistic NCT is used. For example, assuming a constant sonic slowness NCT of 37 μs/ft in the volcanics would yield a predicted pore pressure that accurately matches kick and connection gas data. However, such sonic slowness values (equal to compressional sonic velocities of over 8.2 km/s) are unreasonable and significantly faster than those typically measured in volcanic rocks (Wohletz and Heiken, 1992).

That the pore pressure observations in volcanics in BJP-1 can potentially be 'fitted' using a simple and unrealistic NCT only serves to highlight the dangers in undertaking pore pressure prediction without a solid geological basis, and the ease in which these prediction methods can be abused. In this instance, the volcanics have a constant velocity with depth, and have a pore pressure profile that is broadly lithostatic-parallel. Hence, it is easy to 'trick' any porosity or effective stress based pore pressure prediction methodology into fitting the pore pressure observations simply by selecting a NCT that simulates enough undercompaction to yield matching pore pressures. This 'forced fit' approach to pore pressure prediction is, somewhat cheekily, referred to as "*cheatin' with Eaton*", and is an unfortunate and easy trap to fall into if geologically relevant and realistic approaches are not made.

The simple attempt at pore pressure prediction undertaken herein highlights the great difficulty in both pre-drill and post-drill pore pressure prediction, and thus safe drilling, in the East Java Basin as well as other basins containing non-clastic overpressured rocks. Whilst it is relatively easy to predict pore pressures in the clastic sequences, there is, as yet, no clear or reliable way to predict the pore pressures in the volcanic or carbonate sequences, though using Dxc showed promise. Standard pore pressure prediction methodologies are typically designed to work only in shales, and rely on overpressures being generated by disequilibrium compaction and, thus, having a porosity anomaly. Furthermore, the volcanics and carbonates herein do not have any indication of the sometimes observed petrophysical response directly due to overpressure, even when absent any porosity anomaly (e.g. Hermanrud et al., 1998; Tingay et al., 2009), and which may be predicted from modified Eaton (1972) or Bowers (1994) methods. Hence, overpressures in such low porosity and non-clastic rocks simply cannot be predicted using existing standard industry methods, unless highly questionable variations are made (e.g. unrealistic NCTs, extremely high Eaton exponents, simplification of factors affecting D_{xc}). Furthermore, the occurrence of this thick volcanic sequence was not prognosed prior to drilling (Istadi et al., 2009; Sawolo et al., 2009). The volcanics are not apparent on the poor quality 2D reflection seismic (Figure 2), nor are they observed in nearby offset wells, such as Porong-1, which only encountered Kalibeng shales above the Miocene carbonates (Kusumastuti et al., 2002; Figure 1). Hence, the data from the BJP-1 well is unusual in that it provides both a 'textbook quality' example of disequilibrium compaction overpressures and pore pressure prediction, but also a public example of highly anomalous overpressures in volcanic and carbonate rocks, and the great difficulty of pore pressure prediction in non-clastic lithologies.

IMPLICATIONS FOR TRIGGERING OF THE LUSI MUD VOLCANO

The key controversy surrounding the Lusi mud volcano is the long-running debate about whether the eruption was originally triggered by the major kick that occurred in the Banjar Paji-1 well (Davies et al., 2008; Tingay et al., 2008; Table 1), or by the May 27th 2006 Yogyakarta earthquake (Mazzini et al., 2007; Mazzini et al., 2009; Lupi et al., 2013). The pore pressure data discussed herein is particularly relevant to the most recent study on the triggering debate, in which is it argued that a major change in shallow acoustic impedance contrast acted to reflect and focus the seismic waves generated by the Yogyakarta earthquake (Lupi et al., 2013).

Lupi et al. (2013) originally argued that a 'high velocity layer', located between 1000-1090 m depth at BJP-1, acted as a parabolic-shaped reflector to concentrate the energy of the earthquake seismic waves. It has since been demonstrated that this 'high velocity layer' was actually the result of Lupi et al. (2013) mistakenly using sonic-log measured casing velocities in their compressional velocity model, and thus proposing that a 90 meter thick layer of cement and steel existed in the Earth (Figure 3; Lupi et al., 2014). Lupi et al. (2014) have since acknowledged this mistake, but instead claim that earthquake waves were reflected and amplified by a 370 m/s shear-wave velocity contrast, located at ~900 m depth, and that this contrast is entirely due to a sharp overpressure onset at this depth. Indeed, Lupi et al. (2014) propose that vertical effective stress (VES) changes sharply by 9 MPa at this depth, suggesting a sudden jump in pore pressure by 9 MPa, or an increase in pore pressure gradient from hydrostatic (~10 MPa/km) to highly overpressured (~20.0 MPa/km) at approximately 900m depth.

The pore pressure data compiled herein indicates that no such sharp pore pressure variations exist in either the clastic or volcanic/volcaniclastic sequences (Figure 4). Indeed, the final estimated pore pressure profile (Figure 5) is approximately lithostat-parallel, as expected in disequilibrium compaction overpressures, the most common overpressure generation mechanism in sedimentary basins (Osborne and Swarbrick, 1997), and displays a gradual increase in pore pressure increase from hydrostatic at ~350m to 17.2 MPa/km at ~1300m depth. There is no evidence for the 9 MPa VES change proposed by Lupi et al (2014). Indeed, the ~20 MPa/km pore pressure at 900m depth required by Lupi et al. (2014) to generate their large shear velocity anomaly is far greater than the fracture gradient and lithostat in BJP-1, and is thus impossible (Figure 5).

The pore pressure and vertical stress data herein can be used to directly calculate VES, and demonstrates that VES varies gradually by only 0.6 MPa (changing from 2.7 to 3.3 MPa) from 500-1100m depth. The maximum of 0.6 MPa VES variation in the shallow clays is both far smaller than that proposed by Lupi et al. (2014), but is also over a broader depth range, rather than being a sudden sharp jump. Hence, VES changes are unlikely to result in any significant acoustic impedance contrast under Lusi.

The absence of any sharp jump in pore pressure gradient suggests that no major shear-wave velocity changes exist between the surface and ~1300m at the Lusi location. This is further confirmed by petrophysical analysis of compressional and shear-wave velocities, as well as the absence of any apparent shallow reflectors at the BJP-1 location on 2D seismic (Figure 2). Measured shear-wave velocity data exists below the 13-3/8" casing shoe at ~1090 m depth. Lupi et al. (2014) propose that a sharp shear-wave contrast exists just above the top of measured data (Lupi et al., 2014). However, there is a well-established positive correlation between compressional and shear-wave velocity in clastic rocks (Castagna et al., 1985; Lee, 2010), with compressional and shear-wave velocities always responding in a similar manner, aside from when VES is below 1.0 MPa, or in fully gas saturated formations (neither of which are applicable to BJP-1). Thus, available compressional wave data can be used to reliably predict shear-wave velocity for the shallow clastic sequences (Castagna et al., 1985; Figure 1), and further indicates that no significant shear-wave velocity contrasts exist in the clastic sequences. Indeed, the largest shallow shear wave impedance contrast estimated by the petroleum industry-standard Castagna (1985) method is located at ~840m depth, where two thin sands at the base of the Pucangan Formation result in an ~40m thick zone with a shear wave velocity contrast of only ~35 m/s (Figure 3). The thin sands at the base of the Pucangan (also observed in the Wunut Field) form the only visible acoustic impedance contrast between 520-1350m in the Lusi area. These thin sands form a very poor reflector on 2D seismic, although this reflector (and all other shallow reflectors) is not clearly visible at the Lusi location (Figure 2). Hence, all geological and geophysical data collected in BJP-1, and regional 2D seismic, confirms that no significant velocity contrasts exist in the clastic sequences under Lusi, and only a very weak shear wave velocity contrast may be expected due to the thin base Pucangan sands.

In order to further test the initial shear wave velocity model created herein, an additional three shallow shear wave velocity models have been created using other common petroleum industry methods (Figure 1). Shear slowness was estimated using fuzzy logic and genetic algorithms, trained and tested using available log data (Rezaee et al., 2007; Rajabi et al., 2010). Furthermore, shear slowness was estimated by the same Lee (2010) method used in Lupi et al. (2014) to derive their shear velocity profile, but using the reliable pressure and petrophysical datasets presented herein (Figure 1). All four different methods, using different input datasets, all provide consistent shear-wave velocity models (Figure 1). These models have been further tested by using them to undertake pore pressure prediction, which can be done using shear wave velocity in a similar way to using compressional wave velocity (Ebrom et al., 2003). The pore pressures predicted from the modeled and measured shear wave velocities match with observed pore pressures in the clastic sequences (Figure 5), providing solid verification that the shallow shear wave estimates generated herein are reliable.

The pore pressure data and estimated shear-wave velocities determined in this study are in stark contrast to the pore pressure, VES and velocity models proposed by Lupi et al. (2014.). The data in this study indicates that there is no evidence to support the hypothesis that a significant pore pressure contrast exists at ~900m depth, nor that there are any significant shallow shear-wave velocity changes (of more than ~35 m/s) in the upper 1300m of clastics at the Lusi location. Lupi et al. (2013) also suggest that their results may be further amplified if a three-dimensional, rather than two-dimensional dome exists. However, the geology of the Lusi region is composed of approximately E-W to ENE-WSW trending major folds, with only very minor, gentle and broad folding along a N-S axis (Kusumastuti et al., 2000; Kusumastuti et al., 2002; Shara et al., 2005), and thus there is no valid argument to suggest anything other than a 2D domed structure. Hence, the results of this study indicate that the ‘geometric focusing of seismic waves’ theory proposed by Lupi et al. (2013), whilst interesting, has no basis given that no major compressional or shear wave impedance contrasts exist above the Kalibeng clays.

IMPLICATIONS FOR LONGEVITY AND EVOLUTION OF LUSI

One of the most important issues related to managing and dealing with the Lusi mud volcano disaster is in estimating the likely duration of the mud eruption.

Most common geological disasters (e.g. earthquakes, tsunamis, volcanic eruptions) are extremely devastating, but occur over a relatively brief time frame of minutes to days, and thus efforts can be made to quickly repair and rebuild damaged areas. However, the Lusi mud volcano is an on-going disaster, causing continual gradual damage for over eight years. Hence, it is vital to understand how long the eruption will continue, and how the area will evolve, in order to best manage the disaster (Istadi et al., 2009; Rudolph et al., 2013).

The pore pressure data compiled herein provides some key input data for longevity predictions of the Lusi mud volcano. Initial pore pressures are identified as a key uncertainty in models used to predict the likely longevity of the Lusi mud volcano (Davies et al., 2011). In particular, the data presented herein can be used to place narrower uncertainties on the pore pressures in the Miocene carbonates and the Kalibeng clays, which are proposed to be the primary drivers of the Lusi mud volcano (Istadi et al., 2009; Davies et al., 2011; Rudolph et al., 2011). Indeed, Davies et al. (2011) proposed that pore pressures in the Miocene carbonates were between 13.9 and 17.6 MPa above hydrostatic, whilst the data presented herein indicates that these pore pressures are ~23.0 MPa above hydrostatic.

The volume of overpressured clays available to be erupted is also significantly influenced by the initial pore pressure data presented herein. Istadi et al., 2009 proposed that only a 500m thick layer of overpressured clays were available as a source for erupted mud, but the data herein demonstrate that this is a significant underestimate due to previous use of erroneous sonic velocity data and assumption of a top of overpressure at much deeper depths (Figure 3). However, the data presented herein indicates that the entire 970 meters of Kalibeng clay sequences is highly overpressured, as well as clays in the Pucangan Formation, and thus that potentially more clay material is available for eruption than previously estimated.

The initial pore pressure information herein suggests that the Lusi mud volcano may erupt for longer than has been previously modeled. However, it is important to highlight that this study has not focused on estimating longevity of the Lusi mud volcano, and that this is, in itself, an extremely complex problem in which many variables play a key role. Indeed, it is important, and extremely positive, to note that the eruption rate from the Lusi mud volcano has reduced rapidly in recent years. Eruption rates now average only 10000 m3/day (down from ~100000 m3/day initial rates), and recent analysis of surface deformation predicts a further tenfold decrease in eruption rate by ~2018 (Rudolph et al., 2013).

CONCLUSIONS

This study presents the first in-depth compilation and analysis of pore pressure information from the BJP-1 borehole, and other nearby wells, in order to establish the initial state of pore pressure prior to the triggering of the Lusi mud volcano (as well as providing a comprehensive dataset of petrophysical, drilling and geological data for the region). Available data from fluid influxes, connection gases, elevated background gases, a major kick and mud weight, in addition to observed pore pressures in proximal offset wells and pore pressure estimates based on three petrophysical datasets and corrected drilling exponent, indicates that all rocks from approximately 350m depth down to the Miocene carbonates (located at ~2833m depth) are highly overpressured. Pore pressures follow an approximately lithostatic-parallel profile below the 350m overpressure onset depth, especially in the Pleistocene clastic sequences. Of particular note, this study highlights that high magnitude overpressures exist in non-clastic, and even non-sedimentary, rocks, with pore pressure gradients of over 17.2 MPa/km observed in the volcanic, volcaniclastic and carbonate sequences below 1870m depth.

The pore pressure data presented herein yields key insights into the Lusi mud volcano disaster. The pore pressure, drilling and carefully processed and corrected petrophysical data in this study have significant implications for understanding the trigger to the Lusi mud volcano, and further support the argument that this disaster was the result of a blowout in the BJP-1 well. Furthermore, the data herein provides a valuable resource for future analysis of the likely longevity and evolution of this major mud volcano system. Finally, this study provides a unique example of both ‘textbook quality’ disequilibrium compaction overpressure and anomalously high magnitude pore pressures in non-clastic rocks. The dichotomy of overpressured lithologies highlights our ability to reliably predict pore pressure in classic disequilibrium compaction overpressure, and reiterates the significant challenge facing the petroleum industry as we increasingly target highly overpressured non-clastic reservoirs, such as high pressure carbonate oil fields in Iran and overpressured sub-salt carbonate-hosted oil fields offshore Brazil.

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FIGURE CAPTIONS

Figure 1: BJP-1 lithology, formations, casing points and available petrophysical data, as well as available petrophysical data from the Wunut Field and Porong-1 well, all located within seven kilometers of the Lusi mud volcano (original data sourced from Kusumastuti et al., 2000; Kusumastuti et al., 2002; Lapindo and Schlumberger, 2006; Mazzini et al., 2007; Istadi et al., 2009; Sawolo et al., 2009; Tanikawa et al., 2010; Istadi et al., 2012; Lupi et al., 2014). All depths are in meters TVD relative to rotary table. Petrophysical data has been carefully processed, checked and corrected for significant errors caused by the poor logging conditions (see caliper log). Density data has been estimated for some sections from p-wave velocity data, as per the Gardner (1979) relationship, and provides a good match to measured data from BJP-1 and offset wells. Shallow shear wave sonic slowness data has been estimated using the Castagna et al.

(1985) method, Lee (2010) method and by fuzzy logic and genetic algorithm methods (Rajabi et al., 2010), and provides a reliable match to measured shear wave data. Porosity estimates from sonic, density and corrected neutron porosity log data all yield consistent results and suggest that the shales have relatively constant porosities (35-45%) with depth, while the volcanic sequences have very low porosities (2-10%).

Figure 2: East-west 2D reflection seismic section (modified after Mazzini et al., 2007) with the author's interpretation (two way time in seconds; key reflectors dashed where inferred due to low seismic quality). Seismic quality is generally poor, particularly near the BJP-1 drilling site. In particular, note the lack of any noticeable difference in seismic character from the volcanic sequences, which trend into Lower Kalibeng clays and silts towards the Porong-1 well, seven kilometers to the east (just off of the seismic section). Furthermore, there is a notable absence of any significant or continuous seismic reflectors visible in the shallow sequences above the Kalibeng clays in the immediate vicinity of the BJP-1 well. This is consistent with the absence of any major compressional or shear-wave velocity contrasts in the petrophysical and checkshot velocity data (Figure 1). Listed depths are at the BJP-1 well location and all reflector two way times are verified from BJP-1 checkshot data.

Figure 3: (a) Previously published velocity data for BJP-1, checkshot velocity data, raw field-processed sonic log data and the final carefully processed and corrected compressional sonic velocity data presented herein. (b) BJP-1 casing points, formations and lithologies. (c) Caliper log data from BJP-1. (d) BJP-1

measured shear wave slowness (DTS) and consistent estimates of shallow DTS made using four different methods. Previously published sonic velocity data (Lapindo and Schlumberger, 2006; Istadi et al., 2009; Istadi et al., 2012; Lupi et al., 2013; Lupi et al., 2014) contains numerous errors and artifacts for the entire length of the BJP-1 wellbore. Errors include inclusion of casing velocities, high and low velocity acquisition artifacts caused by borehole rugosity and breakout, and artifacts generated by improper, rapid or unchecked processing. All previously published velocity models are spurious and unreliable and should not be used for any studies on the Lusi mud volcano.

Figure 4: Compilation of all available pore pressure information from the BJP-1 well, as well as the nearby Wunut Field and Porong-1 well and previously published pre-drill and post-drill pore pressure predictions (data sourced from Kusumastuti et al., 2000; Kusumastuti et al., 2002; Lapindo and Schlumberger, 2006; Davies et al., 2007; Mazzini et al., 2007; Tingay et al., 2008; Davies et al., 2008; Istadi et al., 2009; Sawolo et al., 2009; Tanikawa et al., 2010; Istadi et al., 2012). All pressure gradients are in MPa/km (or kPa/m) and depths are in meters true vertical depth relative to rotary table (11.2m above ground level). Where possible, unpublished original data has been verified against secondary data, checked for accuracy and confirmed by reliable published or reported values. Note that Porong-1 appears to have slightly lower pore pressures in the Pucangan and Kalibeng clay sequences than observed in BJP-1 and Wunut, based on WFITs, lower leak-off pressures, slightly faster compressional velocity and higher resistivity (Figure 1).

Figure 5: Predicted pore pressures using compressional sonic, shear sonic, resistivity and corrected drilling exponent (D_{xc}) data, as well as the final estimated pore pressure for BJP-1 utilizing all available data (thick light blue line). Pore pressure predictions use the standard Eaton (1972), with the displayed normal compaction trends (in red), corrected petrophysical and drilling data (in dark blue), shale zones (in purple) and typical exponents of 1.2 for resistivity and D_{xc}, 3.0 for compressional sonic slowness and 2.5 for shear sonic slowness (Mouchet and Mitchell, 1989; Ebrom et al., 2003). The basic post-drill pore pressure prediction undertaken herein provides a very good fit to the observed pore pressure data in the clastic sequences, and is consistent with other published pre-drill and post-drill predictions made using undocumented methods (Tingay et al., 2008; Sawolo et al., 2009). However, standard pore pressure prediction methods using petrophysical data fail to predict pore pressures in the volcanic sequences, and significantly underestimate pore pressure (dark blue dotted line) unless unrealistic normal compaction trends or Eaton (1972) exponents are used. This highlights both the reliability of pore pressure prediction methods in disequilibrium compaction overpressured shales, and the inability of existing petroleum industry methods to predict pore pressure in overpressured non-clastic rocks.

Table 1: Timing of key events during drilling of BJP-1. All dates and times are local (UTC +7 hours). Significant observations and interpretations are italicized in bold. Data is compiled from Adams, 2006; Davies et al., 2008; Tingay et al., 2008; Sawolo et al., 2009, and Davies et al., 2010.

Date and Time	Event
8/3/2006, 1330hrs	Spud BJP-1 well.
14-15/3/2006	Run and cement 20" casing to 364m, ~13m shallower than planned.
18/3/2006	Commenced raising mud weight (MW) due to indicators of high pore pressure.
20/3/2006	Increases in background gas. Hole partially packed off, BHA pulled free with 25 klbs overpull. MW raised to 14.6 MPa/km. Decision made to set 16" casing shallow.
22/3/2006	Wireline logging. Caliper indicates need to ream hole. Reamed with 17.5" BHA to 702m. Indications of pack-off and cavings. MW increased to 14.8 MPa/km for wellbore stability.
24/3/2006	Run 16" liner. Worked through obstruction at 471m. Washed and worked down. Could not run shoe past 666m. Liner shoe set at 666m, ~310m shallower than planned.
25/3/2006	Gas bubbling from hole for several hours. Indications that 16" liner cement was inadequate and that a gas zone behind casing was leaking. Run in and perform liner top cement squeeze.
28-29/3/2006	BHA packed off twice while drilling rat hole. Long open hole LOT performed, 16.7 MPa/km. Squeezed cement. Drill out and repeat LOT, 17.0 MPa/km.
7-8/4/2006	Drilled 14.5" hole to 775m, reaming from 670-680m. Pumps broke. ~16 days for repairs.
24/4/2006	Recommence drilling 14.5" hole with 15.6 MPa/km MW.
25-26/4/2006	Commenced drilling Kalibeng Clays. Indications of high pore pressure at 1028m, MW increased to 15.8 MPa/km. Flow observed at 1067m. Circulate and continue drilling with 15.8 MPa/km mud to 1096m. Flow observed, increase to 16.4 MPa/km mud. Pumped out of hole, tight at 1041m and 983m. Increased cuttings over shakers.
27-29/4/2006	Wireline logged. Reamed into hole. Large volumes of cuttings, MW raised to 16.7 MPa/km. Run 13.375" casing. Well flowing, possible ballooning. Casing shoe at 1091m, ~280m shallower than planned. 50 bbls losses prior to cement job. Partial and then total losses during cement job, some ballooning back. Total of 756 bbls lost displacing and pumping cement, marginal cement job.
5/5/2006	***Perform final LOT.*** Originally interpreted as 18.4 MPa/km, interpretation changed to 19.3 MPa/km on 8/5/2006. Davies et al. (2010) observed that formation breakdown and fracture propagation pressure misinterpreted as leak-off pressure. Correct leak-off pressure 18.56 MPa/km. Curved leak-off test profile suggests 13.375" shoe not sealing due to poor cement job.
6-7/5/2006	Increasing connection gases, background gases and minor flow. MW raised to 17.2 MPa/km and then to 17.3 MPa/km.
9/5/2006	Commenced drilling volcanics and volcaniclastics. ROP drops from 27 m/hr to 1 m/hr.
11/5/2006	***Decision made not run 11.75" liner at 1992m*** and drill to planned 9.675" casing point instead.
21/5/2006	Reached planned 9.675" casing point at 2630m. Drill to 2667m. Raise MW to 17.6 MPa/km. Pull out of hole to run wireline logs, collect sidewall cores and run checkshot survey.
24/5/2006	Checkshot survey suggests top of carbonate could be as deep as 2926m. ***Decision made to continue drilling revised casing point*** at the shallowest of either the top of the carbonates or a maximum depth 2865m.
26/5/06, ~0200 hrs	***H_2S (25 ppm) encountered at 2813m***. First H_2S observed 3 hours before earthquake.
26/5/06, 0554 hrs	***M_w 6.3 Yogyakarta earthquake occurs***. BJP-1 hole at 2829m. Final cuttings from this depth.
26/5/06, ~0602 hrs *or ~0500 hrs?*	Minor (20 bbls) losses observed. ***Inconsistencies in reported time and depth of these losses***. Sawolo et al. (2010) state losses at 0602 hrs, ~7 mins after quake. However, Sawolo et al. (2009) raw data (their figure 12) notes losses at ~2827m and at ~0500 hrs – an hour before the earthquake and shallower than borehole depth at time of quake (correlates with 2827.5m reported 0500 hrs depth). ***Uncertainty over whether losses occurred ~7 mins after quake (and thus possibly related to quake) or whether losses occurred ~1 hour before quake.*** Losses are minor and were not reported during operations, drilling continued without pause.
27/5/06, 0807 - 1122 hrs	Three major aftershocks occur near Yogyakarta. M_w 4.4 at 0807 hrs, M_w 4.8 at 1010 hrs and M_w 4.6 at 1122 hrs. Some authors argue for a connection between aftershocks and later total losses.
27/5/06, 1250 hrs	***Total loss of circulation observed at final hole depth of 2833.7m.*** Total losses reported by Sawolo et al. (2010) as 130 bbls, but inconsistent with mud report. Mud report at 0500 on 28/5/06 states total 607 bbls lost over previous 24 hours, with 142 bbls lost during pull out of hole, suggesting up to 462 bbls lost at TD.
27/5/06 1300 – 2200 hrs	Spotted 60 bbl LCM, pulled out to 2663m. ***Check well – static.*** 600 bbls of new mud made and transferred to trip tank, indicating loss event was possibly greater than reported 130 bbls.
27/5/06 2300 hrs – 28/5/06 0625 hrs	Continued pulling out of hole, pumping roughly every 5 stands. Needed to work pipe while pumping out of hole from 2652m to 2591m. Overpull increasing. Only 50% returns at 2469m. Pull out to 1981m, unable to keep hole full, total volume displacement hard to

	counter - ***indicates losses ongoing continuously while tripping out, verified by losses on mud report***.
28/5/06 0625 – 0730 hrs	***Well flowing at 0625 hrs***. Pumped and pulled 2 more stands. ***Well kicked at 0730 hrs***. Water kick, >365 bbls to surface, 500 ppm H2S and 20% gas. Well shut in 0753 hrs.
28/5/06 0730 – ~1130 hrs	Well control. Stabilized DP pressure 350 psi, max casing pressure 1054 psi. Casing pressure bled off through choke. Three periods of pumping 18.2 MPa/km mud to circulate influx – ***casing pressure spikes then drops while pumping with hole closed, indicating downhole losses during kick, confirmed by mud engineer reporting up to 300 bbls losses***. Sawolo et al. (2010) suggests well dead at ~0805 hrs, but casing and DP pressure increases and trip tank increases demonstrate influxes until ~1030 hrs. BOP opened and well static for 1 hr.
28/5/06 ~1130 – 1430 hrs	Attempting to free stuck BHA. BHA stuck at 1275 m depth. Able to circulate from 1230 - 1420 hrs, but with only partial (50-60%) returns – ***indicates ongoing downhole losses***. ***DP pressure increase and trip tank increase from 1420-1430 indicates kick re-occurring***.
28/5/06 ~1430 – 2100 hrs	Lost ability to circulate ~1430 hrs. ***No further returns from BJP-1 well – indicates BHA totally packed off***. DP pressure increasing without pumping from ~1430 - ~1500 hrs – ***indicates kick still ongoing***. DP pressure slowly drops from ~1500 – 1615 hrs, increases from ~1620-1630 hrs, gradually decreases from ~1630 – 1845 hrs, increases again briefly and then reduces again from 1900 – 2100 hrs – ***indicates ongoing downhole losses with occasional influx***.
28/5/06 2130 – 2300 hrs	Release trapped DP pressure. Spot 40 bbl soaking pill. No returns.
29/5/06 0200 – 0300 hrs	Sharp DP pressure increase – ***indicates influx***. Pressure bled out of DP, 35 ppm H_2S observed at surface. DDR reports "bubbling around surface".
29/5/06 ~0500 hrs	***Lusi eruption commences at the surface***, Gas bubbles containing 5 ppm H_2S "100 feet SW of flare pit". Eruption intermittent with bursts up to 8 m high at ~5 minute intervals.
29/5/06 ~0630 hrs	Pumped 185-230 bbls of 17.3 MPa/km mud down DP. DDR states that "bubbles intensity reduced and elapse time between each bubble is longer". After pumping, eruption bursts reduced to 2.5 m high and at ~30 minutes intervals – ***indicates direct communication between BJP-1 and Lusi mud volcano***.
29/5/06 ~2300 hrs	Pumped 200 bbls 18.8 MPa/km mud with LCM at 4 bbl/min.
30/5/06 0500 – 1000 hrs	Pumped 50 bbls of 18.6 MPa/km cement slurry followed by 100 bbls of 18.8 MPa/lm mud. Wait on cement and monitor eruption, DDR notes "bubbles already decreased in activity since the night" – ***suggests that pumping mud and cement had reduced Lusi eruption rate, further evidence that BJP-1 in direct connection with Lusi***.
30/5/06 2230 hrs	Pumped 100 bbls of 18.6 MPa/km cement slurry to isolate BHA from open hole below.
31/5/06 0330 hrs	Performed injection test at 2.5 bbl/min at 2.55 MPa surface pressure. ***No indication of communication between BJP-1 and Lusi – indicates that either cement slurry had isolated BHA from Lusi, or open hole below BHA had bridged due well being sheared by fracturing or due to rock material brought up by eruption.***
31/5/06 ~0900 hrs	Lusi mud volcano activity increased overnight. Attempts made to control flooding.
31/5/06 0930 – 2100 hrs	Run free point survey. "Pipe free from 8% to 40% over interval of 700 to 3200 feet. Several depths were 100% stuck". Stuck point between 790 and 980m depth. This demonstrates that ***packed off and stuck point has moved 295-485m upwards since ~1200 hrs 28/5/06. Stuck point now inside 13.375" casing, demonstrating that significant rock material was pushed into casing over previous 3 days, confirming that kick was not killed on morning of 28/5/06.***
1/6/06 0500 – 1700 hrs	Run into hole with string shot and cut drill string at 911m depth. Commence pulling out of hole. ***Cracks observed in ground around rig. Cracks oriented between BJP-1 and Lusi eruption***.
2/6/06	Continued pulling out. Cement plugs set at 789-850 m and 640 – 686 m depth.
3/6/06	Rigging down to abandon well. Run in and tag cement plug at 643 m depth, test plug with 8 klbs.
4/6/06 0000 hrs	BJP-1 abandoned and rig released.

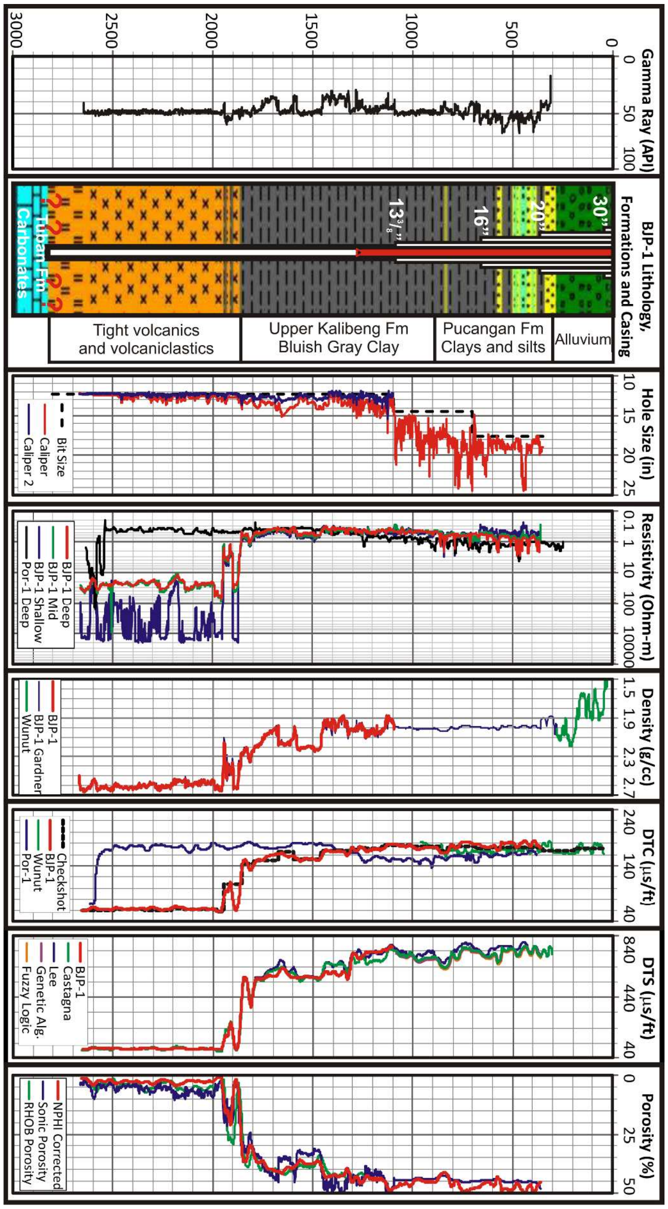

Figure 1
281x510mm (300 x 300 DPI)

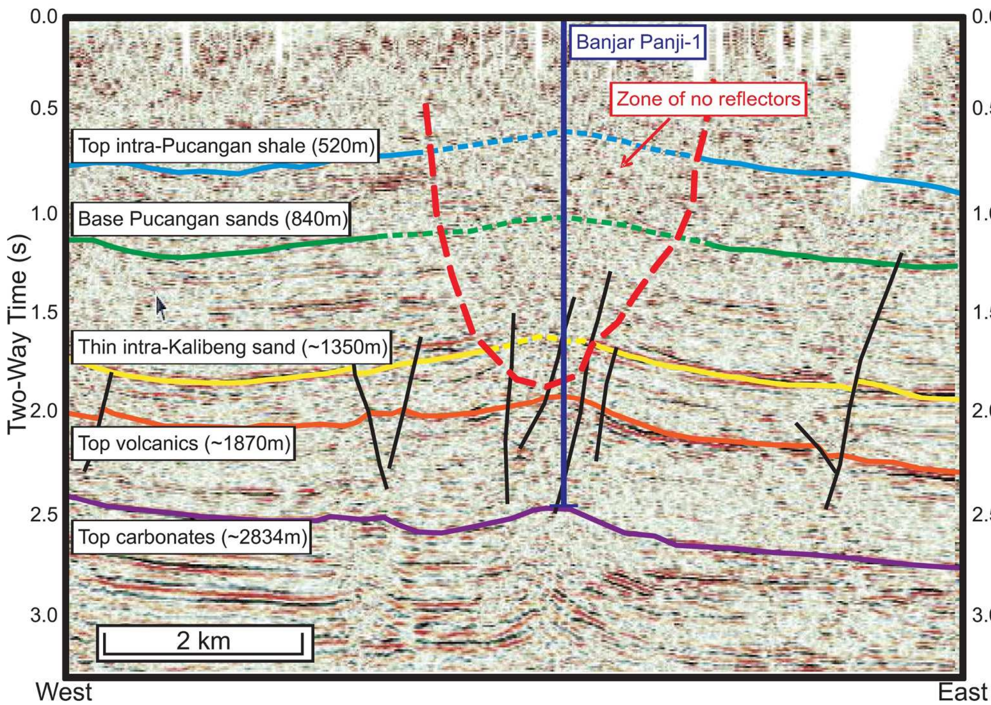

Figure_2
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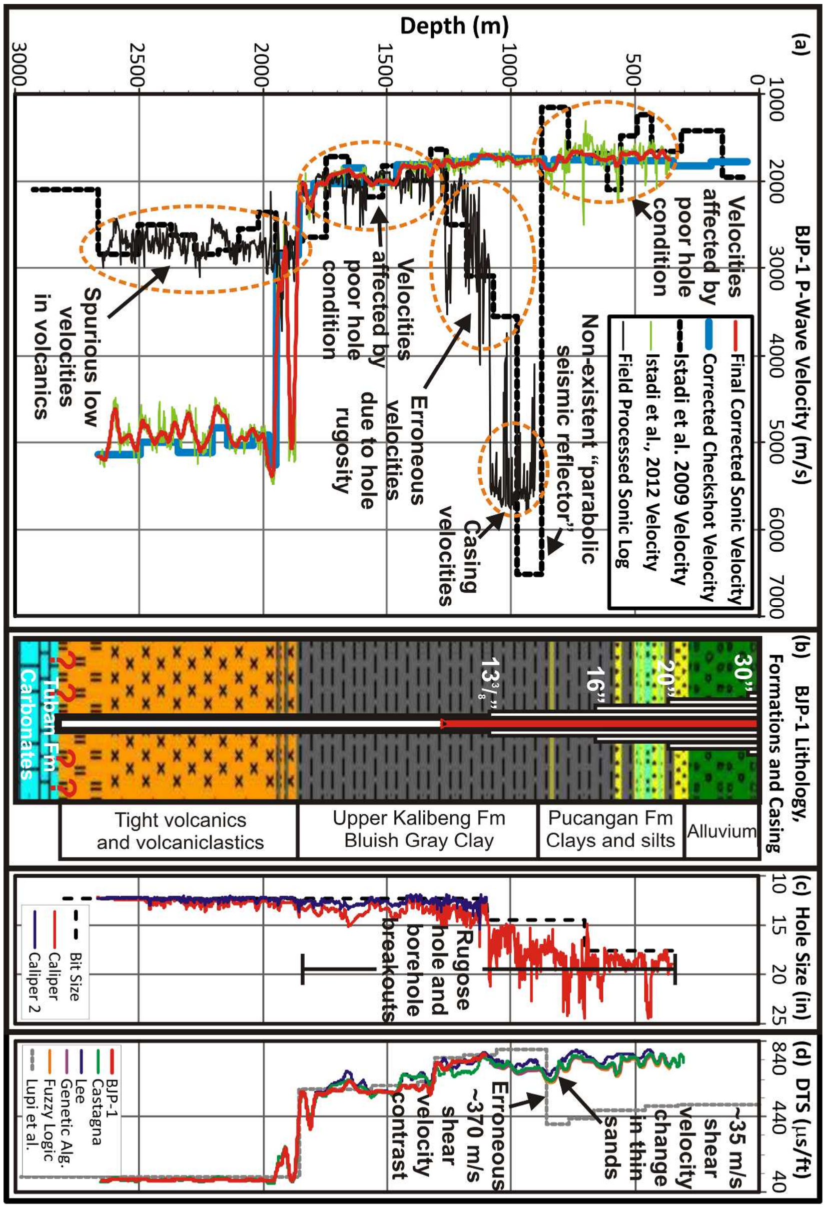

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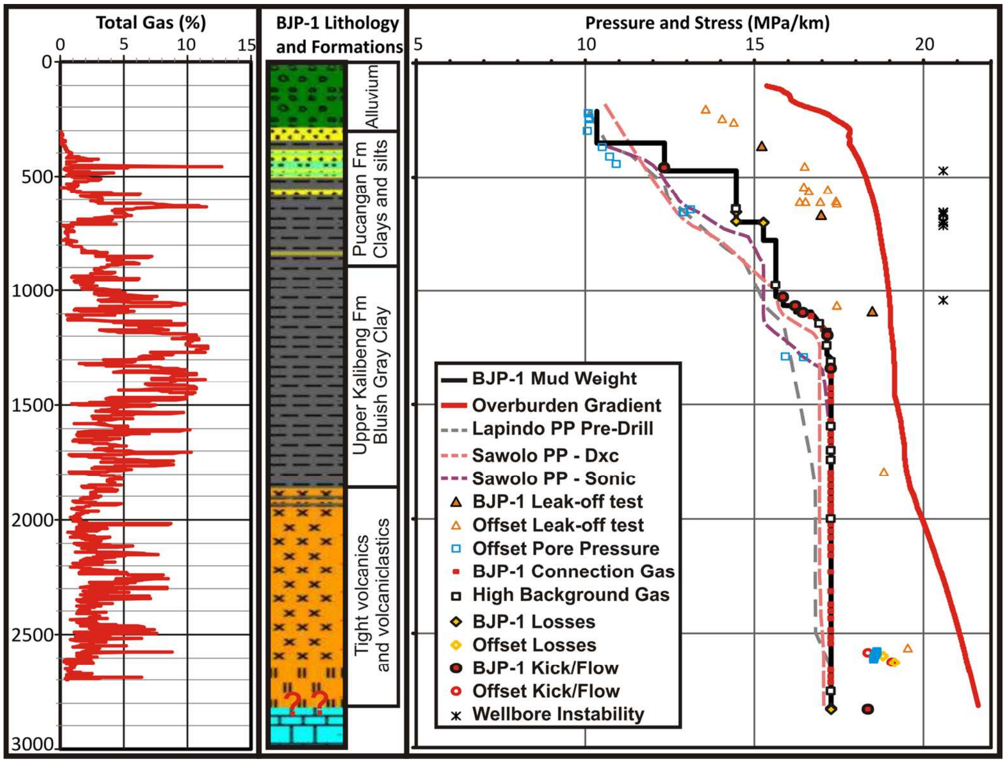

Figure 4
155x117mm (300 x 300 DPI)

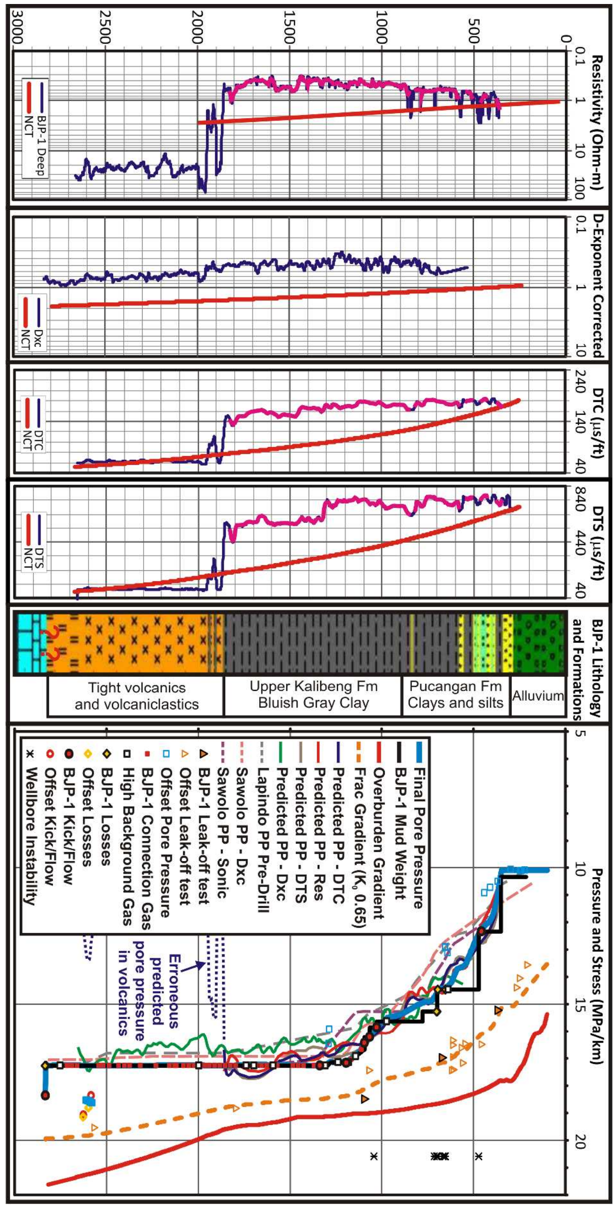

Figure 5
306x605mm (300 x 300 DPI)