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Probabilistic longevity estimate for the LUSI mud volcano, East Java

RICHARD J. DAVIES[1]*, SIMON A. MATHIAS[1], RICHARD E. SWARBRICK[1,2] & MARK J. TINGAY[3]

[1]*Department of Earth Sciences, Durham University, Durham DH1 3LE, UK*

[2]*GeoPressure Technology, Mountjoy Research Centre, Durham DH1 3UZ, UK*

[3]*Department of Applied Geology, Curtin University, Perth, WA 6845, Australia*

**Corresponding author (e-mail: richard.davies@dur.ac.uk)*

Abstract: A new method for estimating the duration of a mud volcano eruption is applied to the LUSI mud volcano in East Java. The estimate is based upon carbonates at depths in the range 2500–3500 m being the water source, with an estimated area of 100–600 km^2, thickness of 0.2–1.0 km, porosity of 0.15–0.25, an initial pressure between 13.9 and 17.6 MPa, and a separate, shallower source of mud (*c*. 1200–1800 m depth). The resulting 50 percentile for the time it takes for flow to decline to <0.1 Ml day^{-1} is 26 years. By analogy with natural mud volcanoes it can be expected to continue to flow at lower rates for thousands of years. Assuming subsidence rates of between 1 and 5 cm day^{-1}, land surface subsidence of between *c*. 95 and *c*. 475 m can be expected to develop within the 26 year time period.

The eruptive behaviour of mud volcanoes is highly variable. Kilometre-scale mud volcanoes in Azerbaijan and Trinidad show evidence for cyclic behaviour: violent, potentially destructive, eruptions generally lasting a matter of hours to days, interspersed with longer dormancy periods (Deville & Guerlais 2009; Deville *et al.* 2010). Metre-scale mud volcanoes near Wootton Bassett (UK) have very low eruption rates, and there are no historical records of violent eruption (Bristow *et al.* 2000). Estimating the longevity of mud volcanoes has not been attempted before because they either erupt in regions of low population density (e.g. Azerbaijan) or are small enough to be benign (e.g. Wootton Bassett, UK). However, the LUSI mud volcano in East Java is unique on Earth as it covers 7 km^2 and erupted in a populated region of Sidoarjo in East Java, causing 13 000 families to lose their homes.

LUSI (Fig. 1) has the highest eruption rate for a mud volcano on Earth, of up to 180 000 m^3 day^{-1}, but rather than being cyclic it has been in a vigourous eruptive state since its initiation on 29 May 2006 (Davies *et al.* 2007, 2008; Sawolo *et al.* 2009). The volcano is subsiding at rates of up to 5.5 cm day^{-1} (Abidin *et al.* 2008; Istadi *et al.* 2009). Initially there were five eruption sites, roughly aligned in a NE–SW direction (Mazzini *et al.* 2007), but subsequently one of these sites became the main central vent, which is now *c*. 50 m wide (Fig. 1). Because of the subsidence and high water content in the erupted water–mud–gas mix, the mud volcano has a low relief (Fig. 1). Unusually, the subsurface geology is well defined by two commercial hydrocarbon exploration wells, one of which was drilled 150 m away from what became this main vent, and 2D seismic reflection across the area. The current continuous nature of the mud flow, coupled with the lack of knowledge of the mud flow's likely duration and evolution, makes management of the disaster extremely difficult and completely different from other geological catastrophes, such as earthquakes and tsunamis.

The aim of this paper is to use the two exploration wells and knowledge of the subsurface from 2D seismic reflection data to propose a probabilistic method for the estimation of the longevity of the LUSI mud volcano, and by doing so estimate the final impact of this humanitarian and ecological disaster.

Subsurface geology

The Banjar Panji-1 gas exploration well, which was drilled 150 m from the mud volcano was targeting the carbonates of the Prupuh Formation. The well had drilled through (1) alluvial sediments, (2) Pleistocene alternating sandstone and shale of the Pucangan Formation (to 900 m depth), (3) Pleistocene bluish grey clay of the Upper Kalibeng Formation (to 1871 m depth), and (4) volcanic rocks and volcaniclastic sandstones at least 962 m thick (Figs 2 and 3). The last cuttings sample contained 5% carbonate and the well had drilled 281 m past the predicted depth of the top of the Prupuh Formation when drilling stopped because of significant drilling mud losses at 2813 m. Mud losses are a common phenomenon in Miocene carbonates in Indonesia. Kusumastuti *et al.* (2002) used seismic reflection data to show that the carbonate build-ups are of elongate form, striking NE–SW, and part of the Prupuh Formation. The Porong-1 well, located 6 km away from LUSI and drilled in 1993, penetrated 55 m of the Early Miocene Prupuh Formation with porosity ranging from 5 to 30% and a water column; other wells drilled on trend penetrated greater thicknesses with porosities from 11 to 32% (Kusumastuti *et al.* 2002). Our interpretation is therefore that the well drilled either to just above or most probably into the Prupuh Formation.

Micropalaeontological recovery from the LUSI mud volcano shows that the source of the mud is from depths of 1300–1800 m within the Upper Kalibeng Formation (Mazzini *et al.* 2007), dominated by overpressured mudstone. The Banjar Panji-1 well provides an uncased hole with diameter 0.3 m immediately above, or potentially into the top of the Prupuh Formation through the low-permeability volcanic and volcaniclastic sandstone and the Upper Kalibeng Formation.

The water in the mud is considered to originate from one of three sources: (1) the mudstones of the Upper Kalibeng Formation, proposed by Mazzini *et al.* (2007) using geochemical criteria; however, phyllosilicate mudstones ($>40\%$ clay fraction) have permeabilities of between 10^{-18} and 10^{-21} m^2 (Yang & Aplin 2010) and are not capable of transmitting water at the rates measured, although the mudstones could contribute to the erupted waters and change their chemistry; (2) the volcaniclastic

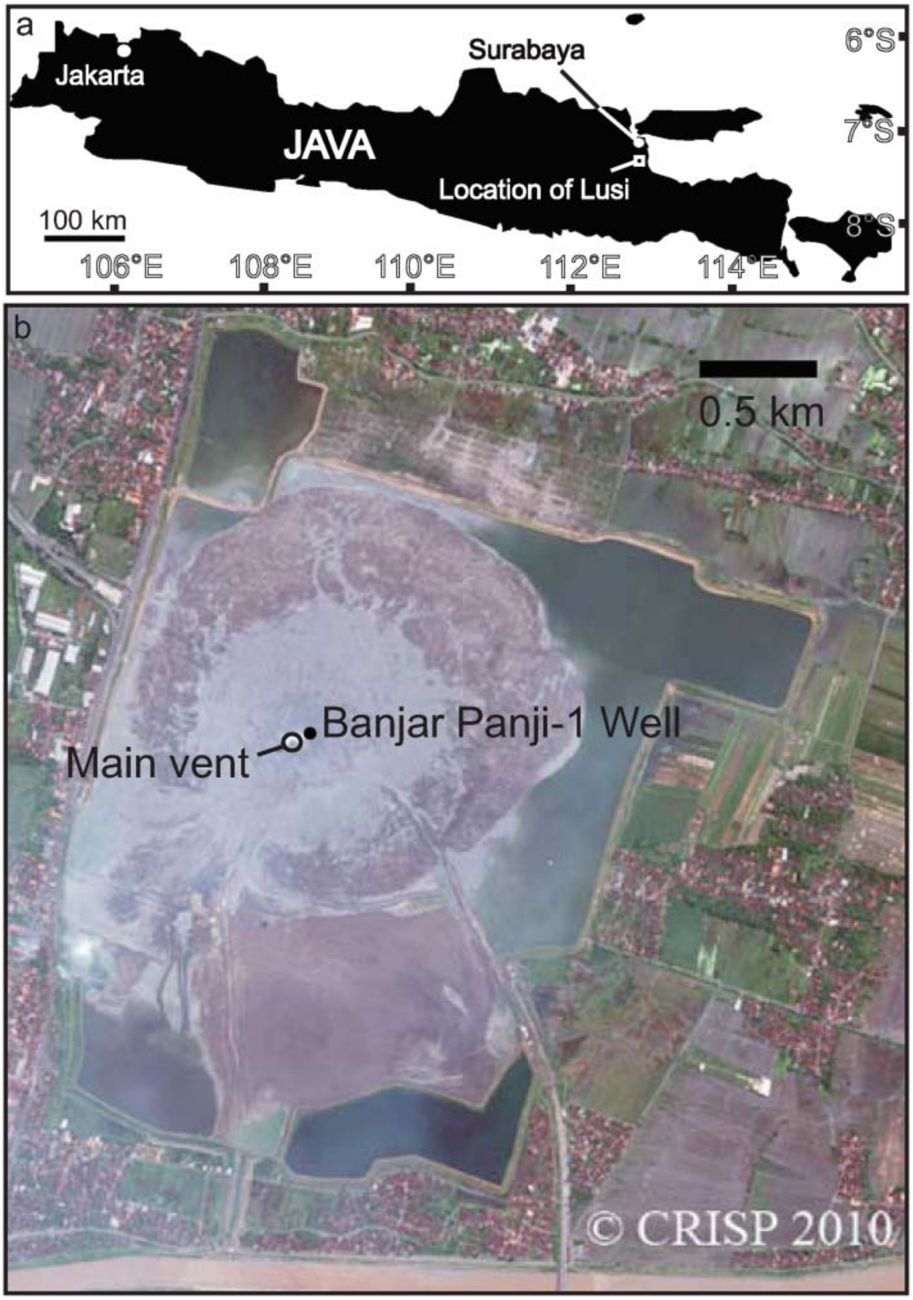

Fig. 1. (**a**) Location map. (**b**) Satellite photograph (May 2010) of LUSI and surrounding area.

sandstone between 1871 and 2830 m depth, but with a bulk porosity of only 0.02–0.06 this will have an extremely low permeability; (3) the carbonate reef build-ups (Prupuh Formation), based on the need for a high-volume and high-temperature fluid source (Davies *et al.* 2007, 2008); these carbonates were originally ascribed to the Kujung Formation by Davies *et al.* (2007), but are more likely to be part of the Prupuh Formation (see Kusumastuti *et al.* 2002). The eruption rate was initially 120 000–180 000 m^3 day^{-1} (Mazzini *et al.* 2007) of which 60% was water (Istadi *et al.* 2009) at an estimated temperature of 100 °C. Down-hole measurements indicate a geothermal gradient of *c.* 42 °C km^{-1} (Mazzini *et al.* 2007). Therefore a high-permeability aquifer at greater than 2.4 km depth is required. The Early Miocene Prupuh Formation has been proven by drilling (Porong-1 well) and is the only formation that meets both these requirements (e.g. Tanikawa *et al.* 2010).

There has been much debate as to whether LUSI was triggered by drilling or natural earthquake (see Davies *et al.* 2008; Sawolo *et al.* 2009; Davies *et al.* 2010; Sawolo *et al.* 2010). Rather than attempting to address this debate further, this paper seeks to investigate the implications of the Banjar Panji-1 wellbore drilling into and depressurizing the Prupah Formation from a hydrogeological perspective. Once a breach to surface is established, it is hypothesized that water initially rises through Banjar Panji-1 wellbore, mixes and entrains shallower mudstones of the Upper Kalibeng Formation (Figs 2 and 3) and then migrates up the Watukosek fault, producing an initial NE–SW-trending alignment of mud volcanoes (Fig. 2). This concept of a deeper source of fluid mixing with overpressured mudstone is consistent with many other mud volcano systems, where the source of the water is deeper and isolated from the source of mud (Bristow *et al.* 2000; Kopf *et al.* 2003; Deville *et al.* 2010). Water migrates

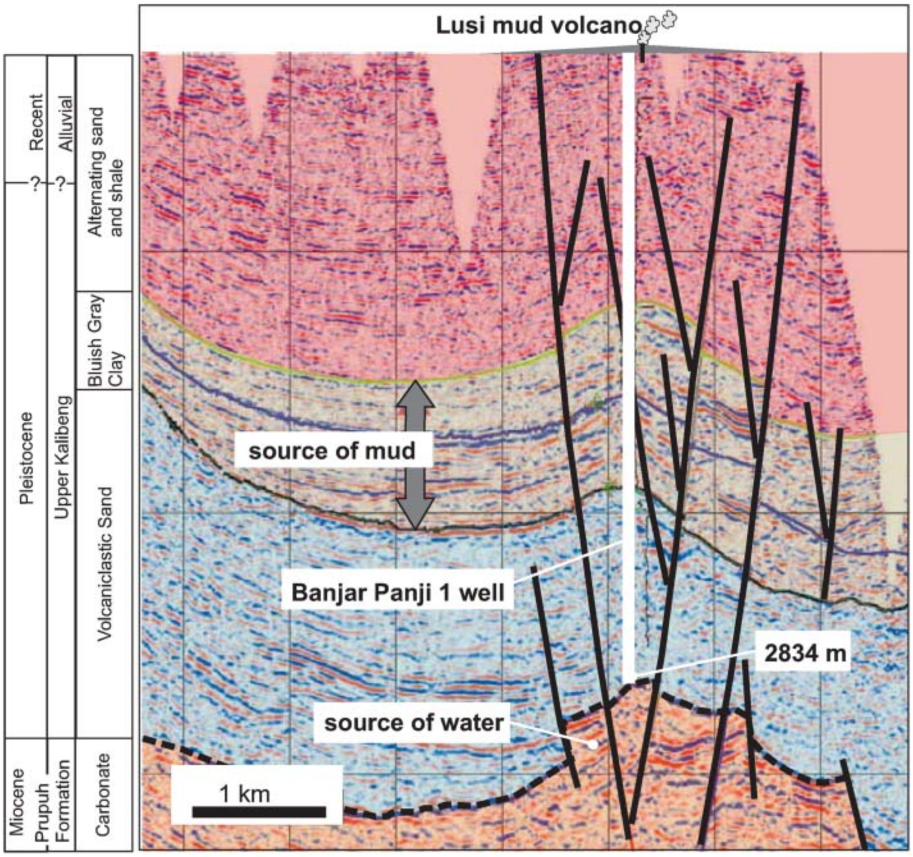

Fig. 2. North–south-oriented seismic line that intersects the Banjar Panji 1 well (after Sawolo *et al.* 2009).

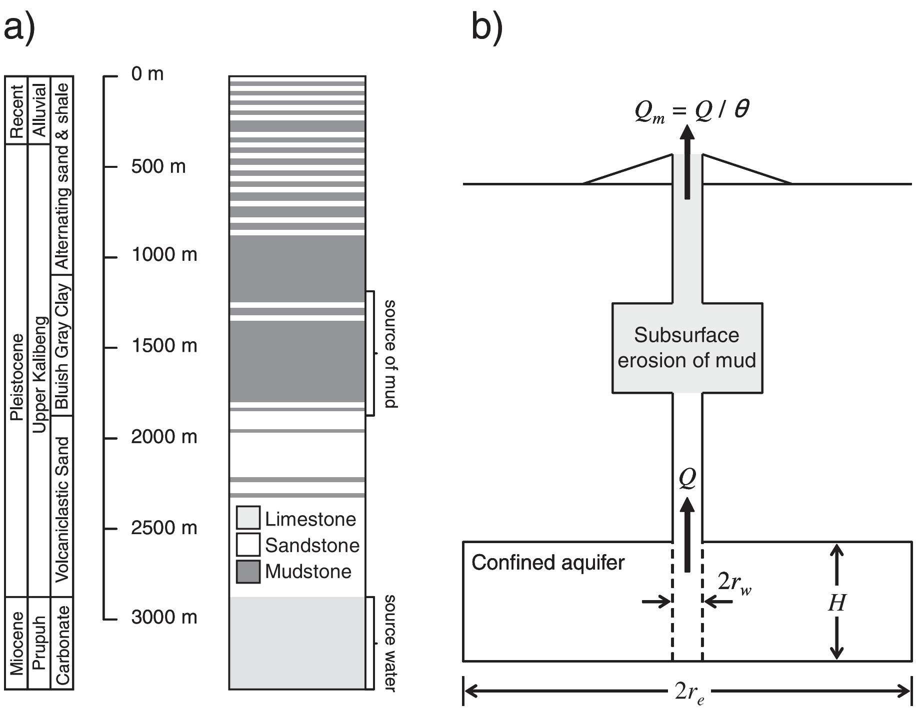

Fig. 3. (**a**) Stratigraphic column for the LUSI mud volcano. (**b**) Schematic diagram of conceptual model.

upwards through faults and fractures, and then intersects argillaceous strata that are thixotropic, overpressured, undercompacted and susceptible to subsurface erosion. The erosion processes are not understood but may involve erosion from the sidewalls of new and existing fractures or plausibly also by a process similar to ‘piping’, where water erodes a conduit, as is observed in some clay-filled embankment dams (Fell *et al.* 2003). For eruption to occur, the pressure of the water source, P [$ML^{-1}T^{-2}$], has to exceed the pressure of a column of mud, water and gas, P_w [$ML^{-1}T^{-2}$]. With time the pressure difference, $P - P_w$, will equilibrate and the eruption rate will reduce.

Deterministic estimation method

Only a few attempts to simulate mud volcano dynamics using mathematical models are reported in the literature. Revil (2002) presented a pressure-wave model to simulate mud volcano genesis. Murton & Biggs (2003) described a viscous gravity current model to simulate surface flows of mud from submarine mud volcanoes. More recently, Zoporowski & Miller (2009) proposed a fluid-flow model for a cylindrical vent to simulate oscillatory eruption rates from mud volcanoes. The source of oscillatory behaviour, in their model, is similar to that more commonly associated with water hammer observed in pipes (e.g. Wylie & Streeter 1978). Zoporowski & Miller (2009) treated the influx of fluid into a finite mud store as either a constant flow per unit area or a constant total flow. In reality, the influx of fluid will decline as pressure within the associated fluid reservoir equilibrates with that of the volcano vent. Rather than concentrating on the short-term dynamics, we focus on simulating the long-term influx decline based on a conventional 1D radial-flow reservoir engineering approach.

Calculation of eruption rate is approximated as follows. Let us consider the equation for axially symmetric, single-phase, Darcian flow in a homogeneous, isotropic and confined aquifer (e.g. Van Everdingen & Hurst 1949; Papadopulos & Cooper 1967)

$$S\frac{\partial P}{\partial t} = \frac{k}{\mu}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial P}{\partial r}\right) \tag{1}$$

subject to the boundary conditions

$$\begin{aligned} P &= P_0, \quad r_w \leqslant r \leqslant r_e, \quad t = 0 \\ P &= P_w, \quad r = r_w, \quad t > 0 \\ \frac{\partial P}{\partial r} &= 0, \quad r = r_e, \quad t > 0 \end{aligned} \tag{2}$$

where S [$M^{-1}LT^2$] is the storage coefficient, P [$ML^{-1}T^{-2}$] is pore pressure, t [T] is time, k [L^2] is permeability, μ [$ML^{-1}T^{-1}$] is viscosity, r [L] is radial distance from the origin of the vent, P_0 [$ML^{-1}T^{-2}$] is the initial pore pressure, r_w [L] is the radius of the vent, r_e [L] is the radius of the aquifer and P_w [$ML^{-1}T^{-2}$] is the pressure at the bottom of the vent. The storage coefficient is defined by $S = \phi(c_f + c_r)$ where ϕ is porosity [–], c_f [$M^{-1}LT^2$] is the fluid compressibility and c_r [$M^{-1}LT^2$] is the rock compressibility (see, e.g. Chen *et al.* 2006, p. 15).

The flow of fluid from the aquifer is found from

$$Q = 2\pi r_w H \frac{k}{\mu}\frac{\partial P}{\partial r}\bigg|_{r=r_w} \tag{3}$$

and the volume of fluid that has left the aquifer is found from

$$V = \int_0^t Q(\tau)\mathrm{d}\tau. \tag{4}$$

The analytical solution for V in the Laplace domain is (see Van Everdingen & Hurst 1949, equation (VII-4)]

$$\hat{V}(s) = \frac{2\pi r_w H k(P_0 - P_w)\alpha}{\mu s^2} \times \left[\frac{I_1(\alpha r_e)K_1(\alpha r_w) - K_1(\alpha r_e)I_1(\alpha r_w)}{I_1(\alpha r_e)K_0(\alpha r_w) + K_1(\alpha r_e)I_0(\alpha r_w)}\right] \tag{5}$$

where $\alpha^2 = sS\mu/k$ and s is the Laplace transform variable as defined by

$$\hat{V}(s) = \int_0^\infty V(t)\exp(-st)\mathrm{d}t. \tag{6}$$

It should be noted that the Laplace transform for fluid flow can be obtained from

$$\hat{Q} = s\hat{V}(s). \tag{7}$$

Equations (5) and (7) can be easily inverted back to the time domain using a numerical Laplace transform inversion algorithm. In this paper we use a MATLAB implementation of the Stehfest (1970) algorithm (as described by Valko & Abate 2004).

Estimates of erupted mud volume, V_m [L^3] and mud flow rate, Q_m [L^3T^{-1}] are found from

$$V_m = \frac{V}{\theta} \quad \text{and} \quad Q_m = \frac{Q}{\theta} \tag{8}$$

where θ [–] is the water fraction of the mud.

Probabilistic assessment

We populate the above model with parameters that reasonably describe the situation of concern. Four of these parameters are well constrained. At 100 °C, the viscosity and compressibility of brine are around $\mu = 5 \times 10^{-4}$ Pa s and $c_f = 0.3$ GPa^{-1}, respectively (Batzle & Wang 1992). The compressibility of the rock (situated beneath 3000 m of overburden), c_r, can be assumed negligible and the vent radius, within the reservoir formation, r_w, is assumed to be 0.15 m, which was the original radius of the Banjar Panji-1 wellbore. It should be noted that it is likely that the wellbore has been completely destroyed in the overburden above from which the mud is sourced. However, within the immediately overlying confining layer, it is reasonable to assume that the well radius remained relatively unchanged.

The remaining parameters are estimated and can only be specified as ranges (see Table 1). Because of lack of information, uniform probability distributions between these ranges are assumed. It should be noted that the aquifer radius, r_e, is related to the plan area, A [L^2] via $r_e = (A/\pi)^{1/2}$.

With these parameters, it is possible to run the model within a Monte Carlo simulation. The process is described as follows. N number of parameter sets were obtained by randomly sampling

Table 1. *Ranges for unknown parameters*

Parameter	Minimum	Maximum
Plan area of aquifer, A (km^2)	100	600
Formation thickness, H (km)	0.2	1.0
Porosity, ϕ (–)	0.15	0.25
Initial overpressure ($P_0 - P_w$) (MPa)	13.9	17.6
Permeability, k (m^2)	10^{-14}	10^{-12}
Water fraction of mud, θ (–)	0.50	0.70

from uniform distributions defined by the ranges in Table 1. A total of 10 000 realizations were generated. These were then conditioned by comparison with estimates of the volume of erupted mud presented in the literature, specifically, 37.3×10^6 m^3 of mud after 1 year (Istadi *et al.* 2009) and 73×10^6 m^3 of mud after 3 years (Tingay 2010). Realizations that failed to reproduce these two data points within ±20% were rejected. In this way, the original set of 10 000 realizations was reduced to only 381. The resulting posterior parameter distributions are presented in Figure 4.

A statistical summary of the V_m time-series (Fig. 5) shows that all realizations pass through ±20% of 37.3×10^6 m^3 and 73×10^6 m^3 after 1 and 3 years, respectively. Furthermore, the 50 percentile result implies that the cumulative volume of fluid released will continue to increase at significant rates until around 10 years. A statistical summary of the Q_m time-series (Fig. 6) shows that the 50 percentile flow rate remains within a narrow range until around 2 years, beyond which it starts to decline. The decline in flow rate occurs as a result of the pressure wave caused by the volcano initiation having reached the boundary of the aquifer. The statistical properties of the time at which Q_m has reduced to <0.1 Ml day^{-1} (considered to be a manageable quantity, a tenth of the rate one would expect from a good water supply well) (Fig. 7) shows a mode at 10 years but the distribution shows log-normal type behaviour. The 5, 50 and 95 percentiles are 10, 26 and 100 years, respectively. Finally, cumulative probability distribution for the permeability of the aquifer (Fig. 4e) predicts that the model permeability ranges from 5×10^{-14} to 7×10^{-13} m^2 (50–700 mD), which is typical of Miocene carbonate reservoirs in the region, further supporting the hypothesis that this is the source of the fluid.

Discussion and implications

Trigger

The trigger for the mud volcano is considered to be due to either drilling (Davies *et al.* 2007, 2008) or the Yogyakarta earthquake (Mazzini *et al.* 2007; Sawolo *et al.* 2009), or a combination of the two. As discussed above, the model presented here is not predicated on either of these interpretations being right. Rather, it is based upon the existence of a vertical wellbore that is drilled to immediately above or into the Prupuh Formation, therefore connecting overpressured source water to the mudstones of the Upper Kalibeng Formation, which is the source of the mud in the LUSI edifice.

Key assumptions

Excluding uncertainty associated with the triggering mechanism, the greatest source of uncertainty in the longevity estimate relates to the subsurface geology, especially the aquifer volume, which is addressed through Monte Carlo simulation of the input data range in Table 1. Seismic images of the subsurface given by Kusumastuti *et al.* (2002) show a relatively unfaulted, stratified carbonate, which can be assumed to have well-connected

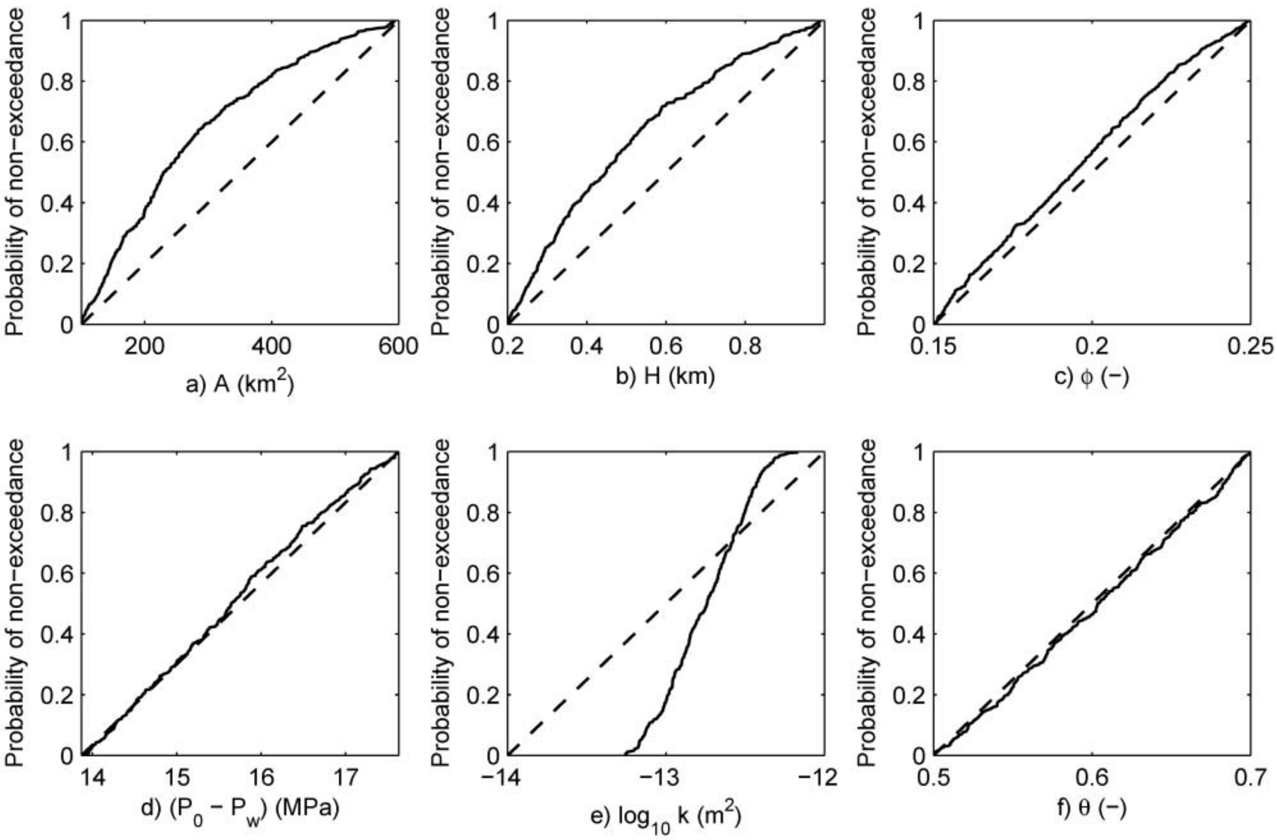

Fig. 4. Prior (dashed lines) and posterior (continuous lines) parameter distributions applied to and derived from the Monte Carlo simulation, respectively. Definition of symbols used on the *x*-axes is given in Table 1.

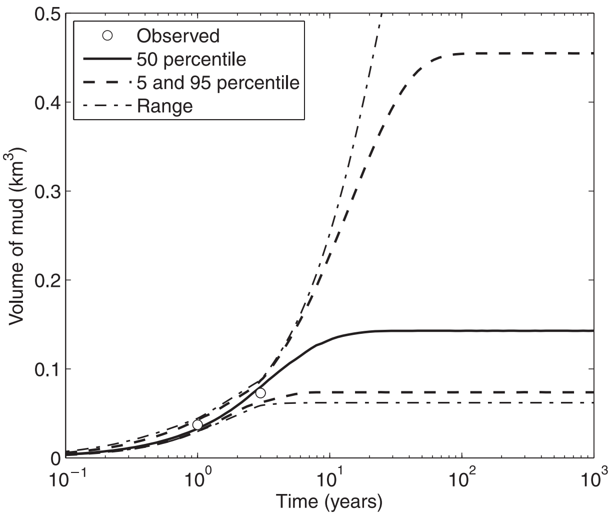

Fig. 5. Statistical presentation for the 381 accepted realizations of volumes of mud as calculated by equation (8). The observed data are the estimates of erupted volumes presented by Istadi *et al.* (2009) and Tingay (2010) after 1 and 3 years, respectively.

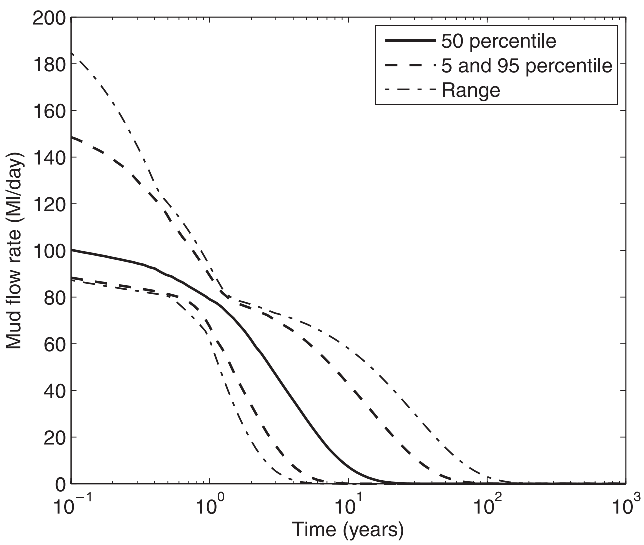

Fig. 6. Statistical presentation for the 381 accepted realizations of mud flow rate as calculated by equation (8).

porosity. Another important assumption is that the source water unit behaves as a closed system and is not exposed to recharge from deeper pore fluid sources. Additionally, the impact of gas buoyancy or expansion and its ability to assist the drive of fluids to the surface is not considered. In natural mud volcanoes, gas ascent and expansion provide lift without the need for a pressure drive from the aquifer. Based upon natural mud volcanoes, this could potentially keep the main vent active at low levels for thousands of years.

Source of water

Taking into account the above, our calculations suggest that the formation supplying the water would require a permeability of between 50 and 700 mD, which is four to eight orders of

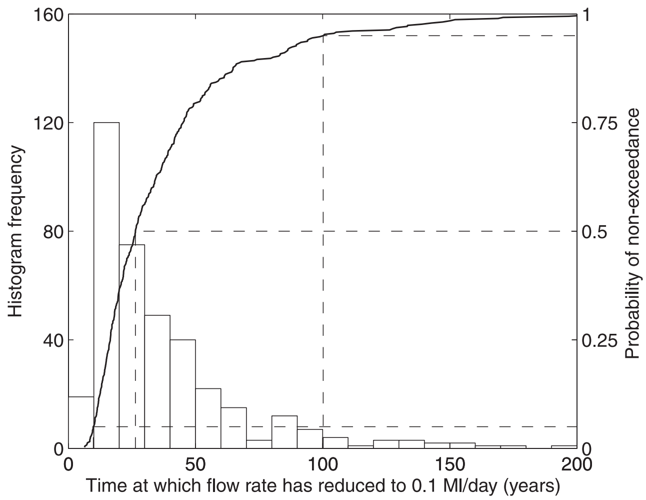

Fig. 7. Histogram and cumulative distribution of the time at which the volcano eruption rate has reduced to 0.1 Ml day^{-1}, obtained from the 381 accepted realizations. The dashed lines mark the 5, 50 and 95 percentiles.

magnitude higher than that which would be expected for a phyllosilicate mudstone, effectively ruling out the mudstones of the Upper Kalibeng Formation as a principal fluid source. As originally proposed by Davies *et al.* (2007), the higher permeability Prupuh carbonate formation probably penetrated by the Banjar Panji 1 well adjacent to LUSI, and mapped on seismic data by Kusumastuti *et al.* (2002), is a much more likely candidate (Tanikawa *et al.* 2010).

Other longevity estimations

Istadi *et al.* (2009) used the volume of what they termed the Upper Kalibeng 1 Formation at a daily constant eruption rate of 100 000 m^3 to estimate the number of years it would take for the source of mud to be depleted. Their estimation was 23–35 years, but their method is probably flawed because (1) the eruption will continue after the mud source is depleted, as the source of fluid and the overpressure is very probably separate from the mud source, and (2) their method assumes a constant eruption rate rather than one that reduces with time, as one would expect during pressure reduction from an overpressured fluid source.

Impact

The 50 percentile estimate for the longevity of LUSI is that it will take 26 years for the flow to reach a rate less than 0.1 Ml day^{-1}. After 26 years the 50 percentile total volume of the mud erupted is 0.14 km^3. In addition, at a subsidence rate of 1–5 cm day^{-1} (Abidin *et al.* 2008; Istadi *et al.* 2009), total subsidence will be 95–475 m. An ancient analogue exists 6 km east at Porong, where a 4 km diameter crater (now filled with sediment) is observed on seismic data as having *c.* 400 m of subsidence.

Conclusions

A detailed approach for estimating the longevity of mud volcano eruption where the source of water is separate from the source of mud has been presented. In this paper, a probabilistic estimate of longevity for the LUSI mud volcano is developed based upon the existence of a vertical wellbore that is drilled to immediately above or into the Prupuh Formation, therefore connecting overpressured source water to the mudstones of the Upper Kalibeng Formation. Applying the analysis to LUSI suggests that the time required for the flow to diminish to less than 0.1 Ml day^{-1} is likely to be in excess of 26 years. During this time the land surface is expected to have subsided by 95–475 m and the total volume of mud is likely to exceed 0.14 km^3.

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