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Discussion

Fluid transport properties and estimation of overpressure at the Lusi mud volcano, East Java Basin (Tanikawa et al., 2010)

Richard Davies[a,*], Michael Manga[b], Mark Tingay[c], Richard Swarbrick[d]

[a] Centre for Research into Earth Energy Systems (CeREES), Department of Earth Sciences, Durham University, Science Labs, Durham, DH1 3LE, UK
[b] Dept Earth and Planetary Science, UC Berkeley, Berkeley CA 94720-4767, USA
[c] Tectonics, Resources and Exploration (TRaX), Australian School of Petroleum, University of Adelaide, South Australia, 5005, Australia
[d] Geopressure Technology Ltd., Mountjoy Centre, Stockton Road, Durham, DH1 3UZ, UK

1. Introduction

The Lusi mud volcano in Sidoarjo, East Java, started to erupt on May 29th 2006 and has displaced 13,000 families. Controversy surrounds whether the mud volcano was caused by drilling of the Banjar Panji 1 gas exploration well (Davies et al., 2007; Manga, 2007; Davies et al., 2008; Tingay et al., 2008) or due to the Yogyakarta earthquake that occurred at 05:54 am on the 27th May 2006 (Mazzini et al., 2007; Sawolo et al., 2009). Constraining (a) pore pressure in sedimentary strata prior to drilling; (b) changes in pore pressure that occurred due to drilling the Banjar Panji 1 well and the earthquake, and; (c) potential routes for fluid to the surface are critical for resolving this debate. These areas are tackled in the recent paper by Tanikawa et al. (2010), who model pore pressure development during burial of sedimentary strata at the site of the eruption and measure the permeability and porosity of outcrop samples of formations of equivalent age and lithology as those penetrated by the well. From this analysis, they conclude that overpressure developed within specific successions, in particular the Upper Kalibeng clays and a deep carbonate formation. They go on to argue that the overpressure made the clay-rich unit susceptible to liquefaction as a result of cyclic deformation during the Yogyakarta earthquake, and that this initiated the mud volcano. In this discussion we begin by summarising the main conclusions made by Tanikawa et al. (2010) and then consider the validity of their most important conclusion that Lusi is a natural disaster. Lastly, we reiterate the compelling evidence (Davies et al., 2008; Tingay et al., 2008) that Lusi is man-made and was caused by an underground blowout at the Banjar Panji 1 well.

2. Main conclusions of Tanikawa et al. (2010)

The main conclusions of the Tanikawa et al. (2010) paper were that overpressure developed within the bluish grey clay, termed the Upper Kalibeng Formation Unit 2, and therefore, these strata were undercompacted and susceptible to remobilisation. They considered the deeper carbonates (termed the Upper Kujung Formation) as the most likely source of fluids. (Note: earlier papers on Lusi (e.g. Davies et al., 2007; Mazzini et al., 2007) referred to the carbonates as the Kujung Formation however, strontium isotope ratios from them indicate they are 16–18 Ma (Kusumastuti et al., 2002), and thus are not the Oligiocene Kujung Formation, but rather should be termed the Prupuh or Tuban Formations (Tingay, 2010) and are thus termed the Prupuh Formation for the remainder of this discussion.) The authors hypothesized that the elevated pressure within the Upper Kalibeng Formation Unit 2, made the sediment more susceptible to the small amplitude static or dynamic stresses caused by the Yogyakarta earthquake, so that small changes in pressure were sufficient to induce liquefaction. The rapid influx of gas and liquid from the deep carbonates flowed through pre-existing pathways formed by natural hydraulic fractures, and this explains the continuous mud eruption at Lusi. In summary, Tanikawa et al. (2010) hypothesize that pore fluid pressure changes caused by the Yogyakarta earthquake caused liquefaction of undercompacted shales and fluid flow occurred through natural fractures.

3. Discussion

The paper provides key new information on the hydrodynamics of Lusi, and we indeed agree with several important points made by the authors. For instance data from Banjar Panji 1 corroborates the modelling by Tanikawa et al. (2010) that the Upper Kalibeng Unit 2 is a fine grained lithology that is overpressured and undercompacted. We also agree that the most likely source of fluid is the deep carbonates. Furthermore, we agree with the model results suggesting that significant overpressures exist in and below the Prupah Formation carbonates. Very high magnitude overpressures were observed in the same section in the Porong 1 well, 6 km away from Lusi.

Although we are in agreement in these areas, there are several conclusions on how the mud volcano was triggered which are at odds with our published research (Davies et al., 2007; Manga, 2007; Davies et al., 2008; Tingay et al., 2008) and given the scale of this humanitarian disaster it is important that these are challenged. The most important of these, is their reasoning that the Yogyakarta earthquake triggered the eruption rather than drilling of the Banjar Panji 1 well. Tanikawa et al. (2010) propose that stress fluctuations induced by the M6.3 Yogyakarta earthquake (2 days prior to the eruption) caused the mud in the Upper Kalibeng Unit 2 to lose strength and liquefy (their abstract and section 7.1). Others have also

* Corresponding author.
E-mail address: richard.davies@durham.ac.uk (R. Davies).

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invoked an earthquake trigger (e.g., Mazzini et al., 2007; Sawolo et al., 2009). We argue herein that this reasoning is incorrect and, furthermore, that the data they present can be used to disprove their own hypothesis.

Owing to the large distance of the earthquake from the eruption site, the time-varying stresses produced by the passage of seismic waves are much larger than the static stress changes cause by slip on ruptured fault. Davies et al. (2008) and Tingay et al. (2008) calculate stress fluctuations of 21^{+33}_{-12} kPa (with a static stress change of ~30 Pa). This is comparable to the amplitude of stress changes for ocean tides, solid earth tides, hydrological loading, and barometric pressure changes from large typhoons. Yet these other phenomena did not trigger Lusi. Despite their similar amplitude, it may be reasonable to suggest that earthquakes might still initiate liquefaction because the period of the stress changes associated with tides or weather effects is much greater than that of earthquakes, and hence the pore-pressure changes produced by long period stress changes may have time to diffuse and not initiate liquefaction. In other words, it may be suggested that the response to long period stress changes may be drained, but the response to earthquake may be undrained. However, using the Tanikawa et al. (2010) measurements' for the Upper Kalibeng Formation Unit 2 of 10^{-18} m^2 for permeability, 10^{-8} Pa^{-1} for specific storage, and a pore pressure diffusion length scale of 100 m, implies a drainage time scale of 10^{11} s (3 kyr). This drainage time scale is much longer than the period of tidal forcing and, thus, nullifies any suggestion that earthquakes may have been able to trigger liquefaction due to their shorter period. Hence, the analysis by Tanikawa et al. (2010) again highlights the key issue that, if tides and weather did not initiate an eruption, it is not likely that similar pressures induced by the Yogyakarta earthquake could have.

Tanikawa et al. (2010) suggests that cyclic deformation may have weakened the mud, resulting in liquifaction. Manga et al. (2009) measured how cyclic deformation affects the strength of mud erupted at the Lusi mud volcano. Manga et al. (2009) found that strain amplitudes greater than 10^{-3} were required to initiate a loss of strength for the range of seismic frequencies (between 0.1 and 10 Hz). This strain amplitude is much greater than that experienced by the mud. In summary, the magnitude of time varying stresses produced by the Yogyakarta earthquake is far too small to initiate an eruption. Furthermore, these results suggest that Lusi was likely not triggered by liquefaction of the Upper Kalibeng Unit 2 clays, but rather that Lusi has resulted from overpressured fluid release from the deep carbonates. Clay was simply being entrained by the fluids en-route to the surface, plausibly by processes similar to 'piping', where water erodes a conduit, as is observed in some clay filled embankment dams (Fell et al., 2003) or by wall sediment erosion of existing or new fractures.

There are a few other (minor) issues about which we disagree. First, Tanikawa et al. (2010) used a sonic log rather than the density log to estimate porosity in the Upper Kalibeng unit 1 (volcanic section). Based upon the density log from Banjar Panji 1 we estimate porosities of 10–13% rather than in excess of 20% (Tanikawa et al., 2010; Tingay, 2010). Second, we know of no mechanisms to create such high magnitude overpressure in the volcanic sequences (Upper Kalibeng Unit 1) because they are relatively incompressible so, we question whether this should be included in overpressure modelling and their prediction of overpressure in this formation. Tanikawa et al. (2010) also proposed that fluids utilised pre-existing hydraulic fractures. Indeed, the model of Lusi's plumbing system being along hydraulic (tensile) fractures (albeit drilling initiated) is a component of the first published model for the development of Lusi proposed by Davies et al. (2007). This may well be correct for fluid flow at depth, but at the surface eruptions were initially aligned in a NE–SW orientation parallel to the trend of the Watukosek fault (Mazzini et al., 2007; Roberts et al., in press) and later eruptions were aligned in an east–west direction parallel to the structural trend (Roberts et al., in press). Neither of these orientations is consistent with a mode I (tensile) fracture as the present-day stress tensor in the Lusi region, from data in the World Stress Map Project, is most likely a strike–slip stress regime with a maximum horizontal stress oriented NNE–SSW (Heidbach et al., 2010; Tingay et al., 2010). Under this stress regime, a tensile fracture would be expected to be oriented NNE–SSW (parallel to the maximum horizontal stress). However, the hypothesized NE–SW oriented fault would be optimally orientated for reactivation under the observed stress regime. This is a minor point, but does have implications and the conclusions made by Tanikawa et al. (2010) on the triggering of Lusi.

4. Is Lusi a logical seal breach point?

The Banjar Panji 1 well and the Lusi mud volcano are often considered to be located above the structural culmination (shallowest occurrence) of the Prupah Formation and have thus been considered as the logical leak point for fluid from the deep carbonates (Tanikawa et al., 2010). However, the Porong-1 well, drilled in 1993, penetrated an adjacent structural culmination, with the same Prupah Formation (Kusumastuti et al., 2002). The long-lived, high volume mud flow of water, mud and gas from Lusi indicate a large connected aquifer supplying high temperature, high pressure fluids encompassing both culminations (Davies et al., 2007). The top of the Prupah was found at 2575 m at Porong-1, while the Banjar Panji 1 well may possibly have just penetrated it at 2833 m (Davies et al., 2007), or the carbonate could have been deeper than this (Mazzini et al., 2007). Assuming both wells were targeting the crest of the carbonate structure, then the Prupah Formation is at least 258 m shallower at the Porong-1 well location and, therefore, this would be the natural hydraulic "leak point". So if one is looking for a natural leak point (rather than a leak point through a borehole), the Porong-1 location provides this, rather than the Banjar Panji carbonate culmination. Indeed, it is probably no coincidence that Porong-1 location shows evidence for a circular shaped collapse feature overlying the carbonates, which is consistent with a palaeo-mud volcano (Kusumastuti et al., 2002; Stewart and Davies, 2006) and is good evidence that this breach has occurred in the past.

5. So what caused Lusi?

The results presented by Tanikawa et al. (2010), coupled with the understanding of the subsurface geology and vent locations developed by many studies (notably Mazzini et al., 2007; Manga et al., 2009; Tingay, 2010; Roberts et al., in press) result in subtle, yet critical, modifications to the geological models of the Lusi eruption. In particular, all Lusi models should now consider that the fluid source is primarily the deep carbonates of the Prupah Formation; that initial fluid flow to the surface was probably via the Watukosek fault, and; that liquefaction is an unlikely mechanism for remobilization of the Upper Kalibeng clays. Taking these key modifications into account indicates that the drilling and earthquake triggering models, often assumed to be completely different, are actually somewhat similar in terms of the probable route taken by fluid to the surface.

The earthquake-trigger hypothesis suggests that shaking by the Yogyakarta earthquake resulted in a transient pore pressure increase (effective stress decrease) that caused reactivation of the Watukosek fault that, in turn, opened up a fluid flow pathway from the deep carbonates to the surface. The drilling-trigger hypothesis suggests that the kick in the Banjar Panji 1 well pumped high pressure fluid into the Watukosek fault, causing the fault to reactivate and open up fluid flow pathways to the surface (Davies et al., 2010; Tingay, 2010). In other words, both models, in essence, suggest that Lusi results from reactivation of the Watukosek fault due to increased pore fluid pressures (decreased effective stress). If this is the case, then the real question behind the triggering debate is actually whether it was the

Yogyakarta earthquake or the kick in Banjar Panji 1 that caused the decrease in effective stress (higher pore pressures) that reactivated the Watukosek fault. Indeed, Tingay et al. (2008) stated that "analysis of the Lusi eruption trigger must primarily examine mechanisms for the initiation and/or reactivation of NE–SW-oriented faults and fractures beneath the eruption site".

The pore pressure increase associated with each hypothesized triggering mechanism is reasonably well constrained. Seismic shaking from the Yogyakarta earthquake is calculated to be at most 21^{+33}_{-12} kPa (Davies et al., 2008). In stark contrast, the absolute minimum value for the pore pressure increase associated with the Banjar Panji 1 kick is 2.42 MPa (with a potential maximum value of 6.9 MPa). Hence, the pore pressure increase associated with the kick in Banjar Panji 1 is, between 117 and 329 times greater than that generated by the Yogyakarta earthquake.

6. Conclusions

We applaud Tanikawa et al. (2010) for their study of the permeability, porosity and potential magnitude of overpressure generation within many rocks encountered in the Lusi region – much of which we agree with. They provide critical new insights into the hydrodynamics of the Lusi system, in particular highlighting the likelihood of overpressure generation in both the Upper Kalibeng Formation clays and deep carbonates. The permeabilities, porosities and pressures highlight that the primary source of fluid erupted from Lusi is the deep carbonates, with clays from the Upper Kalibeng Unit 2 becoming entrained within these fluids en route to the surface. Thus, the results of this study represent a key advance in our understanding of the Lusi mud volcano. However, we disagree with the authors' interpretations of their results, particularly with respect to the triggering of the eruption and the suggestion of liquefaction.

The study's own data and results reveal that pressure dissipation within the Upper Kalibeng Unit 2 clays is slow and, thus, confirms earlier analysis by Davies et al. (2008) that earthquake shaking could not have triggered Lusi as its effect was less than the tides. Manga et al. (2009) demonstrated that liquefaction of the Upper Kalibeng clays was not possible from the Yogyakarta earthquake. Furthermore, the results presented herein, coupled with results from other studies, indicate that Lusi was most likely triggered by pore pressure-induced reactivation of the Watukosek fault. However, the pore pressure increase associated with the kick in the Banjar Panji 1 well was between 117 and 329 times larger than that generated by the Yogyakarta earthquake. These facts can then be coupled with the well known observation that other earlier earthquakes did not trigger Lusi, despite being comparatively larger and closer (Davies et al., 2008). Thus, despite providing intriguing and critical results, the conclusion by Tanikawa et al. (2010) that the Yogyakarta earthquake triggered the Lusi mud volcano lacks any scientific credibility.

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