Initiation of the Lusi mudflow disaster

To the Editor — The Lusi mudflow is a unique disaster. Mud suddenly erupted in an urban area in Java, Indonesia, in May 2006. Nine years of continuous eruption have displaced 39,700 people and cost over US$2.7 billion in damages and disaster management. Intense debate has focused on whether the eruption was naturally triggered by the Yogyakarta earthquake, which occurred two days prior to the eruption and 260 km away[1,2], or was the result of gas drilling operations in the nearby Banjar Panji-1 (BJP-1) well[3,4]. Here we use subsurface gas measurements from the well before and immediately after the Yogyakarta earthquake to demonstrate that an earthquake trigger is unlikely.

The hypothesis of a natural trigger for the Lusi eruption suggests that passing seismic waves led to liquefaction in the Kalibeng clay formation — the source of solids in the erupting mud[1,2]. Clay liquefaction is initiated by changes in effective stress, that is, stress minus fluid pressure. The same changes in effective stress will also cause a widespread release of gas from the liquefied layer: an effective stress drop causes gas release via exsolution, whereas an effective stress increase causes compaction-associated fluid explusion[1,2,5]. Indeed, large gas releases are observed during mud volcano eruptions and if earthquake-induced liquefaction occurred at Lusi[2,6], it should have caused extensive gas release immediately following the earthquake.

The BJP-1 well was located just 150 m from what became the main vent of the Lusi mud volcano. The well was uncased from 1,090 to 2,833 m depth, and so is directly open to fluid exchange with almost the entire thickness of the Kalibeng clays[3,4,7] (Fig. 1). A range of gas measurements, including gas concentration and composition were taken continuously during the drilling operation, starting from March 2006 until the day of the Lusi mud eruption on 29 May, 2006[7,8]. These measurements provide a rare opportunity to determine the background level of gas emissions prior to the Yogyakarta earthquake and Lusi eruption, as well as the source of any emitted gases, and thus make the first direct examination of the response of the Kalibeng clays immediately after the earthquake.

We use daily maximum gas concentration measurements and continuous depth-based measurements[9] to characterize the range of gas values observed in the rock formations intersected by the BJP-1 well (Fig. 1, Supplementary Table 1). We focus on the maximum values observed in the 48 hours before and 24 hours after the Yogyakarta earthquake[7,8] (Supplementary Table 2). No increase in emissions of subsurface gases was measured in the 24 hours after the earthquake, which covers almost the entire period between the earthquake and the major fluid influx, or kick, into the BJP-1 well[7] — the drilling incident that is alternatively considered to be the trigger for the eruption[3,4]. Indeed, maximum gas readings after the earthquake are noticeably lower than in the two previous days, but are within the normal range of gas values recorded to come from the volcanic and volcaniclastic rock formations that underlie the Kalibeng clays, and particularly the calcareous volcaniclastic sequences below 2,600 m (ref. 8).

The post-earthquake gas readings from the BJP-1 well are significantly lower than typical measurements of gas emissions from the Kalibeng clays, particularly with regards to heavier hydrocarbons (such as C_4 and C_5, including butane and pentane) that are diagnostically high in this formation[8]. Increased gas levels would be expected regardless of whether the earthquake had induced dilation (through gas exsolution) or

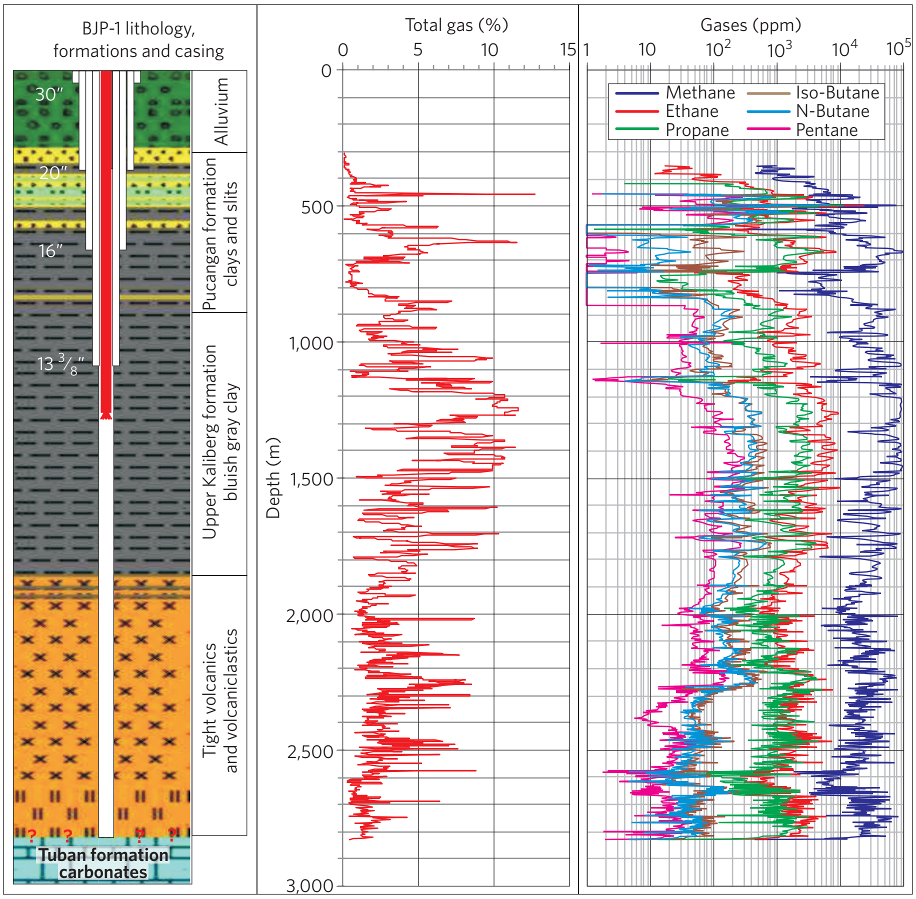

Figure 1 | Stratigraphy, BJP-1 borehole design (protective casing diameters in inches) and measured gas amounts encountered by the well[7,8]. Total gas is the percent of gas, by volume, extracted from drilling mud returned from a specific depth[9]. Gas data are the concentrations of individual gases from individual depths, measured by gas chromatography[9]. The Kalibeng clays contain significantly more gas than the volcanic/volcaniclastics rocks. Liquefaction of the Kalibeng clay layer should generate extensive gas release[2], yet no increased gas flux is observed in the 24 hours after the Yogyakarta earthquake. Gas readings instead fall within the normal range observed in the deep calcareous volcaniclastic rocks (Supplementary Table 2). The position of the BJP-1 drill string and drill bit at time of the drilling kick is highlighted in red. The top of the Tuban formation is assumed to be at 2,833 m depth[3,4,7,8,10].

compaction (higher pore pressures causing increased fluid and gas flow into the BJP-1 well)[2,8]. Any liquefaction or remobilization of the Kalibeng clays is also expected to cause wellbore instability and clay cavings in the drilling mud, yet neither was detected in the period between the earthquake and the kick in well BJP-1[4,7,8].

Identifying the source of the initial emitted fluids is critical to determining the trigger for the mud eruption[1–4,6,7,10]. Because each rock formation that the well passed through has a distinct range of gas readings (Supplementary Table 2), the gas data from the BJP-1 well can be used to fingerprint the fluid source. Minor amounts of hydrogen sulphide (H_2S) were measured 20 m above the base of the BJP-1 well several hours before the earthquake[8]. H_2S was then observed coming from the BJP-1 well during the kick and also from the Lusi vent in the initial days of the eruption[4,7,8,10]. H_2S was not observed at any time while drilling through the Kalibeng clays, despite direct gas measurements from about 60 m^3 of Kalibeng cuttings[8]. The only known source of H_2S in the East Java Basin is from Tertiary carbonate rocks[8,10], although a deeper hydrothermal origin has also been proposed[6]. It is not certain whether the BJP-1 well penetrated carbonate rocks, but the bottom of the BJP-1 well is thought to lie within, or be in communication with, the Miocene-aged Tuban Formation carbonates[3,4,7,8,10] (Fig. 1). Detection of H_2S prior to the earthquake thus provides compelling evidence that an initial source of fluids for the Lusi eruption was significantly deeper than the Kalibeng clays.

A natural hydrothermal origin for the fluids emitted at Lusi has been suggested[6]. In this scenario, prior to the eruption, fluids from a deep hydrothermal system are proposed to have migrated upwards into the Kalibeng clay layer, pre-charging the clays and priming them for liquefaction and remobilization by the Yogyakarta earthquake[6]. However, observations of H_2S coming from the base of BJP-1 well and the absence of any measured H_2S in the Kalibeng clays rule out pre-eruption fluid communication between the clays and deeper rock formations. It is still possible that the eruption was influenced by hydrothermal activity, but such a hydrothermal system must be located within the Miocene carbonates or at deeper levels, and was sealed below the low permeability volcanic/volcaniclastic rocks[8] until immediately prior to the eruption.

When taken together, our measurements of gas emission rates and composition provide key insights into the initial plumbing system of the Lusi mudflow and demonstrate that earthquake-induced liquefaction of the Kalibeng clays did not occur. The drilling trigger hypothesis[3,4,7,10], however, posits a deep initial source of fluids that flowed upwards into the Kalibeng clay layer via the open BJP-1 well — a scenario consistent with gas emission data. We therefore conclude that the Lusi eruption was not triggered naturally but was instead the consequence of drilling operations. ❐

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Additional information

Supplementary information is available in the online version of the paper.

Diverting lava flows in the lab

To the Editor — Recent volcanic eruptions in Hawaiʻi, Iceland and Cape Verde highlight the challenges of mitigating hazards when lava flows threaten infrastructure. Diversion barriers are the most common form of intervention, but historical attempts to divert lava flows have met with mixed success[1,2] and there has been little systematic analysis of optimal barrier design[3–5]. We examine the interaction of viscous flows of syrup and molten basalt with barriers in the laboratory. We find that flows thicken immediately upslope of an obstacle, forming a localized bow wave that can overtop barriers. Larger bow waves are generated by faster flows and by obstacles oriented at a high angle to the flow direction. The geometry of barriers also influences flow behaviour. Barriers designed to split or dam flows will slow flow advance, but cause the flow to widen, whereas oblique barriers can effectively divert flows, but may also accelerate flow advance. We argue that to be successful, mitigation of lava-flow hazards must incorporate the dynamics of lava flow–obstacle interactions into barrier design. The same generalizations apply to the effect of natural topographic features on flow geometry and advance rates[6].

Attempts at lava-flow diversion fall into two categories: forced branching of flows to redirect lava supply, and barriers to confine the flow. Branching interventions divert lava from an existing channel by breaching bounding levees (Supplementary Table 1), but this approach has often been ineffective[2]. Confining barriers constructed perpendicular to the flow direction are used to slow flow advance, but are frequently overtopped, while barriers constructed obliquely to the flow have successfully redirected lava away from infrastructure[1–3,5]. Water-cooling a flow effectively builds a topographic barrier by stalling and thickening the flow front[1,4].

To better inform lava intervention measures, we conduct systematic experiments with viscous flows that intersect V-shaped obstacles with varying internal angles (θ) and oblique obstacles with varying orientations (ϕ; Supplementary Methods). Experiments using both syrup and molten basalt produce a steady-state bow wave upslope of the obstacle, creating a horseshoe-shaped locally thick region that can lead to overtopping of the obstacle