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Lusi mud eruption triggered by geometric focusing of seismic waves

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The Lusi mud eruption in Java, Indonesia, began in May 2006 and is ongoing. Two different triggers have been proposed. The eruption could have been triggered by drilling at a gas-exploration well, as evidenced by pressure variations typical of an internal blowout[1,2]. Alternatively, fault slip associated with the *M* 6.3 Yogyakarta earthquake two days before the eruption could have mobilized the mud[3], as suggested by mixing of shallow and deeply derived fluids in the exhaling mud[3,4] and mud-vent alignment along a tectonic fault. Here we use numerical wave propagation experiments to show that a high-impedance and parabolic-shaped, high-velocity layer in the rock surrounding the site of the Lusi eruption could have reflected, amplified and focussed incoming seismic energy from the Yogyakarta earthquake. Our simulations show that energy concentrations in the mud layer would have been sufficient to liquefy the mud source, allowing fluidized mud and exsolved CO_2 to be injected into and reactivate the Watukosek Fault. This fault connects hydraulically to a deep hydrothermal system that continues to feed the eruption. We conclude that the Lusi mud eruption was a natural occurrence. We also suggest that parabolic lithologies with varying acoustic impedance can focus and amplify incoming seismic energy and trigger a response in volcanic and hydrothermal systems that would have otherwise been unperturbed.

Mud volcanoes typically form in geological settings with high sedimentation rates such as compressional tectonic belts, submarine slopes and, as for Lusi, in inverted backarc basins[5,6]. Fast sedimentation rates and high geothermal gradients dehydrate minerals faster than the fluid product can escape its low-permeability confines, resulting in overpressured and under-consolidated clay (mud) layers trapped at depth.

On 26 May 2006, 47 h before the arrival of mud at the surface, a shallow (12 km deep) *M* 6.3 strike-slip earthquake occurred near Yogyakarta, Indonesia, approximately 250 km distant from the eruption site of Lusi (Fig. 1). The essence of the drilling trigger argument is that 250 km falls outside of the empirically determined distance range of volcanic triggering phenomena[5,7], and drilling with uncased sections of the borehole was underway about 200 m from the eruption site[1,2,8]. Relevant here is that two volcanoes active at that time, Mt Merapi and Mt Semeru, at distances of about 50 and 300 km respectively, from the Yogyakarta epicentre (Fig. 1), both showed a threefold increase in heat flow and erupted volume flux in response to that earthquake[9]. This indicates that the Yogyakarta earthquake produced sufficient seismic energy to provoke a response at distances similar to, and even exceeding, the distance to Lusi.

Before the eruption, the mud layer at Lusi had sufficient shear strength as evidenced by the integrity of the uncased section before

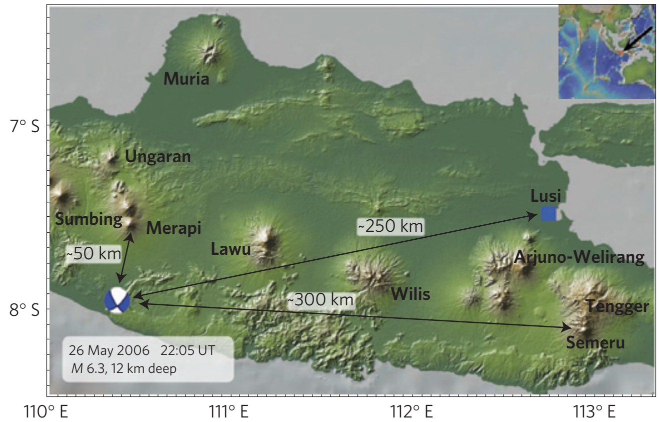

Figure 1 | Map of Java with relevant distances from the Yogyakarta earthquake. The blue square marks the position of Lusi and arrows show the distance between the epicentre of the Yogyakarta earthquake and the systems that responded to that event.

collapse[1,8]. Static stress changes ($\sigma_S \sim 10$ Pa) from the Yogyakarta earthquake at such a distance are irrelevant and dynamic stress changes, σ_D, assuming a shear velocity of 2,500 m s^{-1}, were estimated at $\sigma_D \sim 21+33/-12$ kPa (ref. 1). However, an analysis of the geological structure of Lusi[10] shows strong variations of acoustic impedance with depth, indicating a potentially complicated wave field from incoming seismic energy (Fig. 2). To study the effect of varying acoustic impedances, we carried out high-resolution forward simulations[11,12] using a synthetic data set for elastic waves propagating through the known lithology of Lusi (see Methods).

We simulated frequencies from 0.5 to 1.5 Hz to explore synthetic crustal body waves propagating within Lusi and found that the high-velocity layer that seals the mud source (red level in Fig. 2c) dominates the system. This parabolic-shaped high V_p layer reflects and geometrically focuses body wave energy arriving from below. We use the term 'parabolic seismic reflector' for this phenomenon and the effect of this structure at Lusi was to focus and amplify substantial seismic energy into the overpressured mud layer. Although surface waves are not significant for crustal earthquakes at epicentral distances of 250 km (ref. 13), we nevertheless simulated Rayleigh waves to determine how previous earthquakes (that is, *M* 9.2 and *M* 8.7 Sumatra events in 2004 and 2005) may have affected the system. The surface wave simulations (Supplementary Information) show that the high-velocity layer prevents any significant energy from penetrating to the depths of the mud layer, which may explain why Lusi did not respond to surface waves from more powerful, but more distant, earthquakes[1]. The focusing

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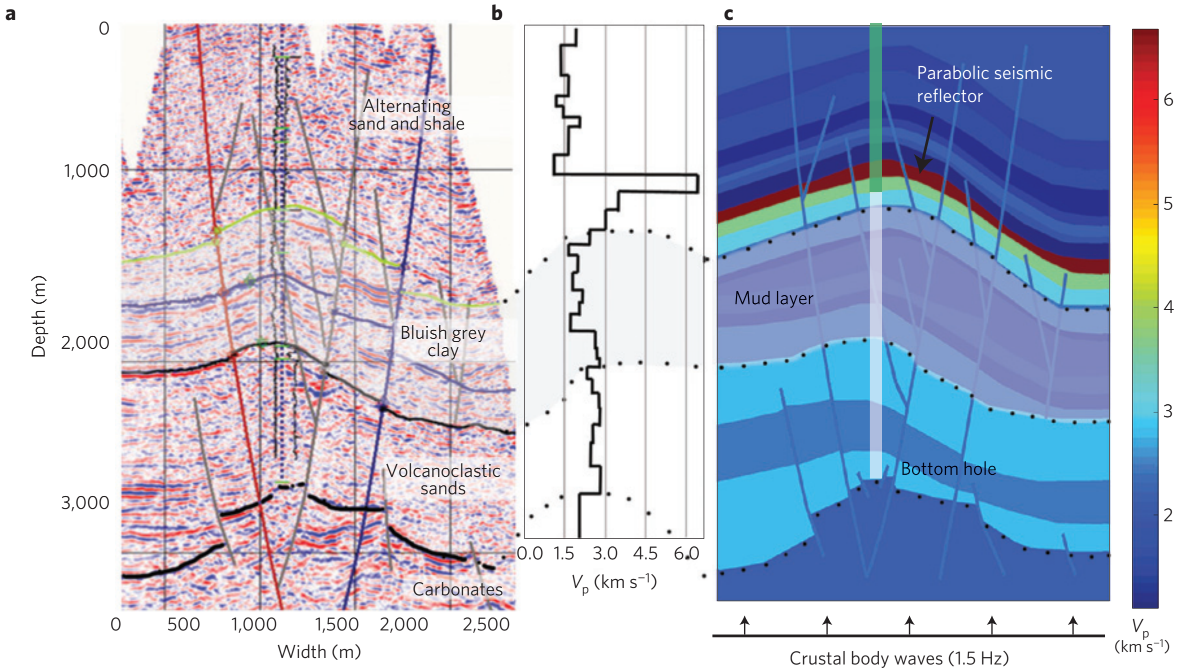

Figure 2 | Geometry, V_p variations with depth and model of Lusi used in the numerical study. a, Seismic profile of the geological structures[8] beneath Lusi used to reconstruct the geology of the model. **b**, Vertical profile for V_p velocities used in the model[10]. The acoustic impedance of faults is not known, so we assumed $\rho = 2{,}000$ kg m^{-3}, $V_p = 2{,}325$ m s^{-1} and $V_s = 1{,}531$ m s^{-1}. **c**, Distribution of V_p velocities in the model domain. The mud layer is shaded grey, the cased and uncased well (not modelled) are shaded green and white, respectively.

effect is frequency dependent in that the effect is reduced for wavelengths longer than the diameter of the reflecting structure, which in our case is about 3 km, resulting in a corner frequency of approximately 1 Hz for an assumed shear wave velocity of 3 km s^{-1} (see Supplementary Information for simulations at 0.5 and 1.0 Hz). The simulation results (Fig. 3) for 1.5 Hz body waves (P and S waves) are plotted using established criteria[14] as maximum energy density, vertical displacement, dynamic stress and shear strain.

Maximum energy densities induced by S waves are more intense and widespread in comparison with the P wave results, showing peaks of over 1 J m^{-3} immediately above and below the parabolic seismic reflector and at the bottom of the wellbore where volcanoclastic sands overlay suspected overpressured carbonates hosting H_2S-rich fluids[2]. Although the overpressured carbonates are essential to the drilling trigger argument, there is no evidence that this layer was breached, while the source of the H_2S could very well have been the shale–clay layer. Energy densities in this range are significant because mud volcanoes have been triggered by energy densities as low as 0.1 J m^{-3} (ref. 15). Furthermore, a peak dynamic shear stress of about 0.1 MPa and a maximum vertical displacement of approximately 1 mm occurred in the mud layer and at the bottom hole. Note that the results in Fig. 3 show the values for an incoming wave of one cycle, but the Yogyakarta earthquake and its aftershocks produced wave trains into Lusi, subjecting the overpressured and underconsolidated mud layer to cyclic loading that further increased pore pressure with each additional cycle of applied shear stress[16]. Increasing pore pressure reduces the shear modulus, so each subsequent cycle propagated into an increasingly reducing shear modulus (that is, impedance), which would further amplify the focused energy. Our calculations for a single wave cycle show shear strains of up to 20 microstrain ($\mu\varepsilon$) within the mud layer. Although it is not known what shear strain magnitude would induce liquefaction at the depths of Lusi, we note that this is within the range of the 10–100 $\mu\varepsilon$ purported to have caused liquefaction of the San Francisco Marina Bay muds (albeit at shallower depths) in response to the 1989 M 7.1 Loma Prieta earthquake[17].

Our results support a scenario where lithology-controlled focusing of the incoming seismic waves into the mud layer resulted in liquefaction and disruption of an aquitard[18] (Fig. 4). This allowed the fluidized mud to inject into an incipient fault plane that set in motion the collapse of this metastable system. Slip on the fault facilitated hydraulic connectivity to a deeply rooted sediment-hosted hydrothermal system[19] that fed (and still feeds) the eruption with a substantial long-term fluid input. This scenario is supported by isotopic evidence of a significant mantle He fraction[4], high lithium concentrations and the observation that the well caved at a depth of 1,275 m, consistent with calculated regions affected by the highest energy density and strain. Finally, large spatial scale liquefaction reconciles the long-known discrepancy between the site of the borehole and the first arrival of mud at five separate locations aligned with the Watukosek Fault between 200 and 1,000 m from the well[8].

The behaviour of the mud layer during the complex process of liquefaction[20,21] leads to two alternative scenarios, which can be simplified into two end-member states; compacting or dilating (Fig. 4a). As fluid pressure increases with each loading cycle, compacting materials liquefy and flow when reaching the flow surface line (FSL). Dilatant materials strain-harden after reaching the FSL because dilatancy reduces pore pressure and flow is arrested. The liquefaction properties of the mud layer beneath Lusi are not known, but both behaviours have been observed in experiments on samples from various mud volcanos[16] and either behaviour could have initiated Lusi. If the mud layer is compacting, then liquefaction reduced the shear strength to near zero and allowed the highly pressured and fluidized mud to inject into an incipient slip plane. If the mud layer is dilatant, flow would be limited from pore pressure reductions concomitant with dilatancy, but that same dilatancy would exsolve large quantities of CO_2 from the pore fluids when the fluid pressure reduced beneath its initial value to produce a mobile mud/fluid/gas mixture. CO_2 exsolution for Lusi was previously attributed to pressure reductions through flow into the fault zone, but this might also be appended to include

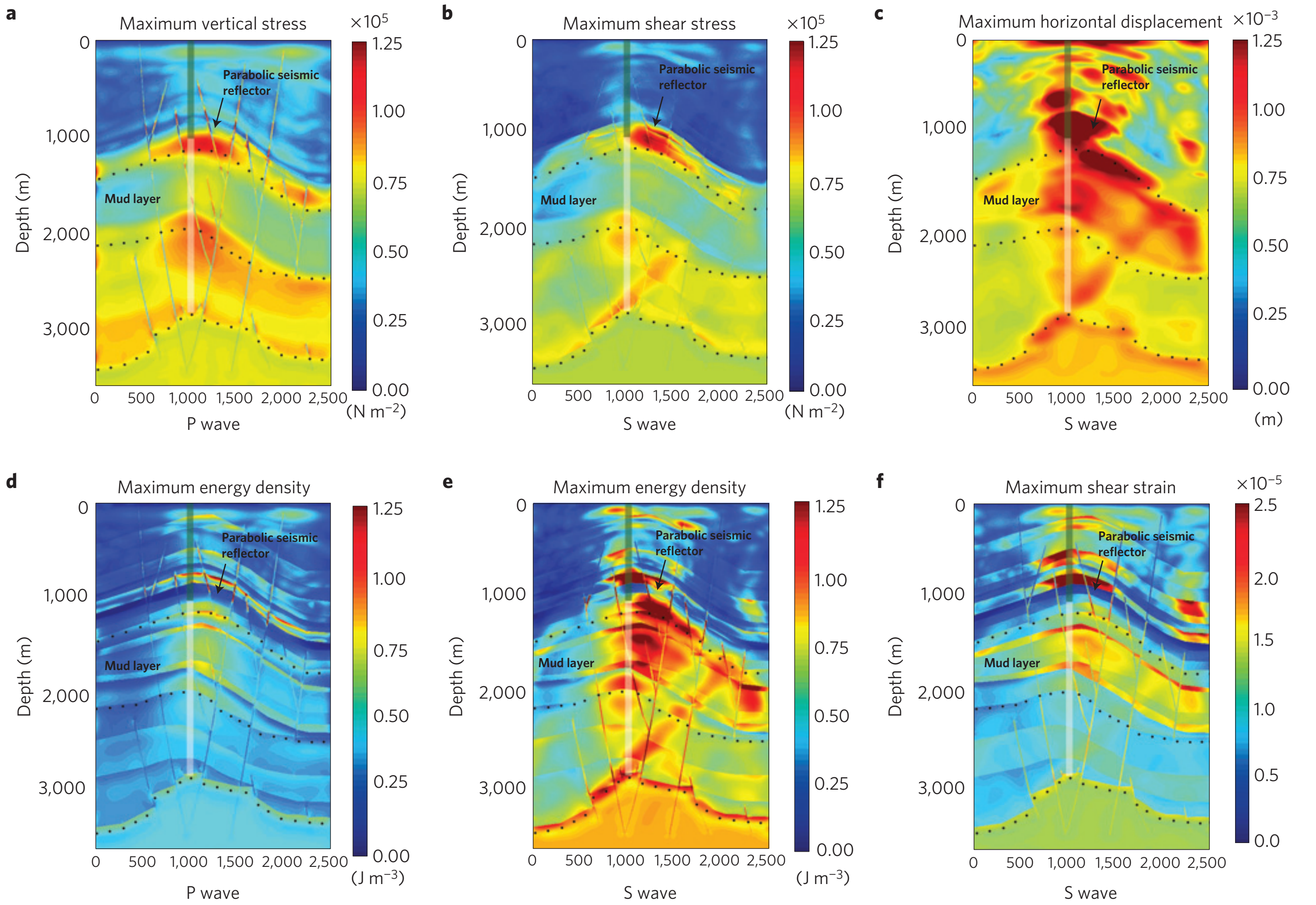

Figure 3 | Results of the numerical study. Simulation results for: **a**,**d**, P wave; and **b**,**c**,**e**, **f**, S wave at 1.5 Hz. **e**, Peak energy density of 1.25 J m^{-3} is reached above the seismic reflector and in the mud layer, demonstrating how the domed structure geometrically focuses energy. Dynamic stress σ_D (**a**,**b**), vertical displacement (**c**) and shear strain ε (**f**) induced by wave propagation shows how the lithology affects their distribution. Peaks of σ_D of 0.25 MPa are observed immediately below the casing, whereas the induced dynamic stress in the mud layer is approximately 0.075 MPa with peaks of 0.1 MPa in the deeper part. Vertical displacements of 1.25 mm occur in the mud layer, inducing peak strains of 20 $\mu\epsilon$.

large-scale CO_2 exsolution from dilatant liquefaction. In either case, cyclic loading from the Yogyakarta earthquake significantly increased pore pressure and loaded the system towards the FSL. High pore pressures were retained in the mud layer because of the very low permeability of the formation[6] and when two powerful aftershocks renewed cyclic loading of this reduced impedance system, geometric amplification probably further liquefied the layer. This mechanism is also supported by drilling mud losses observed shortly after the Yogyakarta mainshock and the two powerful aftershocks. High strain rates in either compacting or dilating systems also substantially reduced the effective viscosity of the mud, thus making it more mobile[3].

Exonerating drilling as the primary trigger for Lusi requires an explanation for the observed mud loss and pressure kicks recorded at the borehole. Liquefaction of the mud layer would have drawn in drilling mud by either a complete loss of strength (compacting liquefaction), or by drawing in drilling mud from the dilatant volume increase and fluid pressure reduction of the mud layer (dilatant liquefaction). More than 21,000 l of drilling mud were lost, translating into more than 200 m of mud column, or roughly 4 MPa assuming a mud loss depth of 1,500 m. This significant pressure reduction allowed a pressure pulse to propagate from deep in the borehole, perhaps from the overpressured carbonates, and through the borehole to provide the reported kick 26 h after the earthquake. Hazardous drilling procedures[2] and drawing fluids up (swabbing) when removing the drill string may have exacerbated the problem, but the borehole was responding only to liquefaction underway in the mud layer. Our results suggest that the borehole was a witness to, and not the perpetrator of, the initiation of Lusi.

The larger implication of our results is that most hydrothermal and volcanic systems host parabolic-shaped lithology with contrasting acoustic impedance[22] that can amplify incoming seismic energy[23]. If the energy focuses on fluid- or magma-rich reservoirs, substantial amplification of loading/unloading cycles can instigate or exacerbate proposed processes of rectified diffusion[24], entrained gas exsolution, or liquefaction. Incoming seismic waves from distant earthquakes are reflected (refracted) by these parabolic seismic reflectors (refractors) that amplify and focus energy, thus triggering a response of the system that would have otherwise gone unperturbed. Because surface waves penetrate to depths that depend on the wavelength, this mechanism may apply to the recently observed correlation between Love wave stressing duration and long-distance earthquake triggering[25].

Our results indicate that Lusi is a natural disaster and a geological rarity of a newborn, tectonic-scale hydrothermal system. Lusi can thus be explored for deeper understanding of earthquake triggering, deep-rooted volcanic hydrogeology, degassing processes, reassessments of longevity and possibly a disaster-to-development opportunity through geothermal energy development and lithium mining of the deeply derived fluids.

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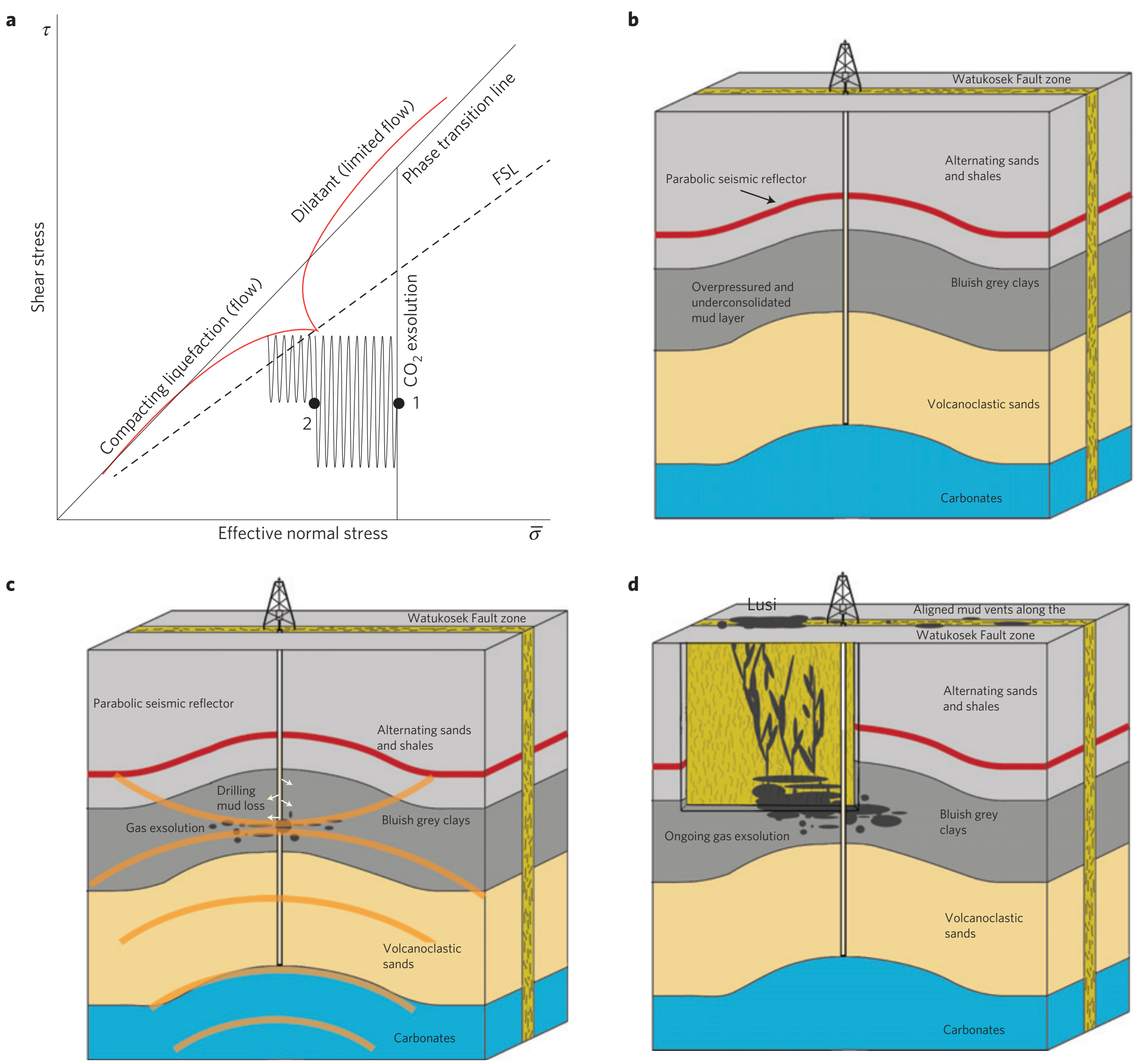

Figure 4 | Conceptual stress path and proposed scenario for triggering the Lusi mud eruption. a, Amplified seismic energy perturbs the initial stress state (1), increasing pore pressure through cyclic shear stressing. Aftershocks (2) cyclically load the (impedance-reduced) mud layer, reaching the FSL. At the FSL, the mud layer either liquefied and lost strength (compacting), or strain hardened (dilatant). Fluid pressure reductions to below initial conditions trigger CO_2 exsolution, mobilizing the mixture of mud, gas and water. **b**, State of system before the Yogyakarta earthquake with high fluid pressures and a narrow drilling window[2]. **c**, Liquefaction from Yogyakarta earthquake and aftershocks drew drilling mud into the layer. **d**, Liquefied mud layer injects and reactivates the pre-stressed Watukosek Fault system.

Methods

The model is based on an interpreted two-dimensional seismic profile[8] and includes all of the relevant structures. The geological formations, their petrophysical properties and acoustic impedances are well constrained by the known density[6] and P-wave velocity V_p (ref. 10; Fig. 2b). We estimated shear wave velocities from the P-wave velocities by assuming bulk and shear moduli of 5.3 GPa and 30 GPa, respectively[1]. The detailed two-dimensional model (Fig. 2c) measures 3.5 km × 2.5 km, with 21 geological layers and faults. The geometry was discretized into a rotated staggered finite-difference grid of 2.5×10^7 nodes with a grid spacing of 0.675 m. Periodic boundary conditions were applied along the sides of the model domain, a free surface at the top of the domain and a displacement boundary condition in the form of a plane wave was input at the bottom boundary. The amplitude of the incoming wave is constrained such that the average vertical displacement at the surface in the simulations is fixed at 1 mm to be consistent with the 1–2 mm vertical displacement observed at Lusi from the Yogyakarta earthquake[1,26].

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Author contributions

M.L. conducted the study, collected the data and constructed the geological model; E.H.S. conducted the numerical studies; F.F. conducted the seismological analysis; S.A.M. designed and coordinated the study and jointly wrote the manuscript with M.L. All authors contributed equally to the content.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to S.A.M.

Competing financial interests

The authors declare no competing financial interests.