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Fluid transport properties and estimation of overpressure at the Lusi mud volcano, East Java Basin

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ABSTRACT

Generation and maintenance of overpressure can prevent sediments from compaction and weaken sedimentary rocks in deep basins. Excess fluid pressure is one of the key factors to explain the disastrous mud eruption that took place in Sidoarjo, East Java, on 29 May 2006, though the mechanism by which it developed is not well known. We measured permeability and specific storage at a confining pressure of 100 MPa in outcrop samples from the East Java Basin. Both permeability and specific storage in our samples showed large stratigraphic variations. The mudstone of the Upper Kalibeng Formation that is thought to be the source of mud at Lusi had the lowest permeability of our samples at around 10^{-19}–10^{-20} m^2, and the permeability of the Upper Kujung Formation limestone was 10^{-16} m^2, which is two orders of magnitude larger than that of the Lower Kujung Formation limestone. In addition, the permeability and porosity of cemented sedimentary rocks showed low sensitivity to effective pressure. From numerical basin analysis of the Lusi site together with laboratory data, we evaluated the evolution of pore pressure and porosity histories and their present distributions. Our results show that high overpressure was generated below the mudstone of the Upper Kalibeng Formation and almost reached lithostatic levels. The modeled fluid pressure variation is consistent with the observed data. The long-lived overpressure at depth is mainly caused by the existence of thick low-permeability sediments and a high sedimentation rate. Undercompaction of the Upper Kalibeng Formation because of overpressurization may have caused the mud to lose strength and cause liquefaction (and hydrofracturing) as a result of small stress fluctuations induced by the Yogyakarta earthquake, which may have ended up causing the mud eruption.

1. Introduction

On 29 May 2006, an unexpected water and mud eruption took place in the Porong subdistrict of Sidoarjo, East Java (Fig. 1a and b). This mud volcano is commonly called Lusi (Lumpur "mud"-Sidoarjo), and the eruption occurred during drilling of the Banjar Panji-1 gas exploration well at a site only 150–200 m away from the point where the eruption started (Davies et al., 2007). After the start of the mud eruption, the rate of mud flow was from 5000 to 120,000 m^3/day for the first three months, and it still continues after three years. The strong flow has begun to cause subsidence, and a caldera has begun to form. On the basis of clay mineralogy, vitrinite reflectivity, and biostratigraphy, the erupted mud is derived from between 1615 and 1828 m depth in the Upper Kalibeng Formation (Mazzini et al., 2007). Geochemical analyses of gas and fluid at the eruption site suggest that the gas and water are sourced from both shallow and deep formations, and may come from as deep as the Kujung Formation.

Davies et al. (2007) suggest that the eruption of mud was triggered by the connection of strata at high fluid pressures to the surface via fractures created either by drilling or as a result of an earthquake (the Yogyakarta earthquake, 6.3 in magnitude, occurred on 27 May 2006). There is some doubt about the earthquake hypothesis as the earthquake occurred two days before the mud eruption and 280 km distant from the well (Davies et al., 2007). Davies et al. (2008) and Tingay et al. (2008) evaluated the possible pore pressure and stress changes triggered by the earthquake, but their estimated changes were only a few tens to hundreds of Pa, and are much smaller than the stress changes that can be caused by tides or variations of barometric pressure. The hypothesis that the eruption was induced by the earthquake is supported by the observation that the partial loss of drilling mud during drilling of the Banjar Panji-1 well occurred 10 min

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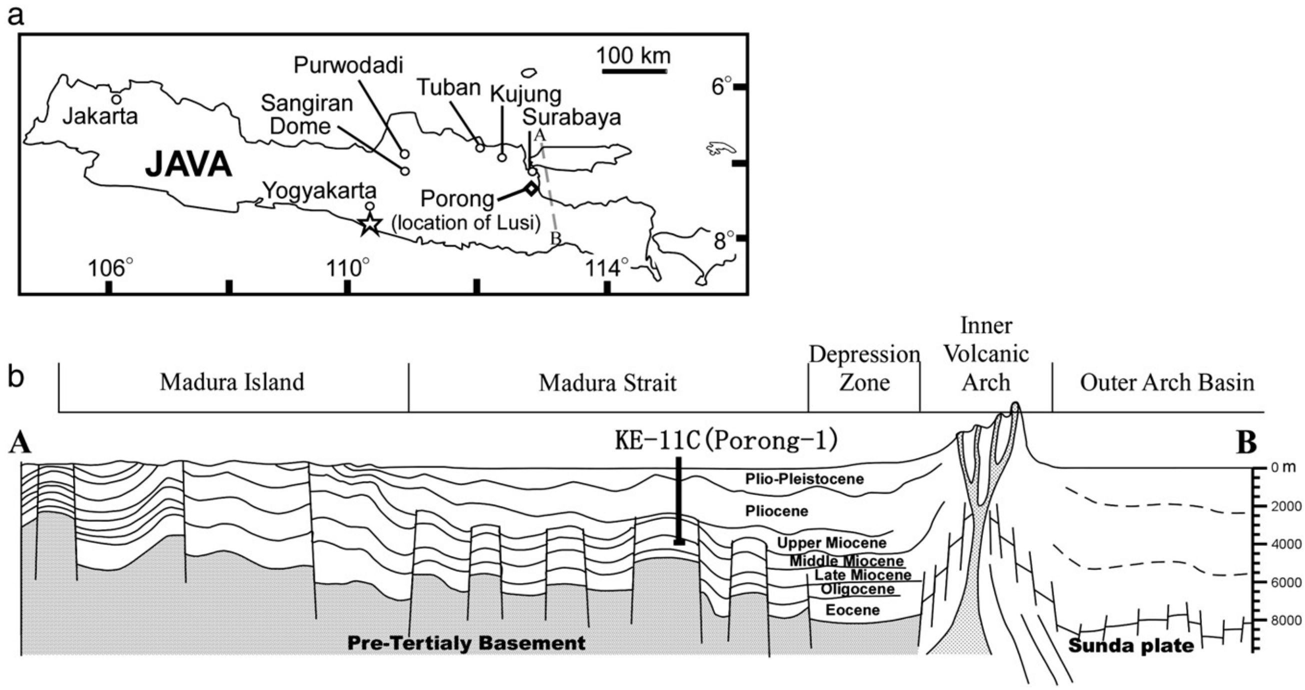

Fig. 1. (a) Map of Java Island showing the location of the Lusi mud volcano and the epicenter of the 2006 Yogyakarta earthquake (shown by a star). (b) North–south cross section across the Madura Strait (after Kusumastuti et al., 2002), and the location of KE-11C well which is near Porong well.

after the earthquake (Mazzini et al., 2007; Tingay et al., 2008). A different trigger mechanism was proposed by Davies et al. (2007, 2008), who suggested that gas exploration drilling triggered the mud volcano eruption. They assumed that there was sufficient influx of formation fluid into the borehole to cause hydraulic fracturing that may have propagated to the surface. Their assumption is based on a theoretical pressure analysis at 1091 m (the shallowest depth in the borehole without protective steel casing), which showed that pore pressure might have approached the formation pressure just before the eruption (Davies et al., 2008). They suggested that the removal of the drill bit between 27 and 28 May caused a kick event (influx of formation fluid and gas into the wellbore), and that fluid pressure generation after the well was shut in because of the kick was sufficient to cause hydrofracturing. The lack of casing below 1091 m increased the potential for hydraulic fracturing. However, Mazzini et al. (2007) argued that the formation of surface fractures observed at the well site during the second day of the mud eruption, with no fluid exiting from these fractures, was caused by shearing rather than by hydrofracturing.

Drilling records and sonic-log data from the Banjar Panji-1 well (Fig. 2) indicate the existence of overpressure in the Kalibeng Formation before the mud eruption. Excess fluid pressure reduces rock strength and, when it exceeds formation pressure, enhances fracturing. If the overpressure at depth was close to lithostatic pressure, even a small perturbation of pore pressure might have caused hydrofracturing. Overpressure caused by loading prevents consolidation of sediments. For high porosity sediments with less lithification, the resultant under-compaction enhances the mobility of sediments and causes fluidization. Such soft sediments at depth can become fluidized and sometimes form mud volcanoes. Mud volcanoes erupt water, fine sediment, fragments of country rock, and, sometimes, oil and natural gas. Lusi has all of these characteristics and is therefore considered to be a mud volcano. Mud volcanoes are most often found in areas where high sedimentation rates together with impermeable sediments lead to the development of high pore pressures (Kopf, 2002).

Several mechanisms have been proposed for the generation of overpressure in thick sedimentary basins (Osborn and Swarbrick, 1997; Wangen, 2001), and it is generally accepted that rapid sediment loading on low-permeability formations is an important factor (Bredehoeft and Hanshaw, 1968). Dehydration reactions, hydrocarbon generation, and the additional influx of water from depth are other possible mechanisms (e.g., Tanikawa et al., 2008). Permeability and specific storage are critical hydraulic properties that control the generation of overpressure and the distribution of fluid pressure at depth (Gibson, 1958; Bethke and Corbet, 1988).

However, fluid transport properties and the mechanism of generation of regional overpressure at Lusi and elsewhere in the East Java Basin are not well understood. Consequently, we investigated the mechanism by which overpressure was generated by using measured transport properties and a simplified one-dimensional basin model. We used outcrop samples from the East Java Basin to assess the fluid transport properties that are likely to exist at the Lusi drilling site.

2. Geological setting

The Lusi mud volcano erupted in the south of the East Java Basin, which is an inverted backarc basin. The structural history of the East Java Basin is divided into two phases: a Middle Eocene to Oligocene extensional phase, and a Neogene compressional or inversion phase. Grabens and half-graben structures were developed during the extensional phase, which was followed in the Neogene by compressional deformation with some wrenching. The most recent sedimentation in the East Java Basin occurred during the Late Pliocene to Holocene (3.6–0 Ma), during which time the southern part of the basin (Kendeng zone) was affected by north-verging thrusts and uplift. The uplift was accompanied by an influx of volcaniclastic rocks from the volcanic arc. From the Oligocene to the Holocene, the basin filled with shallow-marine carbonates and marine muds. The overpressuring was thought to be caused mainly by high sedimentation rates followed by rapid subsidence and maturation of organic materials (Willumsen and Schiller, 1994; Schiller et al., 1994), though detailed transport property data that are strongly connected to pore pressure generation were not reported.