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Satyana, A.H., 2019, Genesis of LUSI Eruption, East Java – Debates of Drilling Accident, Regional Earthquake Trigger, Hydrothermal-Volcanic System: New Evidence from Erupted Materials, in Anggara, F., Kusumah, E., Wibowo, H.T. (eds)., ISPG 1st Memoir: Overpressured Sedimentary Basin: Petroleum Geology & Hazards, p. 16-37.

Genesis of LUSI Eruption, East Java– Debates of Drilling Accident, Regional Earthquake Trigger, Hydrothermal-Volcanic System: New Evidence from Erupted Materials

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ABSTRACT

The LUSI (LUmpur SIdoarjo) – mud eruption in Sidoarjo area, East Java has been erupting for 13 years since its inception in 29th May 2006. While the social problems of LUSI eruption have been mostly completed, the debate of the genesis of LUSI have not yet settled. There are two groups involved in the debate, Group 1 proponents of drilling accident as the trigger of LUSI eruption and Group 2 proponents of Yogyakarta 27th May 2006's earthquake as the trigger of LUSI eruption. Group 1 concentrated their studies on Banjarpanji-1 drilling data, while Group 2 conducted various field studies and analyses of water, gas, and solid samples erupted by LUSI during its development over the last ten years. Based on its erupted materials, LUSI is not a purely mud volcano but a hybrid of mud volcano and hydrothermal system, called as SHHS (sediment-hosted hydrothermal system). A network of seismometers installed by Group 2 resulted in 3D image data revealing that LUSI connects at depth through deep-seated fault (around 6 km deep) to magmatic body of Arjuno-Welirang volcano. The connection of sediments beneath LUSI and magmatic body at depth had provided over-pressured condition which erupted when a perturbation took place. This paper reviews the debate between Group 1 and Group 2 based on the development of LUSI from its inception to its current status, expressing on its erupted materials, determining the actual trigger mechanism and genesis of LUSI mud eruption.

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Introduction

The unpredicted occurrence of mud volcano eruption took place on 29th May 2006 in the Porong district, Sidoarjo, East Java. This phenomenon was named as LUSI (abbreviation of "Lumpur SIdoarjo" or Sidoarjo mud, lumpur is Indonesian language for mud). Others name it "Lumpur Lapindo" expecting the mud eruption existed due to drilling activities as conducted by oil and gas company called Lapindo in Brantas Block, East Java. The name itself between LUSI and Lumpur Lapindo has brought a debate of its genesis/ origin. In this paper the name of LUSI is used since it has general implication without prejudice than that of Lumpur Lapindo, which blame Lapindo's drilling as a cause of mud eruption.

Figure 1. A satellite image records an over-flooding mud of Lusi with red dot symbol indicates sampling locations. The image was dated on August 2014 (Mazzini et al., 2018). The bright grey area denotes the accessible dry mud breccia, while the darker color in nearby active crater represents a large hydrothermal pond.

Triggering mechanism for the inception or genesis of LUSI eruption became the debate. There are two groups of thoughts for the trigger of LUSI genesis: (1) trigger by drilling accident of exploration well called Banjarpanji-1 by Lapindo Brantas (Davies et al., 2007; 2008; 2010; 2011; Tingay et al., 2008; 2015; Tingay, 2014) and (2) triggered by May 27, 2006's Yogyakarta earthquake (Mazzini et al., 2007; 2009; Sawolo et al., 2009, 2010; Istadi et al., 2012).

Evolution and development of LUSI eruption and its erupted materials (mud and fluids) lead to new consideration of LUSI phenomena as developed from mud volcano to volcanic hydrothermal and sedimentary system called as sediment-hosted hydrothermal system (SHHS) (Mazzini et al., 2012; Mazzini and Etiope, 2017; Miller and Mazzini, 2018).

This paper reviews the development of LUSI since its inception (2006) up to the present time (2019), this development can determine better what really LUSI is including its genesis which became the debate. The arguments from the two groups are reviewed, and concluded.

Geologic Setting

LUSI eruption when it was known as mud volcano regionally occur in "elisional" basin called Kendeng Deep (Satyana and Asnidar, 2008; Satyana, 2019–this volume). All of the mud diapirs or mud volcanoes extend along Java to Madura occur in the elisional basin of Bogor-North Serayu-Kendeng-Madura Strait. Further discussion of elisional system and mud diapirism and mud volcanism is provided by Satyana (2019 –this volume). LUSI is located at the southern part of the Kendeng Deep.

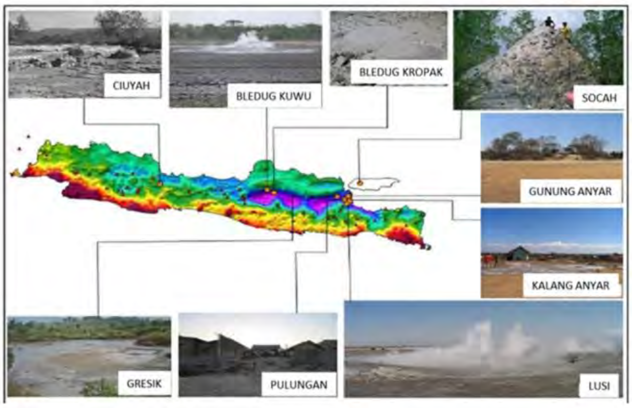


Figure 2. The disseminated sites of either mud diapirs or mud volcanoes along Java to Madura islands (Satyana and Asnidar, 2008). LUSI is included.

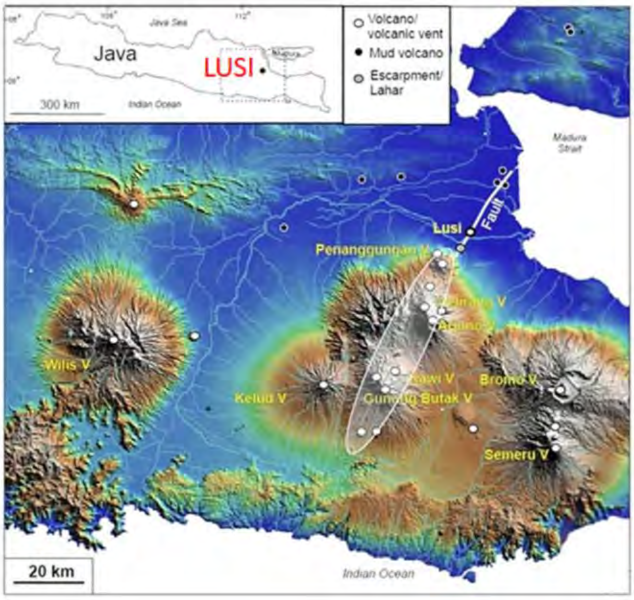


***Figure 3**. The existence of volcanoes, mud volcanoes and volcanic vents, including LUSI is depicted in the elevation map of East Java. It is also noted that the main trend of the Arjuno-Welirang volcano vents linier with the NE–SW trend of Watukosek fault. This fault is suspected hosts the occurrence of other mud volcanoes (Mazzini et al., 2012).*

The origin of LUSI as elisional phenomenon within the Kendeng Deep was discussed by Satyana and Asnidar (2008). Different to other mud volcanoes in the Kendeng Deep, LUSI location is relatively close to magmatic volcanoes to the south (Penanggungan, Welirang, Arjuno, Anjasmoro). This close distance appears to have affected LUSI mud eruption at its later development. As located within elisional basin, the Kendeng Deep in the area of LUSI has very high rate of sedimentation due to deposition of (Mazzini et al., 2018 –based on Banjarpanji-1 well): 1) shallow alluvial sediments (with approximate thickness from 0-290 m), 2) Sandstone - shale alternation of the Pucangan Formation which was deposited during Pleistocene, (up to 900 m depth), 3) bluish - gray clay of the Upper Kalibeng Formation which was deposited on Pleistocene (with thickness up to 1871 m), 4) Plio- Pleistocene volcaniclastic rocks of 962 m thick, Oligo-Miocene carbonate layer of the Kujung Formation including limestones of Prupuh and Tuban Formations (up to ~3.5 km), and 5) Eocene organic-rich shale which presents as source rock of the Ngimbang Formation. Organic-rich sediments of both Upper Kalibeng and Ngimbang Formations are prone for generating hydrocarbon.

The Watukosek fault system is originating from the Arjuno-Welirang volcano complex. This fault extends along the NE Java and has numerous strike-slips faults (Istadi et al., 2009; Mazzini et al., 2009; Moscariello et al., 2018; Sciarra et al., 2018). This fault system is predicted as the host of LUSI mud volcano and numerous nearby mud volcanoes (such as Gunung Anyar, Kalang Anyar and Pulungan mud volcanoes –Mazzini et al., 2018; even mud volcanoes in west Madura Island – Satyana and Asnidar, 2008). The fault is also suspected became the pathway of deep- fluids migration which passed through other structures nearby LUSI (Mazzini et al., 2009; Miller and Mazzini, 2018).

Situating in a region with a geological complex, LUSI occurrence is controlled by couple processes of tectonic and depositional in the sedimentary basin (such as compaction, diagenesis, regime of compressional stress and circulation of deep- fluids) as well as volcanic processes that interconnected (Moscariello et al., 2018).

The Inception of LUSI: Mud Volcano Eruption

As a result of mud volcano eruption, water seepage was found scattered in nearby eruption site. This seepage was detected during the early morning of 29th May 2006, in the Porong area, Sidoarjo, East Java. The widespread occurrence of water seepage which takes place only few hours was then expand into LUSI eruption. The erupted mud materials consists of 60% boiled water and steam. Those materials were ejected several ten meters from the eruption site together with high flares steam of up to 50 m. The massive eruption caused rapid development of circular crater (Mazzini et al., 2007). The subsequent two eruptions occurred on the 2nd and the 3rd of June, 2006, but these eruptions stopped on June 5, 2006.

At that time, the exploration well called Banjarpanji-1 was being drilled by Lapindo Brantas. The initial eruption occurred in 200 m southwest of the well. Two days before the eruption (27th May, 2009), a powerful earthquake stroke Yogyakarta (250 km WSW of Sidoarjo) at M6.3 and its energy propagated to the east-northeast reactivating Semeru volcano (Harris and Ripepe, 2007) and the earthquake energy was also recorded on seismic acquisition by Hess company in offshore Ujung Pangkah.

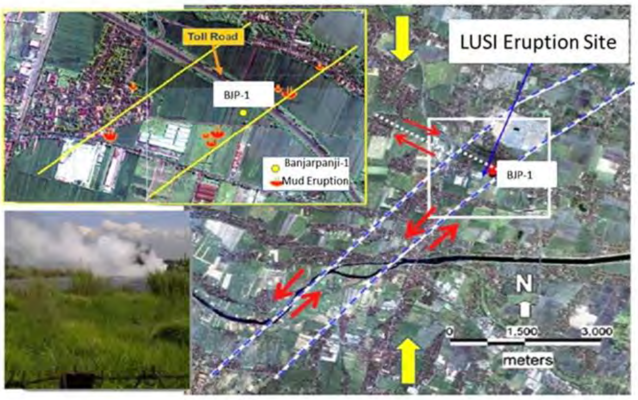


***Figure 4**. Satellite image of initial LUSI eruptions depicts additional five spots of mud gusher which is in line with Watukosek fault lines. The inserted photo which was taken on 29th May 2006, around 9 am or four hours after LUSI eruption shows similar mud burst. This site was located 200 m away from the location of Banjarpanji-1 well (Sawolo et al., 2009). The Watukosek Fault System is predicted based on river bend and escarpment.*

The earthquake in time sequentially affected Sidoarjo area causing partial and total loss in Banjarpanji-1 well (Sawolo et al., 2009). Local structures found as a result of LUSI eruption, such as fractures with dimension of hundred meters long and ten centimeters wide, were observed few days after mud eruption, particularly in the vicinity of Banjarpanji-1 well. The coincidence of LUSI eruption inception and drilling of Banjarpanji-1 well and the 27th May, 2006's Yogyakarta earthquake has been invoked to explain as the mechanism of genesis of LUSI, but causing debates. During the early eruption (August 2006), the volume of erupted mud increased from 5000m^3/day to 120,000 m^3/day, increased to 170,000 m^3/day in September 2006 and reached the high level peak at 180,000 m^3/day in December 2006 (Mazzini et al., 2007). This mud flood in the area had moved the rig and ended the drilling Banjarpanji – 1 well. The disaster then buried villages, forced 60,000 people

***Figure 5**. The signatures of LUSI eruption. (A) After 29th of May 2006 LUSI experienced an increasing level of eruption. The steam dominated fluids mixed with mud were ejected several ten meters; (B) LUSI image from aircraft (3) several sites of mud eruption (4–5) that observed after 29th of May. The trend of sites are aligned with fault with SW–NE orientation, after LUSI eruption sites 4 and 5 were observed and comprised of rich sand; (C) well observed of a long fracture oriented SW–NE in the vicinity of the drilling site; (D) detail image of fracture as shown in figure C; (E) the lateral view of LUSI crater. In this figure, excavator (circled) is used as scale; (F) the bending railway is caused by fault intersection. This phenomenon occurred after the 27th of May earthquake and indicate fault reactivation; (G) seismic image of BJP-1 before LUSI eruption illustrates the occurrence of existing upward dipping strata of piercement structure coincide with SW–NE fault direction (Mazzini et al., 2007).*

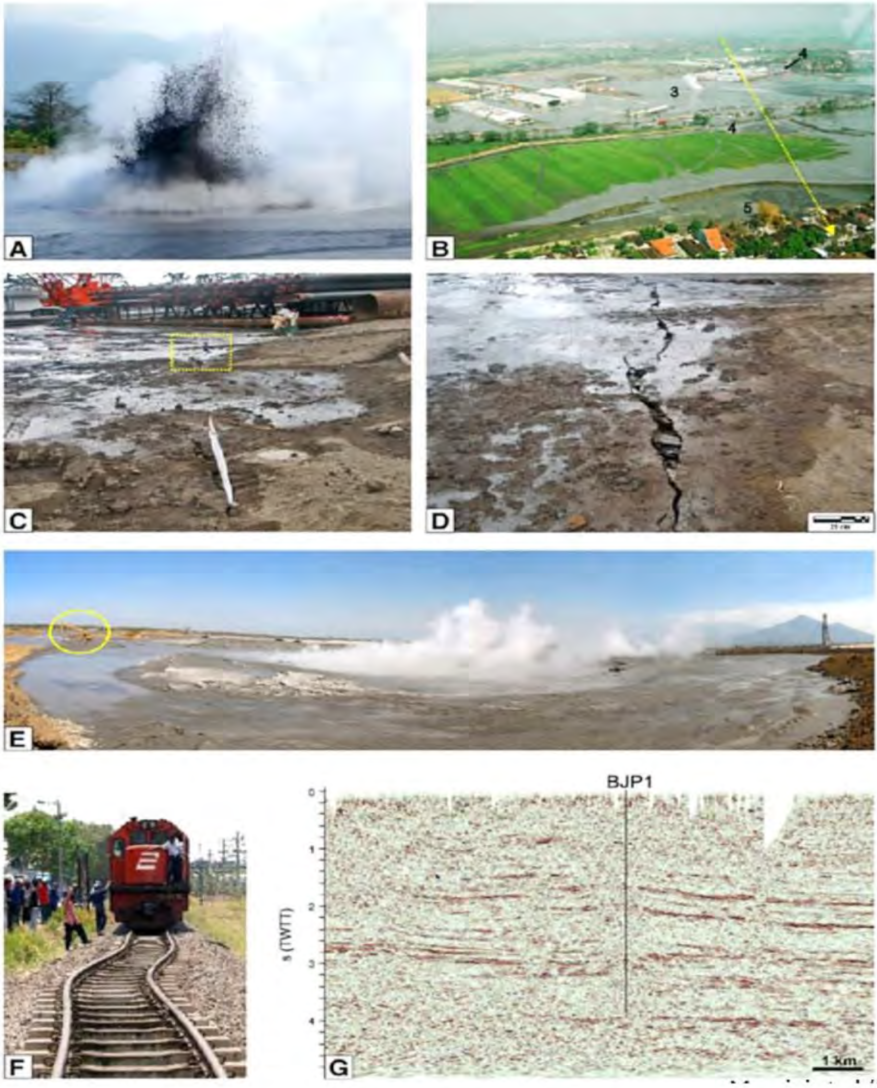


Figure 6. Research investigation and natural disaster mitigation, (A-C) Fluid sampling was carried out adjacent to mud crater and along the channels which radiate from the main crater. (D) Big bubble image of mud bursts at site of vents. (E) Fracture and fault zone are aligned with the LUSI plume and the Arjuno-Welirang volcano complex including Penanggungan volcano. Note : the Watukosek fault is indicated by escarpment on the left side of Penanggungan volcano. (F) The formation of some fractures and creeps in nearby mud crater are linier with the NE-SW trend orientation of Watukosek fault escarpment. Thus, the structures have intersected LUSI. The fractures were observed since the seismic indicate that the system prone to receive the external perturbation. (G) Human activities along the dry mud breccia. (H). Lateral view of the crater which was surrounded by berms in 2007. The main crater shows an active geysering activity (Miller and Mazzini, 2018).

moved from their homes, factories, and infrastructures. No one can stop the eruption. In order to choke the mud flow, thousand of concrete spheres were assembled and lowered into the center of eruption. However, the eruption was unstoppable. Many attempts were carried out to plug the upwelling fluids, such as relief well. This attempt failed since the fractured zone continuously sheared. To store the mud, berms with 10 m high were constructed surround LUSI. These berms covered a region of ~7 km^2, as similar to swimming pool which was filled with erupted mud breccia. The purpose of this attempt is to unleash further disaster once the embankment walls fail (Miller and Mazzini, 2018).Due to its regional setting to occur in elisional basin of Kendeng Deep and its proximity to other mud volcanoe phenomenon in East Java, mud eruption of LUSI has classified as mud volcano (Davies et al., 2007: Mazzini et al., 2007; Satyana, 2007; Satyana and Asnidar, 2008; Tingay, 2010; Istadi et al., 2012). Mud volcano is sedimentary volcanism generated by imbalance gravitational deposition and over-pressured fluid (Satyana and Asnidar, 2008; Mazzini et al., 2012). The initial samplings of Mazzini et al., (2007) showed the mixture of mud breccia with abundant amount of methane gas, as a typical of worldwide mud volcanoes. Preliminary analyses of the erupted materials showed that clay and water were the main sources of over-pressured zone beneath the depth of ~1500–1800 m. The zone occurred as a result of rapid burial and under-compacted condition during fine- sediment deposition. This characteristic indicates most of mud volcano settings. Moreover, the analysed mixture mud and fluid contains strong signature of illitized clay which is commonly found as mud volcano materials.

Development of LUSI: Sediment-Hosted Hydrothermal System (SHSS) Eruption

In comparison with common mud volcano phenomenon, LUSI is an unusual one. There are several reasons for this. First, the eruption did not occur at existing edifice but occurred through pre-existing fractures as weakness zones. Meanwhile, the formation of fresh hydro-fractures is unknown. Secondly, mud has characteristic of high temperature, around 100°C (Mazzini et al., 2007). Finally, mud eruptions occurred shortly, terminated within hours to few days (Kopf, 2003; Mazzini et al., 2007), while LUSI mud volcano has been occurring for more than thirteen years. After more than thirteen years since the inception, the soft mud still existed, with continuous eruption type (Karyono et al., 2017) hosting several migrated vents since 2010. These vents have episodic sequence of eruption with enhanced activity fluid and 20% solid. The temperature of erupted water has remained constant at about 100°C (Handoko Wibowo, Geology Department, ITATS Surabaya, personal communication).

A wide set of data were acquired by researchers from Group 2. They wanted to understand what LUSI really is and the development since its inception. Their studies reveal the development of LUSI. They collected gas and water samples from LUSI in the periods of 2006-2013.

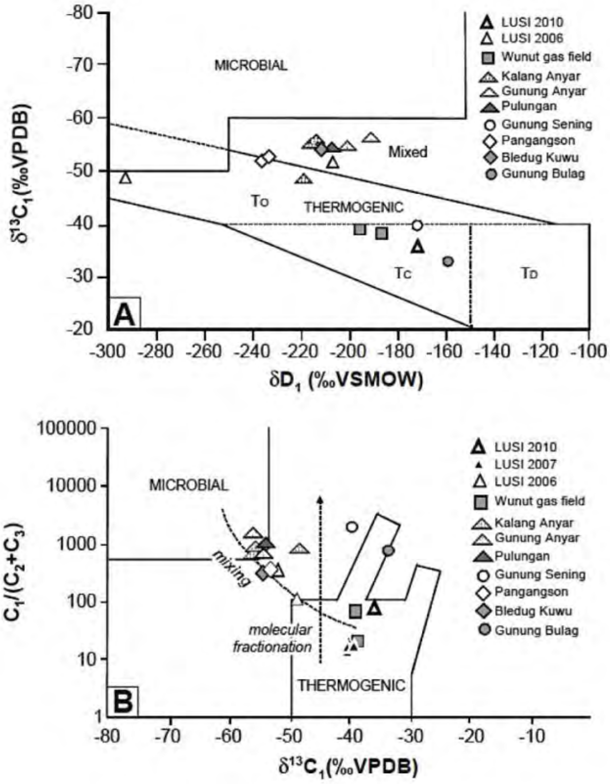


***Figure** 7. The diagrams illustrate a genetic zonation of methane (A: Schoell plot, B: Bernard plot); To: thermogenic with oil; Tc: thermogenic with condensate; T_D: dry thermogenic (Mazzini et al., 2012).*

They collected gas samples to analyze molecular and isotopic composition from some LUSI vents in the nearby mud volcanoes and natural gas field Carat, Wunut, and Tanggulangin, as well as hydrothermal vents of neighbouring Arjuno-Welirang volcano complex. The result of this studies have been published, part of them are listed on References.

Mazzini et al. (2012) summarized the geochemistry of erupted gas of LUSI as cited here. "The boiling fluids erupted in the crater zone are apparently CO_2-dominated, while colder CH_4-dominated and C_2–C_3 bearing fluids are identified at several sites around the crater zone. Gas genetic diagrams, maturity plots and gas generation modelling suggest that the hydrocarbons are thermogenic ($\delta^{13}C_1$ up to $-35‰$; $\delta^{13}C_2$ up to $-20‰$), deriving from marine kerogen with maturity of at least 1.5%Ro, for instance in the ~4400 m deep Ngimbang source rocks. CO_2 released from the crater and surrounding seeps is also thermogenic ($\delta^{13}C$ from -15 to $-24‰$) related to kerogen decarboxylation or thermal CH_4 oxidation in deep rocks, although three vents just outside the crater showed an apparent inorganic signature ($-7.5‰<\delta^{13}C=-0.5‰$) associated to mantle helium (R/Ra up to 6.5). High CO_2–CH_4 equilibrium temperatures (200–400 °C) are typical of thermally altered hydrocarbons or organic matter. The data suggest mainly thermally altered organic sources for the erupted gases, deeper sourced than the mud and water (Upper Kalibeng shales). These results are consistent with a scenario of deep seated (>4000 m) magmatic intrusions and hydrothermal fluids responsible for the enhanced heat that altered source rocks and/or gas reservoirs. The neighbouring magmatic Arjuno complex and its fluid–pressure system combined with high seismic activity could have played a key role in the LUSI genesis and evolution."

Comprehensive geochemistry studies were performed for LUSI materials and then they were compared with materials from surrounding mud volcanoes and volcano-hosted hydrothermal springs (Mazzini et al., 2018). The results of study are cited as follows. "Based on the geochemical characteristics of the waters expelled in the LUSI region, three groups can be distinguished.

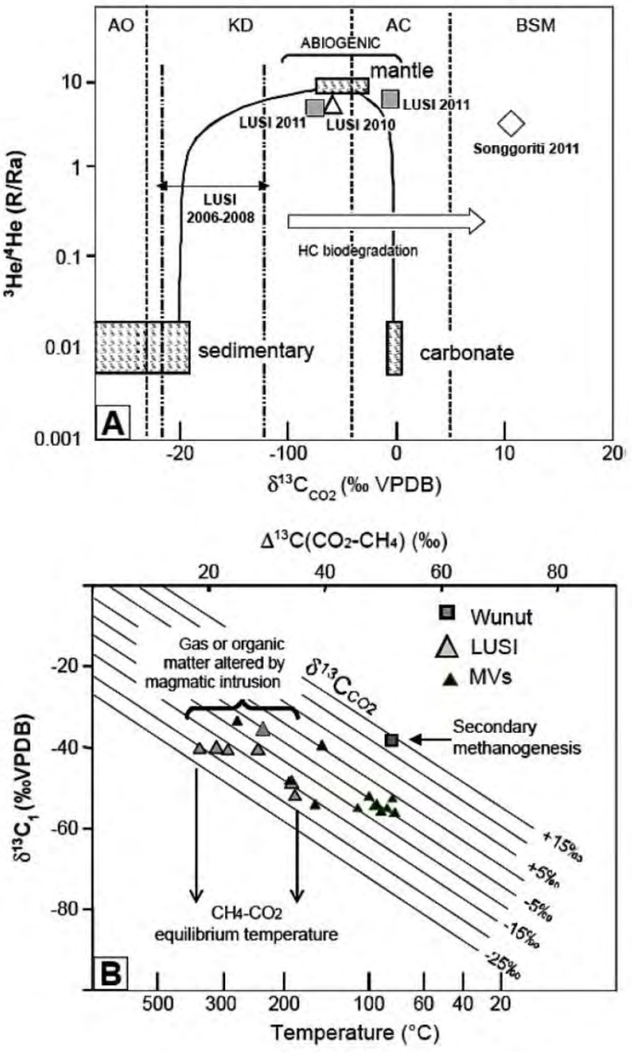


***Figure 8**. (A) He isotopic ratios vs. $\delta^{13}C_{CO2}$. AO, aerobic hydrocarbon oxidation; KD, kerogen decarboxylation; AC, alteration of marine carbonates; BSM, biodegradation and secondary methanogenesis. (B) $\delta^{13}C_{CH4}$ versus difference in stable carbon isotope composition [$\delta^{13}C_{(CO2-CH4)}$] between carbon dioxide and methane of Lusi, Wunut and other MV gases (Mazzini et al., 2012).*

1) meteoric waters expelled in cold springs and artesian wells, 2) hydrothermal waters typically mixed with meteoric waters, and 3) formation water from marine sediments altered by diagenetic processes such as clay-mineral dehydration. Samples collected from the LUSI crater are Cl and Na dominated (up to 527 mM and 471.7 mM, respectively) similar to seawater indicating that altered sedimentary formation waters are predominant in this system. In addition, they are enriched in Sr (up to 808.4 mM) and other elements commonly associated with hydrothermal systems, such as Li (up to 877.6 mM compared to 26 mM in seawater). Some of these elements are up to ten times enriched compared to seawater values. High temperature fluid mineral interactions in the subsurface appear to have facilitated the transfer of Li and other mobile elements into the fluids. High temperature fluid-mineral interaction reactions are also supported by Sr concentrations significantly higher compared to other sampled mud volcanoes in the island. Crater samples also show the highest d^{18}O values (+5‰after correction for evaporation compared to +1‰ at the MV localities). $^{87}Sr/^{86}Sr$ ratios vary between of 0.7077 and 0.7083 and seem to reflect a general mixture of fluids from clay-mineral dehydration, carbonate recrystallization, alteration of volcanic rocks and hydrothermal imprint. Eight years of geochemical monitoring indicate that the composition of the deep-sourced LUSI fluids remain fairly constant through time. Thus our findings show that the LUSI crater waters represent a regional geochemical anomaly, and we suggest that a combination of high temperatures in the source region, and fluid-rock interactions with silicates and, possibly, carbonate-rich lithologies can explain the data. This is consistent with a model where the emitted gases migrate from a deep-seated (>4 km) source region, likely associated with the presence of hot igneous intrusions and/or high T reactions related to the presence of neighboring active volcanoes."

There is also development of clasts that erupted by LUSI. Malvoisin et al. (2018) did the study based on mineral thermometry as performed by Raman spectroscopy and chlorite composition of LUSI erupted clasts. According to the results, some of these specimens derived from two main fluid sources, in which the depths were consistent with the geochemical and geophysical interpretation. Their results of study is cited as follows. "Two main clast lithotypes erupt at LUSI. The first lithotype is a light grey shale returned to the surface from the Upper Kalibeng Formation (the primary mud source) and equilibrated at temperatures below 200 °C.

The second lithotype is a black shale, whose source is the Ngimbang Formation at >3800 m depth, Two distinct temperature clusters are recorded in these black shales: one at 179±17 °C, consistent with the temperature estimate at 3800 m depth with the pre-eruption geothermal gradient, while younger minerals in the same specimen recorded substantial anomalous heating at ~ 250 °C. These high temperatures indicate interaction with a heat source associated with the eruption through mixing with hydrothermal fluids.

This temperature jump suggests rapid heating

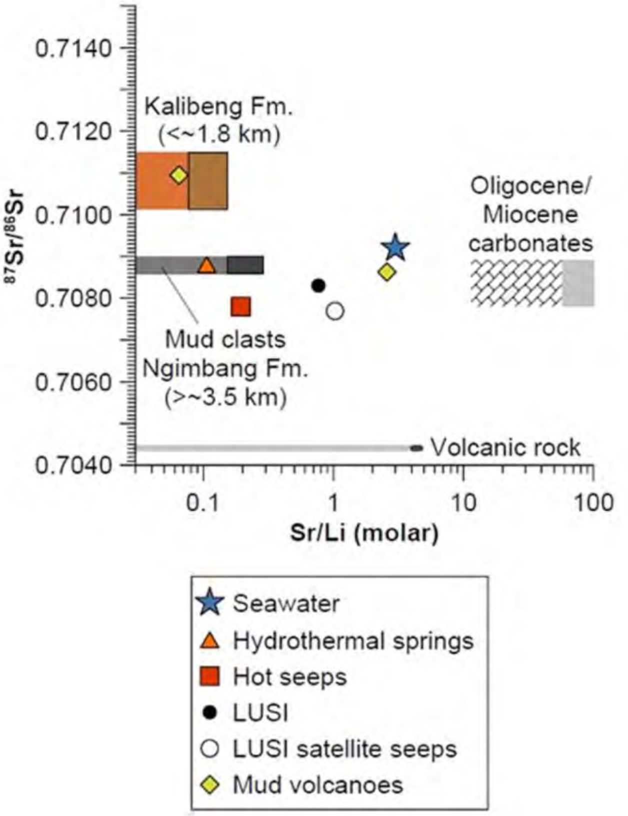


Figure 9. *Sr/Li versus 87Sr/86Sr indicates the ratio of dating and molar with samples taken from the analyzed materials and digested rocks of various stratigraphic formations. LUSI got fluid influx from a deeper and hotter source as indicated by the illitized clays of the Kalibeng Fm, the Ngimbang Fm., the Oligo- Miocene carbonates, and high temperature leaching of volcanic rocks (Mazzini et al., 2018).*

at ~ 4000 m depth, consistent with a scenario of magmatic intrusion and hydrothermal fluids circulation. This rapid and significant temperature increase would initiate devolatilisation reactions of hydrous minerals within the deep sedimentary package and generate substantial (highly over-pressuredd) fluids at depths significantly below the main source of erupted mud. We infer that reactive and thermal pressurization led to a deep and metastable system susceptible to e.g. seismic activity ultimately opening fluid pathways towards the surface along the Watukosek fault system. The two temperatures clusters recorded in the clasts show that conductive heat flow was the dominant heat transport prior to the eruption, while the system is now driven by large-scale convection and advective heat transport. The system appears unstoppable and poses a real and present hazard for the settlements still surrounding the eruption site. Continuous research is necessary to understand this spectacular phenomenon, both for its important scientific relevance, and the societal impact of this natural disaster."

Research by Malvoisin et al. (2018) resulted in similar finding as Shirzaei et al. (2015) whose concluded that surface deformation as performed by multi-temporal interferometric SAR (synthetic aperture radar) revealed both sources of deep and shallow for LUSI eruption. The radar data was taken between May 2006 and April 2011. The investigation also revealed that two regions beneath LUSI, at 300-2000 m and 3500-4750 m depth, undergone volume changes. The cumulative volume is gradually changed, wherein in shallow source, the volume is about 2-3 times larger than the deeper source. With regards to observation and model reconstruction, shallow source has an important role to supply the mud with additional fluids ascended from depths >4 km during eruption timescales. The deep and shallow sources of LUSI were related each other.

Based on the field studies and analyses of LUSI erupted materials (gas, water, mud clasts) since its inception to the present time, the researchers now conclude that LUSI is well understood as a sediment-hosted hydrothermal system (SHSS) rather than a purely mud volcano (Mazzini et al., 2012). Hydrothermal fluids fed LUSI mud eruption and the fluids circulated and migrated from the Arjuno-Welirang volcano complex. The fluids were also reacted with the organic-rich sediments which accumulated in the back-arc basin of East Java. In this case, instead of being a purely sedimentary mud volcano, LUSI is a hybrid system of either mud volcano and sediment-hosted hydrothermal system (Adriano Mazzini, 31 October 2017, to Live Science). Currently, LUSI is more likely a well-established meta- stable system like geyser which perpetually erupting gas, mud clasts, steam, and water.

In 2015, about 31 seismometers were installed by the researchers of Group 2. The instruments were placed around LUSI and the neighboring volcano complex to measure the ground shaking during earthquakes. In addition, they were also used by scientist to create three-dimensional images of the subsurface areas in the volcano complex. The researchers captured the subsurface condition of surrounding LUSI areas and volcanoes using seismometers. This work recorded subsurface data for 10 months. According to the seismic images, the fault system which controlled LUSI occurrence and situated 6 kilometers below surface of sedimentary basin was connected to a tunnel protruding from the northernmost of

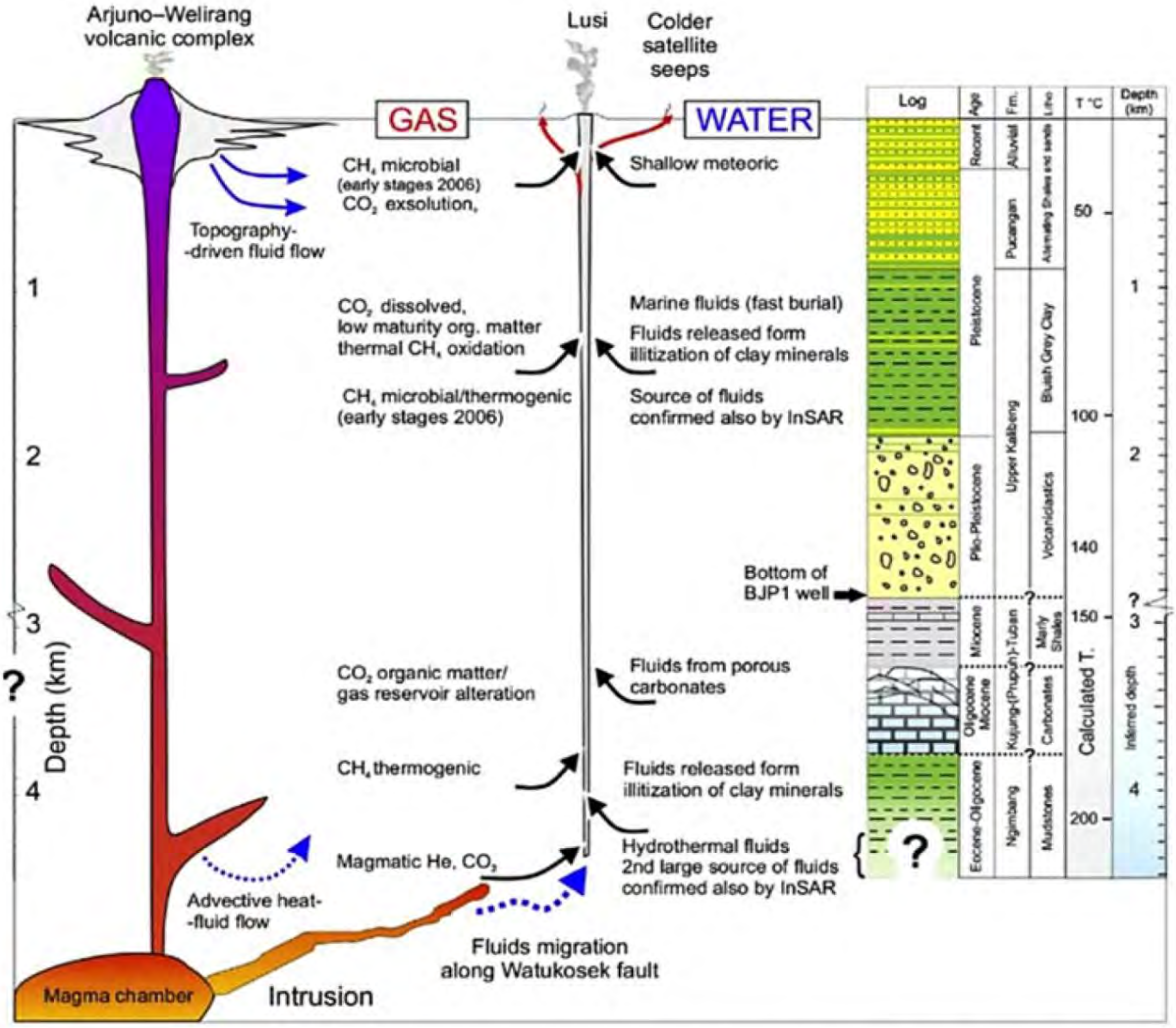


Figure 10. The interconnection conceptual model of LUSI to the Arjuno-Welirang volcano complex Mazzini et al. (2012). This general concept is acquired based on data collection (Miller and Mazzini, 2018).

Arjuno-Welirang's magma chambers.

The erupted water which was analyzed using deuterium isotope revealed a mixture of static magmatic fluids from a deeper depth of more than 20,000 feet. This data indicates the presence of deep basement faults or fractures within the conduit sites. Therefore, the scientist suggest that volcano complex systems are connected to other deep underground. Moreover, LUSI and the Arjuno-Welirang volcano complex somehow linked as identified based on gas samples collected from LUSI. This gas, however, is typically found in magma. The interconnection of LUSI and the Arjuno- Welirang volcano complex enable magma and hydrothermal fluids derived from mantle and intruded to LUSI sediments. The intrusion triggers vast reactions and creates gas. Subsequently, it generates subsurface high pressure. Other finding from the research is the maturation of organic-rich sediments underneath LUSI as produced by the scorching magma from the Arjuno-Welirang volcano. In fact, the entire system was already existed – everything was charged and ready to be triggered. However, no research addresses how LUSI is physically connected to Arjuno-Welirang.

Debates of Genesis of LUSI

There are several debates of the genesis or origin of LUSI mud eruption. The debate focuses on two trigger mechanisms: (1) drilling accident (underground blow out) of drilling Banjar Panji-1 exploration well which was performed by Lapindo Brantas – called here Group 1, (2) tectonic re-activation of Watukosek Fault (where LUSI is located) by the May 27th 2006's Yogyakarta earthquake –two days before LUSI erupted – called here Group 2. The debate has not been settled after thirteen years since LUSI erupted.

Proponents of the trigger mechanism of (1) or (2) still believe their own arguments, respectively. The main proponents of Group 1 with their publications are: Davies et al. (2007, 2008, 2010, 2011, 2018), Tingay et al. (2008, 2014, 2015, 2018), Brumm et al. (2007), Manga et al. (2009), Rudolph et al. (2011, 2013, 2015). The main proponents of Group 2 are: Mazzini et al. (2007, 2009, 2012, 2018), Lupi et al. (2013, 2014, 2018), Istadi et al. (2009, 2012), Vanderkluysen et al. (2014), Sawolo et al. (2009, 2010), Shirzaei et al. (2018), Moscariello et al. (2018), Oberman et al. (2018), Mauri et al. (2018), Svensen et al. (2018), Miller and Mazzini (2018), Malvoisin et al. (2018), Sciarra et al. (2018), Procesi et al. (2019).

Group 1 (drilling trigger) focus their arguments on drilling data of Banjarpanji-1 well that the well underwent underground blowout, causing mud eruption at surface.

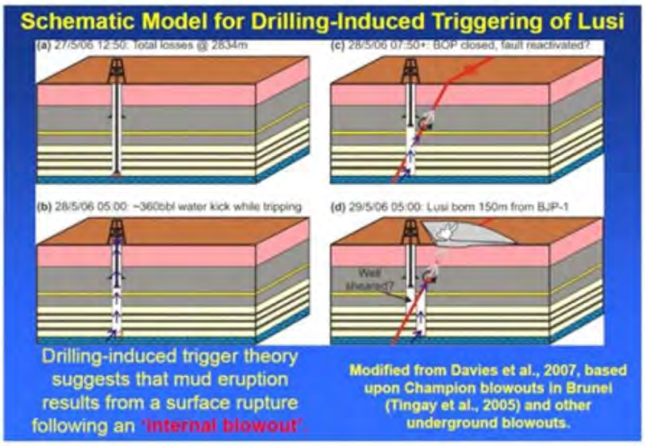


Figure 11. *A schematic model of LUSI eruption which is triggered by drilling of oil and gas (Tingay, 2010).*

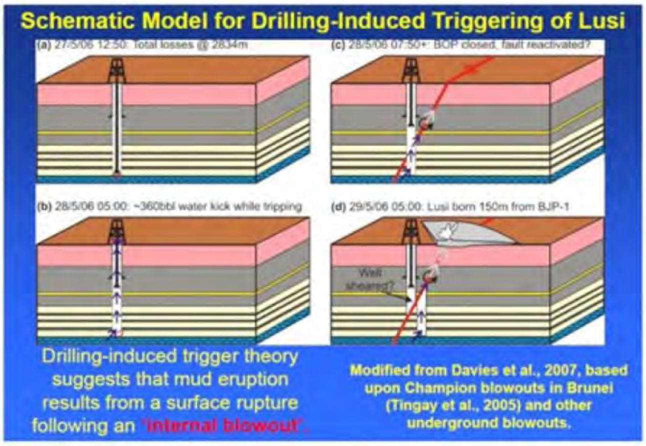


Figure 12. *A schematic model of LUSI eruption which is triggered by Yogyakarta earthquake (Tingay, 2010).*

Most of the researchers refute the argument of Yogyakarta earthquake as triggering factor of LUSI mud eruption. It is because the earthquake is too far from LUSI location and its energy too small to cause the eruption. They claimed that closer and stronger earthquakes previously occurred relative to LUSI location did not cause the eruption, how the more distant and weaker Yogyakarta earthquake caused the LUSI eruption. Group 1 did not conduct any field work related to LUSI development. Their arguments are based only on drilling data of Banjarpanji-1 which were not complete initially due to the proponents of Group 1 are not persons of the company who drilled the well, and they did not take into account all regional phenomena related to Yogyakarta earthquake seen in East Java and Madura, neither the development of LUSI which evolved from mud volcano to SHHS based on its materials later erupted.

Group 2 (earthquake trigger) focus their arguments on the reactivation of the Watukosek Fault by 27th May 2006's Yogyakarta earthquake on naturally prepared over-pressured structure in the area of later LUSI eruption. They conducted extensive field studies and analyses of erupted samples so they knew the development of LUSI from mud volcano eruption to SHHS. They argued that naturally prepared over-pressured structure in the area is resulted from hydrothermal-volcanic system, released as mud eruption when the Watukosek Fault was reactivated by the Yogyakarta earthquake. They argued that Banjarpanji-1 well was intact, there was no underground blow out (Sawolo et al., 2009; 2010), and there was no connection between mud eruption and the well. They re-analyzed the seismic energy of Yogyakarta earthquake and showed that natural-prepared structure of later called LUSI was in the condition of ready to be triggered. The following parts are detail arguments of each group.

Drilling Accident-Trigger of LUSI

On 29th May 2006, there was steam and water eruption followed by subsequent mud eruption presented in a location where no documentation recorded in the East Java during modern time. Davies et al. (2007) argued that this modern "pioneer" mud eruption (the first to occur at this site, but it was not the first, historically – Satyana, 2007, 2008) appears to have been triggered by Banjarpanji-1 (BJP-1) exploration well drilling by Lapindo Brantas. At that time, the well

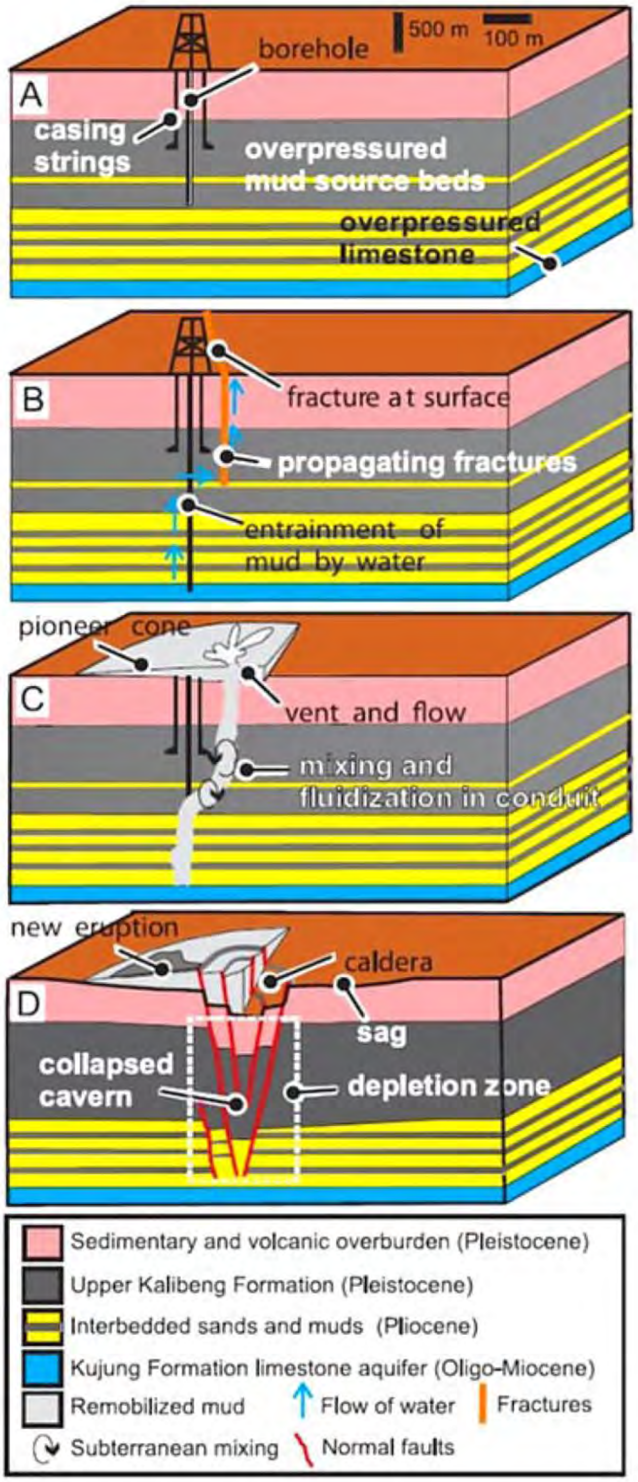
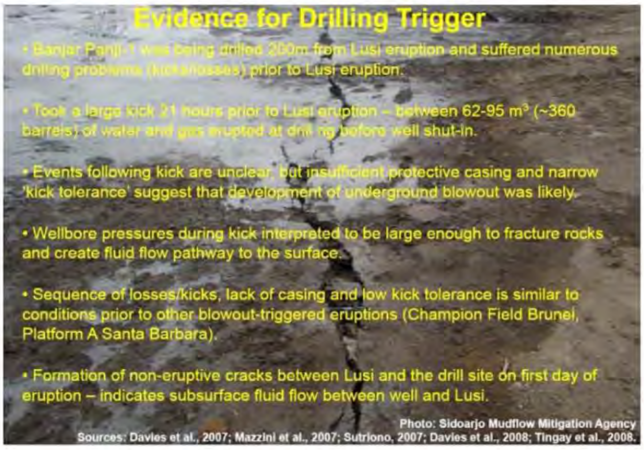


Figure 13*. Three-dimensional schema of four main development stages of the LUSI mud volcano. The first three diagrams depict the evolution between May 2006 and Dec. 2006 (A–C), while the fourth diagram (D) shows the future projected phase of evolution (Davies et al., 2007).*

penetrated subsurface over-pressured zone of porous and permeable limestones at ~2830 m depth. Davies et al. (2007) proposed that the borehole accommodates a pressure connection between limestone aquifers and over-pressured mud in overlying units. As the borehole was not protected by steel casing like a common drilling procedure, the pressure was then induced hydraulic fracturing which driven underground blowout. The eruption emerged when fractures were propagated to surface. After 173 days of mud eruption, the flow rates remain high (7000–150,000 m3 per day) (Davies et al., 2007). A continuous eruption is caused by significant volume of aquifer and driven by aquifer pressure. This process also affects erosion and entrainment of the over-pressured mud. Subsequently, the eruption formed caldera with a gentle sag-like subsidence shaped around the main vent which consists of mud (Davies, et al., 2007). The eruption stage initiates with fracture propagation through significant thickness of over-burden. During this process, mud and fluid are not necessarily coexisted, but can be "mixed" within un-lithified sedimentary strata. The drilling data show that there was water from surrounding bedrock which intruded the 2834 m deep of Banjarpanji-1 well, whilst at depth 1,743 m the borehole was unprotected by steel and cement casing.

The pressure of the exerted water is sufficient to fractured pre-existing faults or even surrounding rock and mixed the underground mud from Kalibeng Formation. The pressurized water and mud materials were then proceed to the surface through a fault system and formed LUSI mud volcano which is located only 200 meter from the drilling site. During the Yogyakarta's earthquake, the fluid pressure at the drilling site of Banjarpanji-1 well was sufficient to initiate hydrofracturing and trigger the eruption of pre-existing mud volcano (Davies et al., 2008).

Counteracting to drilling-trigger mechanism, the proponents of Group 2 published papers (Sawolo et a;, 2009, 2010) addressing aspects of drilling engineering showing that the proponents of Group 1 has lack of complete dataset. The situation becomes puzzling as Lapindo Brantas – the operating company which drilled Banjarpanji-1 well have opened and offered scientists to examine their data, but the proponents of Group 1 only collecting drilling data that supports their hypothesis and disregarded the importance of dataset. If they integrated the available data



Evidence for Drilling Trigger

- Banjar Panji-1 was being drilled 200m from Lusi eruption and suffered numerous drilling problems (kicks/losses) prior to Lusi eruption.
- Took a large kick 21 hours prior to Lusi eruption – between 62-95 m³ (~360 barrels) of water and gas erupted at drilling before well shut-in.
- Events following kick are unclear, but insufficient protective casing and narrow 'kick tolerance' suggest that development of underground blowout was likely.
- Wellbore pressures during kick interpreted to be large enough to fracture rocks and create fluid flow pathway to the surface.
- Sequence of losses/kicks, lack of casing and low kick tolerance is similar to conditions prior to other blowout-triggered eruptions (Champion Field Brunei, Platform A Santa Barbara).
- Formation of non-eruptive cracks between Lusi and the drill site on first day of eruption – indicates subsurface fluid flow between well and Lusi.

Photo: Sidoarjo Mudflow Mitigation Agency
Sources: Davies et al., 2007; Mazzini et al., 2007; Sutriono, 2007; Davies et al., 2008; Tingay et al., 2008.

Figure 14. *Summary of evidence of drilling as the trigger for LUSI eruption (Tingay et al., 2008).*

entirely to make analysis and interpretation, their conclusions would be different (Sawolo et al., 2010). Meanwhile, the proponents of Group 2 have fully integrated the entire dataset and revealed that the Banjarpanji-1 well drilling is not the trigger of LUSI eruption. The drilling-trigger mechanism proposed by its proponents was soundly head on refuted by Sawolo et al. (2009, 2010).

Point of view from drilling debates is addressed based on the available data. Recent paper dismissed the role of drilling activities at nearby well of Banjarpanji-1 and claimed that Yogyakarta earthquake (M6,3) which situated 254 km away from LUSI has triggered the occurrence of LUSI mud volcano eruption published by Miller and Mazzini (2018).

Another researcher, Tingay et al. (2018) however, counteracted the research findings of Miller and Mazzini (2018), and still arguing that drilling Banjarpanji-1 well is a cause of LUSI eruption. Overall, Tingay et al. (2018) disagree with the conclusions of Miller and Mazzini (2018). The abstract of Tingay et al., (2018) is cited as follows. "The cause of the LUSI mud eruption remains controversial". Thus, confirmation of non- intact wellbore and subsurface blowout was received from drilling data and daily drilling reports. Downhole pressure data as taken at LUSI directly record the inception of surface LUSI condition on 29th of May 2006. The data indicate a direct connection between the well and the eruption.

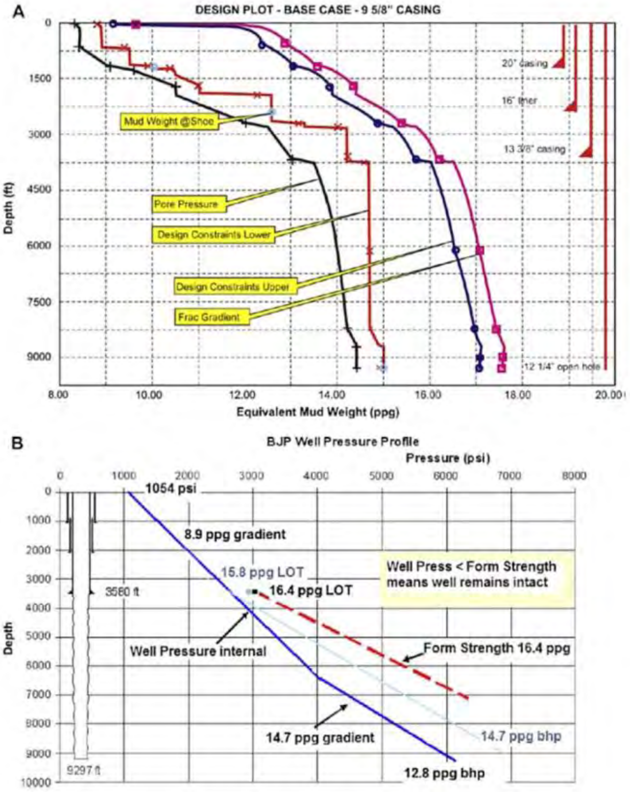


Figure 15. *Design plot of casing through depth check (top). A leading commercial of available casing equipped with software design for 10 bbls kick tolerance and 0.5 ppg gas influx is used to check an actual casing setting depth. This instrument found to be safe for drilling operation, including a planned of 9-5/8 casing at 9300 ft TD. Bottom figure shows wellbore pressure profile and its sensitivity. The plotted pressure data shows safe well condition. Analysis of sensitivity is performed using a bottom hole pressure of 14.7 ppg, and up to 15.8 ppg. Under an extreme prognosis, the wellbore pressure at any depths always shows minimum value below the formation strength. It means that there was an intact wellbore (Sawolo et al., 2009).*

Moreover, the daily drilling reports particularly record LUSI activity as visible alteration of three separate events. These reports also utilize as an attempt to kill mud eruption by pumping down dense fluids to BJP-1 well which provides evidence of a direct link between the wellbore and LUSI. In order to identify the effect of the Yogyakarta earthquake, data from LUSI was compared with other phenomenon of mud eruptions elsewhere driven by earthquakes. The Yogyakarta earthquake has seismic energy density of 0.0043 J/m3, lesser than a quarter of the minimum 0.019 J/m3 seismic energy density that possibly trigger eruption. Furthermore, previous shallow earthquakes with similar frequencies and stronger ground shaking did not trigger LUSI eruption. The BJP-1 well also indicates that the earthquake has no effect for hydrodynamic-interconnection of deep overpressured hydrothermal fluids with the shallow clays of Kalibeng Formation. Thus, researchers use drilling as a favor initiation despite earthquake."

Yogyakarta 27th May 2006 Earthquake-Trigger of LUSI

Yogyakarta earthquake has 6.3 M and occurred on 27th of May 2006 at 5:54 local time or only two days before the inception of LUSI eruption. This earthquake struck the southern part of Java, followed by two aftershocks of 4.8 and 4.6 M that occurred in the respective 4 and 6 hours later (USGS, 2006). In Surabaya, the earthquake magnitude was recorded as 2-3 MM. Whilst, the northern part of Arjuno-Welirang volcano complex which is relatively close to LUSI, the magnitude reached up to 4 MM (US Geological Survey, 2006).

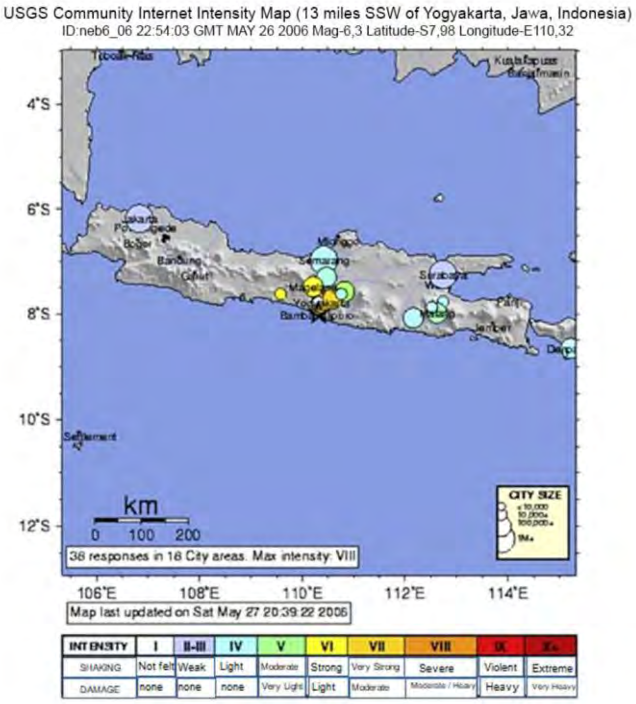


Figure 16. *Felt shaking document map of Yogyakarta earthquake in 2006, with M6.3. The map also illustrates that LUSI had also experienced shaking (USGS, 2006).*

Regional fault at Penanggungan volcano across the escarpment outcrop of Watukosek and extend NE direction towards LUSI. In adjacent to LUSI, this fault intersected the railway and caused significant railway bent as reported after the 27th May during Yogyakarta earthquake. The railway bends indicate a strong lateral activity.

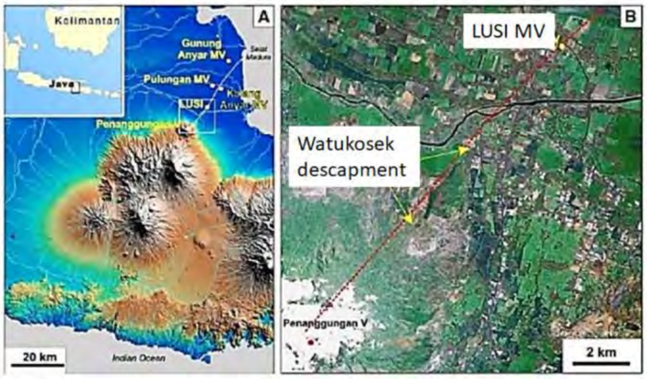


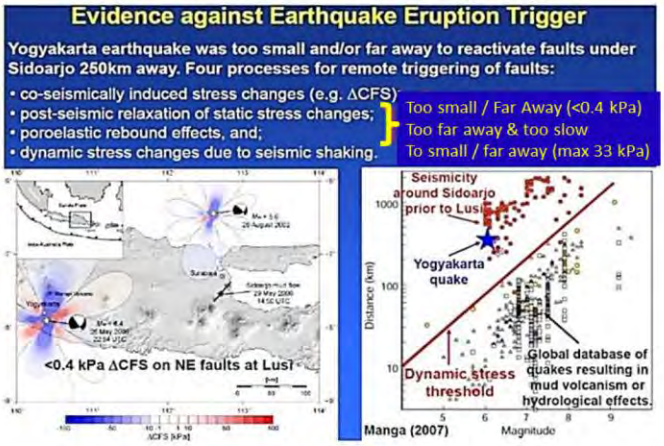
Figure 17. *(A) Elevation map depicts the volcanic arc in the southern part of Java. The northern part is back arc basin, the place where LUSI eruption occurred. (B) detail satellite image of LUSI (framed in image A). This figure shows a fault extends NE-SW from the Penanggungan volcano (white color); passing the river as indicated by river bend and Watukosek escarpment (red dashed line) (Mazzini et al., 2007).*

According to seismic profiles acquired before LUSI eruption, there is an evidence of a piercement structure. This structure has upward dipping strata around the LUSI conduit zone and become an important evidence for active vertical movements of mud underneath LUSI.

Figure 18. *Satellite image oriented SW direction. The vast grey area is occupied by LUSI mud surrounded by embankment. To the SW, geomorphic of river become the evidence of sinistral-strike slip fault as denoted by abrupt changes of the Porong River, the prominent escarpment of Watukosek fault, the neighbouring Penanggungan volcano (that lies approximately ~10 km away) and the Arjuno-Welirang volcano complex. Four white dashed lines notifies the intersected area of sinistral strike-slip fault system of Watukosek. Note that several natural features as mentioned above are controlled by the fault system (Miller and Mazzini, 2018).*

Mazzini et al. (2007) proposed a mechanism that Yogyakarta earthquake took place on 27th of May 2006's has redistributed the stress to some regions in Java. In particular, this contributed to the reactivation of Watukosek fault and extended to LUSI area. The fault system affects the fluid pressure and permeability of surrounding rocks and trigger mud eruption through over-pressured subsurface piercement structure. The mechanism for fluidization through strike-slip faulting is claimed by Mazzini et al., (2009). A periodic reactivation fault is well observed from the ongoing monitoring which also reveals synchronous peak of mud flow rates from the crater.

On the contrary, Manga (2007) argued that previous larger and closer earthquakes did not trigger mud eruption. This event falls well outside of the observed area and has a relationship between earthquake magnitude and distance of hydrological responses. Davies et al. (2008) also stated that either dozens or hundreds of other earthquakes are able to produce greater dynamic strains at the eruption site without triggering an eruption. If the earthquake creates eruption, an unusual sensitive response will exist toward the neighboring mud volcanoes and other hydrologic effects.



Evidence against Earthquake Eruption Trigger

Yogyakarta earthquake was too small and/or far away to reactivate faults under Sidoarjo 250km away. Four processes for remote triggering of faults:

- co-seismically induced stress changes (e.g. ΔCFS);
- post-seismic relaxation of static stress changes;
- poroelastic rebound effects, and;
- dynamic stress changes due to seismic shaking.

Too small / Far Away (<0.4 kPa)
Too far away & too slow
To small / far away (max 33 kPa)

Figure 19. Evidence against earthquake eruption trigger (Tingay et al., 2008).

As for the the 27th May earthquake was too distant and too small to reactivate the Watukosek fault and cause mud eruption as argued by the proponents group (1) (Manga et al., 2009) was re-evaluated by Miller and Mazzini (2018).

With regards to sedimentary volcanism drove by the buoyancy and over-pressured conditions in the sedimentary basin, LUSI is determined as volcanically linked hydrothermal system rather than mud eruption (Mazzini et al., 2012; Mazzini and Etiope, 2017).

An argument of earthquake triggering mud eruption phenomena need to be revisited since there was an evidence of regional tectonic of hydrothermal system in conjunction with the nearby volcano complex. Other evidence is overwhelming, particularly the near and distant earthquake response toward magmatic and hydrothermal systems. Appending the argument of Manga et al. (2009), figure 20 illustrates plot diagram where Miller and Mazzini (2018) documented responses to distant earthquakes. The figure clearly elucidate that there was no correlation between the limit line of Manga et al. (2009) and the general trigger. Therefore, it is important to categorize LUSI with volcanic/ hydrothermal systems since it is being defined as a volcanically- linked hydrothermal/ geothermal systems. In order to reject the argument of Yogyakarta earthquake effect toward LUSI eruption, the figure is depicted and denoted that LUSI plot falls directly in line with other example (Miller and Mazzini, 2018). An increase flow rates of LUSI is also depicted in the figure to notify the LUSI responses toward distant earthquake.

Recent observation shows that LUSI hydrothermal system significantly responds to seismic energy which lies 200 km distant of strike-slip earthquake (M5.7) as evidenced by the increasing flow rates from 80,000 m3/day to 120,000 m3/day. Moreover, Yogyakarta as a powerful crustal earthquake, able to trigger LUSI eruption through subsequent interaction between highly over-pressured and trapped fluids within the Ngimbang sedimentary layer. Interestingly, combination plot data with the results of Delle Donne et al. (2010) falls within the range. This result implies that Delle Donne et al. (2010) plot is more reliable to triggering LUSI eruption phenomena than the approach of Manga et al. (2009).

Often raised from proponents of drilling-trigger is various arguments "since other larger earthquakes did not trigger LUSI, then it must be drilling". Lupi et al, (2013) addressed this problem as follow. An inspection is carried out toward earthquake catalogue as follows : 1) surface waves do not affect LUSI after long-period tele-seismic events predominated (Lupi et

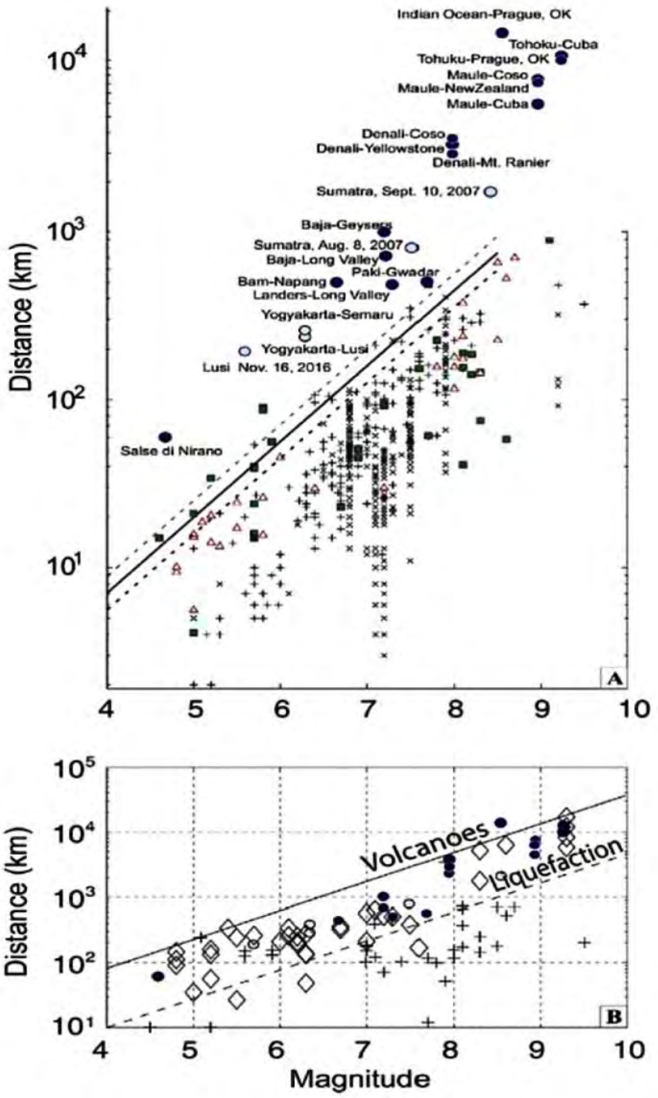


Figure 20. *(A) Modified plot data from Manga et al. (2009) to identify the responses of various trigger systems from distant earthquakes. The original figure depicts the arbitrary empirical cutoff. Response of some individual system toward distant earthquake is shown by light blue circles while dark blue dots represent other earthquake-trigger responses. (B) A triggered response from distant earthquake (Delle Donne et al., 2010), The increasing responses of LUSI flow rates triggered by distant earthquake are shown by light blue points. Donne et al. (2010) plot is more suitable when it applied based on investigated triggering phenomena (Miller and Mazzini, 2018).*

al., 2013), there are eight events that potentially produce an equal strong or stronger ground motion than the Yogyakarta earthquake, 2) two earthquake events (a M7.6 dip-slip subduction zone earthquake at 350 km distant and a M5.6 to the north) are at least one magnitude smaller, and more importantly 3) the depths of all eight events have no constraint and the motion laterally spread to 33 km, thus placing them into the 20-35 km depth range. An earthquake magnitude of 4.8 at 50 km distance in 1992 is the only unambiguous event outside the ground motion error bars. However, the focal depth is still unknown, so the effect of this earthquake toward LUSI eruption is still questionable. In fact, the only powerful shallow crustal earthquake in Java is Yogyakarta earthquake, in which the body waves dominated earthquakes. The waves were amplified by acoustic impedance contrasts at LUSI (Lupi et al., 2013), thus, it would be susceptible to ground motion amplification from the Moho critical reflected waves. The earthquake felt in all Java regions, such as in Jakarta which is 430 km away to the west and in Surabaya which lies 300 km to the east, and even felt in Denpasar, Bali (530 km). Although Jakarta and Surabaya experienced mild shaking of Mercalli Scale II-III, it reached Mercalli Scale IV in Bali, and magnitude V in the Arjuno-Welirang volcano complex. The higher level of magnitude in Arjuno- Welirang complex was then used as hypothesis to be linked to LUSI eruption.

A numerical study of body wave propagation of Yogyakarta earthquake (with measured ground surface displacements near LUSI as a constraint) shows that seismic energy reflected off the (diapiric) parabolic seismic reflector with the given contrast impedance. Thus, it would focus the energy into the shallower mud layer and generate liquefaction (Lupi et al., 2013; 2014). The same focused energy is produced from a contrast impedance between highly over-pressured (low velocity layer) and normally compacted sedimentary layers. Rudolph et al., (2015) was then re-evaluated the previous study where any impedance contrast was eliminated and showed no effect. His study was then focused on a deep and highly over-pressured mud layer of the Ngimbang formation which was sealed by high-impedance volcanoclastic sedimentary layer. With the concomitant amplification of seismic energy into the deeper mud layer during simulation, the volcanoclastics play role as a substantial reflector of seismic energy into the Ngimbang formation.

For the first century, the earthquake was documented as triggering factor of mud eruption. It also denotes that small eruption becomes an earlier series of eruption aligned with geological fault. Hence, the scientist needs to consider about the effect of earthquake toward mud eruption (Davies and Manga, 2017 –acknowledged by proponents of Group 1).

Review

There is significant difference between Group 1 and Group 2 in the methods of understanding what LUSI is.

Group 1 focus on examining drilling data of Banjarpanji-1 well (which are not complete data set according to Group 2). Group 1 have not conducted field study or analyzed erupted samples during the inception and development of LUSI. They use drilling data only to accommodate their argument against Group 2. The publication of peer-reviewed scientific journals of Group 1 is less than those of Group 2.

Group 2 is the owner of the drilling data because some members of the Group 2 come from the oil company which drilled the Banjarpanji-1 well, so they had reviewed drilling data more thoroughly than Group 1. Group 2 have conducted various and continuing field studies and analyzed all of erupted materials since the inception of LUSI and during its development to the present time.

Comparing the methods of Group 1 and Group 2, it is understandable why Group 1 keep believing that drilling Banjarpanji-1 is the trigger of LUSI eruption. They concentrated only on drilling data and did not take into account regional context and all analyses of erupted materials during the development of LUSI eruption although these analyses and their interpretations have been published by Group 2. Group 2 is understandable why they do not call LUSI anymore as a mud volcano but SHHS (Sediment-Hosted Hydrothermal System) since they have seen the development of LUSI from mud volcano system to SHSS.

Since the inception of LUSI, drilling is used to blame the case of mud eruption due to data limitation (Davies et al., 2007). This set also promotes media creation which multiplies by a very quick time response from new publication. Davies et al. (2007) claims a drilling trigger and disseminates his argument to the media. Drilling trigger scenario of Group 1 had a substantial media advantage. Several scenarios were debated in AAPG Conference in Capetown, South Africa in 2008. The argument debate has exacerbated the event, although at the end of a LUSI session, the conference chairman undertakes a voting. The entity opinion was taken based on a majority vote as shown by a number of conference participant which raised their hand. If majority participant vote for drilling trigger, it will quickly relayed to the media as the evidence of LUSI triggering factor. This kind of vote, however, is unheard of, since the opinion was taken from random people who were sitting on scientific session. Nonetheless, the proponents of drilling trigger allow the media to blow up this vote as proof-of-cause and it has entrenched the public perception. Meanwhile, they held a meeting in Capetown to examine the whole drilling dataset of Lapindo (Sawolo et al., 2010), and neglect onsite data collection to reach conclusions. Eventually, public receives an enormous consequence in the sector of economic, social and political. One of the immediate consequences was the refusal of international community to assist in solving the disasters and tend to leave the victims homeless and helpless.

It is believed that there was uncertainty in the initial cause of LUSI, but drilling arguments might have played a part since this is an easiest way of thinking. The existence of drilling operation in the center of mud eruption causes drilling became a primary factor that generates mud eruption. However, the inception investigation until over the last ten years observation, overwhelm various findings toward borehole response, regional setting and a natural system. Miller and Mazzini (2018) claimed that if the eruption triggered by drilling, LUSI would be the only example throughout geological history of a tectonically driven system caused by a 30 cm diameter borehole (Miller and Mazzini, 2018).

The approach of Group 1 relies mainly on borehole logs which makes a scientific disadvantage. This group also neglects the importance of active fault system at a larger regional scale. Thus, various explanations have changed over the time to make a drilling trigger viable. Unfortunately, the findings also have limited options of conceptual models which decipher the behavior and geological evidence of this system. Conversely, Group 1 proponents combining a borehole concerns in explaining the system changes from mud volcano to SHSS eruption. The Group 1 never address this change in their argument. It is the fact, based on analyses of erupted materials, that LUSI has evolved from mud volcano eruption to sediment-hosted hydrothermal system (SHSS), or a hybrid of sedimentary-volcano and magmatic-volcano with hydrothermal phenomena.

Group 1 did not take into account extensive regional evidence that occurred following the 27th May 2006 earthquake indicating the reactivation of the Watukosek Fault, showing a disturbance on regional subsurface plumbing system by

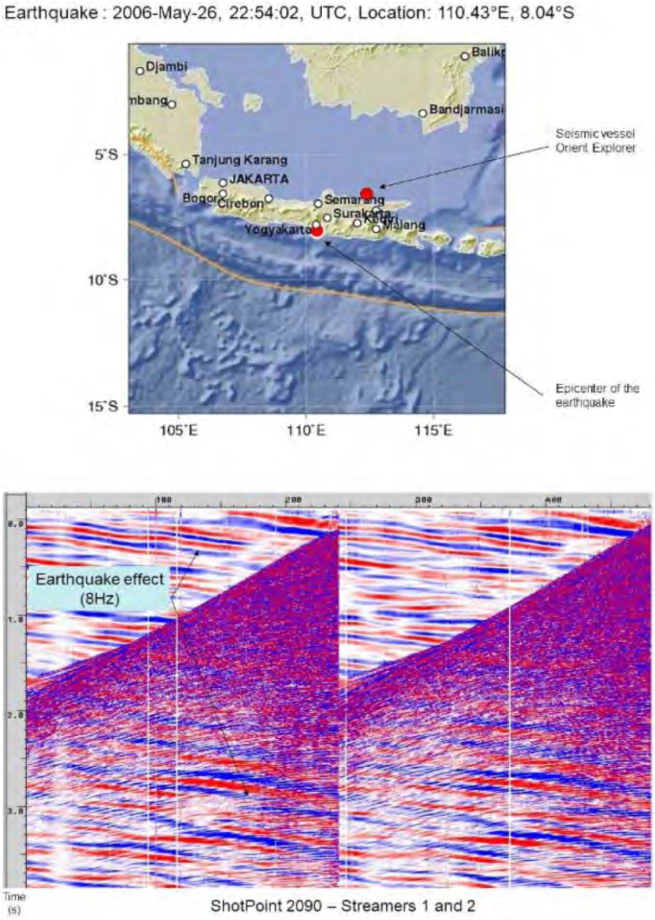


Figure 21. *Recording of the first shot of seismic data in Ujung Pangkah waters by seismic vessel Orient Explorer at 27th May 2006 show an effect of earthquake at Yogyakarta, recorded 34 seconds after the main shock struck Yogyakarta.*

earthquake event. The following points list the evidence (Satyana and Asnidar, 2008; Miller and Mazzini, 2018).

1. Energy propagation of the Yogyakarta earthquake was mainly eastward and northeastward as shown by the trend of its aftershocks and the areas affected.
2. The Yogyakarta earthquake was recorded in Ujung Pangkah waters to the northwest of Surabaya 34 seconds after the main shock and its energy disturbed seismic recording which was being surveyed in offshore Ujung Pangkah, seismic data recorded this.
3. Merapi and Semeru volcanoes underwent increased activities (Harris and Ripepe, 2007) (although Semeru location farther than LUSI distance from the epicenter).

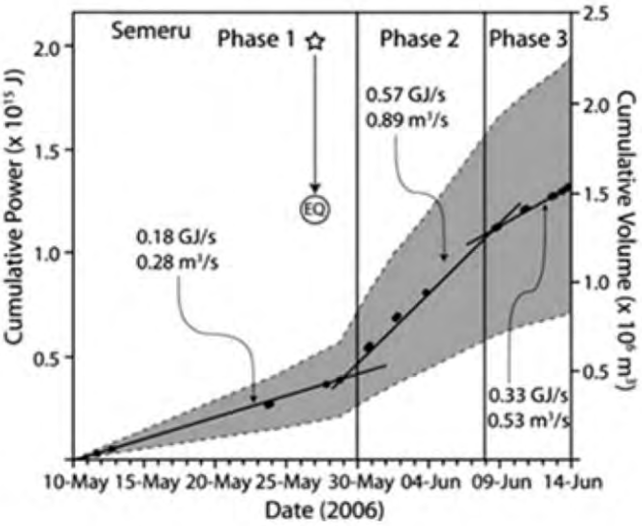


Figure 22. *Plotting graph of cumulative power and gas volume of Semeru (gray zone), where heat and volume fluxes were integrated. Filled circle indicates the mid- point of each daily measurement which is interconnected with linear best fit line. The position of the earthquake (EQ) is marked (Harris and Ripepe, 2007).*

4. Several villages in Sidoarjo and surrounding eruption sites reported NE-SW oriented fractures.
5. Increasing activity of gas and mud expulsion was reported at other 40 km more distant mud volcanoes hosted by the Watukosek fault system (Mazzini et al., 2007). Existing mud volcanoes in Bangkalan area, Madura were also reactivated two days after the Yogyakarta earthquake.
6. Dropping level of water well was reported in the villages which were located at 40 km away to the NE direction of LUSI (e.g. farther from the epicenter).
7. Sudden production changes were recorded in the Tanggulangin, Carat and Wunut fields, Sidoarjo region (Mazzini et al., 2009).
8. Drilling mud losses in Banjarpanji-1 well was recorded after the earthquake. Subsequently after two strong aftershocks of Yogyakarta earthquake, the well underwent a total loss of drilling mud (Sawolo et al., 2009). It is worth to note that the movements along the fault have activated the subsurface imbalance, reduce the sealing capacity and increase permeability (Mazzini et al., 2007).
9. There is a positive correlation/ pulsation between rates of mud eruption of LUSI and swarms of earthquakes measured 300 kms around the site, high rates followed the occurrences of earthquakes.

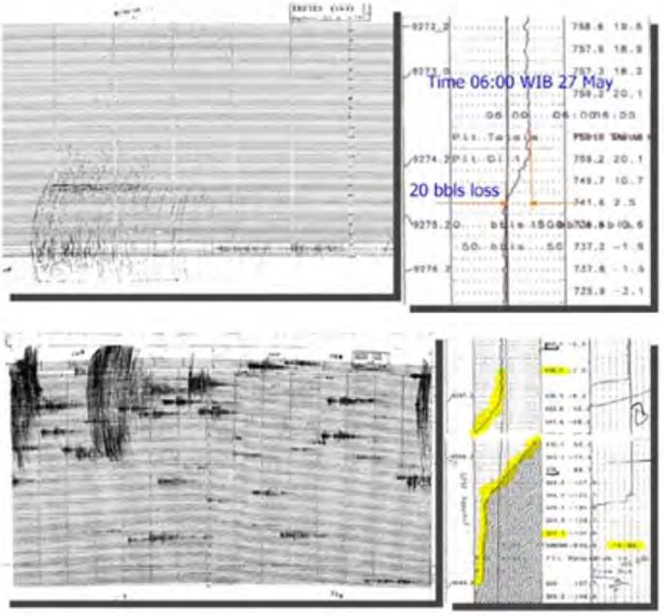
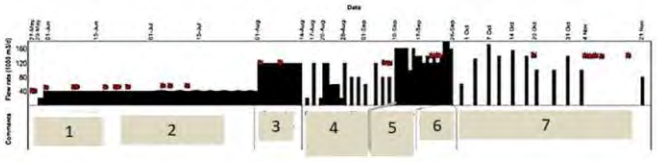


Figure 23. *Top right figure shows Yogyakarta earthquake caused loss of 20 barrel drilling mud (top) as reported by mud logger. This report informed during the real time about seven minutes after the earthquake occurred. The top left figure shows the seismograph reading of the Yogyakarta earthquake at 05:54 WIB on 27 May 2006 as informed by Tretes BMG station about 15 km away. The bottom right figure shows complete loss of 130 barrel mud circulation from the wellbore that occurred two hours after two aftershocks. These mud losses generate a compelling argument about the existence of temporal connection between the earthquake and Banjarpanji well (Sawolo et al., 2009).*



1. Rapid mud content increas after inCal burst of gas/water H_2S ~ 35 ppm, LEL 20%.
2. Constant flow during the month of June, pulsating during July H_2S ~ 7 ppm, LEL 5%
3. Sudden flow increase, H_2S ~ 24 ppm
4. Pulsating activity (30 min on/off), gradual flow decrease, peaks concide with longer amounts of H_2S ~ 24-35 ppm and LEL 10%
5. Activity suddenly increases after eartquakes pulsating behaviour of eruptions
6. New peak of activity after a swarm of earthquakes
7. Daily monitoring of mud eruption interrupted the 26" of September. Reported in the hystogram relative values compared to previous monitoring.

Figure 24. *Daily rate monitoring report of mud eruption at the LUSI site. Peak volume of H_2S and CH_4 gas were found coincide with the stronger eruption periods. Remarkable earthquake was shown by star symbol, where the measured magnitude was M3.7 with epicenter about 300 km away from LUSI (Source USGS). There was no monitoring report during the months of June and July 2006 and less accuracy for the remaining part of the record. Monitoring was then conducted every 4 days after the 26th of September. The emission of measured CH_4 concentration in the gas clouds is notified by LEL, 20% of the gas emission corresponds to 10,000 ppm (Mazzini et al., 2007).*

No one can predict for how long LUSI will continue to erupt. Despite a fairly common phenomenon of mud volcanoes on Java, LUSI is defined as a hybrid between a mud volcano and a hydrothermal vent. Moreover, as hybrid system LUSI is connection to the nearby volcano, so the system will keep the sediments cooking over the years. In other words, LUSI is not going to stop in the near future. Now, 13 years after it first eruption, it is understandable why the mud flow stay exist. It is because the deep subsurface condition of LUSI is connected to a nearby volcanic system.

Group 1 of drilling trigger proponents will have difficulties in explaining how a 2830 m deep of the well played a role as conduit for bringing volcanic fluids and solids from over 4000 m depth, erupted at surface. A perturbation to the already existing over-pressured system subsurface should be a natural origin, not a drilling by human, let alone imply regional perturbation as listed above. A vast database from scientific research of field observations and erupted sample analyses collected over the last ten years and all regional perturbations have occurred, those data consistently determine that LUSI is a natural system.

New Mechanism of LUSI Genesis

The most relevant conceptual model for genesis of LUSI terms as a substantial heat source in organic- rich sedimentary package of NE Java basin from perpetual migration of magmatic intrusion and hydrothermal fluids of nearby Arjuno-Welirang volcano complex. This system already existed –continuously charged and ready to be triggered. A natural perturbation has triggered the system to erupt with refer to field observation and fluid sampling measurement acquired since its inception.

It is Group 2 which fulfils this model (Mazzini et al., 2009, 2012). The authors propose geochemical evidence and argued that there was a steam plume above the LUSI vent which was dominated by CO_2 gas and hydrocarbon gasses. Furthermore, there was an indication of isotopic gas signatures which indicates fluids as mantle contribution (e.g. $d^{13C}CO_2$, helium with R/Ra as high as 6.5) mixed with CH_4 and CO_2 gasses. These isotopic gasses were generated within high temperature (up to more than 400°C) and these gas characteristics are impossibly present where typical sedimentary volcanism (mud volcano) phenomena occurred in the sedimentary basin. This is because the required temperature to generate gas reactions did not support even in relatively high geothermal gradient areas like Sidoarjo (i.e. 42 °C/ km). Therefore, additional heat source from neighboring volcanic complex is needed. The authors proposed a simplest scenario of an intrusive body emplacement and hydrothermal fluid migration into back arc basin and passed through an obvious weakness zone of the Watukosek fault system. A respective process of sedimentary rocks alteration and maturation of organic matter occurred with the substantial role of heat source. Besides, the process also generates other gas from additional mantle fluids by evolving metamorphic reactions and increasing clay illitization through dehydration process at shallower depths. These whole processes took place in over-pressured zone of deeper depth, such as in the Eocene organic rich shales of Ngimbang Formation as observed from petrographic, geochemical and surface deformation data. The Ngimbang formation lies at least 1000 m below the Banjarpanji-1 borehole. This formation was known as becoming source rock and comprised of organic-rich shales and coal seams in the lower part. The shale rock has varies TOC content between 1.6 and 5.7 wt %, while the coal seams have 67 wt% of TOC (Satyana and Purwaningsih, 2003, Mazzini et al., 2012). This formation is overlain by the Oligocene-Miocene (Kujung-Prupuh and Tuban Formations) which comprises of carbonates and marly clays. The Kujung – Prupuh and Tuban Formations are sealed by hydraulically tight volcanoclastics.

The next over-pressured scenario is carried out using numerical model by simulating the geochemical reactions with the released heat trigger from a deep- seated intrusion. The intrusion is situated in the volcanic arc. The result shows that contact metamorphism and the hydrothermal fluid migration play a significant role in generating a considerable influx of fluids and realistic sources for the LUSI gas (Svensen et al., 2018). The over-pressured condition also existed prior to LUSI inception as identified by the presence of piercement structures and fluid-charged zones observed in vintage seismic lines (Mazzini et al., 2009; Moscariello et al., 2018). Most of these informations and scenarios have been systematically neglected by drilling-trigger proponents without any reasons.

The hydrothermal scenario of Mazzini et al. (2012) utilizes a magmatic intrusion of the Arjuno-Welirang volcano complex which is located adjacent to the Penanggungan volcano complex or about ~ 10 km SW of the Lusi crater. This scenario represents the formation of youngest cones in the NE regions as the natural progressive scope of northeastward volcano complex. The intrusive bodies contribute to the regional compressional tectonics besides become an evidence of wide propagation over short period. The example of magma intrusion- drive mud eruption is shown in Saudi Arabia, in 1999 which intruded from over 12 km depth to 4 km depth in two weeks (Pallister et al., 2010).

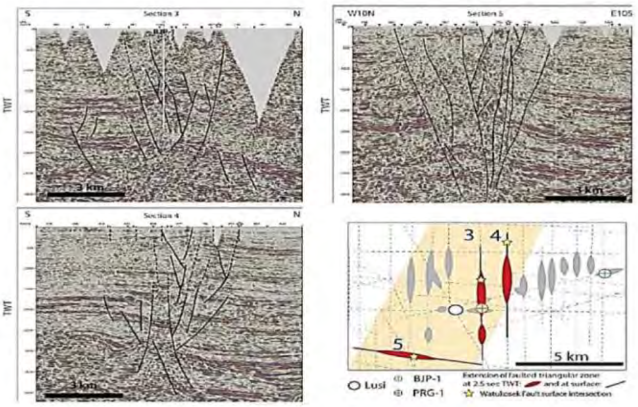


Figure 25. *The fault pattern seismic images of Eastern Watukosek Fault System zone along seismic sections 3, 4 and 5. The surface trace of the Watukosek fault is indicated by red arrows while white dashed line delineates the top of the Miocene carbonate buildups (Moscariello et al., 2018).*

The East Java also has a history of a similar intrusion case which possibly produced several immediate effects. For the first effect, the emplacement of very high temperature intrusion bodies (exceeding 1000°C) would immediately generate maturation of organic-rich clays litologies and even hydrocarbons which were abundant within sedimentary package and occupied underlying LUSI. This genetic sequence leads to the quick formation of extraordinary large fluid volumes, while the volcanoclastics present as a sealing cap which traps the additional fluid to become fluid over-pressureds. These over- pressure fluids are susceptible to slight earthquake perturbations either near or far.

The mechanism of LUSI genesis is therefore calls for highly over-pressured region at deeper depth than total depth of Banjarpanji-1 well as a consequence of high temperature reactions of intrusions and hydrothermal fluids migration.

Ground shaking and shallower layers of over-pressured fluid zone from the Yogyakarta

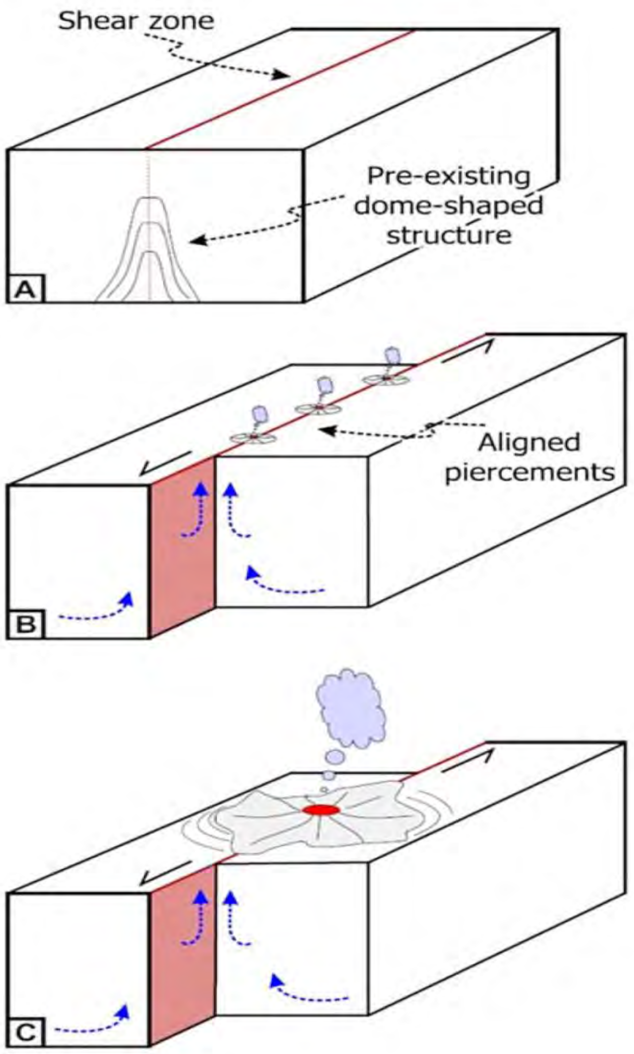


Figure 26. *Schematic illustration of eruption mechanism along strike- slip faults (not to scale). (A) Pre-existing dome-shaped structure transected by tectonically shear structure including Watukosek fault system that crosses LUSI location; (B) the strike-slip fault activation after the Yogyakarta earthquake; fluids draining took place from sedimentary units through the fault zone; fault zone presents as preferential pathway to allow fluids reach surface; the formation of several craters with NE–SW orientation coincide with the fault zone; (C) the overflow mud exceeding the crater volume (later called LUSI) and covers surrounding eruption sites. The collapse areas have an ellipsoidal shape following the trend of the Watukosek fault (Mazzini et al., 2009).*

earthquake stimulated fluid flow and injected the over-pressured sediments. The motion also generated subsequent slip of the Watukosek fault system. A drilling trigger perception was assumed based on this deep pressure pulse that migrated up to the fault zone directly linier to drilling well operation. In this case, the well Banjarpanji-1 was affected by a natural perturbation which triggered LUSI eruption, the well itself is not the trigger for eruption.

According to the integrated data set, LUSI was known as naturally geological system that undergone a critical state and susceptible to small external natural triggers. It is worth to say that the whole system already existed, naturally charged and ready to be triggered. Any kind of perturbation, such as an earthquake can trigger this system to erupt. Therefore, the 6.3M Yogyakarta earthquake in Central Java that occurred just two days before LUSI eruption implied regionally by reactivating the Watukosek fault system and triggered the LUSI eruption. LUSI is a natural system that ultimately occurred, living and die naturally when ready.

Conclusions

1. Debates of the genesis of LUSI eruption fall under two groups, Group 1: drilling accident of Banjarpanji-1 as the trigger, and Group 2: Yogyakarta 27th May 2006 as the trigger. There are significant differences of methods of studies of the two groups. Group 1 concentrated on drilling data of Banjarpanji-1 well. Group 2 conducted various field studies and analyzed erupted materials from LUSI area and addressed its regional implications.
2. Based on the last over ten year development of LUSI and its erupted materials, it is known that LUSI is a SHHS (sediment-hosted hydrothermal system – Mazzini et al., 2012). LUSI is a hybrid between a mud volcano and a hydrothermal vent, neither purely sedimentary mud volcano nor a hydrothermal volcanic system.
3. A network of seismometers installed in LUSI area resulted in 3D image data revealing that LUSI connects at depth through deep-seated fault (around 6 km deep) to magmatic body of Arjuno-Welirang volcano.
4. The connection of sediments beneath LUSI and magmatic body at depth had provided over-pressured condition which erupted when perturbation triggered by 27th May 2006's Yogyakarta earthquake took place. Regional

data set are in favor of this earthquake. Drilling trigger cannot explain the origin of erupted water, gas, and clasts which are volcanic in nature and the development of LUSI from mud volcano to a sediment-hosted hydrothermal system (SHHS).

5 The well Banjarpanji-1 drilled in the time LUSI eruption started was affected by a natural perturbation triggering LUSI eruption therefore, the well itself is a victim, not the trigger for the eruption.

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