Bridging surface and subsurface observations from the geysering Lusi eruption, Java, Indonesia

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Abstract
The spectacular eruption of Lusi started in NE Java, Indonesia, on the 29th of May 2006 and is still ongoing. Since its birth Lusi presented a pulsating activity marked by frequent eruptions of gas, water, mud and clasts. The scope of this study is to bridge subsurface and surface observations to describe Lusi's behavior.
Based on visual observations, Lusi's erupting activity is characterized by four recurrent phases: (1) Regular bubbling activity; (2) Clastic geysering; (3) Clastic geysering with mud bursts and intense vapor discharge; (4) Quiescent phase.
With a temporary network of 5 seismic stations deployed around the crater, we could identify tremor events related phases 2 and 3. One of the tremor types shows periodic overtones that we associate with mud wagging in the feeder conduit. Based on our observations we support the scenario of Lusi being a sedimentary hosted hydrothermal system with a clastic-dominated geysering activity.

1. Introduction
On the 29th of May 2006 numerous SW-NE aligned sites erupting hot mud appeared in NE Java in the Sidoarjo district (FIG. 1A). Within weeks a prominent eruption site, named Lusi, flooded a surface of nearly 1.5 km^2. The mud-flooded area became gradually bigger in size. Today a 10 m high embankment frames a region of 7 km^2 to protect the surrounding settlements hindering Lusi to flood the region any further. Currently Lusi is still active and, to our knowledge, the largest, ongoing and most destructive mud-erupting system on Earth.
Since the early stages, Lusi showed high temperatures (i.e. temperature gradient of 42 °C/km, with crater temperatures of ~100°C) and a pulsating behavior with powerful mud and vapor bursts occurring every ~30 minutes. These observations combined with fluids analyses led Mazzini et al (2007) to propose the concept of "quasi hydrothermal system". Further geochemical analyses of the erupted fluids (98% water, 1.5% CO_2, 0.5% CH_4, Mazzini et al. 2012, Vanderkluysen et al. 2014) confirmed the hydrothermal signature and high temperature reactions. Mazzini et al (2012) described Lusi as a newborn *Sedimentary-Hosted Hydrothermal System* (SHHS) with pulsating activity fed by magmatic fluids migrating from

the neighboring Arjuno-Welirang volcanic complex. This definition provided a distinct classification of the Lusi phenomena which differs from the other used term mud volcano. Converging definitions and characteristics extracted from various authors define mud volcanism, or *sedimentary volcanism*, as typically methane-dominated, which initiation is commonly driven by gravitative instability, occurring in "cold" sedimentary basins typically related to the presence of natural hydrocarbon reservoirs with eruptions usually lasting hours or up to some days (e.g. Milkov, 2000, Dimitrov, 2002, Kopf, 2002, Abrams, 2005, Revil 2002, Etiope, 2015). While some authors still include in the sedimentary volcanism definition also manifestations connected with hydrothermal activity, others (since the 60's) stress the fact that SHHS are substantially different. In fact these hybrid systems result from magmatic or hydrothermal CO_2-rich and vapor-rich fluids, related to igneous intrusions and high temperature geothermal fluids, crossing or interacting with organic-rich and CH_4-rich sedimentary rocks, resulting in the production of complex high temperature gas mixtures of different origin. Lusi has the same characteristics of other known SHHS hybrid systems described in other localities worldwide (e.g. Helgeson, 1968; Von Damm et al., 1985; Welhan and Lupton, 1987, Simoneit, 1988, Jamtveit et al., 2004; Svensen et al, 2004, Zarate-del Valle and Simoneit, 2005, Svensen et al., 2009; Mazzini et al., 2011, Mazzini et al., 2014, Ciotoli et al., 2016).

Since its birth, Lusi behaved with long term flow rate fluctuations as well as short term (i.e. approximately every 30 mins) events of enhanced activity. In this study we test the proposed SHHS scenario investigating and documenting the short term events monitored during field campaigns in 2015 and 2015, collecting surface and subsurface observations and providing arguments to define Lusi as a (so far undocumented) clastic-dominated geysering system.

2. Methods

2.1 Seismic stations in the embankment area

To monitor Lusi's activity, we deployed 5 seismic stations inside Lusi's embankment from the 4th to the 10th of November 2014 (Fig. 1B). We used one broadband (Trilium 120s compact, BB01) and four short-period sensors (Leinartz 3Dlite, SP01-SP04) equipped with Taurus digitizers. The sampling rate was set to 100 Hz. The sensors were buried at approximately 1 m depth, thermally insulated and covered with sediments (i.e. clays) to improve the signal to noise ratio and deployed on a concrete plate. All sensors were located between 400-1200 m from the eruption center. In a second experiment on June 11th, 2015 a short-period sensor (SP05) was placed at the edge of the crater, in the southern part. The experiment was replicated again between November 9-11th with two sensors (BB01, SP06) deployed at the Northeastern crater edge. The three experiments held the same type of waveforms showing the consistency of our findings.

2.2 **Visual observations**

During the second experiment and its replication, the seismic recording was coupled with a HD camera positioned in the embankment (Fig. 1B), with the purpose to continuously record Lusi's eruptive behavior and link it to the seismic activity. The camera recorded 3 h of crater activity on June 11th, and 18.5 h on November 9-11th 2015. The images where then analyzed and the eruptive phases classified. The video camera time record was synchronized with the logging of the seismometer with a synchronization error as large as 1s.

3. Results

3.1 Visual observations: eruption cycles

Based on visual observations and HD camera records, we identify four phases characterizing Lusi's activity.

1. **Regular bubbling activity** (Fig. 2A)**:** This phase consists in the constant emission of mud breccia (i.e. viscous mud containing clay, silt, sand and clasts up to 10 cm in diameter) associated with the expulsion of water both in a liquid and vapor state as well as other gasses (Mazzini et al. (2012), Vanderkluysen et al. (2014)). The typical duration of this phase is about 5 minutes but has been observed up to 10 min.

2. **Enhanced bubbling and mud bursts** (Fig. 2B): This interval consists in limited vapor emissions and vigorous mud bursting activity at the crater site. This phase typically initiates with decimeters sized bubbles that appear scattered throughout the crater zone. Within a few seconds the bubbles increase in size reaching up to 5-10 meters in diameter and height. This phase is typically short-lived with a duration of about 30 s.

3. **Enhanced bubbling with intense vapor** (Fig. 2C)**:** This interval is characterized by a noisy and vigorous degassing discharge and a dense plume that may be rising up to 100 m above the ground. Occasional strong winds may disperse the plume and reveal that during this phase large bursts (i.e. like in phase 2) still occur inside the crater. During this phase there is a significant increase of the water level of the streams that radially flush the mud from the crater. This observation indicates that an increased amount of water is also discharged during this phase. The duration may vary between 2-10 minutes.

4. **Quiescent phase** (Fig. 2D): This interval marks the end of the venting activity with no gas emissions or bursts observed. During this phase the system is reaching an almost complete halt that may last from 1 to 2 minutes.

In Fig. 3 we show two 3 h eruptive cycles, as observed on June 11th 2015 (A) and November 11th, 2015 (B) that show snapshots of Lusi's eruptive behavior. Each phase has a distinct color and is plotted at a different height to facilitate the reading. The interval durations are not uniformly distributed and may vary from one cycle to another. Only about 50% of the cycles include all the 4 described phases. On average two cycles occur every 30 minutes. In November 2015 (Fig. 3B) the length of phases 2 and 3 increased. Overall, throughout the observation period, the regular phase 1 activity is more frequent but variations may occur in the other phases depending on the monitoring period. The time intervals between the phases could be subject to change. Due to a lack of systematic observation, we can only hypothesize that dry and wet seasons have an influence here.

3.2. Characterization of seismicity at Lusi

We analyzed the records from the seismic stations during the one-week recording and could identify two types of seismic signals beneath Lusi:

i) Microseismic events: These events are characterized by a sharp onset of the P-waves with clear S-wave arrivals (Fig. 4A, upper part). The frequency band for these seismic events ranges from 5 to 25 Hz (Fig. 4A, lower part). The signal duration is about 20s. During the one-week deployment we observed 3 VT-events with magnitudes around MI 1.7 +- 0.1 that could be clearly identified by all 5 seismic stations and that are also picked up by some of the regional permanent stations that are operated by the BKGM. The epicenters fall inside the embankment.

ii) Tremor events: these can be divided in 2 categories.

- The tremor-type-1 events have dominant frequencies ranging from 5 to 10 Hz (Fig. 4B, lower part) with an emergent behavior. From the signal envelopes (Fig. 5A) we can identify a typical tremor duration of 20-30 s. During the one-week recording we identified a total of 154 tremor-type-1 events on at least three stations.
- The tremor-type-2 events are roughly three times more powerful than the tremor-type-1 events (Fig. 5). We observe 7-8 equally spaced overtones that are visible from 2-15 Hz (Fig. 4C). The overtones are narrow-banded in the beginning and end of the tremor, whereas they become 'broadband' coincident with the highest signal amplitude. No difference in amplitude between the fundamental frequency and the higher harmonics is observed. This tremor type typically lasts from 80 s to 180 s (Fig. 5B). During the one-week recordings we identified a total of 34 tremor-type-2 events on at least three stations.

On the spectrograms of the stations in direct vicinity of the crater (SP05, SP06) we observe a continuous excitation of the 15-20 Hz frequency band (Fig. 4 B, C). This excitation is absent for the stations located a bit further away from the crater edge (e.g. Fig. 4A).
In general we notice a remarkable difference in the signal to noise ratio in the station nearby the crater compared to the ones located further away. This could be due to the strong attenuation effect of the clay filling the embankment around Lusi, which may damp the noise generated by the upwelling fluids in the crater. This is supported by the delay of first arrivals of P-waves at some seismic stations. The station closest to the crater is SP04 (about 700 m far from the eruptive crater) while the most distant is SP02 (about 1200 m). The delay of P-waves arrival at SP02 is about 2 s compared to the arrival of P-waves at SP04. This implies a strong attenuation of the seismic signal over a very short distance (i.e. 500 m).

3.3 Relation between seismic and eruptive activity

To investigate whether the observed tremors are related to the eruption activity, we coupled the HD camera and seismic records. We observe that 90% of the tremor events are associated with the enhanced phases 2 and 3. The onset of such signals precedes the visual evidence of enhanced activity phases at the surface by typically 3 (+/- 1) s.

4. Discussion

4.1 Dynamics at crater site

Both tremor types appear to be connected to the erupting behavior of Lusi, and most specifically to phases 2 and 3 (enhanced bubbling with mud bursts and intense vapor). The tremor type-1 resembles with its features degassing events on volcanoes (Ripepe et al. 2010). Tremor type-2 shows very distinct, regularly spaced overtones as observed from harmonic tremors. This tremor could be related to mud wagging in the feeder conduit while the gas bubbles ascend (Bercovici et al 2013).
In general, we do not always observe the tremors on all five stations positioned around the crater edge, suggesting that this attenuation could be related to a very shallow origin of the signal. Considering a consistent delay of 3 ± 1s between the signal recorded by the seismic stations and the visual observation of the eruption, we use a simple geometric calculation (see appendix) to roughly approximate the signal origin depth as 30 m. Although using a different approach, this depth estimate coincides with the one calculated by Vanderkluysen et al. 2014 where the authors suggest the decompressional boiling to occur.

4.2 Lusi and geysering activity

The vigor and the periodicity of the observed venting phases observed at Lusi resemble those of water-dominated geysers observed at other settings (e.g. Kedar et al. 1998). For this reason we propose for Lusi to call the phases enhanced bubbling and mud bursts (Fig. 2B) and enhanced bubbling with intense vapor (Fig. 2C) clastic geysering and clastic geysering with intense vapor, respectively, (see video in online supplemental material). In general two physical models have been proposed (and adjusted through time) to explain the mechanisms governing traditional geysering activity. Mackenzie (1811) suggests a contorted plumbing system with a large cavity where rising bubbles build overpressure of steam that is periodically released through pipes. The alternative and most broadly diffused model suggests a vertical conduit with sudden flashing of superheated water into steam when hydrostatic pressure drops (Bunsen, 1847).
We believe that none of the two models described above is *per se* applicable at Lusi. Firstly, Lusi is clastic-dominated and, unlike the water-dominated geysers that commonly occur in cemented rocks, shows different rheologies and reactions occurring in its conduit. Secondly, Lusi's plumbing system might be much more complicated since the eruption site seats upon a fault system (i.e. Watukosek fault system) (Mazzini et al 2009).
We therefore suggest a preliminary model that explains the observations and the collected seismic data. High temperature fluids are vented in the Lusi conduit rising from high pressure to low pressure levels. As the fluids approach the shallow subsurface, they reach the water vapor region and the sudden pressure drop triggers flashing and the exsolution of the dissolved CO_2 and CH_4 following a model similar to that described by Mazzini et al (2012) and Vanderkluysen et al (2014). The periodicity of the four described phases (Fig. 3) is not precisely regular. We suggest that this irregularity could be related to the random and semi-continuous discharge of water and clastic material that slightly alters the morphology at the crater site after each geysering event. Therefore, the pressure decrease required to initiate fluids flashing (i.e. volume of water and mud removed from the crater site to cause hydrostatic pressure drop) does not occur systematically (e.g. unlike described in Ingebritsen and Rojstaczer, 1993).
The presence of vigorous bubbling activity during phase 2 and the absence of an aqueous vapor plume expelled, suggests that anyhow significant amounts of gas are being released

during this phase. The most likely candidates to propel this type of activity are CO_2 and CH_4. We propose that during the initial geysering phase these two gasses move faster towards the surface producing these large bubbles. The aqueous vapor reaches the surface later interacting with additional CO_2 and CH_4 and initiates the phase 3.
Geochemistry shows that Lusi fluids migrate from great depth through several sedimentary formations (Mazzini et al 2012). We suggest that the rise of deep fluids reaching the more deformable Kalibeng Fm. at around 1-1.5 km triggers effects of inflation/deflations inside this easily eroded pakage, therefore contributing to a periodical charge and discharge of the system. Fluids then upwell along the fractured zone below Lusi (Mazzini et al 2009) to trigger the geysering activity described above.

The presence of a periodical geysering behaviour at Lusi is consistent with the activity of an erupting hybrid phenomena such as a SHHS. These results strengthen the hypothesis that in the Lusi region are present all the ingredients necessary to trigger sedimentary volcanism phenomena and that this process was accelerated, enhanced and chemically altered by the activity of the connected Arjuno Welirang magmatic complex. The final result was the most spectacular clastic-dominated erupting geyser on Earth.

5. Conclusions

The results reported herein document the first detailed description of the erupting activity observed at Lusi during three field campaigns. We coupled visual observation with seismic records showing that Lusi is marked by four phases that replicate in cyclic order in time. The documented activity of Lusi can be summarized as:
1) Regular bubbling activity, 2) Clastic geysering, 3) Clastic geysering with intense vapor, 4) Quiescent phase.
With the seismic stations, we record microseismic and two distinct types of tremor within Lusi's embankment. The tremor events are associated with Lusi's activity phases 2 and 3. Of particular interest is the tremor type 2 that shows harmonic overtones that resemble harmonic tremors due to magma wagging in volcanoes.
We propose a mechanism fueling Lusi geysering activity that occurs at relatively shallow depth. The origin of the currently erupted fluids is deep. In our proposed model deep hot hydrothermal fluids upwell along the faulted geological units (e.g. Mazzini et al. 2009). The deep fluids reach an accumulation reservoir located in the Kalibeng Fm. (~1-1.5 km) that inflates and deflates according to the flow rate reaching the reservoir. The hot fluids are then vented to the surface along a conduit promoting flashing and exsolution reactions releasing CO_2, CH_4 and aqueous vapor. When the deep fluid mixture phase separates the coalescing, imploding and exploding bubbles initiate the geysering activity.
Our multidisciplinary approach is an effort to understand the mechanism ongoing at this new geological phenomenon. To our knowledge Lusi represents the first documented example of a sedimentary hosted hydrothermal system with clastic–dominated geysering activity.

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Figure 1: a) Map of Java. B) Elevation map of Eastern Java with the volcanic arc and back arc basin in the North east of the Island. LUSI and other mud volcanoes are located along the Watukosek fault system (black line). c) Aerial view of the LUSI mud volcano showing the positions of the short-period stations SP01-SP04 and the broadband station BB01 deployed during the 5-days field experiment (red inverted triangles), as well as the position of the cameras (Cam1, Cam2, black square) and the associated short-period stations SP05, SP06 and the broadband station BB02 (blue triangles) within the embankment area.

Figure 2. Four phases of the eruptive cycles at the Lusi eruption site: A) Regular activity with the constant emission of mud breccia, B) Geysering with intense bubbling, initiation if the geysering activity, C) Geysering with intense vapor, powerful geysering activity, D) Quiescent phase where no activity is observed

Figure 3. Three hours of eruptive cycles at the Lusi mud volcano in (A) June 11th, 2015 and B) November 11th, 2015. The different colours and column heights represent the four different cycle phases: Regular phase (green), intense bubbles (blue), intense vapor (red) and quiescent phase (yellow).

Figure 4. Exemplary waveform and spectrogram of the different types of seismic events that we find at the Lusi mud volcano: A) Microseismic event (SP02), B) Tremor type-1 with dominant frequencies between 5-10 Hz, lasting for about 30 s (SP01), C) long-lasting Tremor type-2, exciting frequency bands from 5-15 Hz with clear harmonic overtones (SP06).

Figure 5. Amplitude envelopes of the two tremor types, as recorded on SP01. The red thick line is the average envelope. A) Thirty-seven tremor type-1 events typically lasting about 30 s. B) Twelve tremor type-2 events lasting for 80-180 s.

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