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Monitoring of LUSI Mud-Volcano - a Geo-Pressured System, Java, Indonesia

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ABSTRACT

The LUSI mud-volcano is the dominant surface manifestation of a geo-pressured, low temperature geothermal system in Java. It started with an eruption of hot fluids and mud at the end of May 2006, close to an uncompleted, 2.8 km deep oil exploration well, two days after a major earthquake. The mud discharges from a concealed crater have been irregular with inferred long-term volume rates between 1 and 1.5 m^3/s and have continued ever since. The flooded area increased from c. 1 km^2 in June 2006 to c. 6 km^2 in May 2007; it displaced c. 40,000 people. The area has been enclosed and divided by a network of huge dams. The discharged hot liquid mud came initially from depths around 1.7 km where formation pressures of c. 30 MPa and temperatures of 100 deg C (gradient of c. 40 deg C/km) prevail. Pore pressure decrease in the upper sediments caused the initial subsidence over an area of the order of c. 7 km^2 after one year. The resulting subsidence bowl has accommodated only part of the extruded mud whose spreading is constrained by the huge dams.

Monitoring of subsidence and mud discharge began in June 2006 but ceased in April 2007 when sites were flooded. Satellite records (INSAR analysis of radar data) have been used to monitor subsidence of the not flooded region during that period. The rather short (< 2 km) wave length of subsidence during the first year points to shallow (< 0.5 km) source depths of de-compressed sediments. Interpretation of IKONOS satellite photos allows an assessment of heat discharged by the central steam plume and the upwelling mud column. The heat loss by steam discharge over the crater has fluctuated between c. 3 and 150 MW, losses due to hot mud discharges were always > 200 MW. Discharge trends during 2008 pointed to an overall irregular decrease of steam and mud losses which, however, was followed by a renewal of discharge activity in February 2009. The rate of gas discharges (mainly CO_2 and CH_4) from the central crater and gas discharges over the flooded area have not been measured yet. Micro-earthquake and micro gravity surveys were started in 2006 and repeated in May 2008 together with a ground temperature survey.

1. INTRODUCTION

The presently active LUSI mud-volcano is the dominant, central, surface discharge feature of a geo-pressured, low temperature geothermal system. It started with a major eruption of hot fluids and mud on 29 May 2006, close to the 2.8 km deep Banjar Panji-1 (BJP-1) exploration well, drilled by PT Lapindo near Sidoarjo in E Java (for location see Figure 1). Minor eruptions occurred a few days later along a c. 1 km long segment within a probably c. 250 m wide, NE trending fracture zone. Only the first eruption centre, c. 200 m SW of the BJP-1 well, has remained active. At the start of eruptions, the 2.8 km deep well had encountered a sequence of over-pressured and under-compacted Pleistocene sediments below 1.3 km depth. The well was not cased below 1 km depth which facilitated rupturing within the fracture zone; an M 6.2 earthquake had occurred on 27 May 2006, about 200 km away in Central Java.

Figure 1: Location map of LUSI mud volcano near Sidoarjo (Java)

Gas (CH_4, CO_2, minor H_2S), hot water, and hot mud at boiling point ascended to the surface, initially with a flow-rate of c. 0.5 m^3/s. The discharge fluctuated and increased on average to > 1 m^3/s after 2 months with fluctuations reaching an inferred peak discharge rate of c. 1.5 m^3/s in December 2006. The terrain around the discharge centre is rather flat (3 to 10 m a.s.l. within a radius of a few km). The size of the flooded areas increased rapidly from c. 1 km^2 in June to 6.5 km^2 in May 2007. The flooded area has been encased and contained by an extensive dam building program. Monitoring and assessment of discharge rates, subsidence (using GPS), and fluid characteristics began in June 2006. Surveillance included micro gravity-, resistivity- and micro seismic surveys at irregular periods up to April 2007. Some results of this first monitoring period have been published. The aim of the first publications (Mazzini et al., 2007, Davies et al., 2008.) was to prove or disprove the importance of a possible triggering effect of the drilling operation. Attempts to predict future subsidence and mass accumulation were based mainly on earlier monitoring data collected until May/June 2007 (Istadi, pers.com.). Monitoring efforts declined after May 2007 but were taken up again in April/May 2008 with new micro-gravity- and micro-earthquake surveys, augmented by a few shallow ground temperature studies. The mud discharge from the central vent has continued unabated since June 2006.

Since most monitoring studies were made at irregular intervals, often by different groups from different organisations, it has been proposed to continue with a more coherent and regular monitoring programme of important parameters and features of the mud-volcano with the aim of detecting trends which might allow a prediction of short-and long term changes. Such programme, if successful, could assist socio-economic planning aimed at mitigating the catastrophic effects of the LUSI eruption which has already caused the displacement of up to 40,000 people who lived in the now flooded areas. Based on discussions with engineers from Badan Penanggulangan Lumpur Sidoarjo (BPLS), involved in the ongoing containment (management) of the mud discharge, and scientists who undertook some of the earlier monitoring, as well as using published and unpublished reports, papers, and satellite photos, an assessment of the monitoring efforts is given here.

2. HEAT- AND MASS TRANSFER THROUGH LUSI

The heat- and mass transfer processes which occur at LUSI have to be defined to understand the importance of parameters which can be monitored. For this we use the analogue of treating the discharges of the mud volcano as features of a low temperature geothermal system where heat and mass is transferred from a reservoir to the surface involving buoyancy forces.

2.1 The Geo-Pressured Reservoir and Its Reservoir Fluids

Data from the BJP-1 well and the c. 1 km deep adjacent relief wells RW01 and RW02 (Mazzini et al., 2007, Davies et al., 2008, Tingay et al., 2008) were used to obtain a geological section of the geo-pressured reservoir encountered by the wells (see Figure 2). The data show that part of the reservoir consists of under-compacted and over-pressured bluish-grey clay deposits (plastically deformable) which were encountered in the uncased section of the well between c.1.2 and 1.85 km depth. Here, formation pressures of c. 20 and c. 30 MPa respectively prevail. The associated anomalously high pore pressures are contained within a sequence of rather impermeable layers. Sonic and neutron logs point to layers with high porosities (up to 35 %) at these depths. Geo-pressured volcano-clastics with average porosities of c. 20% occur from 1.85 km depth to bottom (c. 45 MPa pressure and c. 135 deg C near bottom hole). Microfossils in the mud ejected at the beginning point to initial mud source depths of c. 1.2 to 1.8 km. The buoyancy force required to lift a geo-pressured mud mixture via a 1.6 km quasi-vertical feeder system to the surface is c. 27 MPa. This would allow discharge of a gas-rich mud/ liquid mixture with a density of < 1730 kg/m^3. Assuming a particle density of 2,500 to 2,600 kg/m^3, a total liquid content of > 50% is indicated for this limit.

All geo-pressured sediments are fully saturated. The free liquid fraction of the liquid/mud mixture discharged at the surface appears to have changed with time. Initially c. 60% (by volume) of the discharge was hot water; this proportion has decreased with time (c. 40 % in 2008). The values, however, are only estimates. Chemical analyses of water samples collected during 2006 have shown that the discharged liquids derive from marine pore fluids (their content of 20 g/kg NaCl is equivalent to a c. 60 % paleo-seawater content).

The surface characteristics of the LUSI mud-volcano are anomalous if compared with those of other mud volcanoes exposed over geo-pressured systems elsewhere (Dimitrov, 2002; Kopf, 2002) where cooler, rather viscous mud discharges produce mounds of mud. Boiling temperatures at the surface have not been reported for any of these features. The temperatures at the bottom of the BJP-1 well are also anomalously high if compared with temperatures in other geo-pressure systems where temperatures of c. 135 deg C occur only below 4 km depth (Griggs, 2005).

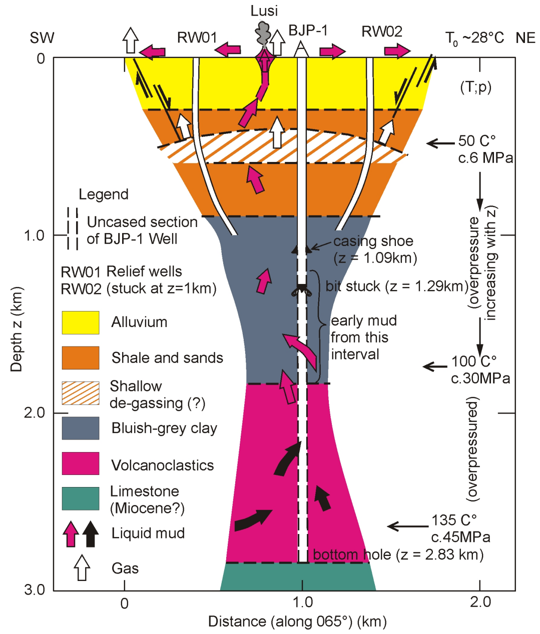

Figure 2: Simplified geological section of strata encountered by the 2.83 km deep BJP-1 exploration well showing spot temperature and pressure data at given depths and inferred fluid discharge paths.

2.2 Surface Manifestations and Discharge Characteristics

Irregular discharge of hot liquid mud has been confined to the central eruption centre. A set of vertical satellite photos, published since 07.08.06 on the CRISP website, constitute now the most important monitoring resource data (see Figure 3). The volume of discharged steam can vary by an order of magnitude during a time span of a few weeks. Steam has always been discharged by a set of small, bunched steam vents that occurred within an inner area with a diameter **di** of c. 50 m towards the end of 2006. This inner area is surrounded by a circular, light-grey coloured mud ring caused by an up-flow of gas bubbles (see inset of Figure 3). The diameter (**dm**) of the upwelling mud area increased continuously from c. 50 to 90 m in 2006 and fluctuated between c. 75 and 130 m during 2007 and 2008. The discharge of steam from vents in the inner area (with diameter **di**) can be compared with that of fumaroles over high-temperature geothermal systems (Hochstein and Bromley, 2001). Wafting steam over the outer discoloured mud zone is the result of evaporation which is enhanced by the rough surface caused by the continuous ‘popping’ of gas bubbles. Minor and irregular mud eruptions of the central ‘crater’ have occurred during the whole time.

Gas is discharged by the central ‘crater’, by vents in the flooded areas (concentrated discharge) and also outside the flooded areas through the soil (diffuse discharge). The gas discharge (mostly CO_2 and CH_4) has not been monitored yet. Within the flooded area, discharge is ephemeral. CRISP satellite photos show that during 2008 concentrated gas discharges waxed and waned at nine sites in the flooded area between the central crater and the W boundary dam. Seven ebullient gas discharge centres covered a total area of c. 3,500 m^2 in October 2008. All gas discharges outside the central crater are cold discharges due to volume expansion near the surface.

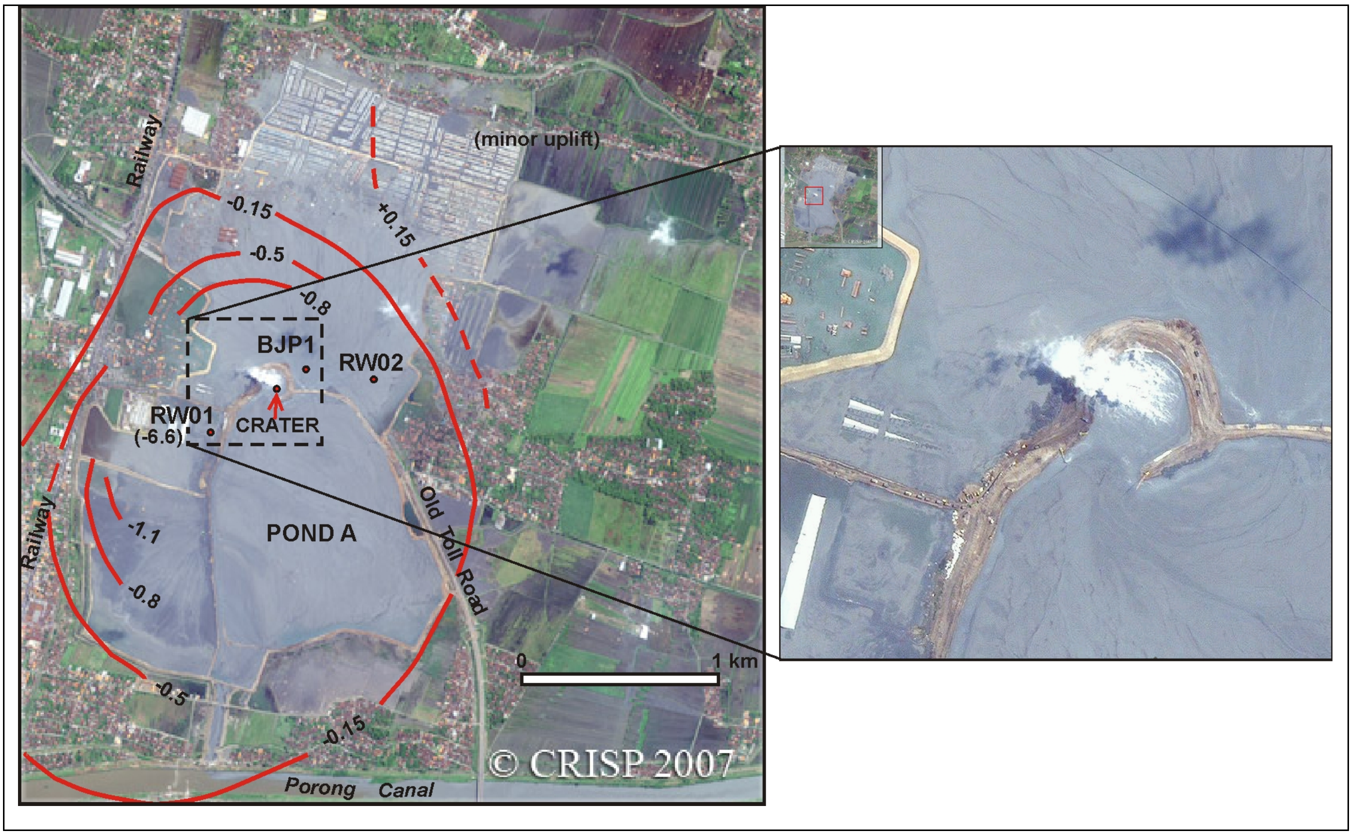

Figure 3: Satellite (IKONOS) photo (05.06.07) of the area flooded by the LUSI mud flow. Shown are also contours of subsidence rate (m/yr) from an INSAR analysis of ALOS satellite data (taken from Abidin et al., 2009). The LUSI discharge centre is enlarged in the right hand inset showing the steam cloud plume, the outer gas-discharging mud ring (slightly lighter grey tone) and the horse shoe shaped inner, circular dam.

Surface temperatures of the upwelling mud in the central part of the crater are close to boiling; spot readings between 94 and 97 deg C have been reported several times. Daily temperature measurements during a 20 day period in June 2008 recorded mud temperatures between 88 and 110 deg C (mean of 94 +/- 5.5 deg C). The maximum was observed after a large, distant earthquake had occurred (Istadi, pers.comm.). The surface mud temperatures decrease rapidly from c. 94 deg C in the centre to c. 40 to 45 deg C at the edge (**dm**) of the de-gassing mud ring.

Temperatures at c 1.7 km and 2.7 km depth in the deep well point to mean vertical geothermal gradients of c. 42 and 39 deg C/km respectively. The large gradients are most likely due to a rather low thermal conductivity of the highly porous, liquid saturated reservoir rocks. The fast equilibrating (K/Mg) geo-thermometer, applied to analyses of fresh liquids from the crater (cited in Mazzini et al, 2007), yields equilibrium temperatures of c. 80 to 120 deg C which correspond to fluid temperatures prevailing between c. 1.2 to 2.3 km depth. Isotope data of the same samples show large δO^{18} shifts similar to those of young palaeo-pore fluids with high marine content as encountered, for example, in Gulf Coast (US) oil and gas wells (Faure, 1986). Because of the affinity of observed isotope data with those of pore fluids of gas wells in non-volcanic settings, a volcanic heat input is not required to explain the anomalous temperatures in the BJP-1 well.

2.3 Steam Discharge

Discharge of the hot, liquid mud is associated with several heat transfer processes. One of the processes involves boiling of ascending pore waters at shallow depth beneath the crater and the discharge of a steam plume over the crater. The plume contains not only steam and gas, but also air which enters it at the bottom during steam ascent. Studies of fumaroles in NZ by Hochstein and Bromley (2001) have shown that projected steam-cloud areas are proportional to the total steam-cloud volume **Vc** which, in turn, is proportional to the heat loss **ΔQc**. Meteorological parameters, such as air pressure, air temperature, humidity, and wind speed, all affect the steam cloud volume. A schematic view of the steam discharge over the crater is shown in Fig.4a; a summary of all parameters used for the analysis of heat transfer by steam and mud discharge is listed in Fig. 4b.

For a given constant heat output of **ΔQc,** the steam cloud volume **Vc** varies with air pressure ($\mathbf{p_0}$), air temperature ($\mathbf{T_0}$), and relative humidity ($\mathbf{rh_0}$) from day to day. However, these parameters did not change much between the days when the published IKONOS satellite photos were taken (always recorded during cloudless days and c. 90 min before meridian time).

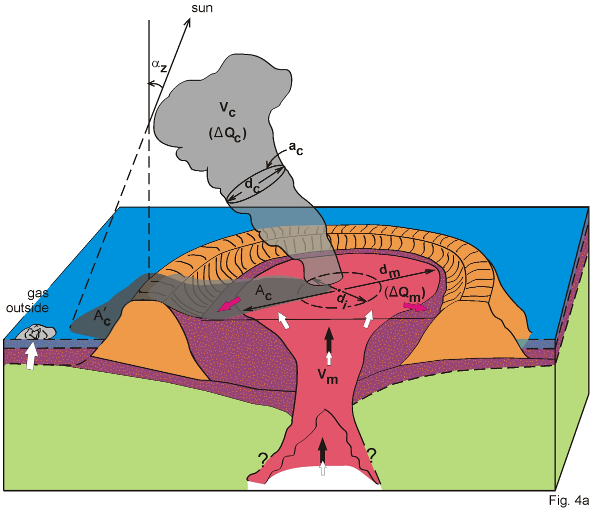

Figure 4a: Perspective view of LUSI mud discharge centre and characteristics of mud flow and central steam-cloud used in the text.

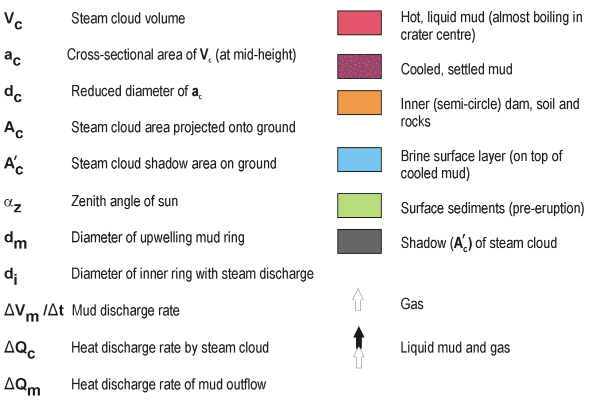

Figure 4b: Legend of parameters and symbols used in Figure 4a.

Using meteorological data from the nearby Surabaya airport, it was found that $\mathbf{p_0}$ showed the smallest changes (less than 0.2 % with respect to an annual mean of 1010 mbar at noon). The air temperature $\mathbf{T_0}$ also showed little variation since during nine different satellite crossings in 2007, for example, $\mathbf{T_0}$ differed at noon by less than +/- 2 deg C from the annual mean of 28 deg C. Only the relative humidity $\mathbf{rh_0}$ showed slightly larger variations (c. +/- 5% with respect to a mean of 75%). For the steam cloud shown in the inset of Fig.3 the values at 10:30 on 05.05.07 were: $\mathbf{p_0}$ = 1009 mb, $\mathbf{T_0}$ = 26.5 deg C, $\mathbf{rh_0}$ = 79 %. Hence, steam clouds shown on the IKONOS satellite photos taken at different months over the LUSI mud volcano can be compared allowing for reductions of $\mathbf{V_c}$ with respect to $\mathbf{T_0}$ and $\mathbf{rh_0}$.

The volume $\mathbf{V_c}$ can be approximated by:

$$\mathbf{V_c = F\, a_c\, s_c} \qquad (1)$$

Where **F** is a dimensionless form-factor (significantly affected by windspeed), $\mathbf{a_c}$ the cross-sectional area perpendicular to the long axis of the plume at mid height, and $\mathbf{s_c}$ the slant distance of the long axis of the plume. Assuming that **F** is close to unity, the diameter $\mathbf{d_c}$ of area $\mathbf{a_c}$ is proportional to the cloud volume $\mathbf{V_c}$. Using the zenith angle $\boldsymbol{\alpha_z}$, the projected length of the cloud on the ground ($\mathbf{l_c}$),and the shadow length ($\mathbf{l_s}$), the approximate height of the steam cloud ($\mathbf{h_c}$) can also be obtained. Following the approach of Ryan et al. (1974), it was assumed that the heatflux due to evaporation at the base of the steam cloud is proportional to the vapour pressure difference ($\mathbf{e_s}$ – $\mathbf{e_b}$) where $\mathbf{e_s}$ is the saturation vapour pressure at the mud surface of the crater and $\mathbf{e_b}$ the water vapour pressure in the atmosphere close to the base. Assuming that $\mathbf{e_s}$ is almost constant, changes in $\mathbf{V_c}$ and $\mathbf{a_c}$ are therefore proportional to changes with respect to $\mathbf{e_b}$ of a 'reference' steam cloud with the average annual parameters of $\mathbf{p_0}$, $\mathbf{T_0}$, and $\mathbf{rh_0}$ listed above. The reduction can be simplified by considering only changes applied to the diameter $\mathbf{d_c}$, a parameter which is also proportional to $\mathbf{V_c}$. The effect of time-variable changes in **p** and **T** was found to be small and was neglected. The reduction of the $\mathbf{rh_0}$ effect can also be applied to the projected cloud area $\mathbf{A_c}$, i.e the area visible in the satellite photo, which, in turn, is proportional to the heat loss **ΔQc** (Hochstein and Bromley, 2001).

An assessment of satellite photos taken, for example, during 2006 at days with little wind showed that $\mathbf{V_c}$ values of the steam plume over the LUSI crater, reduced for humidity effects, varied between c. 1,000 and c. 500,000 m^3 on 09.10.06 and 06.12.06 respectively. This points to a larger than two orders of magnitude variation within a 2-month period. The reduced area $\mathbf{a_c}$ of the plume at mid-height varied between c. 100 and c. 3,000 m^2 for the two days. Using the zenith angle of the sun and shadow length of the steam clouds, the height $\mathbf{h_c}$ of the plumes was found to be c. 10 and c. 250 m respectively. Comparing these values with reduced NZ fumarole data, a heat loss **ΔQc** on the order of 3 and 100 MW respectively is indicated for the two cases. Satellite photos show that the large value for the 06.12.06 steam cloud was exceeded only a few times in the satellite photo sequence during the next two years. Large changes in $\mathbf{V_c}$ can occur even within a week as indicated by changes in steam cloud characteristics on satellite photos taken on 17.09.06 ($\mathbf{V_c}$: 1,000 m^3) and 25.09.06. ($\mathbf{V_c}$: 150,000 m^3). Such variations appear to be the result of pulsating 'slug' flow discharges.

2.4 Volume- and Mass-Flow Rates of Liquid Mud

Rates of discharged mud volume (in m^3/d or m^3/s) were estimated during the first 11 months from accumulated mud thicknesses in the flooded areas. The first estimates appear to be the more accurate ones. The specific density of the mud increases with time due to dewatering and mud compaction. Thickness estimates are also affected by subsidence which induces some groundwater to reach the surface. For June/July 2006, the original, average mud flow estimates were c. 0.5 m^3/s which increased to c. 1.1 m^3/s and 1.4 m^3/s in August and September 2006 respectively (neglecting densification). For May 2007 the last estimate was c.1.3 m^3/s. Pulsating discharge activity was noticed between middle of August and middle of September 2006 when discharge rates could vary by half an order of magnitude during a period of a few days.

The LUSI mud management policy was aimed at changing the radial mud outflow to a sectorial outflow (to the south). To achieve this, a high-standing, semi-circular dam was constructed (completed by the end of August 2006) which directed the flow to the south (see Figure 3); mud was allowed to accumulate to form a c. 7 m high, broad mound but increasing mud viscosity retarded outflows. From mid 2007 onward the deposition pattern of the mud flows was changed when excavators were used on the inner dams to promote mud movement towards the Porong Canal (at the S margin of Figure 3). Mud outflow was also controlled by maintaining a rather high (surface) level of the central crater by continuously raising the crest of the confining circular dam to compensate for ongoing subsidence. Initially, separated brine was drained by a new canal in the south. After its silting, mud-slurry was pumped from stations near the S dam into the Porong Canal. This required ‘thinning’ of the mud by adding river water to reduce the solid components of the slurry to c. 45% (per volume unit). The total daily capacity of the slurry pumps was c. 120,000 m^3/d when working in 15 hr long, daily shifts. The removal of c. 100,000 m^3/d of ‘original’ mud was equivalent to a maximum slurry removal rate of c. 1.15 m^3/s. Average monthly pumping data of mud slurry for the period of May 2006 to December 2008 (reduced by a factor of 0.87 to allow for mud dilution) are shown in Figure 5b. Mudflow management by slurry pumping constitutes an important monitoring procedure.

Details in satellite photos from the CRISP website can be used to infer trends in energy transfer via the steam plume (**ΔQ_c**) and the outflowing mud column (**ΔQ_m**). The equivalent diameter **d_c** of the steam plume at mid-height and the quasi-circular, upwelling mud area (with diameter **d_m**), are such parameters. Plotting the diameter **d_c** of the reduced cross-sectional area **a_c** together with the diameter **d_m** of the upwelling mud versus time, shows an acceptable correlation (see Figure 5a). These data can be compared with the inferred and observed mud discharge rate for the first 12 months of the LUSI activity (see Figure 5b). It appears that the average mud discharge rates reached a peak in December of 2006 (c. 1.85 m^3/s) as a result of increasing up-flows stimulated by a sequence of earthquakes. It caused a huge mud eruption around 06.12.06 that breached the semi-circular, inner dam.

Mud discharge rates probably fluctuated between 1 m^3/s and 1.5 m^3/s during 2007 and 2008 as indicated by the trend of the diameter **d_m** of the upwelling mud from January 07 until December 08 (see Figure 5a). Peak values of **d_m** (c.120 m) were reached during March to June 2008 when mud discharge rates also reached their peak (probably c. 1.5 m3/s). Discharge rates **ΔQc** (via the plume) are proportional to the reduced cross-sectional area **a_c** and its equivalent diameter **d_c** and point to (order of magnitude) variations between c. 15 and 100 MW from September 2006 to August 2007 - with a generally declining trend from January to December 2008. In between (September to December 2007), heat transfer by steam also declined.

Using the inferred mud discharge rates shown in Figure 5b, approximate subtotals of c. 20 and c. 40 Mill m^3/yr of discharged mud are indicated for the years 2006 and 2007/2008 respectively (i.e. total of c. 100 Mill m^3 from June 2006 to December 2008). However, a total of c. 35 Mill m^3 of mud was removed from the originally flooded area by mud pumping during 2007 and 2008. The net volume of mud deposited in the flooded LUSI area until December 2008 was therefore c. 65 Mill/m^3, equivalent to an average (unconsolidated) mud thickness of c. 10 m over a flooded area of c. 6.3 km^2.

2.5 Heat Discharge and Transfer Rates

The total anomalous heat transfer of the LUSI mud-volcano is approximately given by the heat discharged via the steam cloud (**ΔQ_c**) and that by the hot, upwelling mud (**ΔQ_m**). The magnitude of evaporative and conductive losses from the hot mud surface can not be assessed yet. However, the anomalous heat discharged by the upwelling mud can be assessed separately for its liquid and its solid portion. If we assume, for example, a mean surface discharge temperature of 95 deg C, a reference mean annual T of 28 deg C, a particle density of 2,500 to 2,600 kg/m^3 for the solids, an initial (near surface) liquid proportion of 50 to 60%, and appropriate specific heat capacity values for liquid and solids, this points to an anomalous heat discharge **ΔQ_m** of c. 215 MW per m^3 of liquid mud. For an inferred maximum discharge rate of c. 1.5 m^3/s, a heat loss of c. 320 MW is indicated. For the large eruption period around 06.12.06, when the inner circular dam was breached and **ΔQ_c** was .>100 MW, a total of at least 400 MW would have been transferred to the surface.

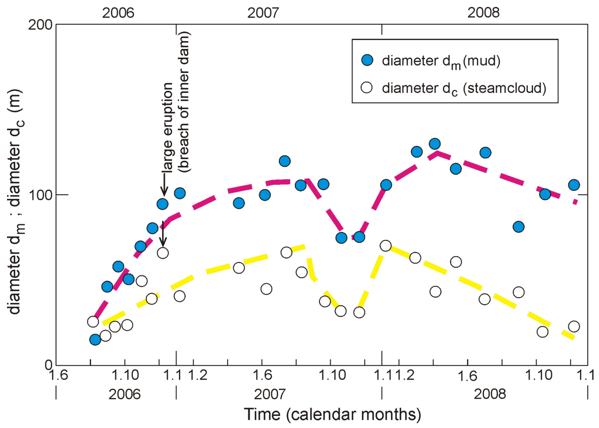

Figure 5a: Plot of diameter d_m of the upwelling hot mud ring (crater region of LUSI mud discharge) versus time (August 2006 to December 2008). Also plotted is the equivalent diameter d_c of the cross-sectional area a_c of the steam cloud, reduced for changes in relative humidity.

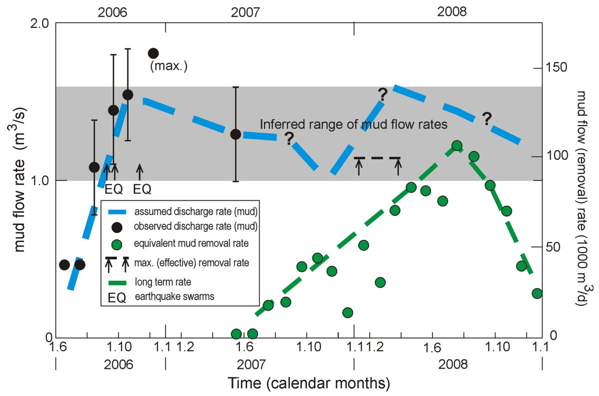

Figure 5b: Plot of average and inferred (mud) volume discharge rates (in m^3/s) versus time (August 2006 to December 2008) of LUSI mud flow. Also shown are mud removal rates from pumping (reduced for mud ‘thinning’) versus time for the period June 2007 and December 2008 (courtesy Mr.Soffian, BPLS).

Although representative mud discharge rates are not known since April 2007, it can be inferred from earlier observations and trend data cited in this paper that the present-day heat loss is still > 200 MW. The hot liquid mud, in turn, cools by evaporation and conduction. Together with expansion cooling of rising gas, this reduces surface temperatures from c. 95 deg C in the inner discharge area to c.40 to 45 deg C just outside the upwelling mud ring. Near the pump stations it is further cooled by addition of cool river water. The mud cooling pattern is visible in IR satellite photos.

2.6 Gas Discharge

Gas discharge is significant, both as diffusive and concentrated discharge. Widespread diffusive discharge occurs in settlements along the W and SW boundary dams (i.e. outside the flooded area) and has led to their partial or total evacuation. Some concentrated gas discharge occurs not only at the central crater but also at several centres in water-covered stagnant pool areas. In the western flooded pond area, water/gas upwellings could be observed, driven by escaping CO_2 and CH_4 gas (see example in Figure 6). The total area of seven centres with 'ebullient' gas discharge in the northern ponds was at least 4,000 m^2 in October 2008. Ebullient discharges visible on satellite photos showed an increase during 2008 but disappeared in early 2009. Smaller gas discharges have been observed at smaller sites which appear to be at or close to inferred fractures. However, none of the gas discharge centres in the western ponds, active during 2008, were close to documented smaller eruption sites mapped in June 2006.

Figure 6: Photo of ebulliant gas discharge centres near the western boundary dam (visible in the back); October 2008.

Specific gas and steam flux data have not been obtained yet. Gas samples were taken during the second half of 2006 from the crater steam plume together with some gas seeps and were analysed in terms of non-condensable gas species but not for water vapour (Mazzini et al., 2007). Other reports refer to estimates of non-condensable gases by 'gas-sniffer' instruments. Assuming that most gas over the crater comes from deep fluids where temperatures between 100 and 135 deg C and pore pressures between 30 and 45 MPa prevail, the solubility of both major gases in pore fluids can be estimated by using, for example, solubility data cited by Lu and Kieffer (2009). Allowing for salinity, a discharge of c. 1.5 m^3/s of liquid mud could produce maximum CO_2 and CH_4 mass discharge rates of c. 2 kg/s and 0.7 kg/s respectively. The likely total volume of greenhouse gases discharged by the LUSI mud-volcano is therefore large and should be assessed in more detail. A ground based gas-flux survey, especially for areas within already evacuated villages outside the dams, is indicated.

3. OTHER MONITORING SURVEYS

Several surveys have been undertaken since June 2006 to assess the extent and the effects of the mud eruptions. GPS and geodetic surveys were carried out between June 06 and June 07 to assess subsidence. These surveys were not repeated. Other surveys, however, were repeated at irregular periods such as micro-gravity and micro-seismic surveys. In 2008 shallow ground temperature surveys were added to the programme.

3.1 Assessment of Subsidence

Earlier GPS surveys occupied stations located mainly in the then not-flooded part of the subsiding area but showed significant variation of short term rates between adjacent stations (Istadi et al., in prep; Abidin et al., 2008). After flooding of the N sector in December 2006, subsidence surveys could only be undertaken on dams where soil compaction disturbed measurements. At the relief well site RW01 (see location in Figure 3), subsidence was recorded for 123 days between September 2006 and January 2007 (average subsidence c. 1.8 cm/d). Another 33 day long GPS record of subsidence was taken between November and December 2006 at relief well site RW02 (apparent subsidence c. 3.8 cm/d). Both sites, however, were located on rapidly constructed ground platforms.

An independent assessment of subsidence between May 06 and February 07 was obtained by analysing radar data recorded by the ALOS satellite using the INSAR method. Results of this study (Fukushima et al., in press; Abidin et al., 2009), converted to subsidence rates in m/yr, are shown in Figure 3. Other long-term subsidence information comes from observations of sites not affected by soil compaction, such as the cemented, 4 m high standing conductor pipe at well RW01 where a total subsidence of c. 8 m (with reference to the nearby carriage dam) is indicated when visited by us in October 2008. This estimate points to a long-term subsidence of at least 4.5 m/yr (over a 22 months period). Railway tracks were lifted along and outside the W boundary dam to compensate for local subsidence of the order of 1 m between 2007 and 2008. These data indicate that most of the early subsidence data derived from spot GPS surveys contain errors owing to site effects and should not be interpreted in terms of long-term estimates. The caveat also applies to the previously cited GPS readings at the RW02 site taken over a one month period for which an apparent subsidence rate of c. 14 m/yr was predicted.

Construction and maintenance of all dams at the LUSI site has been a tremendous labour-intensive effort (c. 70 Mill t of fill has been used for the construction of these dams over a two year period) although all dams, especially the c. 15 m high, inner circular dam, suffer additional subsidence as a result of compaction.

3.2 Interpretation of Subsidence

Possible causes of the subsidence and its pattern (shown in Figure 3) have been investigated by Fukushima et al. (in press), namely: loading effect of the deposited mud layer, subsidence due to the creation of an equivalent vertical mud conduit, as well as pore pressure decrease and/or removal of mass at depth. The effects of the first two are insufficient to explain the magnitude of the observed subsidence. Limits of the third explanation were investigated by computing subsidence patterns for a set of oblate spheroidal models resulting in best fits for models with compaction centres between c. 0.6 km and 0.7 km depth. These depths are much shallower than the inferred source depths of the mud discharged at the surface.

Because of the important implication of these findings, we used characteristics of other compaction-subsidence models (Geertsma, 1974) to assess the maximum depth ($\mathbf{z}_{\mathbf{max}}$) of an anomalous compaction centre from the characteristic wavelength $\lambda/2$, where λ defines the (horizontal) distance of the subsidence anomaly. For data in Figure 3, along a profile (070°) running through RW01, a range of $\lambda/2$ data was obtained which yield z_{max} values between c. 0.5 km and 0.7 km; the early subsidence rate at RW01 becomes an important controlling parameter in the assessment of λ. Our treatment is less rigorous than that of Fukushima et al. but produces a similar result. It can be inferred that subsidence has been caused by pore pressure reduction of sediments at rather shallow (< 0.7 km) depths (sediments at these depths were probably also over-pressured). An inferred section of the shallow de-gassed sediments is shown in Figure 2. The triggering mechanism for the discharges is unknown but is probably not related to activities during the last drilling phase of the 2.8 km deep uncased well before the LUSI eruption.

3.3 Micro-Gravity Surveys

Two separate micro-gravity studies were made with the aim of detecting the likely location and magnitude of subsurface mass withdrawal. The first study used three surveys between August and October 2006 and was undertaken by ITB staff. The second study involved four surveys during May to July 2008 by BMG staff. In each case, the gravity data were not reduced for station height changes between start and end of the survey nor for near-surface mass changes (changes of ground water level and other near-field effects). Such reductions are a fundamental requirement for the interpretation of gravity anomalies caused by underground mass removal (Hunt, 1995). The computed lapse-time anomalies of both micro-gravity studies contain therefore systematic errors and can not be interpreted in terms of underground mass changes.

3.4 Micro-Seismicity and Ground Temperature Surveys

A second micro-earthquake survey was made between May and July 2008 coinciding with the micro-gravity study (BMG, 2008). Three-component seismometers were installed at seven stations close to the circumference of the flooded area. A total of c. 60 local events were observed. All, except probably one, were of shallow origin (< 0.5 km depth). The epicentre of most events occurred in the S and E quadrant at distances of c. 1.5 to 2 km from the eruption centre; a single event occurred in the N sector, also c. 2 km away from the mud discharge centre. The shallow seismic velocity structure of the flooded area is not well constrained and is disturbed by near-surface, gas-rich sediments.

Monitoring of ground temperatures was started in May/June 2008 (80 sites); a repeat survey was made in October 2008 (65 sites). Temperatures were measured at 0, 1 and 2 m depth (occasionally at 1.5 m) along the foot of dams inside the flooded areas and near short road segments outside. During the 2nd survey, shallow T-profiles were also measured along the inner dam-hot mud boundary around the semi-circular dam and extended towards the pumping stations. With reference to climate data from Surabaya airport, anomalous 'cold' and 'hot' ground temperatures could be defined for data from 1 m depth (T < 23 deg C was defined as 'cold' and T > 33 deg C as 'hot'). The observed mean minimum and maximum air temperatures do not exceed 25 and 31 deg C respectively during the whole year.

'Cold' ground temperatures, sometimes as low as 19 deg C, were measured on the inner N side of the semi-circular dam and near the outer W, NW, and S boundary dams. All 'cold' sites were close to nearby gas discharge features. Anomalously 'hot' temperatures (up to 47 deg C) were observed over short, outer segments at the foot of the circular dam. The 'cold' temperatures are probably caused by near-surface expansion of rising gas (for rising CO_2 a pressure drop of 1 bar can be associated with a cooling effect of c. 0.7 deg C). Sites with 'hot' temperatures at the foot of dams are affected by conductive heating. Hot mud temperatures down to 2 m were also measured during the 2nd survey. At stations near the gas-charged mud ring (inner margin of circular dam) temperatures were still 90 deg C at 2 m depth but the mud had cooled rapidly to c. 40 deg C at the surface, possibly due to the combined effect of gas expansion and evaporation. The second survey also detected anomalously 'cold' ground in the SE sector outside the dam which had suffered a dam breach in early 2008.

4. MORE RECENT DEVELOPMENTS

Details listed in the previous chapters cover developments and activities of the LUSI mud-volcano from June 2006 to December 2008. Towards the end of this period there was a decline in heat transfer by steam and hot mud (see trends in Figure 5a). However, recent IKONOS satellite photos show again an increase in eruptive activity. In February 2009 the high-standing semi-circular dam around the mud discharge centre (see Figure 3) was severely breached and could no longer be repaired.. The outpouring mud quickly filled the low lying ponds in the N and W sectors. By March 2009, the confining semi-circular dam had subsided and was flooded. Partly dried and drained ponds in the northern quadrant were flooded again, together with smaller enclaves along the W boundary dam (Figure 7). The total flooded area increased to c. 10 km^2.

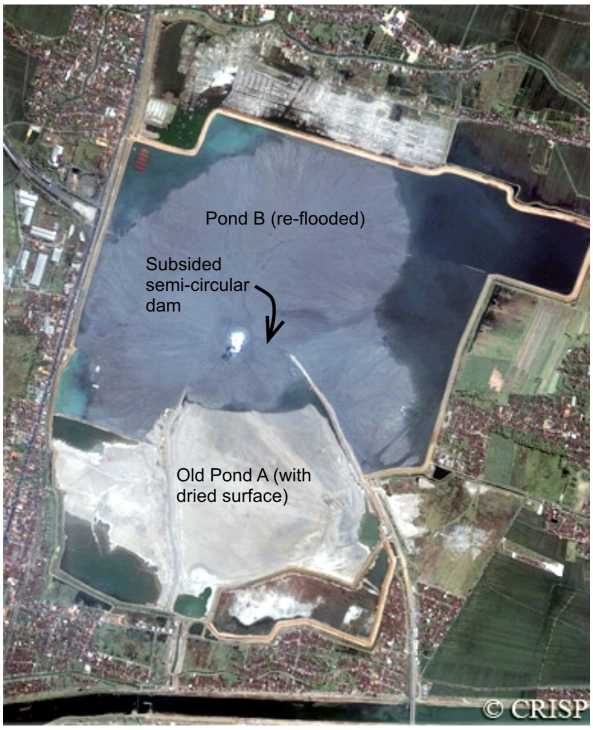

Figure 7: Satellite (IKONOS) photo (24.06.9) of the area flooded by the LUSI mud discharges.

A significant increase of the steam cloud volume $\mathbf{V_c}$ over the crater occurred in February 2009 if compared with values observed during the 2nd half of 2008. The diameter $\mathbf{d_m}$ of the de-gassing mud ring around the crater also increased in size at the same time up to 150 m. It was the largest diameter ever noticed, although some of the increase might have been caused by the sinking of the constraining semi-circular dam structure. It appears that highly active eruptive phases that have caused large dam breaches in the past or caused large increases in mud outflows, as indicated by the sudden increase in the diameter of the gas-charged mud ring, are associated with some long-term periodicity. Large eruptive events with massive outpourings of mud have occurred, for example, in December 2006, during the first months of 2008, and again at the beginning of 2009.

Smaller (groundwater?) ponds have also appeared outside the outer, confining dams pointing to widening and deepening of the subsidence area. The wavelength of subsidence is now about 3.3 km indicating that compaction of deeper de-pressured sediments is occurring. It is likely that widening of the subsidence bowl will continue.

5. CONCLUSIONS

The LUSI mud volcano that erupted near Surabaya (Java) at the end of May 2006 is the dominant surface manifestation of a geo-pressured, low temperature geothermal system. It has discharged hot liquid mud close to boiling point temperature already for more than 3 years and has flooded in March 2009 an encased area of more than 10 km^2. Other manifestations include wide-spread gas discharges (mainly CO_2 and CH_4). The hot mud rises from >1.7 km depth. In comparison with other mud volcanoes described in the literature (Kopf, 2002), the LUSI manifestations are anomalous because of the rather low viscosity of the discharged hot liquid mud with its high gas component that has produced an extensive ‘mud flood-plain’ (‘mud-lake’) which strictly can not be classified as a ‘mud volcano’. However, the term ‘mud volcano’ has been used for LUSI in earlier publications and is used here as well.

The active mud discharge centre exhibits a sub-surface crater structure and occurs close to the 2.8 km deep uncompleted oil and gas exploration well (BJP-01). Two different hypotheses have been put forward to explain the triggering of the eruptive event. One hypothesis suggests that a large earthquake (M 6.2) in Central Java, which occurred two days prior to the first mud eruptions on 29 May 2006, caused fracturing within an already existing fracture zone thus triggering the event. The other hypothesis implies that a blowout, as a result of drilling problems in the unprotected c. 1.7 km long bottom section of the BJP-01 well, was the triggering event. Each hypothesis on its own is not fully supported by monitoring results.

Several detailed monitoring studies were made during the first ten months after the first mud eruptions. They included assessments of volume and mass flow-rates, subsidence and surface movement, geochemistry, micro-gravity, and micro-earthquake (MEQ) surveys. Many results were affected and disturbed by soil compaction at sites located on dams and in protected enclaves. Only a few long-term GPS surveys and long-term level changes of a few engineering sites provide some representative long-term subsidence rates which are of the same order of magnitude as rates obtained from an INSAR analysis of satellite-borne radar data observed in 2006/7. Modelling of subsidence patterns points to subsidence caused by compaction of de-pressured sediments, initially at c. 0.6 to 0.7 km depth. An analysis using a half-wavelength approach produces a similar result.

The time-lapse anomalies of micro-gravity surveys conducted in 2006 can not be interpreted because changes in station height were not recorded. The same applies to repeat gravity surveys undertaken in 2008. MEQ studies in 2006 and 2008 showed that shallow seismic events mainly occur beneath the southern sector and the southern margin of the subsidence area pointing to a triggering surface loading effect. The data do not allow a more detailed interpretation because of the rather inhomogeneous near-surface seismic velocity structure. Two shallow ground temperature surveys were carried out in 2008 and showed that anomalously low temperatures at 1 m depth (a few deg C below mean annual minimum air temperature) occur near gas discharge centres pointing to a Joule-Thompson effect by rising gases (dominantly CO_2). Another short-term (20 days) monitoring survey of mud discharge temperatures of the LUSI ‘crater’ showed that the temperature of the liquid mud varied between 88 and 110 deg C with the highest temperatures occurring after a large, distant quake.

Satellite (IKONOS) photos published at roughly monthly intervals constitute important long-term monitoring data that allow an assessment of heat and mass discharged at the crater by the always present steam plume and the upwelling mud. The published photos were all taken under almost cloudless conditions, c. 1 ½ hr before local noon. Meteorological conditions are rather constant at that time throughout the year. Heat transfer by direct steam discharge can be assessed from the steam cloud volume reduced for small variations in relative humidity. The steam losses were found to fluctuate between c. 3 MW and 150 MW during the last 3 years. Heat losses by hot mud discharge could be assessed for the first 10 months for which a few volume discharge rates are known. Two months after the first eruptions, the heat transfer by hot mud increased from c. 100 MW to c. 300 MW. It was found that the diameter of the steam cloud at mid-height and that of the gas-charged outer mud ring around the crater show some correlation that can be used for trend analysis.

The data indicate short and long period variations which are most pronounced in steam cloud changes. Short-term variations occurring during periods of less than a week and often during one day point to some ‘slug flow’ of the liquid component. Voluminous mud discharges which can cause dam breaks and excessive mud flooding seem to follow some periodicity. Such large discharges occurred at the end of 2006, and again during the first months of 2008 and 2009. There are no clear trends which point to an overall long-term decline of steam and mud discharge activity.

In view of the present uncertainty in predicting future activity trends of the LUSI mud volcano, installation of a well co-ordinated and regular monitoring programme is required. This should include quantitative assessment of the green-house gas discharges about which nothing is known yet. In addition, analysis of more recent radar data should be continued as well as monitoring of subsidence in non-flooded areas outside the confining dams.

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