LUSI - Birth of a Mud Volcano
(History and Impact of Mud Volcano disaster in East Java)

Bambang Istadi
Lapindo Brantas Inc.
June 2007

Appears approx. 200m from BJP-1 well
Forms a lineament
Geyser behavior (?) (Empty chambers periodically before new burst)
Pulsations
Forming an upwelling or volcano like structure

LUSI - Sidoarjo Mud Volcano
Extrusion in grass field NOT in the drilling site or the BJP exploration well

Survey point Banjar Panji 1 Well Toll Road Bjp-1

1. Sumur bor +/- 80 m keluar air + pasir hitam.
2. Keluar air pekat dari lantai.
3. SEMBURAN PERTAMA 29 MEI 2006 150 M SW DARI SUMUR
4. SEMBURAN KEDUA 1 JUNI 2006 150 M NE DARI SUMUR (Keluar air semburan di lima titik)
5. SEMBURAN KETIGA 1 JUNI 2006 500 M NE DARI SUMUR

Gempa Jogya : 27 Mei 2006

-SAAT INI HANYA DI LOKASI SEMBURAN PERTAMA YANG MASIH AKTIF
Cracks at the rig site

Cracks at location was not followed by gas or fluid coming out, suggest that it was not caused by pressure, but dislocation due to earth movement.

LUSI eruption sites

The broaches were in one straight line, not typical of underground blowout.
**WATUKOSEK FAULT LINEAMENT**

- 2 parallel faults
- River aligned along fault line
- Escapement - up thrown block of fault
- A very long propagating fracture appears due to tectonic activities / earth quakes in the region

**LUSI and faulting**
Kalang Anyar Mud Volcano

KALANG ANYAR
(South of Juanda Airport)

Kalang Anyar MV

- Microbial colonies
- Salts/Halide
- Oil Seeps
1. Rapid sedimentation and burial trapping excess water
2. Sedimentary loading resulting in abnormally high pore pressures in undercompacted shale formations
3. Mud volcanoes appear to be related to lines of fracture, faulting, or sharp folding.
4. Eruptions can occur when mud and sand are squeezed upwards by seismic forces.
5. A disturbance of the gravitational instability may trigger the beginning of flow, which may be orogenic tectonism.
6. The sudden release and upward expansion of dissolved gases may also play a key role.
Mud Volcanoes in South Timor

Photo: Courtesy of Dr. Untung Sumotarto (BPPT)

Close-Up of Mud Volcano Peak in South Timor

Photo: Courtesy of Dr. Untung Sumotarto (BPPT)
Mud Volcanoes at Semau Island, west of Timor

East Java: Geological Setting

- Convergence of plate boundaries and the subduction of the oceanic plate
- Northern part of Java: backarc basin, Tectonically active Kendeng zone
  - Extensional regime → Rapid subsidence and burial
  - High sedimentation rate → Under-compacted unstable shales
  - Deposition of organic-rich sediments → production of Hydrocarbon

→ ideal setting for MV
the source of the mud volcano is highly plastic, undercompacted mud or shale or a mud diapir. Commonly appear related to fracture, faulting or sharp folding in the earth’s crust.

**Mud volcano** commonly is the result of a piercement structure created by a pressurized mud diapir/overpressured shale.

**CONTROL MECHANISM**

- Presence of a layer or zone in which has a lower density than the overlying rock units.
- The low density material to have an ability to flow.
- A disturbance of the gravitational instability to trigger the beginning of flow, which may be:
  - Orogenic tectonism
  - piercement structures
  - high pressure release
Geological setting and geodynamics control the distribution of mud volcanoes in East Java.

Analogues

BLEDUK KUWU
ACTIVE MUD VOLCANO
(PURWODADI)

GRESIK MUD VOLCANO
Related to the Banjarpanji-1 well?

Possibilities?
Partial loss of drilling mud 10 minutes after earthquake, 7 hours later complete loss circulation.  
- Suggest possible connection.

No evidence of Kujung Formation penetration.

Initial 320,000 bbl/day mud flow is impossible from a single 12-1/4” hole size.

Gas+water kick entered the well bore during loss circulation, and brought up to surface while tripping and pumping out.
- No high pressure and/or annulus evacuation by gas/water.

Initial Shut in Pressure of 350 psi. Found gas/water (8.9 ppg) flow to surface,
- Hydrostatic pressure in the annulus will be less than the formation strength.
- Very unlikely could break the formation.

Able to pump and circulate mud after broaches
- Proves NO communication between bit and the broaches.

Why The Broaches Did NOT Come From The Well ?

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Did the May 27 Yogyakarta trigger the mud volcano?

Mw 6.3
Distance ~250 km

Surabaya: II-III MMI (Modified Mercalli Intensity), 3.0-3.9 Mw (Moment Magnitude)

Karang Kates: III-IV MMI, 4.0-4.9 Mw

Pasuruan II-III MMI

Tretes III-IV MMI
RELATION BETWEEN PLATE MOVEMENT, PLATE INTERACTION AND EARTHQUAKE DISTRIBUTION

Re-activation of old faults due to sudden inbalances zones of earthquake hypocentres

Release of accumulated pressure in strained interacting rocks

Fault reactivation

Piercement structures
Reactivation of pre-existing faults?
Mt. Semeru

Effective March 29, the East Java Office of Energy and Mineral Resources and Semeru Volcanic Observatory increased the danger level of Mt. Semeru to Alert Level 2 (Code Yellow – Danger). The East Java Office of Energy and Mineral Resources urged tourists and others not to climb Mt. Semeru higher than 1 kilometer from the top.

Visual observations showed increased sulfurous gases 50-75 meters from the crater and numerous gas explosions rising 300-600 meters up from the crater.

http://earthobservatory.nasa.gov/NaturalHazards/Archive/May/2009/semur_tmo_20060320_1kg.jpg
Just three days after an earthquake struck Java, on May 27, 2006, the Semeru Volcano showed signs of heightened activity. The Moderate Resolution Imaging Spectroradiometer (MODIS) flying aboard NASA’s Terra satellite took this picture on May 30, 2006. In this image, Semeru’s summit is outlined in red. The outline indicates that MODIS detected unusually high surface temperatures. To the west of the summit are gray-brown clouds that dissipate as they move westward. These clouds could result from volcanic ash emitted by the Semeru Volcano.

**How Much Mud?**

- Survey of height of mud on 16 points
- 3D Analysis was used to calculate the volume of the mud.
- Area of Mud: 1,108,444 m² or 110.84 ha
- Circumference: 6523 m
- Volume: 1.1 million m³
- Discharge rate:
  - 50,785 m³/day

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<tr>
<th>Date</th>
<th>Area (ha)</th>
<th>Volume (m³)</th>
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<tr>
<td>Aug 29, 2006</td>
<td>349.78</td>
<td>4,430.037</td>
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<td>Sep 20, 2006</td>
<td>349.78</td>
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<td>Oct 20, 2006</td>
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<td>Nov 20, 2006</td>
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<tr>
<td>Dec 24, 2006</td>
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<td>10,249.476</td>
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</table>
Main tectonic regimes favourable for mud volcanism

Compressional regime - Active continental margin. Accretional complex

Rapid subsidence-burial Passive continental margin or back arc setting with high sedimentation rate.

Indonesia: perfect location for MV manifestation where both regimes occur

Modified from Akhmanov (2006)

Overpressure Zones

Density and shear and compressional sonic suggest the presence of overpressured zones. These are probably highly plastic, undercompacted shale, controlled by rapid sedimentation, trapped water results in overpressured condition.
Positive correlation is indicated between mud samples and cuttings & swc from depth section 4000' to 6000' based on foram and nannofossil assemblages similarities. Deposited in Middle to outer shelf.
Banjarpanji-1 SWC: 5600 ft

Positive Correlation
Kerogen composition correlatable with SWC from 5600 ft

Thermal Maturity Profile BPJ-1
Correlation of Surface Mud and Cuttings/SWC

- Surface mud is interpreted to have been sourced from 5100 – 6300 ft depth interval
- Moderately mature source rocks to generate liquid hydrocarbons.
Origin of water

- **Salinity** 39% lower than seawater
- **Enriched** in B, Ca, Li, Na, Sr, Br
- **Depleted** in K, Mg and SO4
- **Enriched** in 18O and depleted in 2H
- LUSI fluids formed by **diagenetic modifications** and dilution of seawater
- Possible input of **meteoric water**
- Strong influence of fluids from dehydration of clays
- Possible input of fluids from **upper porous sandstone unit** (6360-6385 ft)
- No real evidence of fluids from **Kujung**
- Large amount of water from depth >5700 ft (i.e. T>100 °C)

After Mazzini 2007

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Principal scheme of smectite-illite transformation with water expulsion during the burial history (after V.N. Kholodov)

progressive burial

<table>
<thead>
<tr>
<th>Pressure increasing (within interval run through the zone)</th>
</tr>
</thead>
<tbody>
<tr>
<td>volume difference (volume to compact when water expelled)</td>
</tr>
</tbody>
</table>

After burial at diagenesis face and removed by transformation

upper seal burial at diagenesis face

water escape scenarios

upper or lower seals breached by scenario
Water escape curves from smectitic rich sediments during illitization.
HOT MUD FLOW MECHANISM - HYPOTHESIS

- Two types of pressure control the fluids flow in the rock formation – geothermal-hot water and HC-gas (+shale pore P?)

- Hot water can move vertically along 3,000 m channel due to:

  \[
  (↑↑↑) \text{P}_{\text{sat}} \text{ (hot water)} + \text{P}_{\text{HC-gas}} + \text{P}_{\text{shale}} \gg \text{P}_{\text{Hydrostatic}} \quad (↓)
  \]

  ~ 40 bars \quad + \quad (?) \quad + \quad 2-3\text{ppg equiv.} \quad 300 \text{bars}

  depend on T reservoir

- Pressurized hot water cut and erode the shale formation at the upper level
Seismicity

- 27-05 earthquake
- Earthquakes recorded within 300km radius from LUSI site
- Filtered earthquakes M>3.5
- 27-05 to 31-12: 41 earthquakes

Observed flow patterns

- Pulsations (approx every 30 min.) → higher amount of mud and gas released
- Geyser behaviour (?) (Empty chambers periodically before new burst)
- Correlation seismicity-mud flow. Periodical reactivation of the system?

Source USGS
Summary - Part 1

- Stratigraphy and tectonic activities in Sidoarjo area is potentially high in forming mud volcanoes.
- Unlikely to stop eruption permanently
- Mud extrusion could release the overpressure but difficult to predict the timing when it would stop
- Inconclusive & contradictory evidence to conclude drilling was the trigger of the mud extrusion
- ERUPTED MUD
  - LUSI fluids correspond to 5300-6000 ft
  - Foram + nannofossil section 4000-6000 ft
  - Thermal maturity suggest input from 5100 - 6300 ft
  - Kerogen composition correlates with SWC from 5600ft
  - Diagenetic transformation of clays, 4 groups defined between 3600-6000ft.

Impact of Mud Volcano Disaster
Mud Volcanoes can not be stopped - Implications

- **Initial Transitional Phase towards Isostatic Adjustment**
- Geohazard risks vs. Mud overspill risk
- Subsiding area become:
  - Hill, if extrusion > subsidence
  - Flat, if extrusion = subsidence
- Local analogies: Bleduk Kuwu, Gn Anyar, Kalang Anyar, Paleo Porong Mud Volcano (Seismic), etc
A: Subsiding area become a Hill

Azerbaijan Giant Mud Volcanos

- **Size** from m to 4km (>5km offshore)
- **Height** from m up to 500 m
- **Roots** of feeder channel up to 15 km (i.e. Below Maycopian?)
- Usually situated along **anticlines**
- Associated with **HC reservoirs**

B: Subsiding area become Almost Flat

- **Low relief** (6m)
- **Bleduk Kuwu Scenario** (Active Mud Volcano, Purwodadi)
**Local Analogue**

Possible structure collapse near wellbore may create a lake with a radius of 1-2 km

Residual Gravity Data shows Gravity Low

Example: Porong Collapse Structure (7 Km dari BJP -1)

**Geohazard Risks**

- Neo Tectonic movements along Watukosek fault lineament,
  - differential movements which trigger shear stress
  - Presence of fractures due to reactivation of pre-existing faults
- Vertical and Horizontal movements
  - Accelerated Subsidence due to unloading of overpressured shale
  - Loading, compaction of soil and land settlement due to weight of mud
- Flooding due to:
  - Bundwall Sliding and collapse
    - Unstable and critical as they were constructed in emergency situation as temporary mud containment made of soil and rock matrix
    - Bundwall exerting high hydrostatic pressure causing it to crack and collapse
Need area for overspill mud extrusion

- Larger area of overspill is needed if mud cannot be managed, disposed or controlled.
RAILROAD DEXTRAL MOVEMENT at KM 39.2

27 September 2006

GEOHAZARD RISK AREAS

Railroad movement

Mass Flow Direction/recharge

Microgravity

mGal

0 1,500 3,000 meters
Bundwall Section 43 sliding / subsidence

width 5-10 cm

Bundwall fracture on Section 43

width 5-10 cm
The risk of catastrophic collapse is low but the ongoing subsidence and lateral movement will continue. Subsidence is up to 3cm / day in parts but mostly around 1cm / day or less.

Key risks: Gas & water pipeline (shear & subsidence); Rail road (shear/ faulting & subsidence); Toll road (subsidence); Relief wells (subsidence, shear → casing integrity)

Current work: Simulation using current data and further set of GPS measurements, micro-seismic and micro-gravity to predict the shape and condition of the affected area in years to come, i.e. 5, 10, 20 or 30 years from now

Monitoring and risk mitigation

Terima Kasih
Backup slides

Porong Delta Depositional Rate
(1938-Present)

- Prograding
- 3.5 km in 70 years (50m/yr)
- Porong river debit 75-1500m³/sec
- Mud extrusion debit: 0.6m³/sec
SUMMARIES OF MUD VOLCANO ANALYSIS - BANJARPAJI-1

- Analysis of Hazardous Waste Characteristics (the characteristics are: explosive, flammable, reactive, toxic, infectious, and corrosive.) Analysis indicates that mud volcano is reactive if it is exposed in extreme condition of PH: < 2 or pH > 12, while mud pH is 6-7. Other characteristics are non hazards. So the mud hazard level is low.

- TCLP (Toxicity Characteristic Leaching Procedure) tests indicate that all parameters are below threshold limit values (TLV). So the mud is non hazardous waste.

- Toxicity test using LD-50 method indicates the mud is non hazardous waste.

- Toxicity test using LC-50 method indicates the mud almost non toxic.

Note:
Mechanical Analysis of mud volcano indicates that the mud can be used as construction material such paving blocks, bricks, asphalt hotmix, and concrete blocks.

SUMMARIES OF FORMATION WATER ANALYSIS - LUSI

- Analysis with reference of Kep Men LH No. 42 Year 1996 about Threshold Limit Value (TLV) for Waste Water Resulted From Oil & Gas and Geothermal Activities. For Onshore discharge (7 parameters), 5 parameters are below TLV, while 2 parameters (COD and Phenol) are above TLV. For Offshore discharge, all parameters are below TLV.

- Analysis with reference of SK Gubernur Jatim No. 45 Year 2002 about TLV For Industrial Waste Water and Other Activities in East Java Province, Attachment II, Group III. There are 32 parameters measured, 27 parameter are below TLV, while 5 parameters (TSS, TDS, BOD, COD, and Phenol) are above TLV.

Note:
KLH: After treatment, the formation water can be discharged to nearby river or to sea.
SUMMARIES OF BASELINE ANALYSIS OF WATER IN KALI PORONG
(±3 KM FROM BANJARPAJI-1)

- Baseline Analysis of water in Kali Porong refer to PP RI No. 82 Year 2001 about Management of Water Quality and Control of Water Pollution, Group III. There are 33 parameters, 25 parameters are below TLV, while 8 parameters (Cu, Zn, Pb, Nitrite, BOD, COD, Detergent, and Phenol) are above TLV.

- Conclusion: Baseline of water in Kali Porong indicates above TLV for the parameters: Cu, Zn, Pb, Nitrite, BOD, COD, Detergent, and Phenol.

Note: There are industries along the Kali Porong