# The 'LuSi' Mud Eruption of East Java


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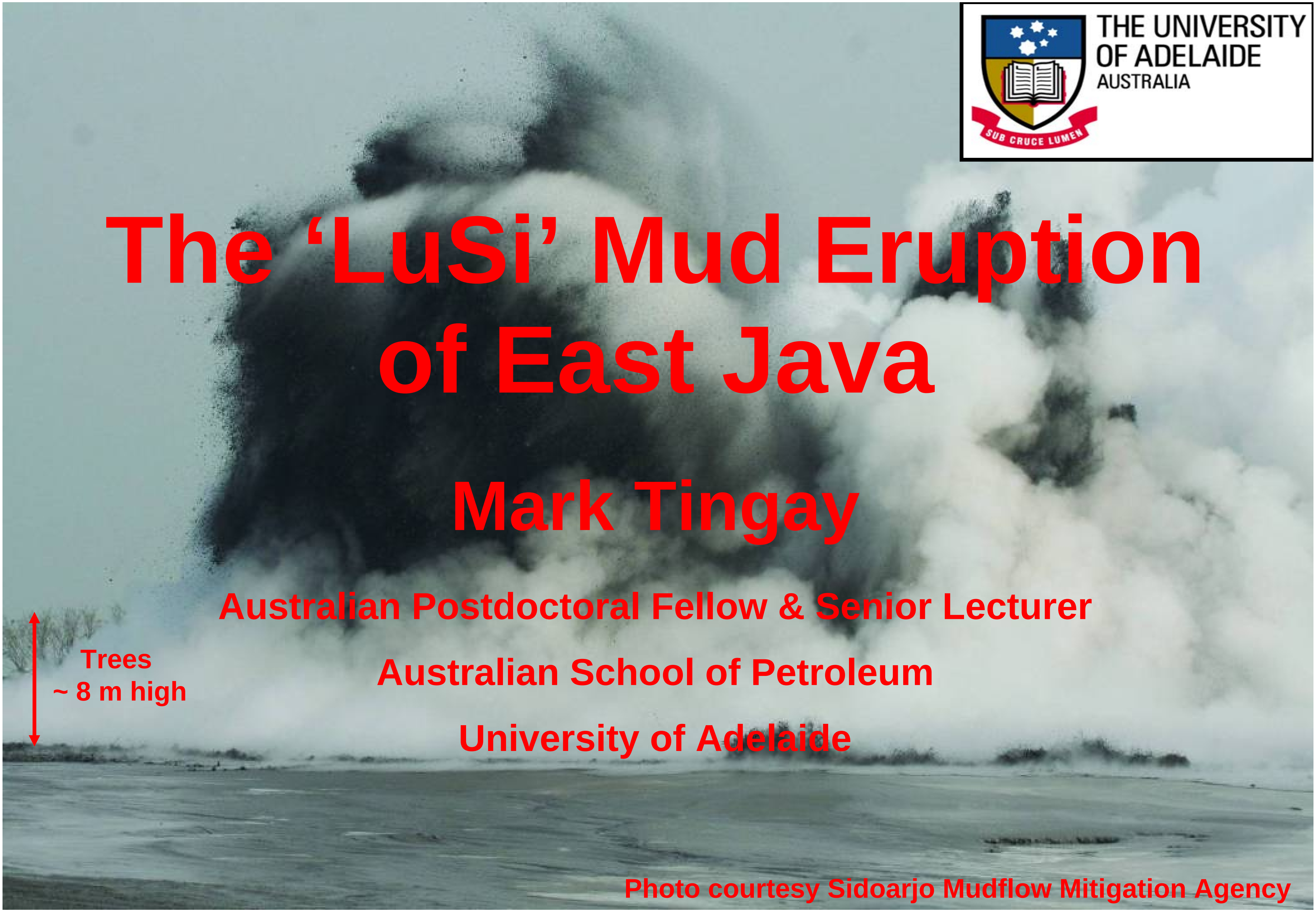



Photo courtesy Sidoarjo Mudflow Mitigation Agency

# Birth of Lusi – Mud Eruption 29th May 2006

Flow rates started at ~5000 $m^3$/day.
Jumped to ~150000 $m^3$/day in August.
Averaged ~64000 $m^3$/day since.

Source: Sidoarjo Mudflow Mitigation Agency, Lapindo Brantas, Davies et al. 2007; Mazzini et al 2007.

Lusi: 2nd August 2006

Photos courtesy of Sidoarjo Mudflow Mitigation Agency

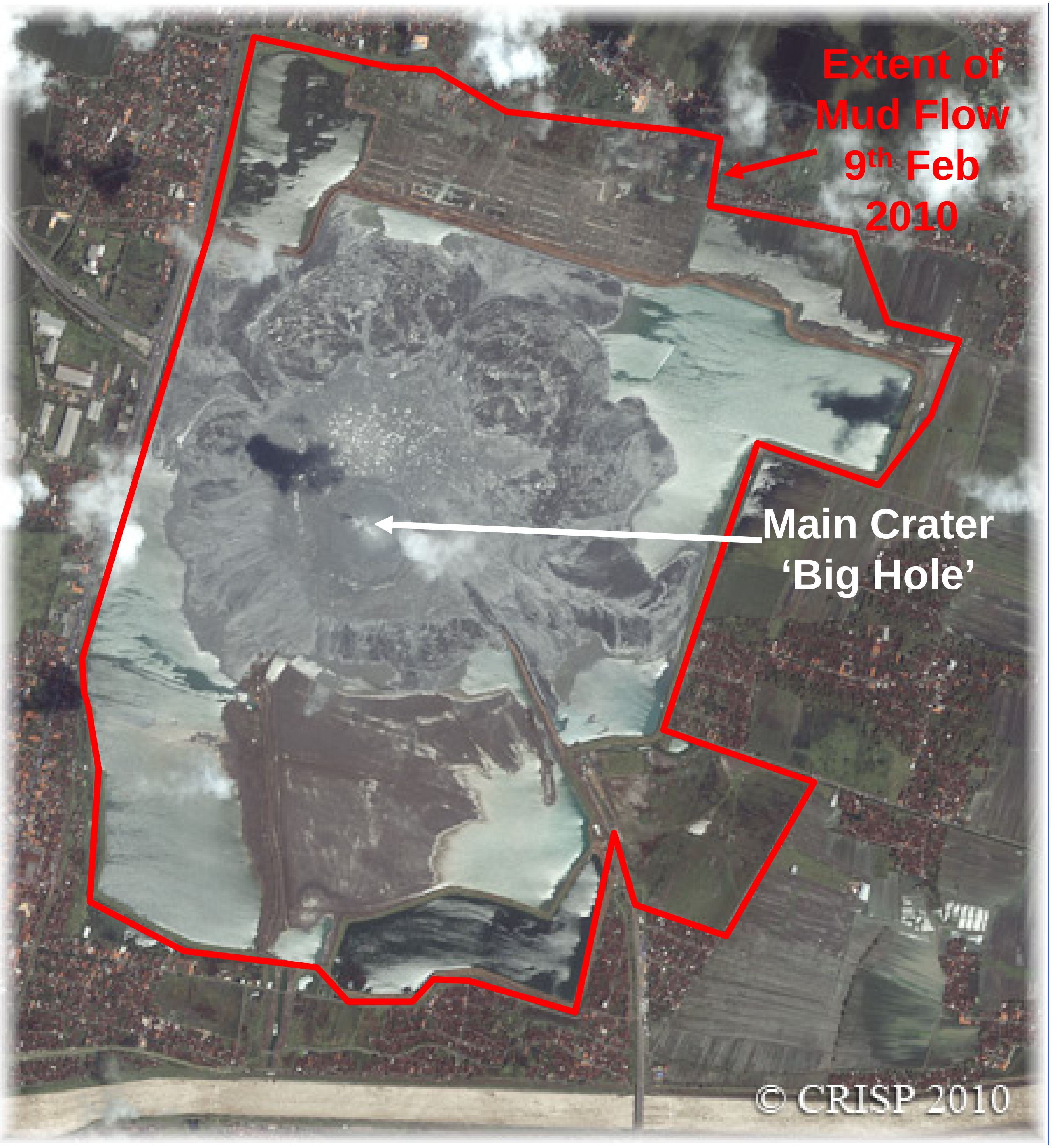
**Mud flow displaced ~40000 people, 12 villages, >10000 homes, ~100 schools, factories & mosques (>US$420 million damage!).**

**Source: Sidoarjo Mudflow Mitigation Agency, Mazzini et al., 2007, Time Asia 2008**

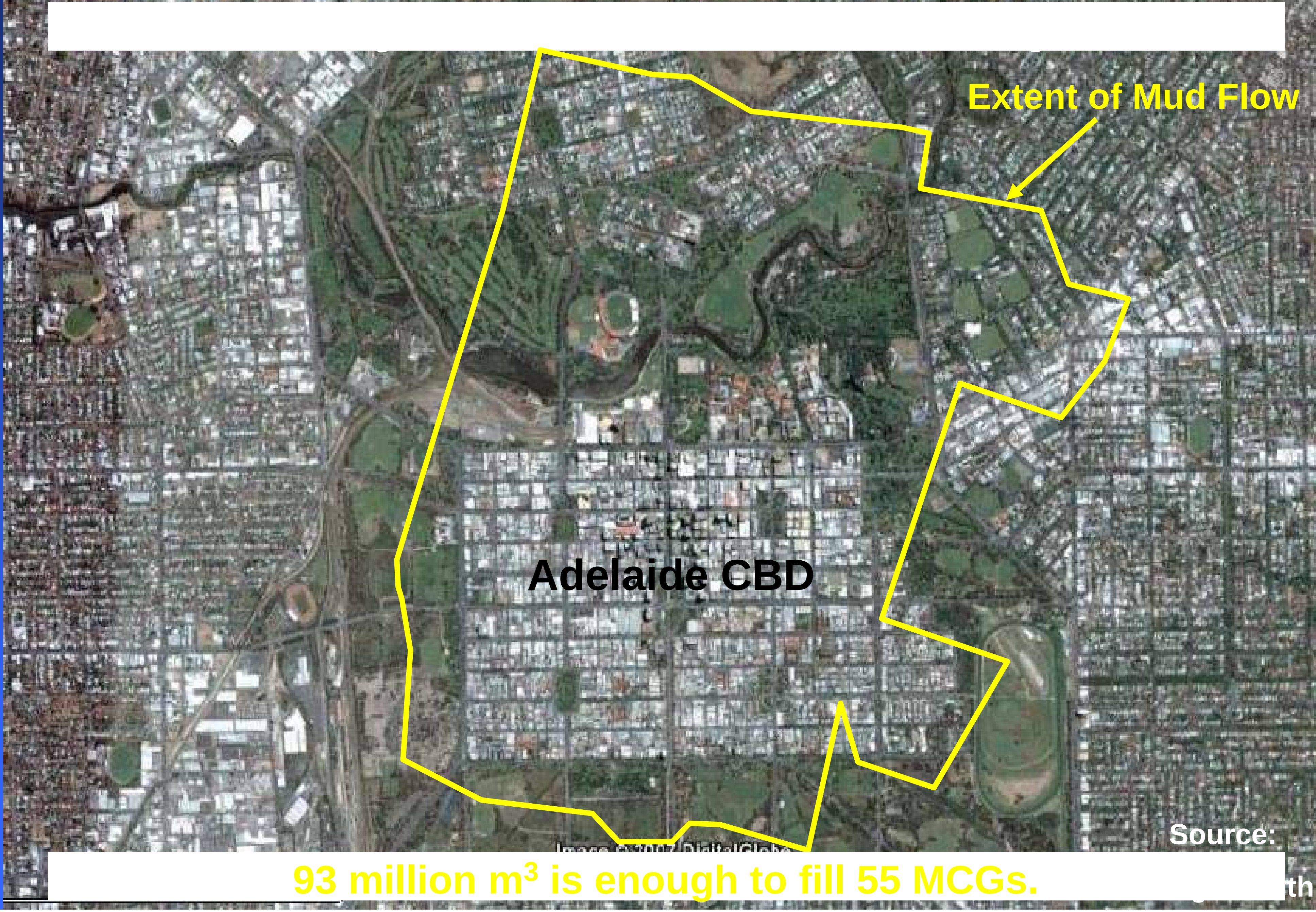
**Photos: M. Tingay and Channel 9 Australia, May 2007**

Mud has covered area of ~10 $km^2$ contained within series of dams.

Total mud erupted is >0.09 $km^3$ (93 million $m^3$) at an average rate of ~64000 $m^3$ per day



# Scale of Lusi Mud Flow




93 million $m^3$ is enough to fill 55 MCGs.

## Video Footage of the Lusi Eruption Area

August-Sept 2006, © Greenpeace, shown with permission

# Video Footage of the Lusi Eruption Area

Late May 2007, Courtesy Channel 9 Australia.

# Controversy: What Triggered the Lusi Eruption?

**Two distinct and competing theories:**

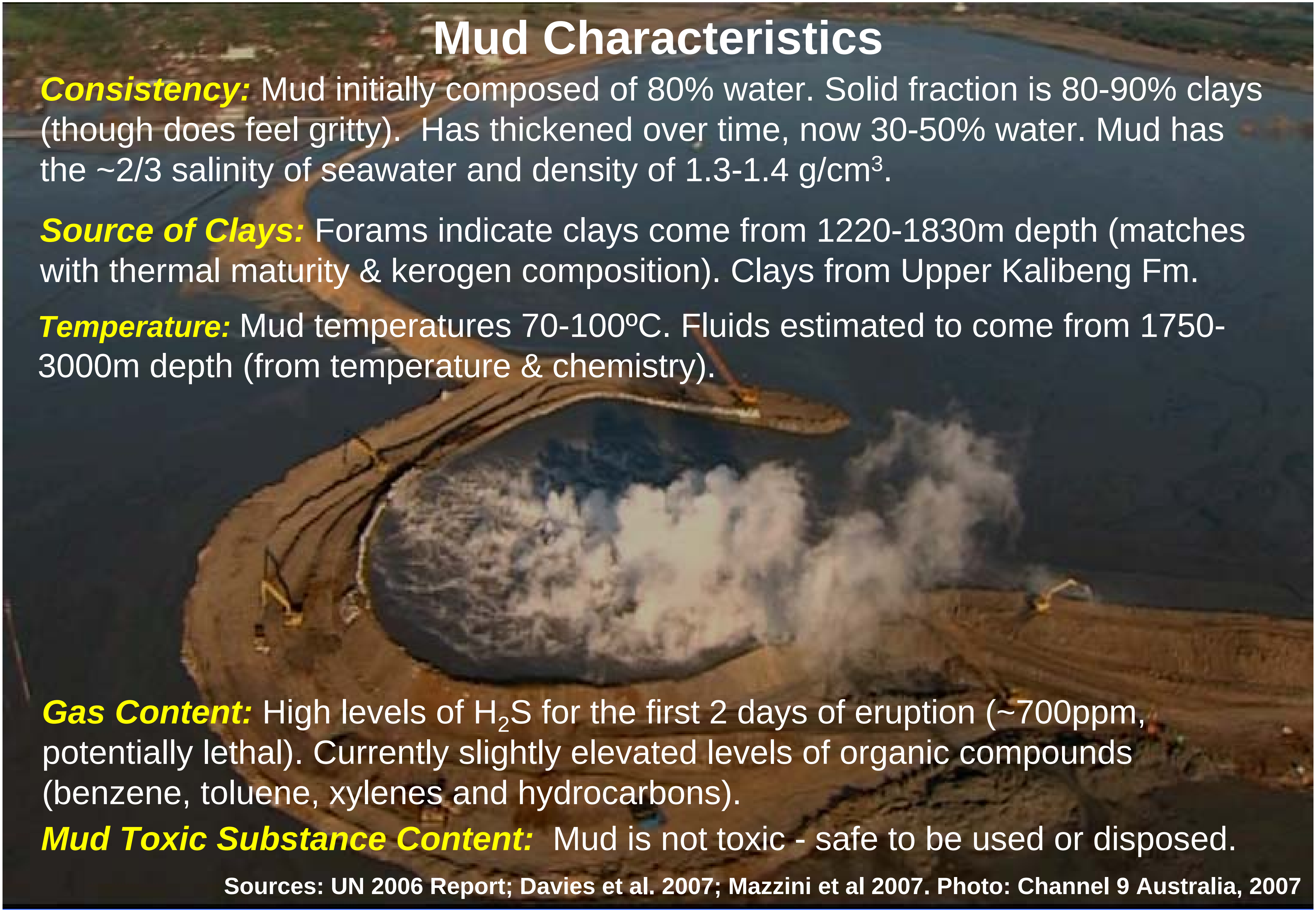
1. **Eruption was triggered by 27th May 2006 Yogyakarta earthquake.**
2. **Eruption triggered by internal blowout in nearby Banjar Panji-1 well.**

Photo: © Greenpeace, reproduced with permission

# The Sidoarjo Mud Flow, East Java

- BACKGROUND
- MUD VOLCANOES AND MOBILE SHALE FEATURES
- ERUPTION TRIGGERING #1: EARTHQUAKE HYPOTHESIS
- ERUPTION TRIGGERING #2: DRILLING HYPOTHESIS
- LUSI – FUTURE SCENARIOS

Photo: M. Tingay May 2007



# Mud Characteristics

***Consistency:*** Mud initially composed of 80% water. Solid fraction is 80-90% clays (though does feel gritty). Has thickened over time, now 30-50% water. Mud has the ~2/3 salinity of seawater and density of 1.3-1.4 g/cm$^3$.

***Source of Clays:*** Forams indicate clays come from 1220-1830m depth (matches with thermal maturity & kerogen composition). Clays from Upper Kalibeng Fm.

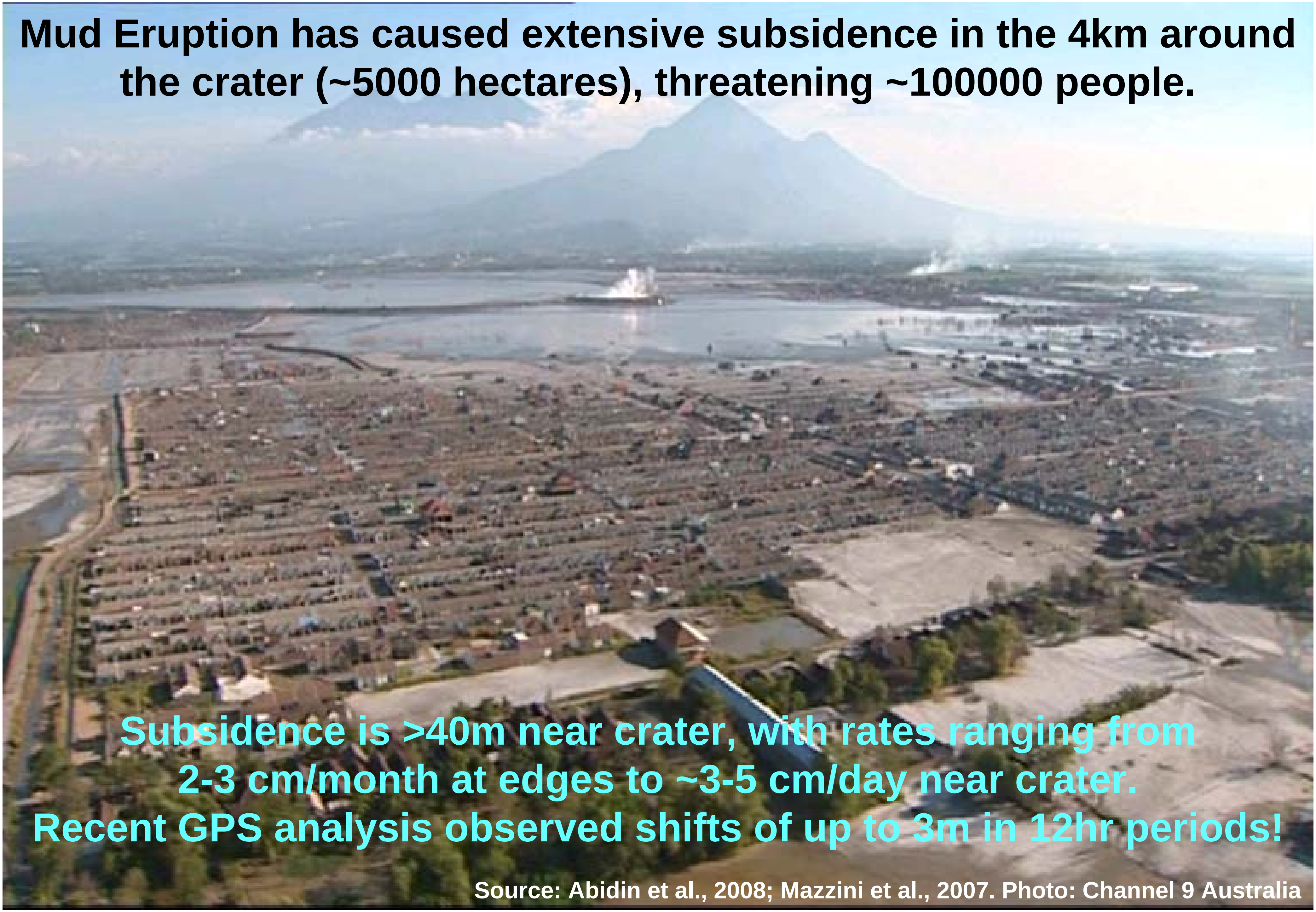
***Temperature:*** Mud temperatures 70-100ºC. Fluids estimated to come from 1750-3000m depth (from temperature & chemistry).

***Gas Content:*** High levels of $H_2S$ for the first 2 days of eruption (~700ppm, potentially lethal). Currently slightly elevated levels of organic compounds (benzene, toluene, xylenes and hydrocarbons).

***Mud Toxic Substance Content:*** Mud is not toxic - safe to be used or disposed.

**Sources: UN 2006 Report; Davies et al. 2007; Mazzini et al 2007. Photo: Channel 9 Australia, 2007**

## Mud Eruption has caused extensive subsidence in the 4km around the crater (~5000 hectares), threatening ~100000 people.



**Subsidence is >40m near crater, with rates ranging from 2-3 cm/month at edges to ~3-5 cm/day near crater.**
**Recent GPS analysis observed shifts of up to 3m in 12hr periods!**

Source: Abidin et al., 2008; Mazzini et al., 2007. Photo: Channel 9 Australia

# Gas Pipeline Rupture – 22nd November 2006

- Subsidence-induced landslide ruptured the East Java Gas Pipeline.
- The 50m fireball resulted in 14 dead and 13 injured.
- A further three people have been killed in heavy equipment accidents.

Photo: Lapindo Brantas
Photo: M. Tingay May 2007

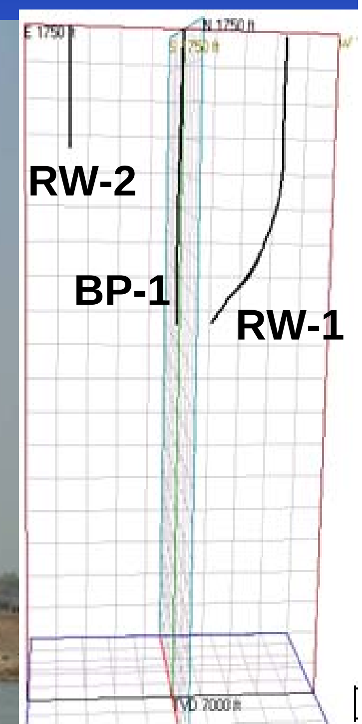
# Efforts to Kill and Contain Mud Flow

1. Snubbing/sidetracking of Banjar Panji-1 to ‘fish’ bit and kill/cement/plug open hole - attempt unsuccessful. Casing still present, no fluid moving up outside of upper 400m of casing.

2. Relief wells drilled to try and intersect and kill/cement/plug BJP-1 open hole. Relief-1 got close to BJP-1 but was plugged & abandoned due to numerous kicks, losses, wellbore stability issues and inability to run casing. Relief-2 abandoned.

**Source: Lapindo Brantas**






**Photos: Sidoarjo Mudflow Mitigation Agency, Lapindo Brantas**

# Efforts to Kill and Contain Mud Flow

3. Approximately 400 concrete ‘ball-and-chains’ dumped into crater. Some sets went down 800m! No reduction in flow, plan abandoned.

4. Mud diverted and pumped into Porong River. Original screw pumps quickly failed due to temperature and viscosity of mud. Mud now being mixed with river water before being pumped and sluiced into river.

Sluicing into Porong River

Photo: M. Tingay May 2007

**Dropping ‘Ball and Chains’**

**Photo: Sidoarjo Mudflow Mitigation Agency**

Spillway for sluicing mud into river

**Photo: M. Tingay May 2007**

Screw Pump

**Photo: Sidoarjo Mudflow Mitigation Agency**

# Efforts to Kill and Contain Mud Flow

5. Plan to build 50 m high coffer dams: Thought that raised mud can exert enough negative pressure to stop mud flow (difficult & doubtful!).

Plans to build integrated apartment and sports complex into mud dam!


**Source: Ir. Djaja Laksana and Sidoarjo Mudflow Mitigation Agency. Image courtesy: Ir. Djaja Laksana**

# Efforts to Kill and Contain Mud Flow

6. Prayer and sacrifice of ~420 animals (often alive).

Also not successful – animal sacrifice banned since late 2006!

Photo © Jawa Pos Newspaper, reproduced with permission


Photo M. Tingay May 2007

Source: Sidoarjo Mudflow Mitigation Agency, Jawa Pos

# The Sidoarjo Mud Flow, East Java

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- LUSI – FUTURE SCENARIOS

Photo: M. Tingay May 2007

# Mud Volcano Basics

Mud volcanoes are where subsurface mud is extruded at the surface.

Mud volcanoes can be lakes/pools ('salses') or cones ('gryphons') and can be small features (cm's) or up to 250 m high and several km's wide.




# Mud Volcano Basics

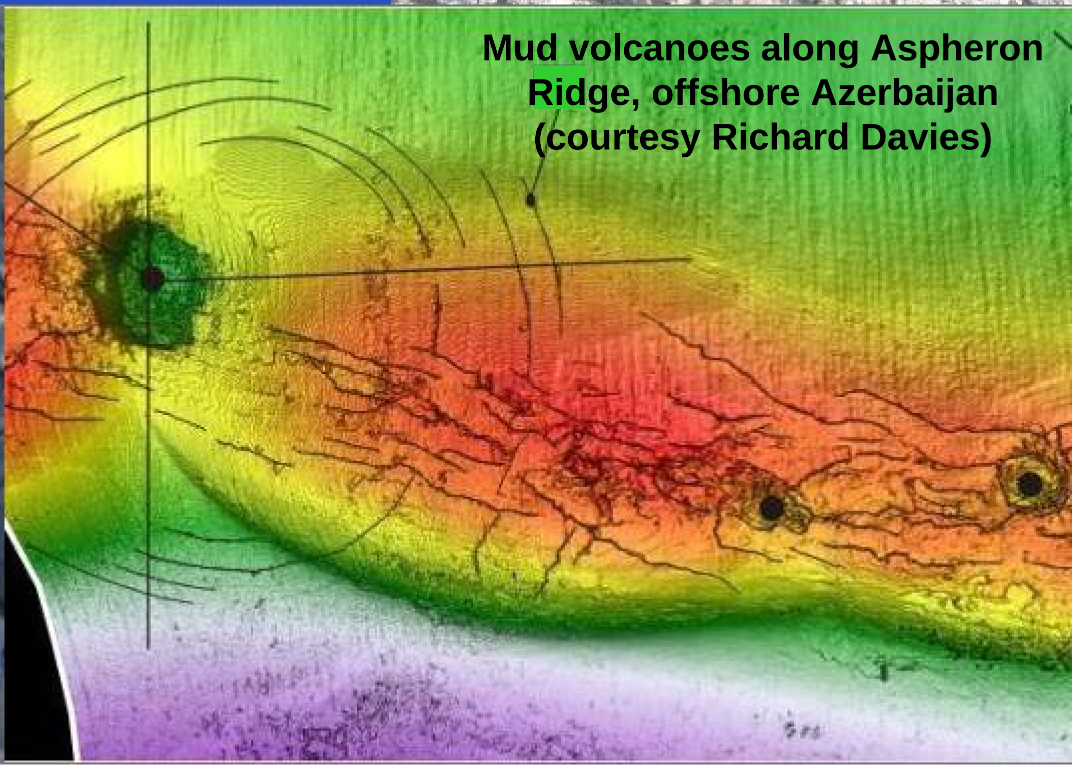
- Usually occur along tops of anticlines or faults.

- Often associated with hydrocarbons.

- Mostly ‘cold’ and caused purely by depositional conditions, but can also be linked to magmatic volcanism (e.g. New Zealand, Yellowstone).

Oily mud volcano in Azerbaijan
Photo M. Tingay 2006

Cold mud in Azerbaijan,
Photo M. Tingay 2005



Mud volcanoes along Aspheron Ridge, offshore Azerbaijan (courtesy Richard Davies)

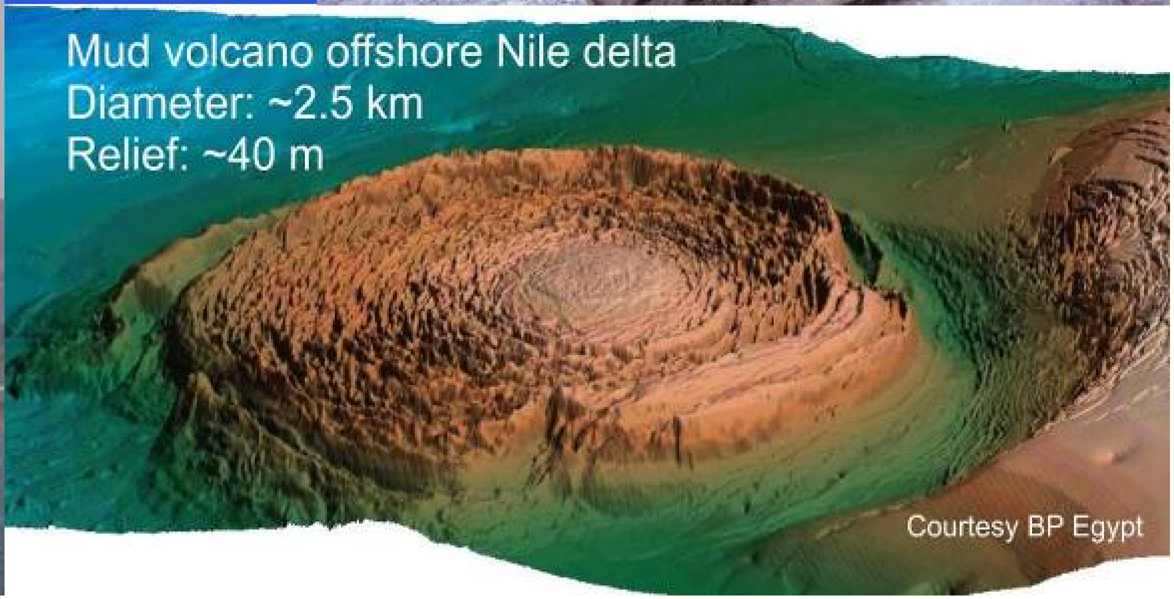
# Worldwide Occurrence of Mud Volcanoes

- Predominately submarine, but also occur in many onshore areas (e.g. Azerbaijan, Iran, Trinidad).
- Common in basins that were rapidly deposited or are in tectonically active regions.
- Flow rates typically low (1's-100's $m^3$/day), can erupt violently for short periods ($10^5$-$10^6$ $m^3$/day).

**Mud Volcano, near Miri, Sarawak, Malaysia**

**Photo: Chris Morley**

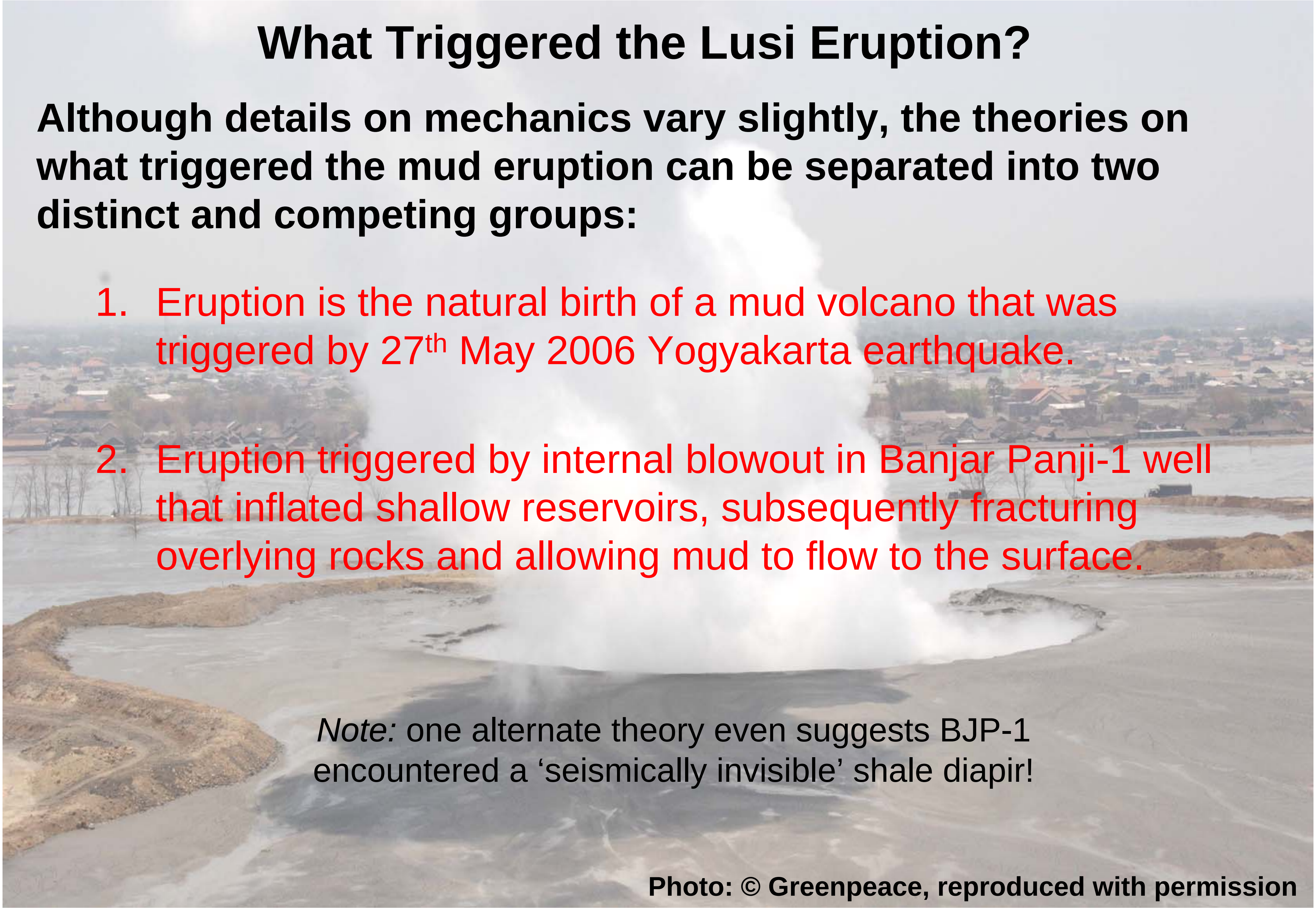
**October 2001 major eruption of Lokbatan, Azerbaijan (Aliyev et al. 2002)**



# Mud Volcano Systems: Some Major Questions

- What is the nature of shale diapirs: similar to salt diapirs or more akin to magmatic intrusions?
- Mechanics of mobilization in extremely overpressured conditions: piercement/diapiric rise or stoping/fracturing?
- Geometry of volcano feeder system: conical vent or dykes?
- Single or multiple sources of mud: mobilized overpressured shale or high pressure fluids entraining clays?
- What triggers mud volcanoes and shale mobilization: e.g. earthquakes, faulting, variable loading, lateral compression?

***LUSI GIVES US A CHANCE TO STUDY A MUD ERUPTION FROM ITS BIRTH.***



# What Triggered the Lusi Eruption?

**Although details on mechanics vary slightly, the theories on what triggered the mud eruption can be separated into two distinct and competing groups:**

1. Eruption is the natural birth of a mud volcano that was triggered by 27th May 2006 Yogyakarta earthquake.

2. Eruption triggered by internal blowout in Banjar Panji-1 well that inflated shallow reservoirs, subsequently fracturing overlying rocks and allowing mud to flow to the surface.

*Note:* one alternate theory even suggests BJP-1 encountered a 'seismically invisible' shale diapir!

**Photo: © Greenpeace, reproduced with permission**

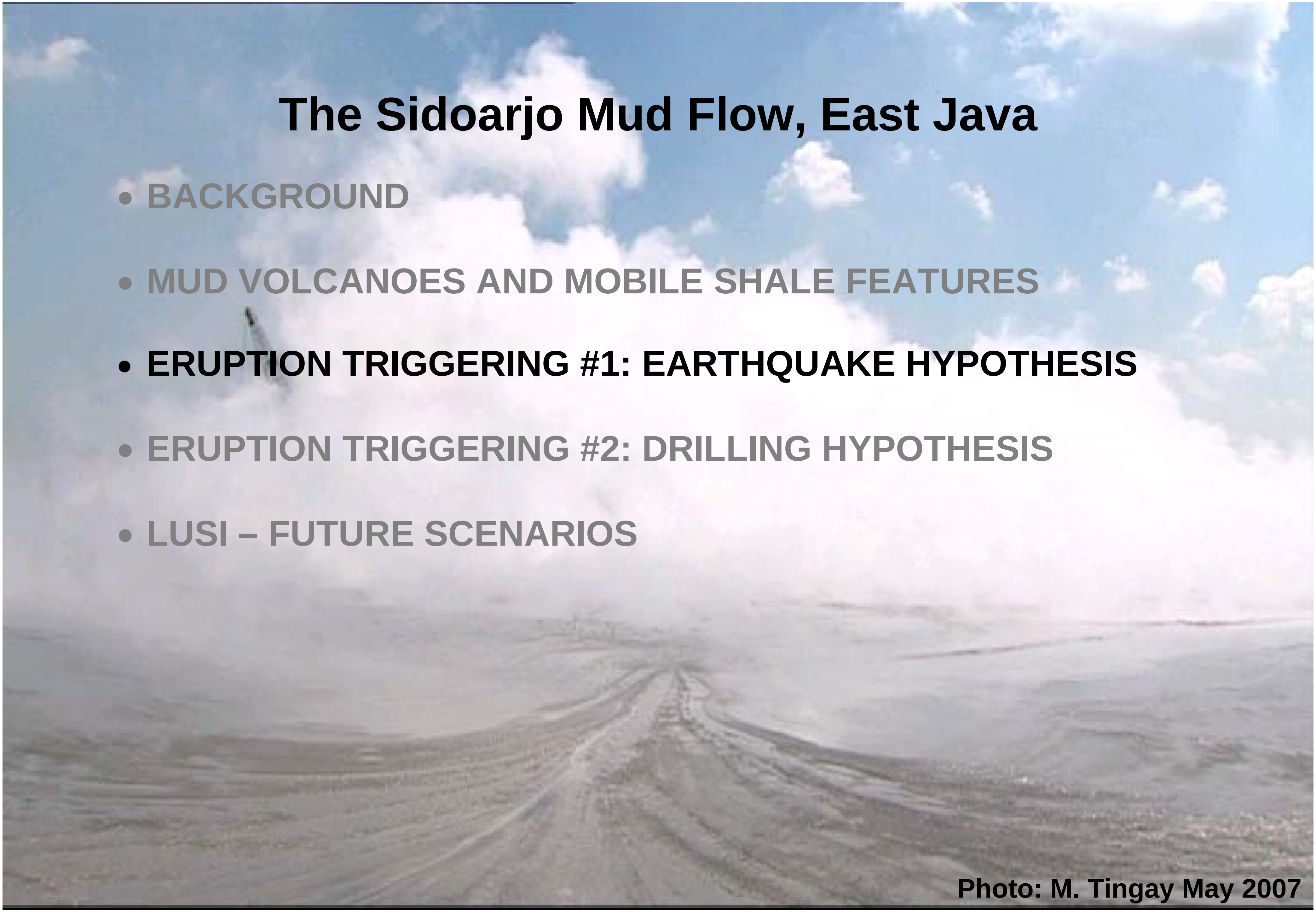


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Photo: M. Tingay May 2007

# Earthquake Trigger For Lusi?

• Yogyakarta (250km from Lusi) was shook by a Magnitude 6.3-6.4 earthquake two days prior to the eruption (~I-II intensity at Lusi).

• Earthquake occurred at 5.40am local time on the 27th of May 2006 (~2 days prior to Lusi initiation) and killed an estimated 6000 people.

• ***Theory:*** quake reactivated existing NE-SW oriented fault. Fault became permeable between 1200-3000 m depth, enabling overpressured fluids to entrain mud and escape to surface (20 bbl losses in BJP-1 seven minutes after quake).

• Harris and Ripepe (JGR, 2007) observed that the Yogyakarta quake caused a 2-3 fold increase in heat flow from two igneous volcanoes, Merapi (50km from quake) and Semeru (300km from quake) in the 3-9 days after quake.

# Evidence for Earthquake Eruption Trigger

- Many natural mud volcanos (e.g. Kalang Anyar) are within 50 km of Lusi.
- Evidence of faulting following the eruption, suggesting fault triggered eruption (OR eruption triggered faulting!).
- Closer and higher magnitude earthquakes caused mud volcano eruptions offshore of Iran in 1945 (Makran earthquake) and 1999 (Malan Island; Kopf, 2002) and Azerbaijan (Mellors et al., 2007).
- Large earthquakes (>M7.5) have triggered fluid eruptions and liquifaction thousands of kilometres away (Husen et al., 2004).

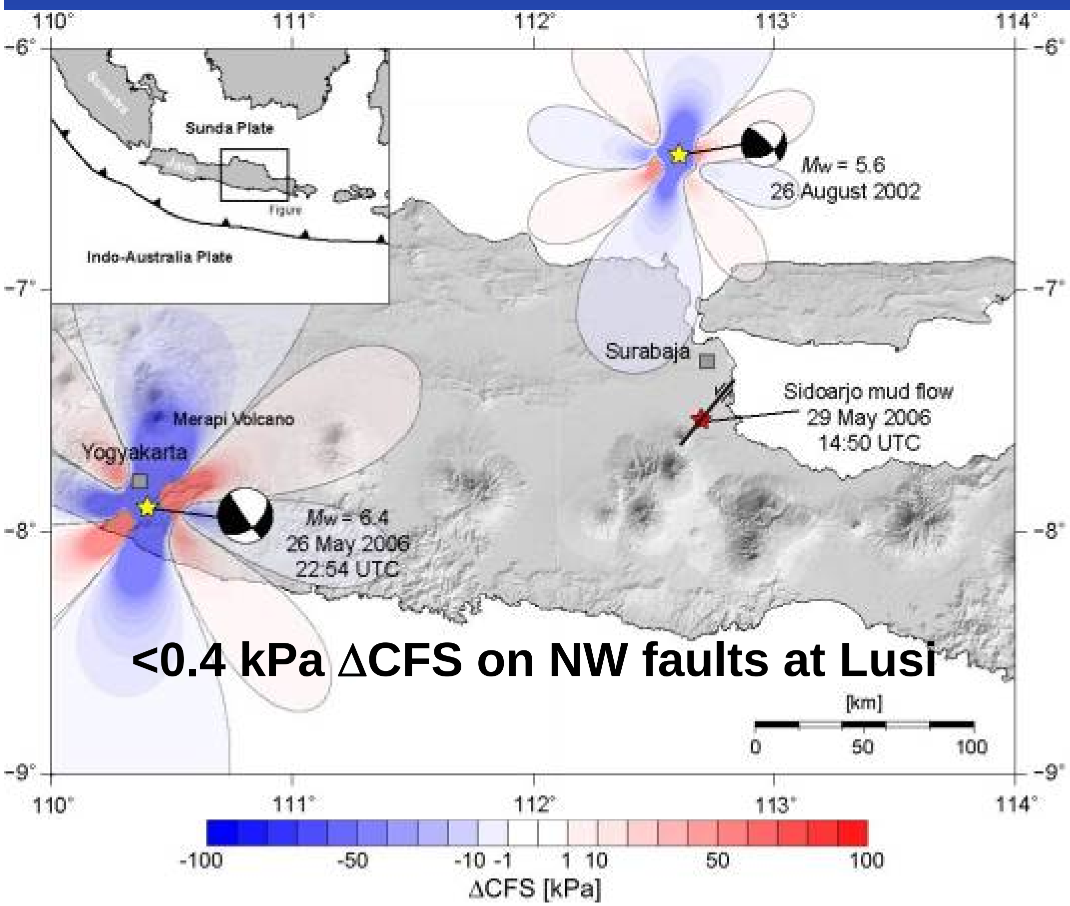
Kalang Anyar mud volcano

Photos: Lapindo Brantas
Sept 2006

# 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); Too small / far away (<0.4 kPa)
- post-seismic relaxation of static stress changes;
- poroelastic rebound effects, and; Too far away & too slow
- dynamic stress changes due to seismic shaking. Too small / far away (max 33 kPa)



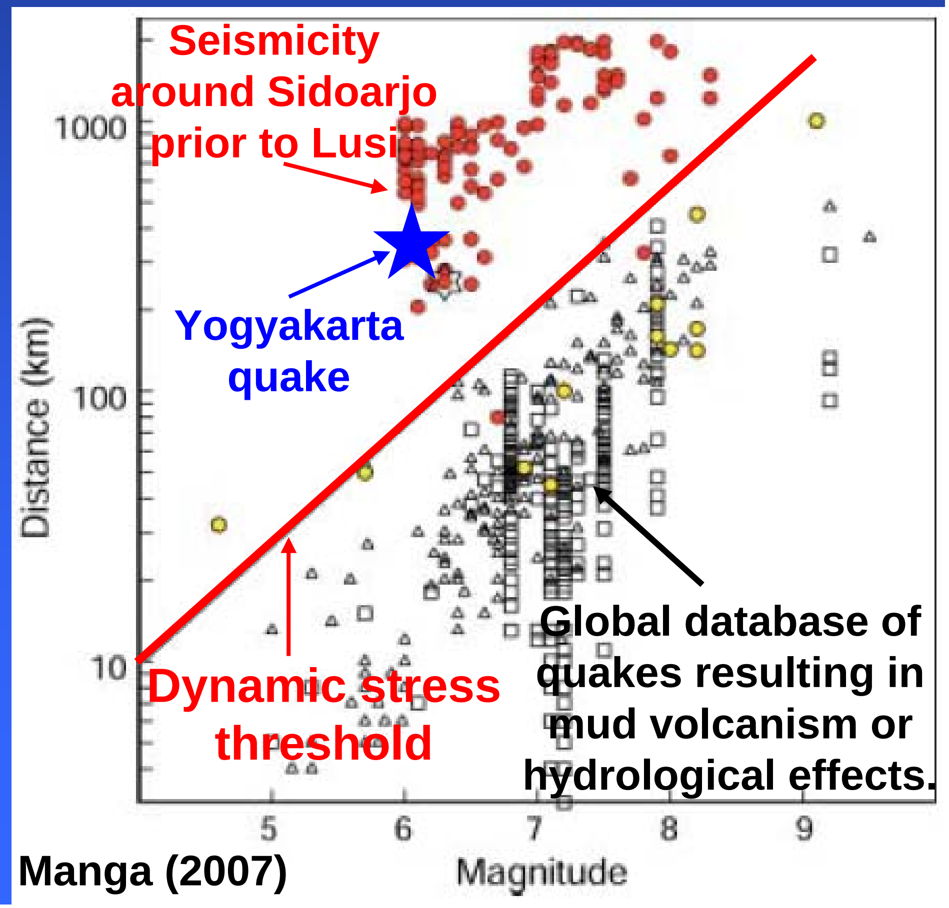



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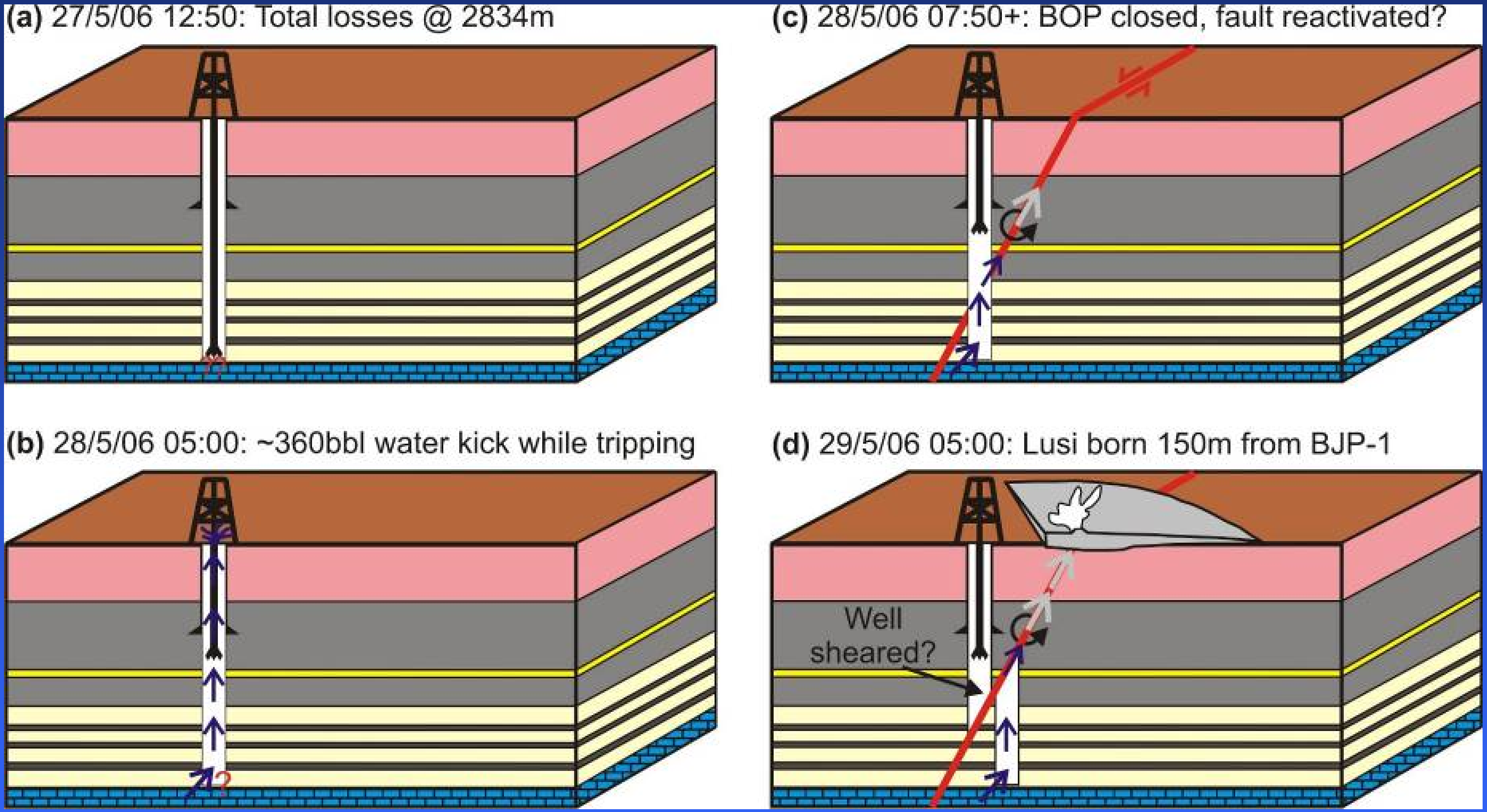
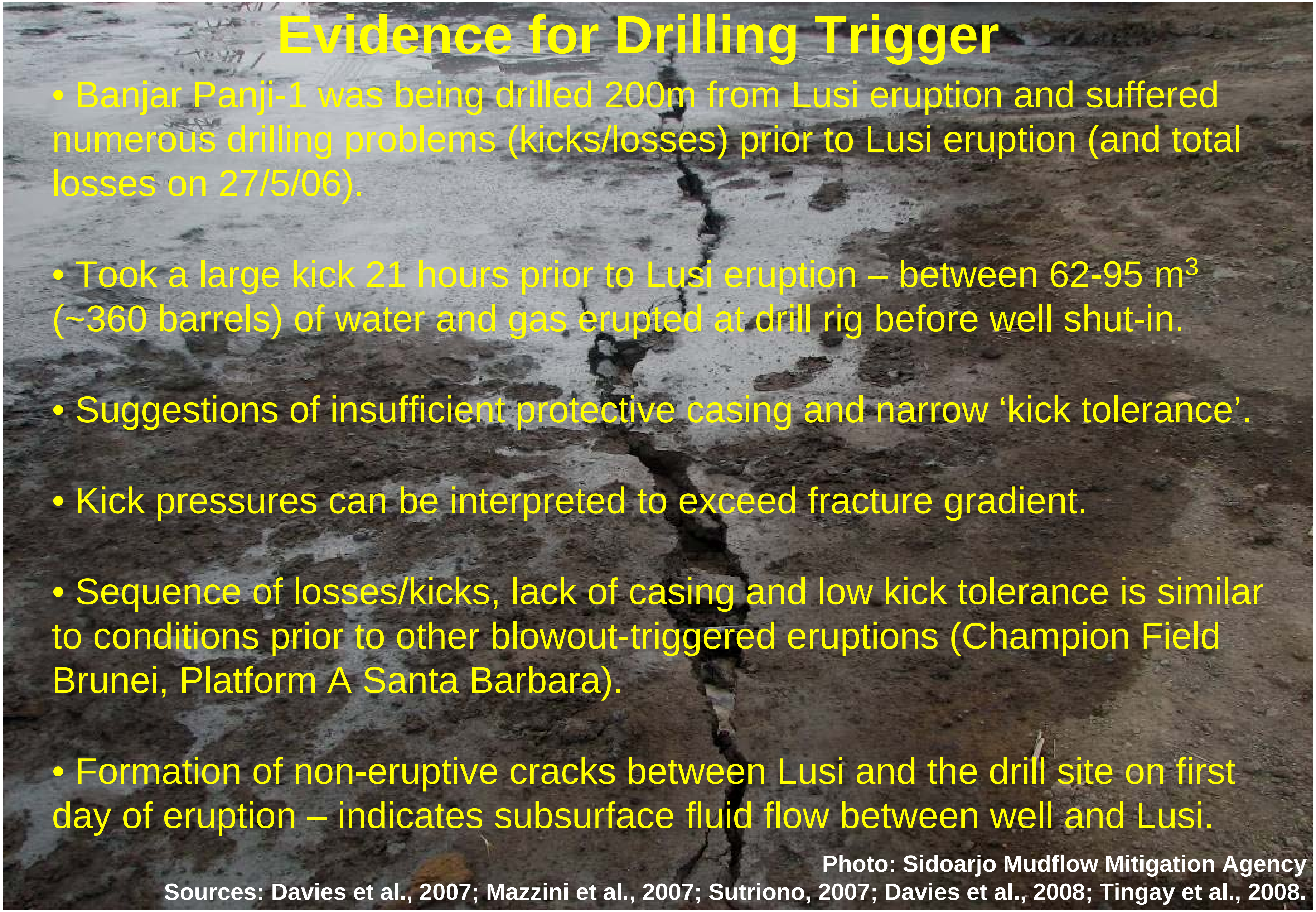
**Photo: M. Tingay May 2007**

# Schematic Model for Drilling-Induced Triggering of Lusi




Drilling-induced trigger theory suggests that mud eruption results from a surface rupture following an **'internal blowout'.**

**Modified from Davies et al., 2007, based upon Champion blowouts in Brunei (Tingay et al., 2005) and repoprts of other underground blowouts.**



# 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 (and total losses on 27/5/06).

• Took a large kick 21 hours prior to Lusi eruption – between 62-95 $m^3$ (~360 barrels) of water and gas erupted at drill rig before well shut-in.

• Suggestions of insufficient protective casing and narrow ‘kick tolerance’.

• Kick pressures can be interpreted to exceed fracture gradient.

• 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.**

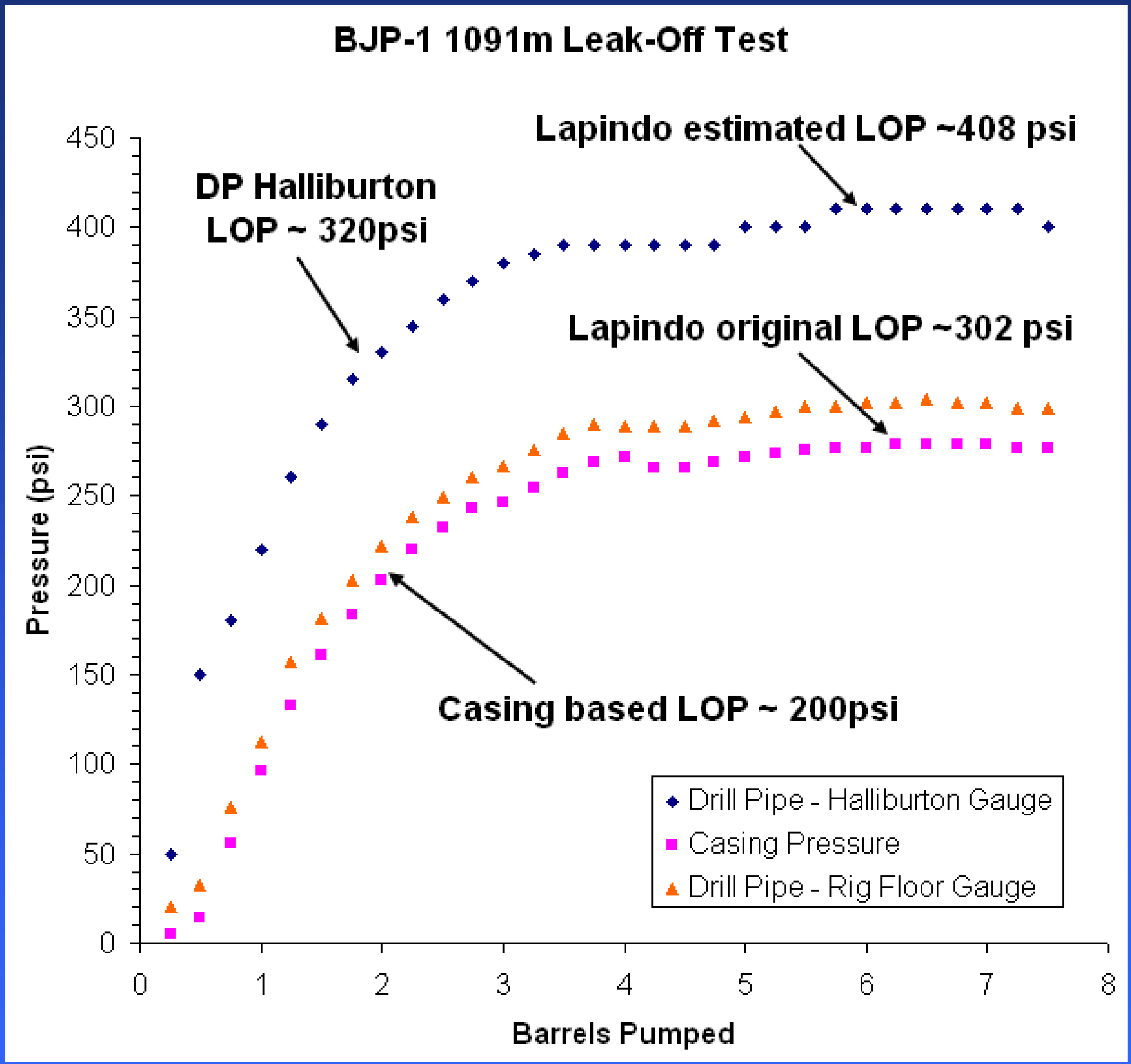
# Time Line of Key Events

- 06:02 May 27$^{th}$ – ~20 bbls mud losses (7 mins after quake), continued drilling.
- 12:50 May 27$^{th}$ – total loss of circulation (>130 bbls lost), bit at 9297’ (2834m).
- 13:00-22:00 May 27$^{th}$ – pumped 60 bbls LCM, well static, begin POOH.
- 07:00-11:00 May 28$^{th}$ – *Well kicked* (bit at 4182’), influx ~360bbls water (30% hole volume) and 500ppm $H_2S$, BOP shut-in (~08:00). Well killed (volumetric method).
- 11:00-14:20 May 28$^{th}$ – *BOP opened*, bit stuck but able to circulate, fishing.
- 14:20-21:30 May 28$^{th}$ – Fish stuck, ability to circulate well ceases .
- 21:00-23:00 May 28$^{th}$ – 40 bbls soaking fluid pumped, *pumping with no return*.
- 02:00-04:00 May 29$^{th}$ – Preparing to cut string, more $H_2S$ detected, rig evacuated.
- 05:00 May 29$^{th}$ – Mud eruption reported by villagers ~200m from well.
- 10:00-23:00 May 29$^{th}$ – Pumped mud (385 bbls total) with LCM at up to 16 ppg.
- May 30$^{th}$ - June 1st – injection tests, mud flow continues, install plugs, cut pipe.

**Source: Sawolo et al., 2009**

# Data Uncertainty – Muddy Waters!

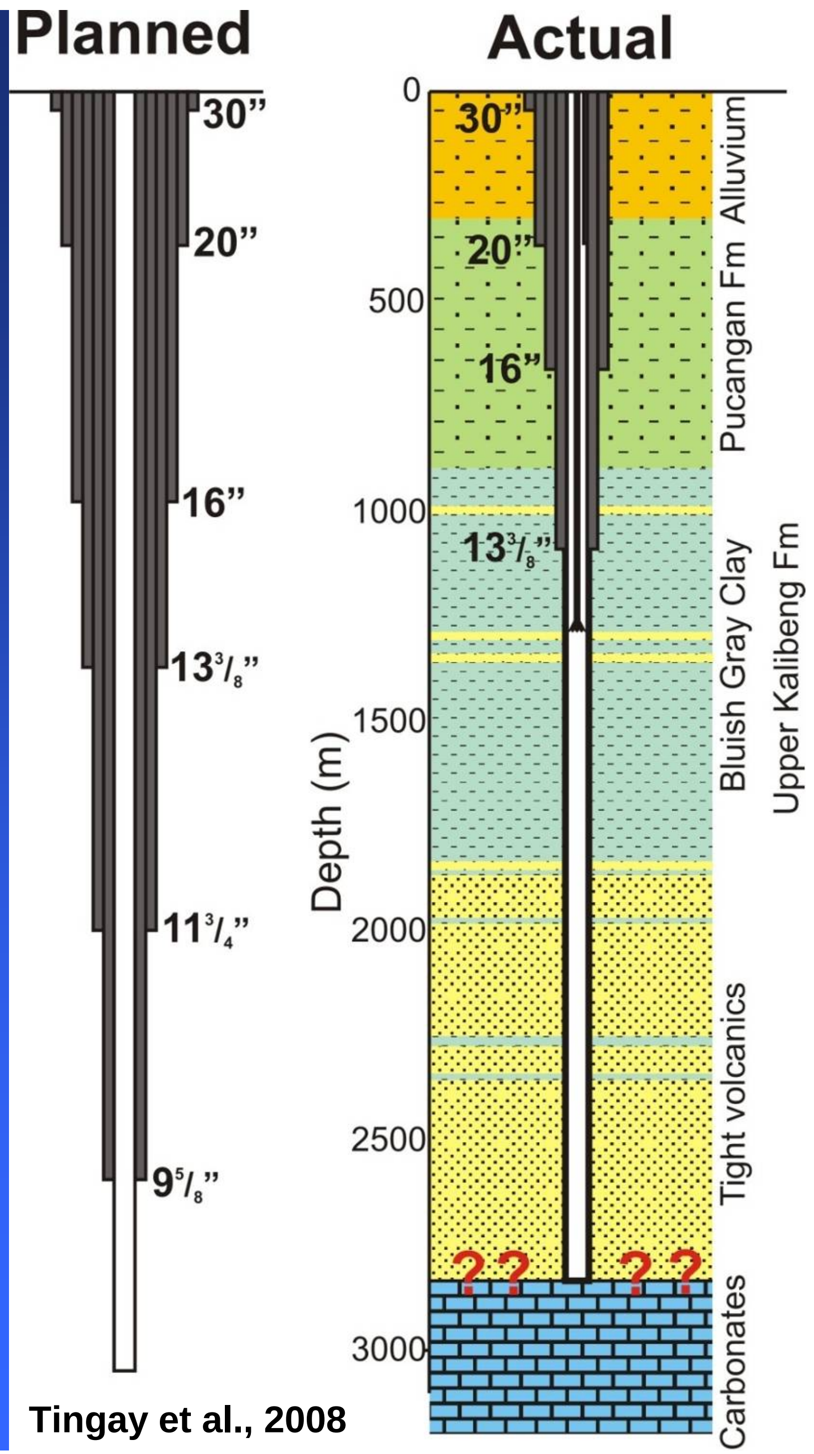
- ***Every 'fact' or 'figure' has a high degree of uncertainty!***
- e.g. Five reported leak-off pressures from 15.3-16.4 ppg (range of 208 psi or 1.4 MPa)!
- Three different gauges, two different methods!
- Further uncertainty by use of OBM: compressibility, thermal expansion and gel strength influences average mud density.




***This LOT is a microcosm of the whole triggering debate! Downhole pressures, geology, surface observations and events – all subject to uncertainty and different interpretation!***

# Planned versus Actual Casing Design in Banjar Panji-1

- Banjar Panji-1 planned to have six casing points <610m (<2000') apart.
- Losses and stability issues resulted in shallower 16" and 13 3/8" casing points.
- Planned 11.75" casing point skipped and 9 5/8" casing point postponed.
- 9 5/8" casing planned to be set *inside* target carbonates – despite 15.8-17 ppg pressures in carbonates 7 km away.
- Total of 1742 m of open hole section (1091-2833 m) prior to complete losses and kick on the 27th/28th May.



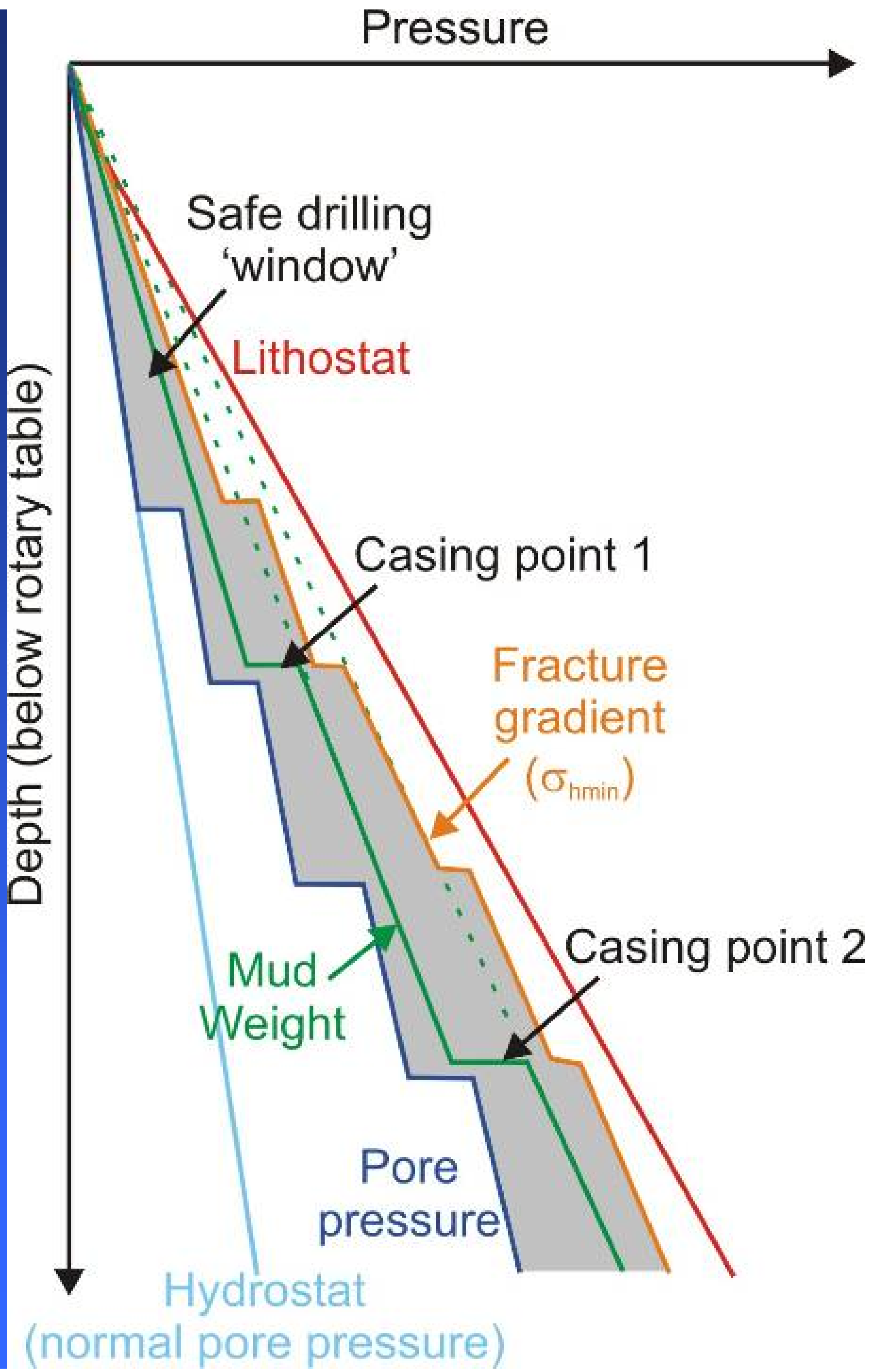

Tingay et al., 2008

# Why Set Casing?

• Mud weight must be maintained between pore pressure and fracture pressure – known as the 'safe drilling window' or 'kick tolerance'.

• Casing is set to strengthen upper section of hole and allow higher mud weight to be run.

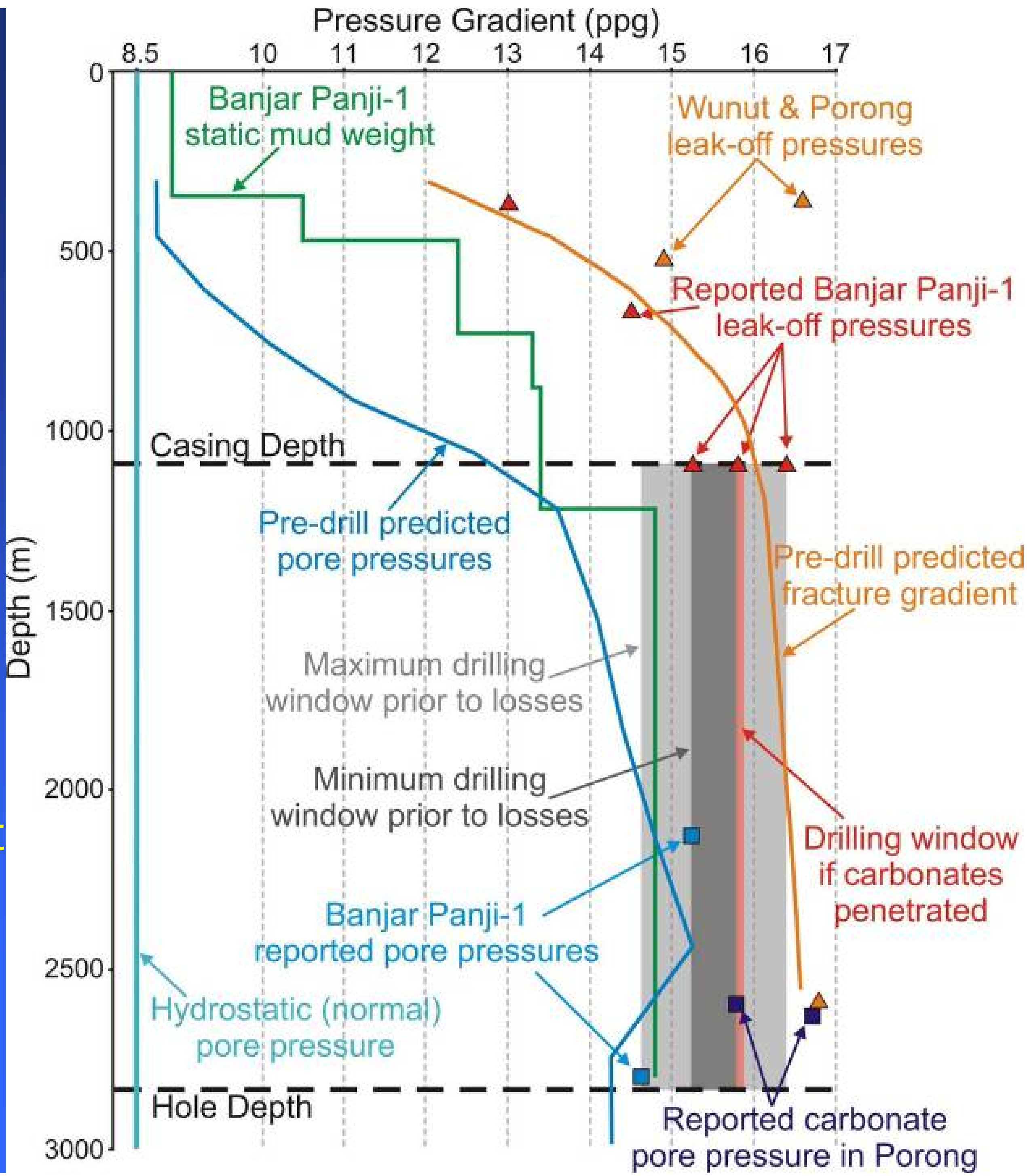
• Major internal blowouts occur when drilling window 'closes' – mud weight cannot be balanced to prevent kicks and losses.



# Kick Tolerance in Banjar Panji-1?

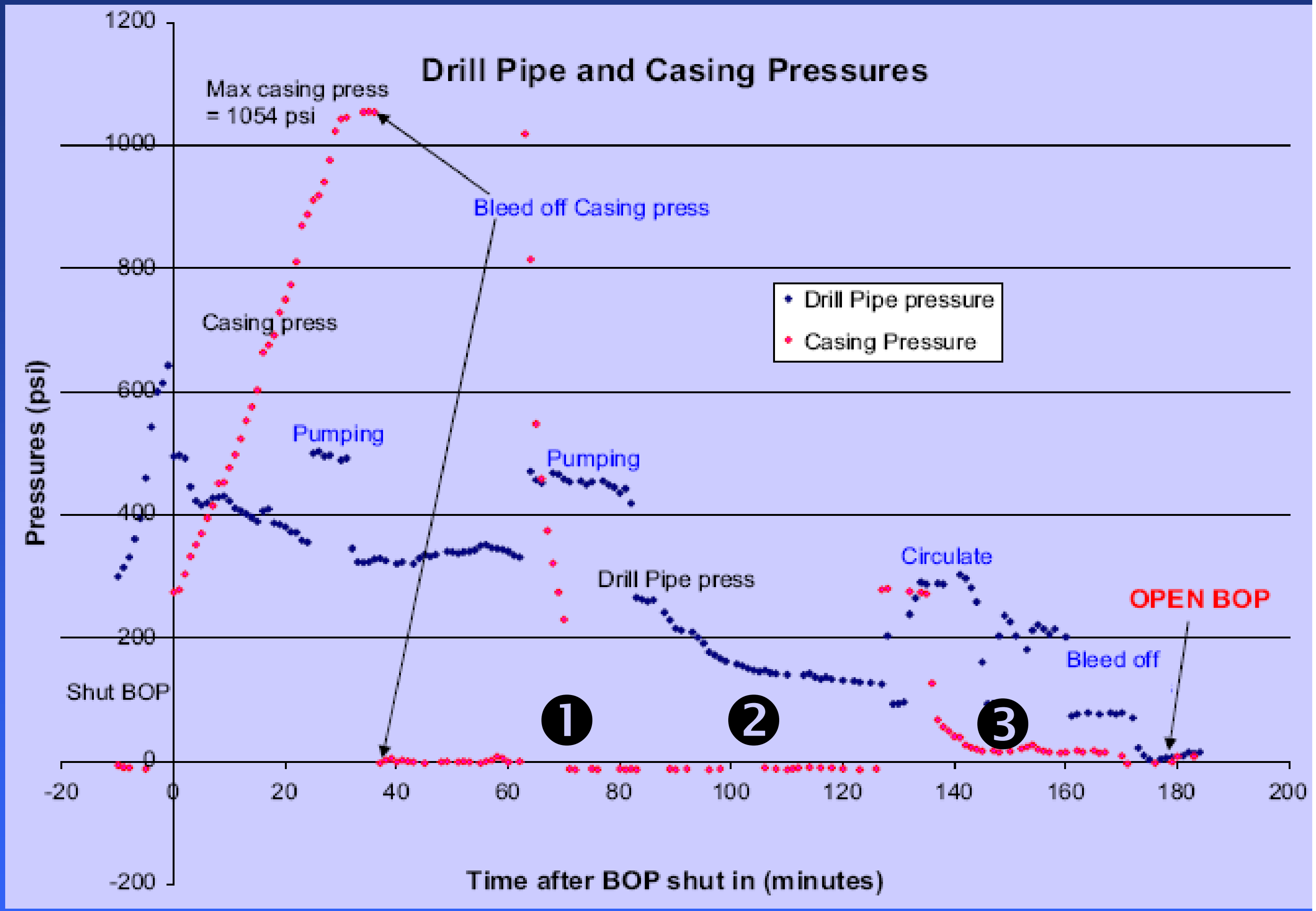
- Narrow drilling window in uncased section (≤1.8 ppg).
- However, drilling window may have been 0.05 ppg.
- Drilling window <0.6 ppg if carbonates encountered.
- Drilling window at casing shoe was 10-333 psi prior to kick.
- Low kick tolerance – difficult well control situation.
- Kick pressures >335 psi.

**Tingay et al., 2008**



# Other Evidence for Fracturing During Kick?

- Sudden drop in casing pressure in 2nd pumping? ❶
- Slow reduction in drill pipe pressure even when BOP closed? ❷
- Further pumping with no casing pressure? ❸




*BOP shut-in – why no pressure in annulus? Where is all the fluid going? Leakage through fractures? Well blockage?*

# Evidence Against Drilling Trigger

- Pore pressures in open hole section and deep carbonates poorly constrained or unknown – no accurate direct pressure tests taken.
- Confusion and uncertainty over events following kick – *<u>the drilling data can be interpreted in a variety of ways</u>*.
- Drilling data only provides information at bit (stuck at 1293m) and casing shoe (1091m) – nothing is known about what took place in well below the bit.
- Well was re-opened and could be circulated several hours after kick – not typical of blowout.
- Attempts to kill mud eruption by injecting high density fluid into well failed, though were reported to reduce rate of mudflow.
- Uncertainty over whether deep carbonate formation was penetrated nor whether these are the primary source of water for the mudflow. *<u>Source of erupted water remains unknown</u>*.

**Photo: Mark Tingay, May 2007**

**Sources: Davies et al., 2007; Mazzini et al., 2007; Sutriono, 2007; Davies et al., 2008; Tingay et al., 2008.**

# Lusi Triggering Summary

***Intense scientific, social and political debate over anthropogenic vs natural eruption trigger (and >US$420 million bill!)***

- Yogyakarta earthquake occurred 2 days prior to eruption – but calculations indicate quake was an order of magnitude too small to have triggered the mudflow.

- BJP-1 was drilled wth narrow safety tolerances and experienced drilling problems, including major kick, that suggest drilling trigger for mudflow.

- Data uncertainties remain and interpretations vary - trigger for the Lusi mud eruption may never be conclusively (i.e. legally) proven.

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Photo: M. Tingay May 2007

# How Long Could It Go On For?

- Lusi is unusual as it has maintained high flow rate for a long period of time.

- Mud volcanoes can last for 10’s to hundreds of thousands of years.

- Internal blowout in Brunei lasted over 20 years (even with relief wells).

- Initial estimates vary from 6 years (Boots & Coots) to over a 5-130 years (best estimate ~30 years; Swarbrick et al., in reviews).

- Lusi will die out when pressures in subsurface reach equilibrium with surface – but we have no idea what volume of fluid is being sourced. Could die out over a few months, years or centuries!

# Future Problems: Ongoing Subsidence

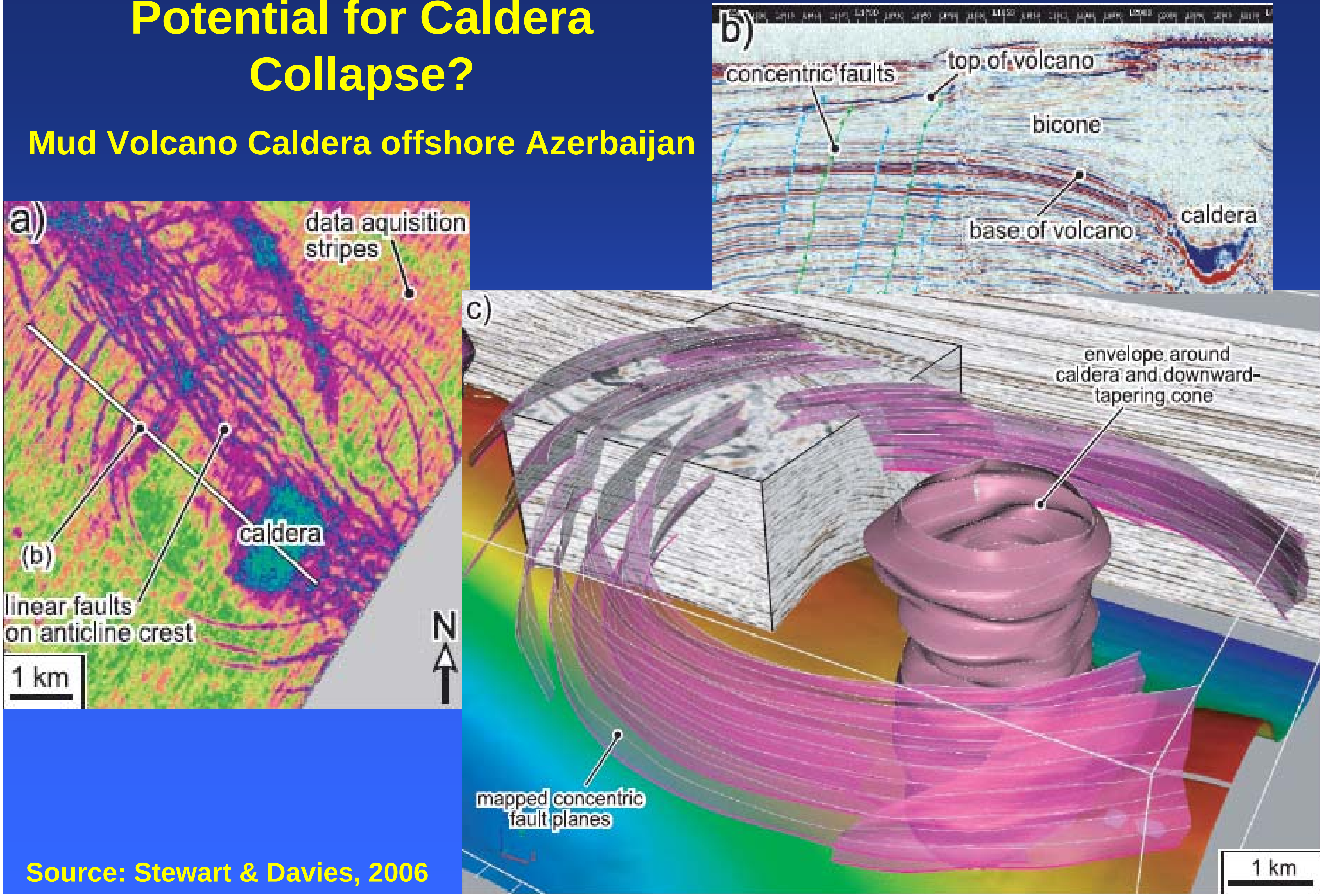
**Mud Eruption has caused extensive subsidence within 4 km of the crater (~22 km$^2$), threatening ~100000 people.**

**Subsidence rapid but mostly constant (plastic) – however, recent GPS studies measured shifts of 3m within 12 hour periods.**

Source: Abidin et al., 2008; Mazzini et al., 2007. Photo: Channel 9 Australia

# Potential for Caldera Collapse?

## Mud Volcano Caldera offshore Azerbaijan



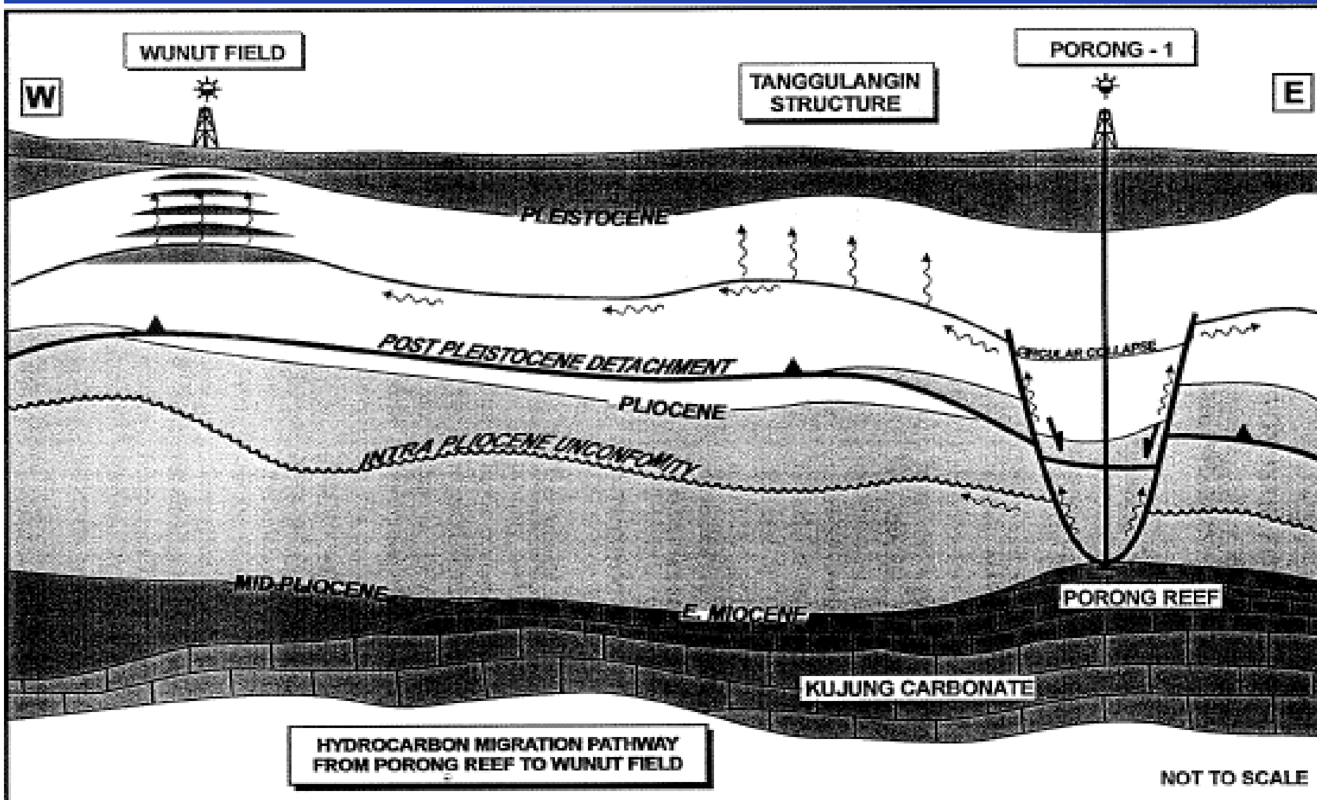

Source: Stewart & Davies, 2006

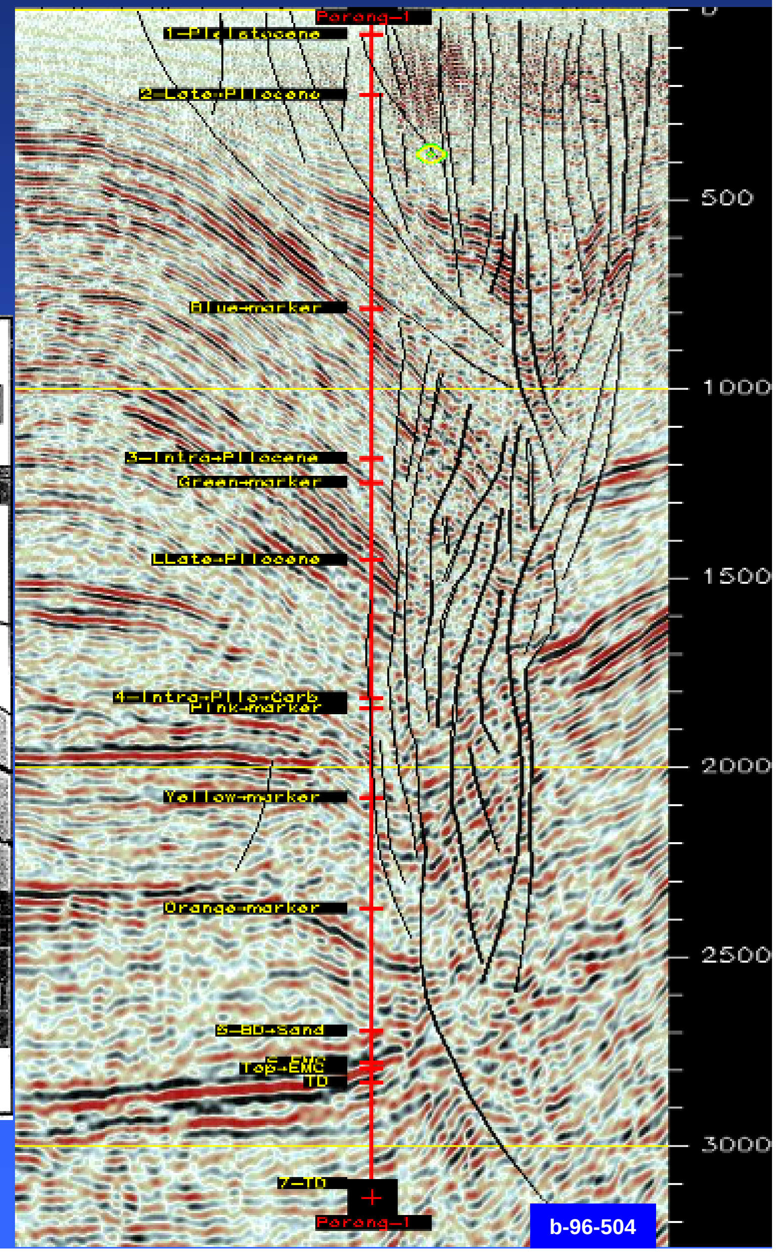
# Potential for Caldera Collapse?

Collapse of the adjacent Porong (300m) structure just 7 km from Lusi – suggests similar eruption has occurred in Porong.

Rapid caldera collapse could be catastrophic in this densely populated area!

Seismic across 2km diameter, 300m deep Porong collapse structure.




Source: Seismic courtesy of Lapindo Brantas; Cross-section from Kusumastuti et al. (1999).

# <u>Acknowledgements and Thanks:</u>

**Durham, UK:** Dick Swarbrick and Richard Davies for discussions on Lusi eruption.

**Germany:** Oliver Heidbach for earthquake triggering analysis, Birgit Müller for discussion on mechanics of mud volcanos.

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# Any Questions?