What Caused the Lusi Mudflow Disaster in Indonesia?*

Mark Tingay[1]

Search and Discovery Article #41791 (2016)**
Posted April 25, 2016

*Adapted from oral presentation given at AAPG International Conference & Exhibition, Melbourne, Australia, September 13-15, 2015.
Editor's note: Please refer to earlier, related article, Search and Discovery Article #50187 (2009).

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Abstract

The 'Lusi' mudflow on Java is a unique geological disaster in which a new mud volcano suddenly erupted in an urban area, burying over 11000 buildings. The mudflow, which has been erupting continuously for 9 years, has displaced 40000 people and caused over US$2.7 billion in damage. Intense debate has focused on whether the disaster was triggered by a drilling kick in the adjacent Banjar Panji-1 (BJP-1) well (1 day earlier, 150m away), or whether the eruption was a natural event induced by the 2006 Mw6.3 Yogyakarta earthquake (2 days earlier, 250km away). Both theories argue that an event changed the effective stress under Lusi, with some studies proposing that high pressures during the drilling kick initiated hydraulic tensile fracturing, while the 'earthquake-trigger' hypothesis argues that shear stress increases caused strike-slip reactivation of the nearby Watukosek fault. Yet, neither theory has been fully quantitatively tested, as data has not previously been available on the initial state of stress and rock mechanical properties under Lusi. In this study, the pre-eruption stress and pore pressure state under Lusi is determined, and a new petrophysical log suite used to estimate rock mechanical properties. The initial state of stress is then used to test all known triggering theories, by examining the stress changes induced by the earthquake and drilling kick and determining whether fracturing or fault reactivation was likely to have occurred. The results demonstrate that the earthquake was too small, on its own, to trigger the Lusi eruption. Furthermore, this study results in a new triggering model, in which the drilling kick, and not the earthquake, caused catastrophic shear failure of the borehole wall, and subsequent reactivation of the Watukosek fault. These results indicate that the Lusi disaster is one of the most destructive examples of human-induced faulting ever witnessed.

Selected References

Davies, R.J., M. Brumm, M. Manga, R. Rubiandini, R. Swarbrick, and M. Tingay, 2008, The East Java mud volcano (2006 to present); an earthquake or drilling trigger?: Earth and Planetary Science Letters, v. 272/3-4, p. 627-638.

Lupi, M., E.H. Saenger, F. Fuchs, and S.A. Miller, 2014, Corrigendum to Lusi mud eruption triggered by geometric focusing of seismic waves: Nature Geoscience, v. 7/9, p. 687–688.

Manga, M., 2007, Did an earthquake trigger the May 2006 eruption of the Lusi mud volcano?: Eos, Transactions American Geophysical Union, v. 88/18, p.201.

McMichael, H. 2009, The Lapindo mudflow disaster: environmental, infrastructure and economic impact: Bulletin of Indonesian Economic Studies, v. 45/1, p. 73-83. Website accessed April 10, 2016, http://cip.management.dal.ca/publications/The%20Lapindo%20mudflow%20disaster-%20environmental,%20infrastructure%20and%20economic%20impact.pdf.

Mazzini, A., H. Svensen, G.G. Akhmanov, G. Aloisi, S. Planke, A. Malthe-Sørenssen, and B. Istad, 2007, Triggering and dynamic evolution of the Lusi mud volcano, Indonesia: Earth Planetary Science Letters, v. 261/3–4, p. 375–388.

Mazzini, A., A. Nermoen, M. Krotkiewski, Y. Podladchikov, S. Planke, and H. Svensen, 2009, Strike-slip faulting as a trigger mechanism for overpressure release through piercement structures: Implications for the Lusi mud volcano, Indonesia: Marine and Petroleum Geology, v. 26/9, p. 1751–1765.

Sawolo**,** N.**,** E. Sutriono, B.P. Istadi, and Darmoyo, 2009, The Lusi mud volcano triggering controversy: Was it caused by drilling?: Marine and Petroleum Geology, v. 26, p. 1766-1784.

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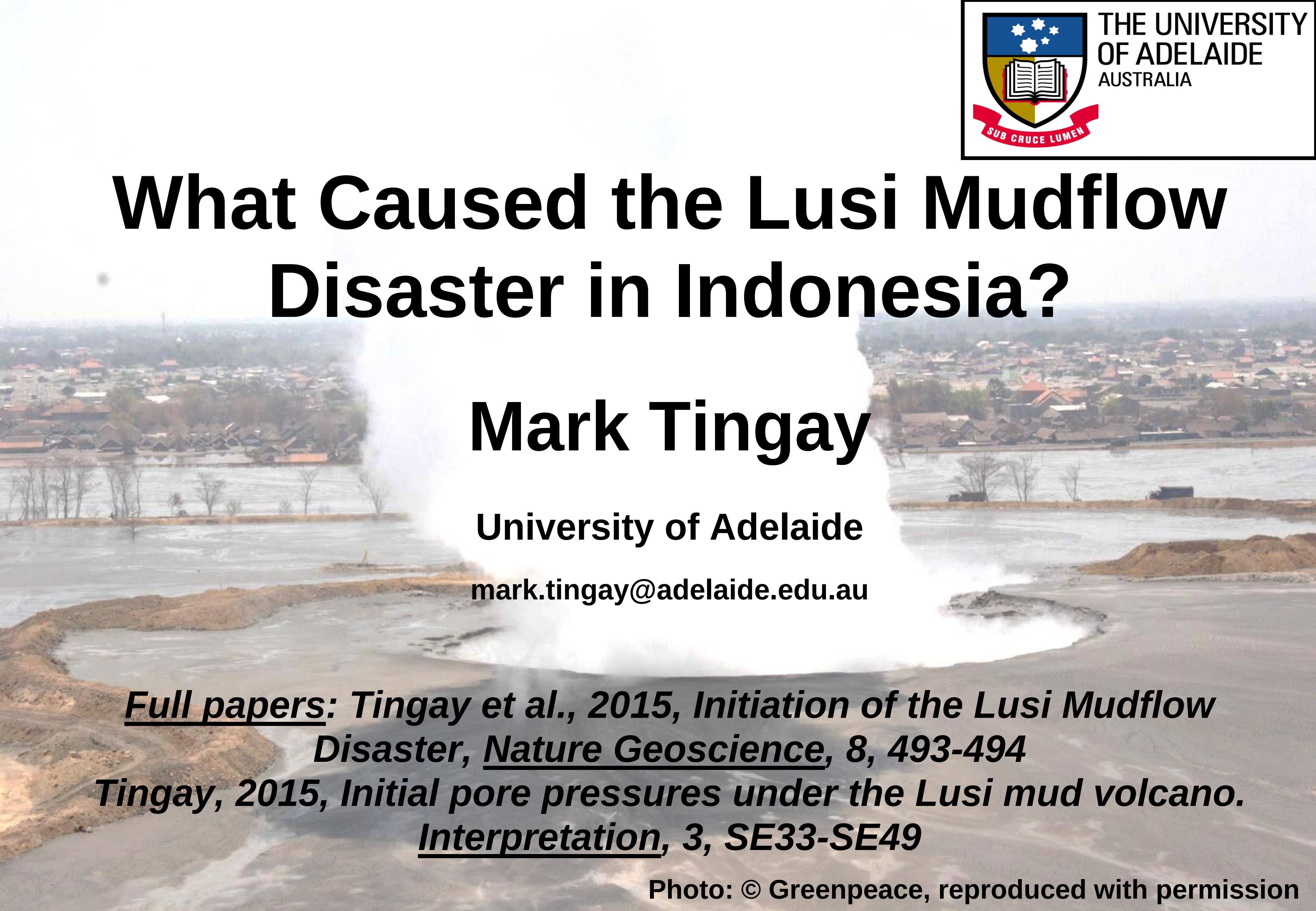
Tingay, M., 2015, Initial pore pressures under the Lusi mud volcano: Interpretation, v. 3/1, p.SE33-SE49.

Tingay, M., O. Heidbach, R. Davies, and R. Swarbrick, 2008, Triggering of the Lusi mud eruption: Earthquake versus drilling initiation: Geology, v. 36/8, p. 639–642.

Tingay, M, O. Heidbach, R. Davies, and R. Swarbrick, 2009, The Lusi mud eruption of East Java: Search and Discovery Article #50187 (2009). Website accessed April 10, 2016, http://www.searchanddiscovery.com/documents/2009/50187tingay/ndx_tingay.pdf.

Tingay, M., M.L. Rudolph, M. Manga, R. Davies, and C.-Y. Wang, 2015, Initiation of the Lusi mudflow disaster: Nature Geoscience, v. 8, p. 493–494.



What Caused the Lusi Mudflow Disaster in Indonesia?

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***Full papers*: Tingay et al., 2015, Initiation of the Lusi Mudflow Disaster, *Nature Geoscience*, 8, 493-494**

Tingay, 2015, Initial pore pressures under the Lusi mud volcano. Interpretation, 3, SE33-SE49

Mud flow displaced 39700 people, 12 villages, 11241 buildings, >US$600 million property, >US$2.7 billion damage/management.

Source: BPLS, Mazzini et al., 2007, McMichael, 2009, Science 2011.

Photos: M. Tingay, BPLS and Channel 9 Australia

Mud covers area of >6 km^2, contained within dams.

Mud is >40m deep in places.

Total mud erupted is >0.1 km^3 (100 million m^3) at an average rate of ~30000 m^3 per day

>20% the volume of Sydney Harbour.

Ongoing >9 years, predicted to last ~20 years.

Image: 22/7/2006, Courtesy Lapindo

Controversy: What Triggered the Lusi Eruption?

Two distinct and competing theories

1. Eruption triggered by 27th May 2006 M_w6.3 Yogyakarta earthquake.

2. Eruption triggered by blowout in nearby Banjar Panji-1 gas exploration well.

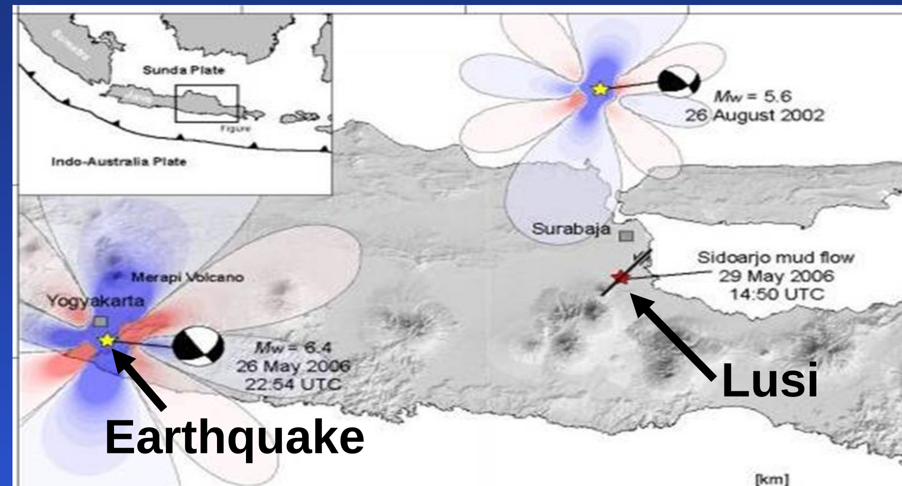


Image sources: Tingay et al. (2008) & BPLS

What Caused the Lusi Mudflow Disaster?

- BACKGROUND
- DATA REVIEW AND PORE PRESSURES
- TESTING TRIGGERING HYPOTHESES
- NEW TRIGGERING MODEL AND SUMMARY

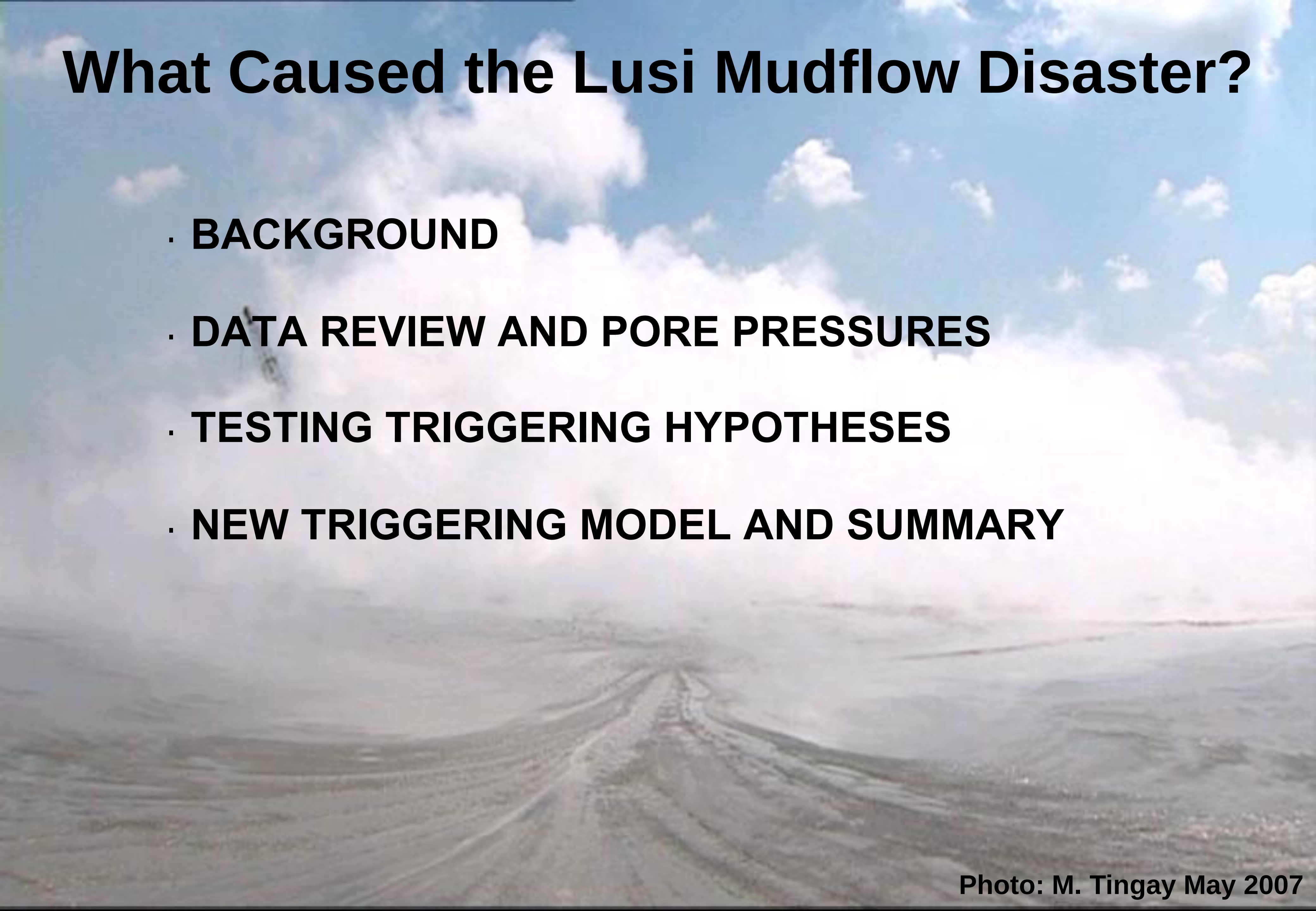
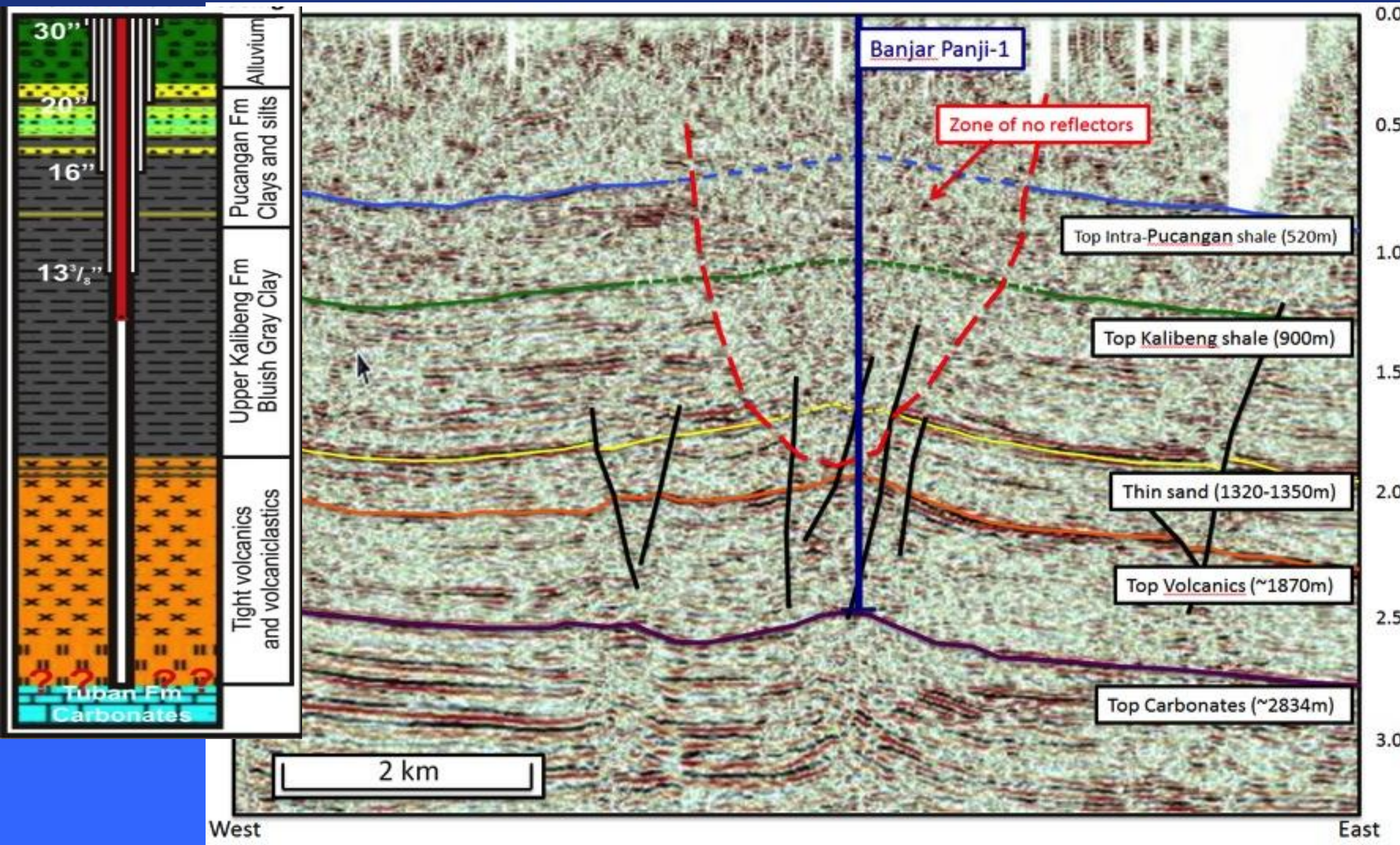


Photo: M. Tingay May 2007

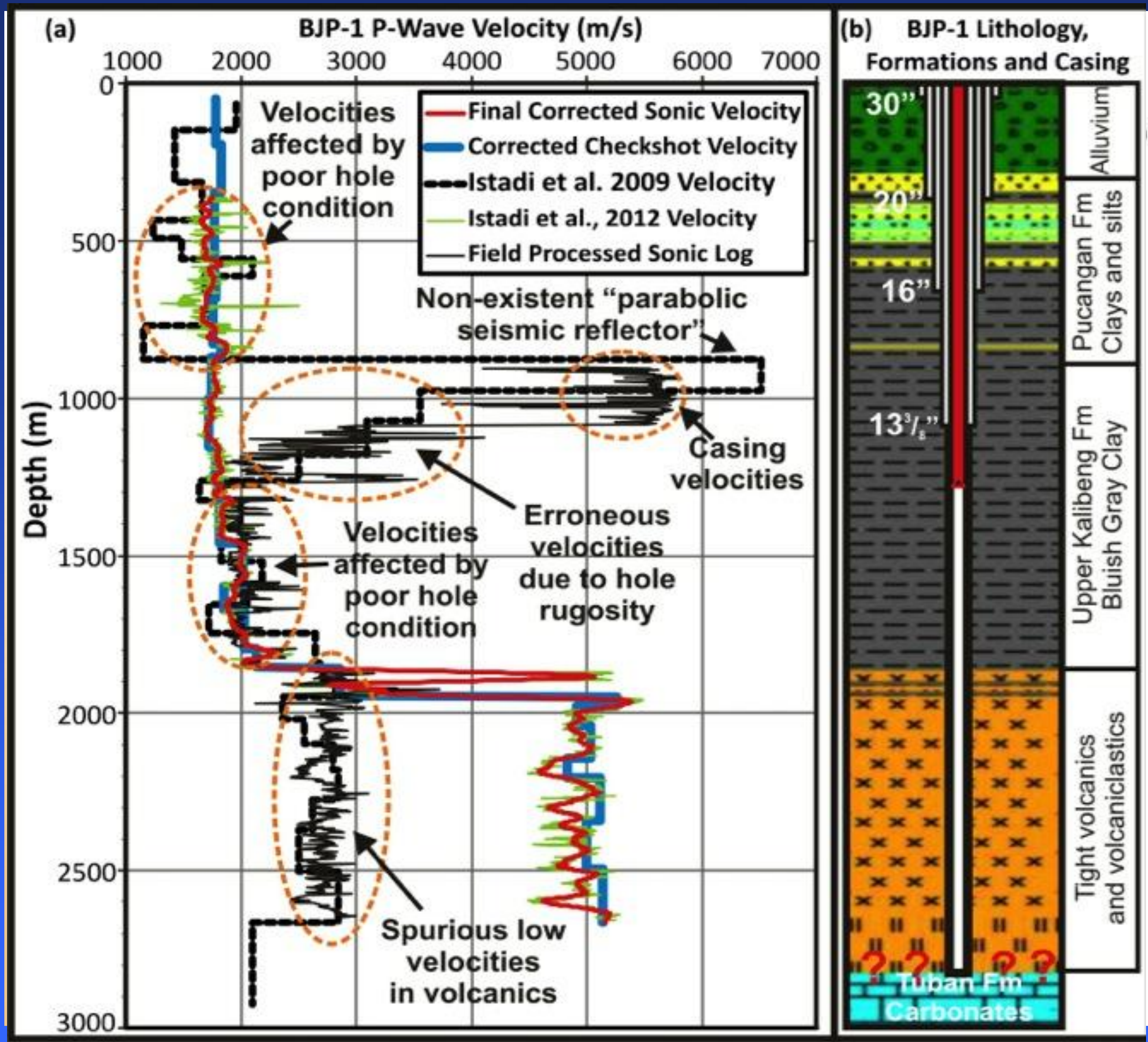
Local Geology: Lusi and Banjar Panji-1



Data Problems

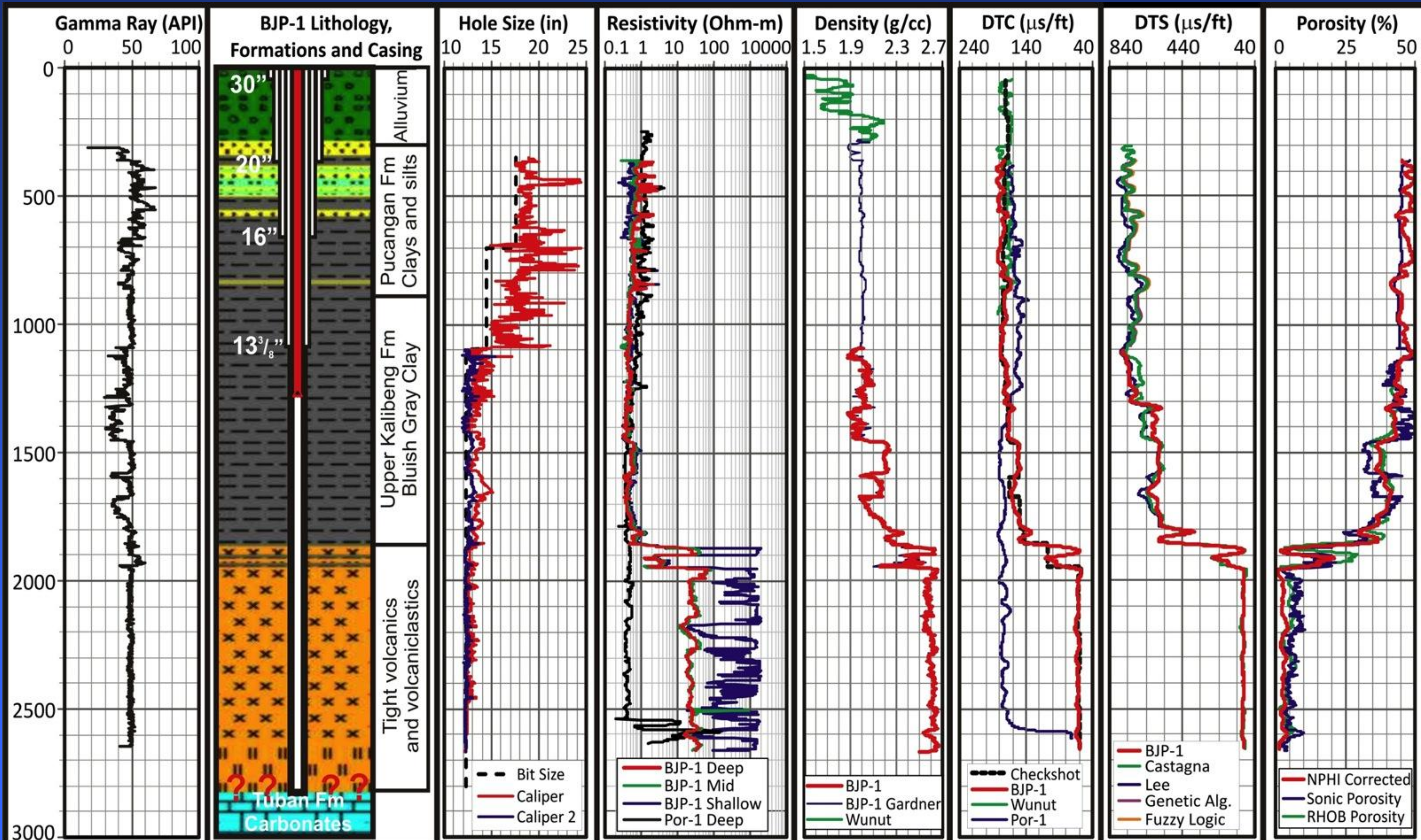
Data available from papers, reports, DDRs, mud logs, wireline logs, seismic, offsets.

BUT data reveals numerous errors, artifacts, inconsistencies and varying or ambiguous interpretations!



Examples of erroneous data for BJP-1. Source: Sawolo et al., 2009, Lupi et al., 2013, Tingay, 2015

New Petrophysical, Drilling & Geological Dataset



Newly processed and QC'd petrophysical dataset and stratigraphy for BJP-1. Source: Tingay, 2015

New Petrophysical, Drilling & Geological Dataset

Table 1. Timing of key events during drilling of BJP-1. All dates and times are local (UTC +7 h). Significant observations and interpretations are italicized in bold. Data are compiled from Adams (2006), Davies et al. (2008, 2010), Tingay et al. (2008), and Sawolo et al. (2009).

Date and time	Event
8/3/2006, 1330 h	Spud BJP-1 well.
14–15/3/2006	Run and cement 20″ casing to 364 m, ~13 m shallower than planned.
18/3/2006	Commenced raising mud weight (MW) due to indicators of high pore pressure.
20/3/2006	Increases in background gas. Hole partially packed off, BHA pulled free with 25 klbs overpull. MW raised to 14.6 MPa/km. Decision made to set 16″ casing shallow.
22/3/2006	Wireline logging. Caliper indicates need to ream hole. Reamed with 17.5″ BHA to 702 m. Indications of pack-off and cavings. MW increased to 14.8 MPa/km for wellbore stability.
24/3/2006	Run 16″ liner. Worked through obstruction at 471 m. Washed and worked down. Could not run shoe past 666 m. Liner shoe set at 666 m, ~310 m shallower than planned.
25/3/2006	Gas bubbling from hole for several hours. Indications that 16″ liner cement was inadequate and that a gas zone behind casing was leaking. Run in and perform liner top cement squeeze.
28–29/3/2006	BHA packed off twice while drilling rat hole. Long open hole LOT performed, 16.7 MPa/km. Squeezed cement. Drill out and repeat LOT, 17.0 MPa/km.
7–8/4/2006	Drilled 14.5″ hole to 775 m, reaming from 670 to 680 m. Pumps broke. ~16 days for repairs.
24/4/2006	Recommence drilling 14.5″ hole with 15.6 MPa/km MW.
25–26/4/2006	Commenced drilling Kalibeng clays. Indications of high pore pressure at 1028 m, MW increased to 15.8 MPa/km. Flow observed at 1067 m. Circulate and continue drilling with 15.8 MPa/km mud to 1096 m. Flow observed, increase to 16.4 MPa/km mud. Pumped out of hole, tight at 1041 m and 983 m. Increased cuttings over shakers.
27–29/4/2006	Wireline logged. Reamed into hole. Large volumes of cuttings, MW raised to 16.7 MPa/km. Run 13.375″ casing. Well flowing, possible ballooning. Casing shoe at 1091 m, ~280 m shallower than planned. 50 bbl losses prior to cement job. Partial and then total losses during cement job, some ballooning back. Total of 756 bbl lost displacing and pumping cement, marginal cement job.
5/5/2006	***Perform final LOT***. Originally interpreted as 18.4 MPa/km, interpretation changed to 19.3 MPa/km on 8/5/2006. Davies et al. (2010) observe that formation breakdown and fracture propagation pressure misinterpreted as leak-off pressure. Correct leak-off pressure 18.56 MPa/km. Curved leak-off test profile suggests 13.375″ shoe not sealing due to poor cement job.

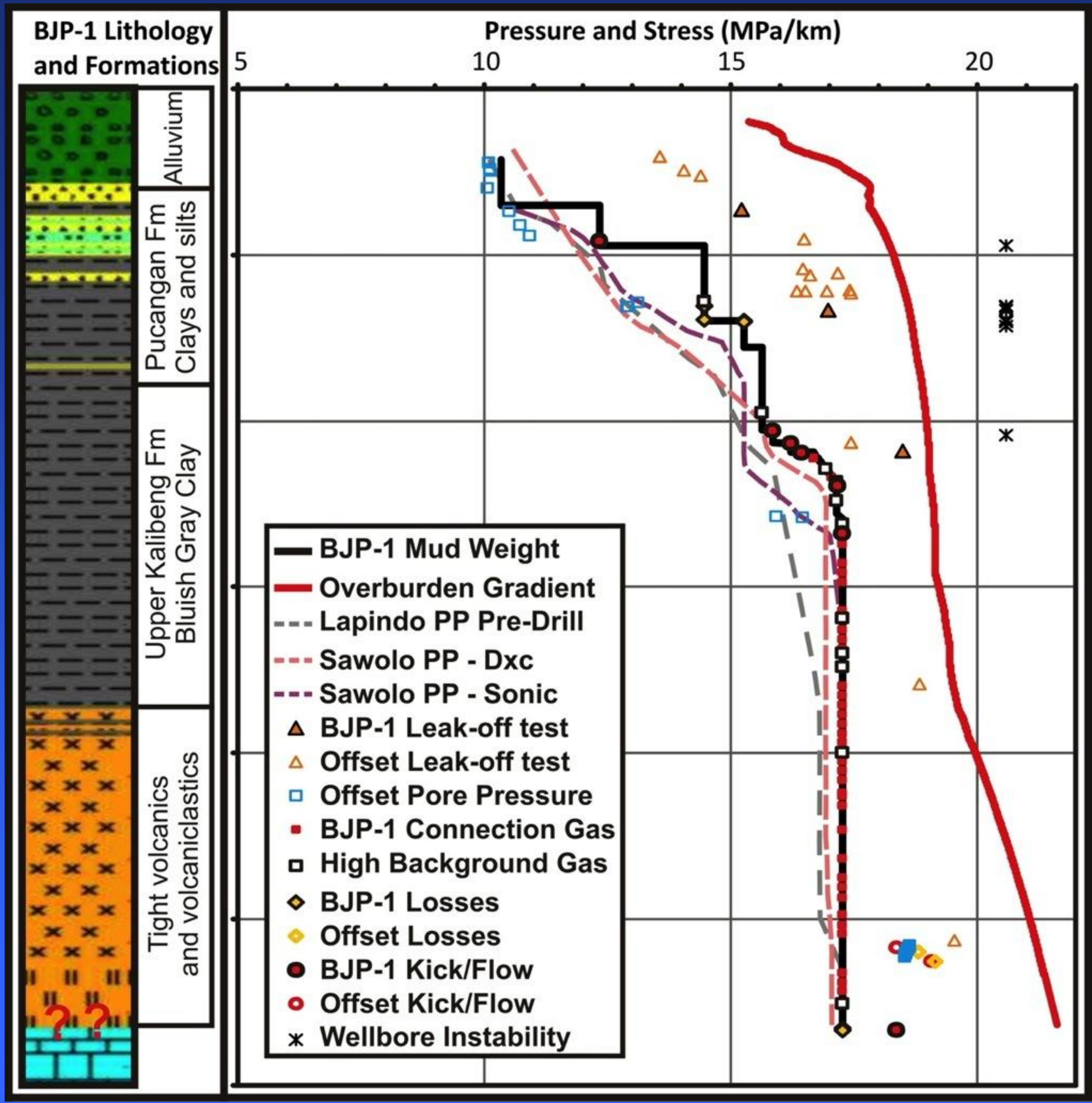
Example of new QC'd BJP-1 drilling events summary. Source: Tingay, 2015

Pore Pressure Data

7 influxes/kicks, 40 connection gases, 13 high background gas events, mud weight, offset well data, LOTs, etc.

Shallow overpressure (350m), constant vert. effective stress

High PP in volcanics and carbonates.



New compilation of BJP-1 and offset PP, LOT and vertical stress data. Source: Tingay, 2015

What Caused the Lusi Mudflow Disaster?

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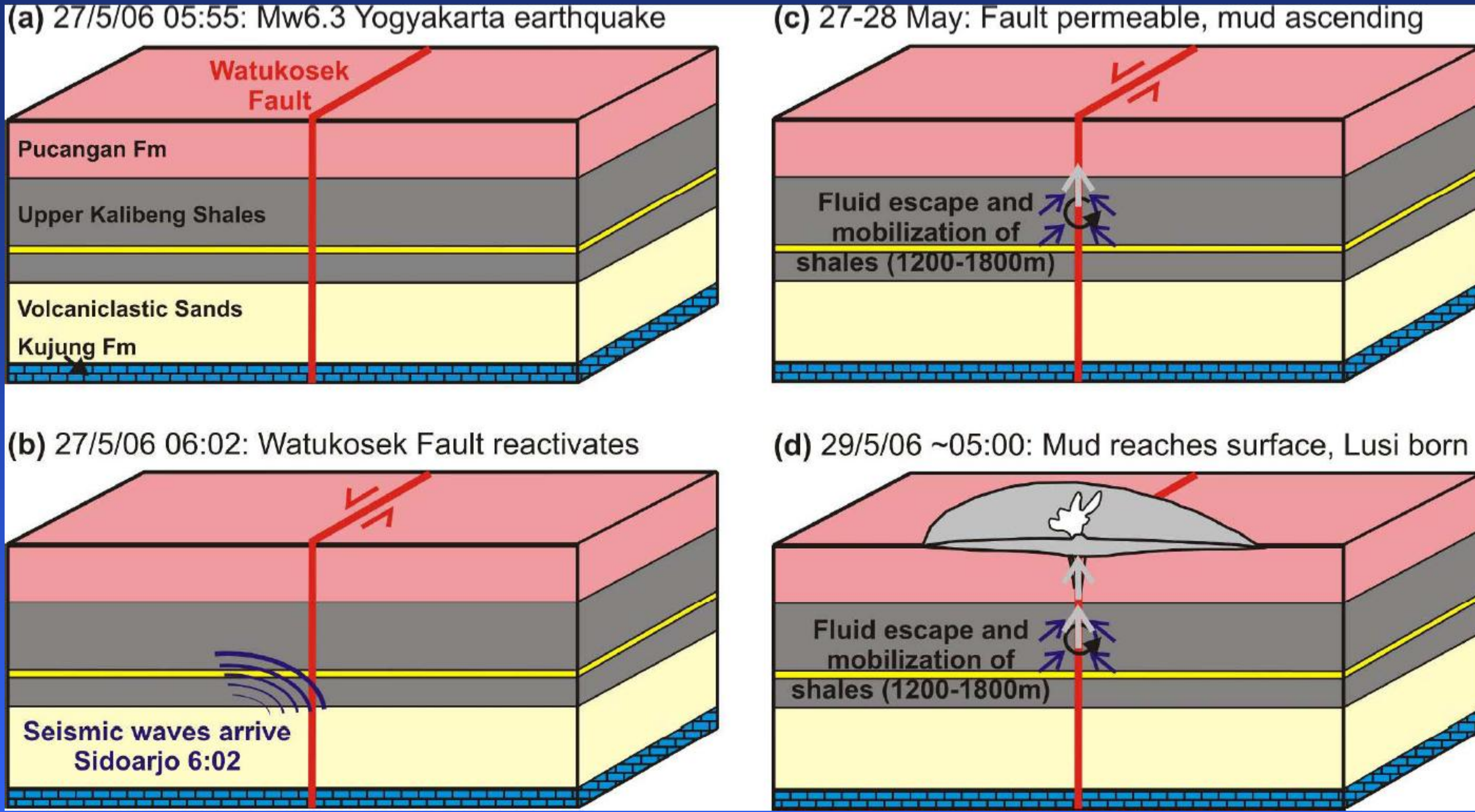
- **TESTING TRIGGERING HYPOTHESES**
- NEW TRIGGERING MODEL AND SUMMARY

Photo: M. Tingay May 2007

Schematic Model for Earthquake Triggering of Lusi

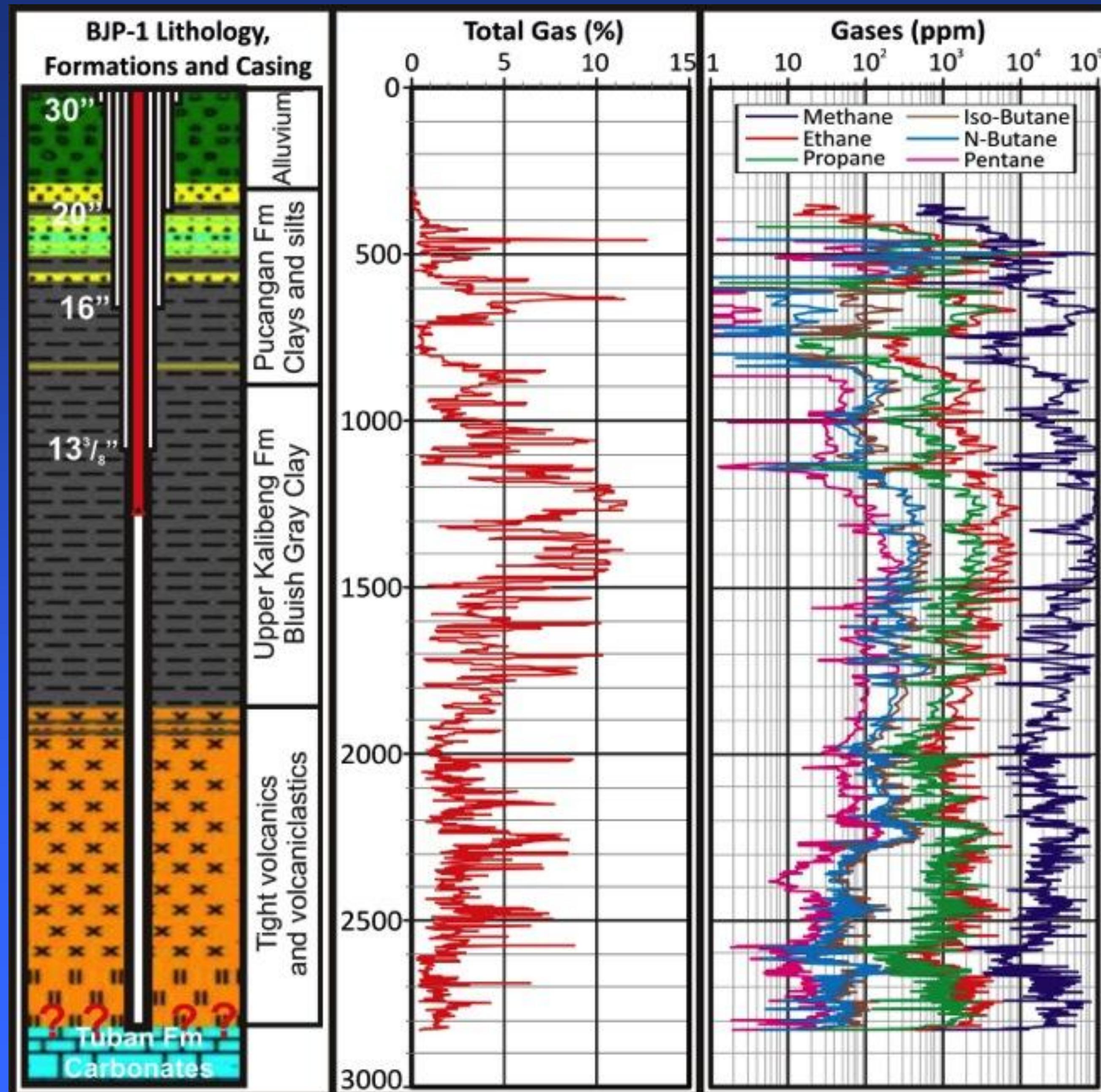


Lusi caused by remote fault reactivation. Shaking causes liquefaction and gas exsolution in Kalibeng shales, which triggers an effective stress drop and fault reactivation.

Sources: Mazzini et al., 2008; Tingay, 2010; Lupi et al., 2013

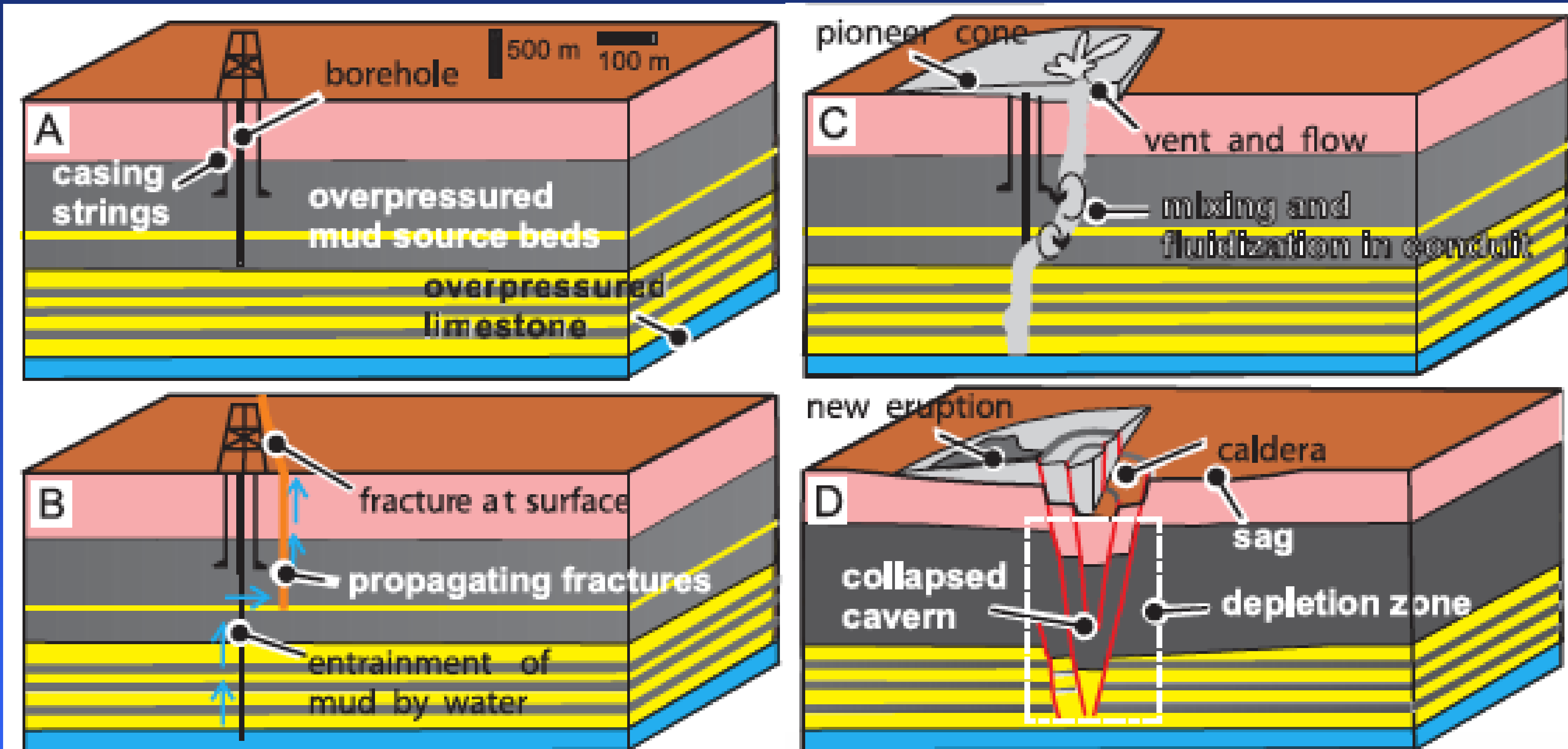
New Data: No Evidence for Clay Liquefaction

- Liquefaction associated with gas exsolution.
- BJP-1 was open to 800m of Kalibeng clays, and had standard mud gas equipment operating.
- In the 24 hours after quake, gas readings were normal and actually slightly less than in the previous 2 days. Indicates no earthquake-induced liquefaction.
- H_2S observed at base of well, during kick and initial Lusi eruption. Suggests initial eruptive fluids from carbonates, not shallow clays.



Tingay et al., *2015, Nature Geoscience.*

Schematic Model for Drilling Trigger of Lusi

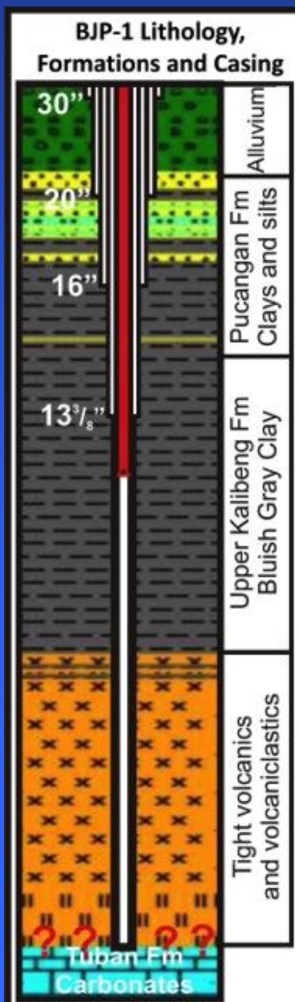


Mud eruption suggested to be surface eruption caused by an underground blowout. Pressure spike during kick caused hydraulic fracturing.

Source: Davies et al., 2007

1D Geomechanical Model for BJP-1

- New petrophysical dataset used to build pre-eruption 1D MEM.
- MEM can be combined with stress/pressure changes estimated for kick and earthquake to test likelihood of shear or tensile failure.



PR	E (GPa)	G (GPa)	K (GPa)	UCS (MPa)	Frict Angle
~0.4	~0.5	~0.3	~5.5	~3.8	~15°
~0.4	0.4-0.7	0.5-0.6	6.0–8.0	3.0-5.5	14-19°
~0.15	~27-33	~21	~33	70-90	39-42°
~0.18	~22	~17	~21	~50	~35°

- Used published dynamic/static and UCS/friction angle relationships.
- Poroelastic model with 0.0003 and 0.0012 strains. Calibrated to LOT and breakouts.
- Test published stress and PP changes: used maximum from quake and minimum from kick.

Underground blowout: Was well integrity lost in kick?

- Kick was large enough to potentially induce tensile failure for 380m of the wellbore below casing shoe.
- Shear failure significantly more likely. *Kick sufficient to induce fault reactivation for 650m of the wellbore length!*
- Quake too small. Stress changes would need to be over 8x larger to trigger reactivation.
- Combined Quake and drilling? Quake + ECD may be just sufficient to induce shear failure at casing shoe?

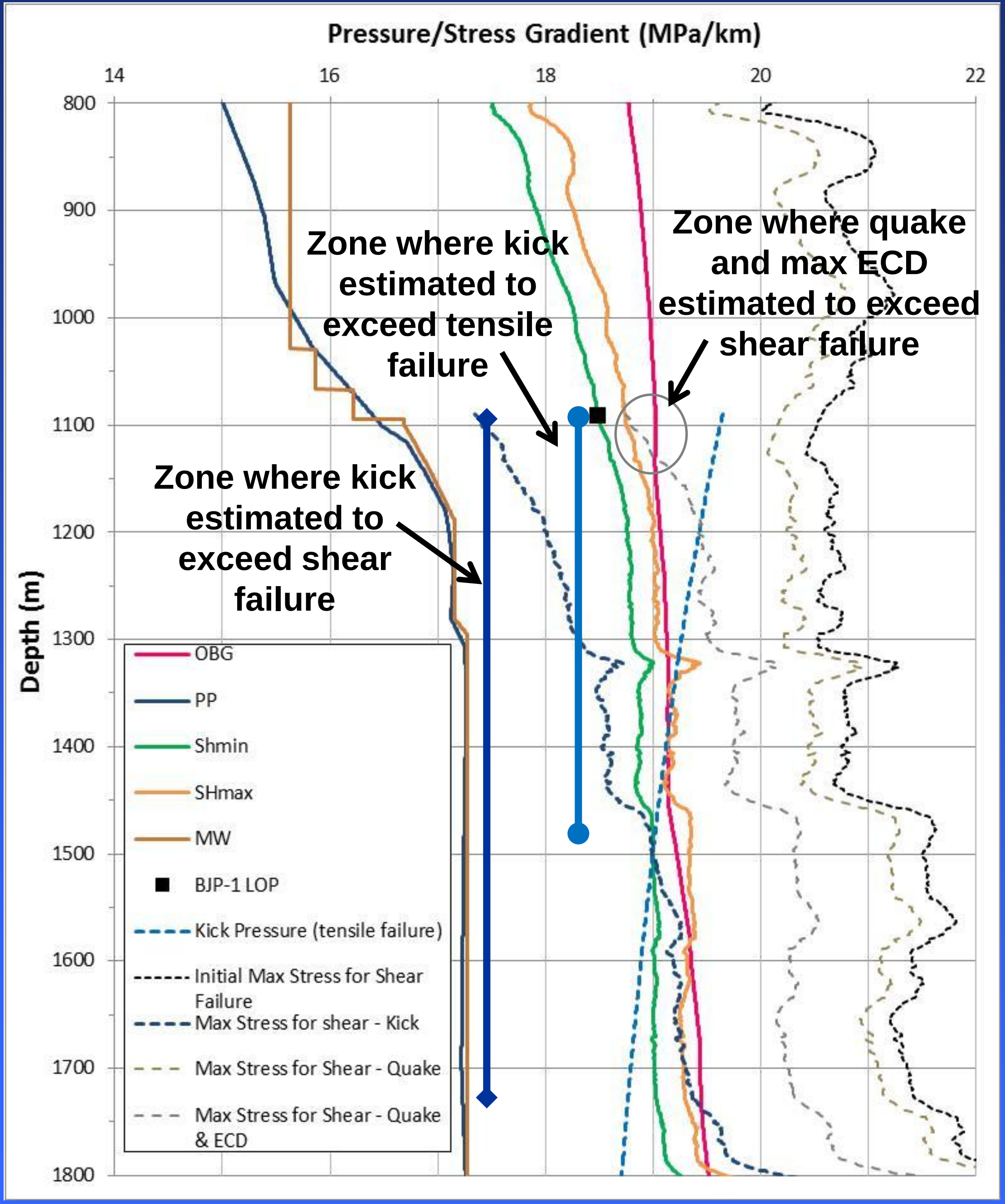


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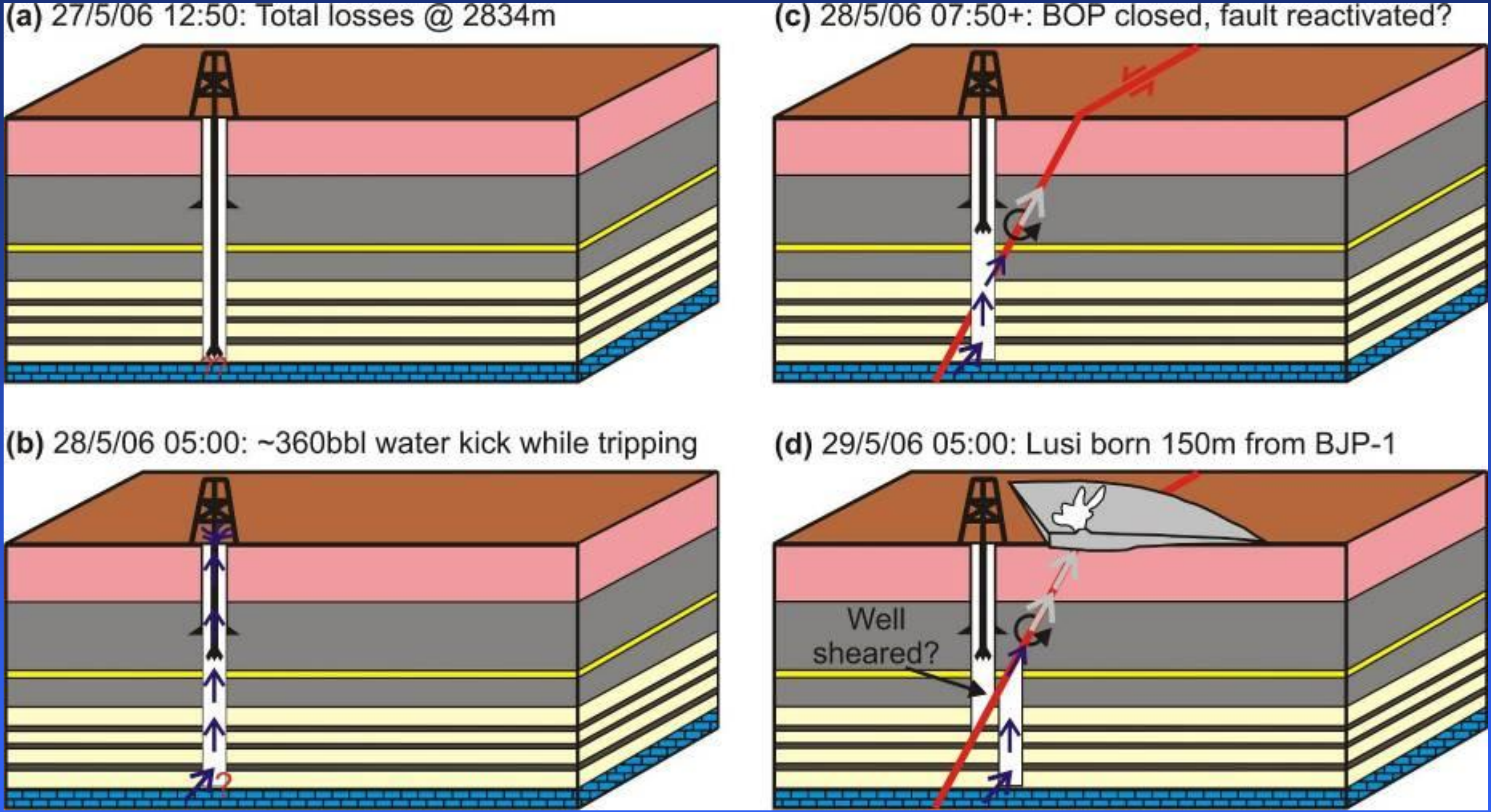
Photo: M. Tingay May 2007

Schematic Model for Drilling-Induced Triggering of Lusi



Mud eruption is a surface eruption caused by an underground blowout. Pressure spike during kick resulted in faulting or fault reactivation.

Summary and Implications for Safe Drilling

• New dataset of petrophysical logs, drilling data and events, PP, mud gas, lithology and stratigraphy for Lusi.

• Overpressures observed from shallow depths and varying lithology.

• Poroelastic geomechanical model used to test possible disaster triggers. Earthquake too weak. Kick able to induce fault reactivation.

• Geomechanical model results confirmed by mud gas data that demonstrates earthquake did not trigger clay liquefaction.

• Root causes considered to be poor well planning (ignoring offset well data), deviation from well design (skipping two planned casing points) and well control procedures (slow kick detection and management).

• Public and freely available dataset for learning the value of proper planning and execution for safe drilling.

Acknowledgements and Thanks:

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

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Indonesia: Handoko Wibowo and Hardi Prasetyo (Sidoarjo Mudflow Mitigation Agency); Rocky Sawolo, Bambang Istadi & Adi Kadar (Lapindo Brantas) for Lusi reports and images and BJP-1 data.

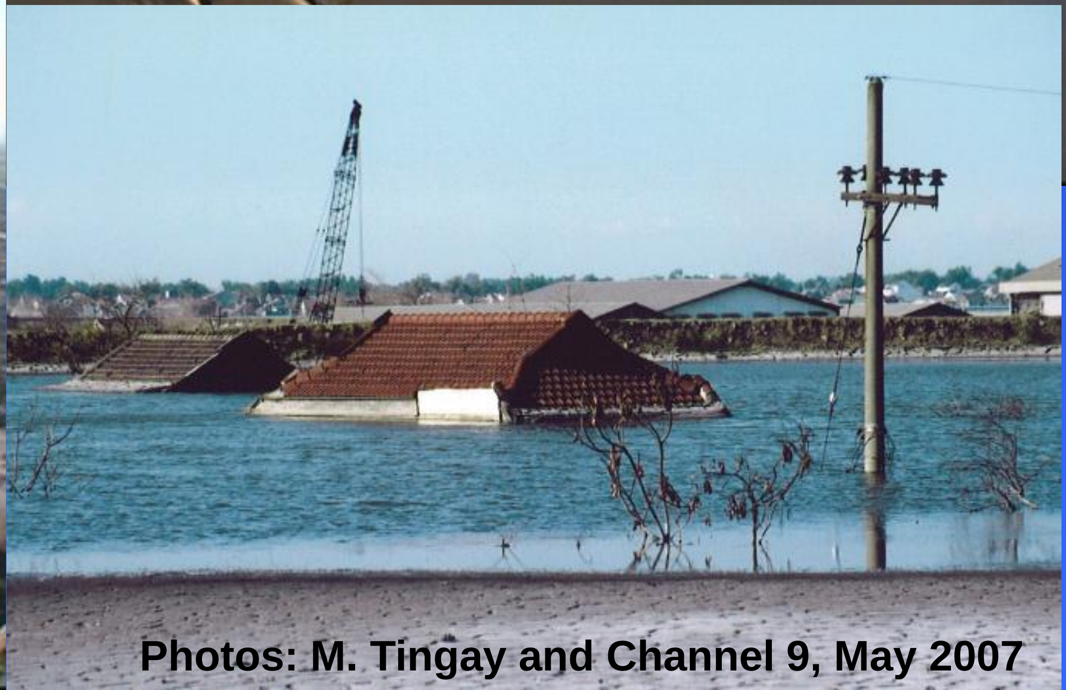
Adelaide: John Kaldi for comments on geology of East Java Basin; Ric Daniels, Keith Boyle, Dennis Fischer and Richard Hillis for discussions on drilling data interpretation and petrophysical processing.

Brunei: Chris Morley for discussions on mobile shale features.

Thanks to Howard Sacre (**60 Minutes, Channel 9 Australia**), Grace Duran (**Greenpeace**) and Rohman Budijanto (**Jawa Pos**) for photos of Lusi.

Any Questions?


Refugee shelter


Photos: M. Tingay and Channel 9, May 2007

Additional Slides for Potential Questions

A Major Controversy!

Triggering of the Lusi mud eruption: Earthquake versus drilling initiation

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Geology, August 2008; v. 36; no. 8; p. 639–642; doi: 10.1130/G24697A.1; 3 figures.

Earth and Planetary Science Letters 272 (2008) 627–638

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The East Java mud volcano (2006 to present): An earthquake or drilling trigger?

Richard J. Davies [a,*], Maria Brumm [b], Michael Manga [b], Rudi Rubiandini [c], Richard Swarbrick [d], Mark Tingay [e]

nature geoscience

LETTERS

PUBLISHED ONLINE: 21 JULY 2013 | DOI: 10.1038/NGEO1884

Lusi mud eruption triggered by geometric focusing of seismic waves

M. Lupi[1†], E. H. Saenger[2], F. Fuchs[1] and S. A. Miller[1*]

The Lusi mud eruption in Java, Indonesia, began in May 2006

Marine and Petroleum Geology 26 (2009) 1766–1784

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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The LUSI mud volcano triggering controversy: Was it caused by drilling?

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Accepted in Geophysical Research Letters, doi: 10.1002/2015GL065310

Influence of seismicity on the Lusi mud eruption

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Initiation of the Lusi mudflow disaster

To the Editor — The Lusi mudflow is a unique disaster. Mud suddenly erupted in an urban area in Java, Indonesia, in May 2006. Nine years of continuous

Supplementary Table 1). We focus on the maximum values observed in the 48 hours before and 24 hours after the Yogyakarta earthquake[7,8] (Supplementary Table 2).

recorded to come from the volcanic and volcaniclastic rock formations that und... the Kalibeng clays, and ... calcareous ...

Marine and Petroleum Geology 27

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Discussion

Sawolo et al. (2009) the Lusi mud volcano controversy: Was it caused by drilling?

R. Davies [a,*], Michael Manga [b,*], Mark Tingay [c], Susila Lusianga [d], Richard Swarbrick [e]

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Special section: Abnormal pore pressure and associated environmental and geohazards

Initial pore pressures under the Lusi mud volcano, Indonesia

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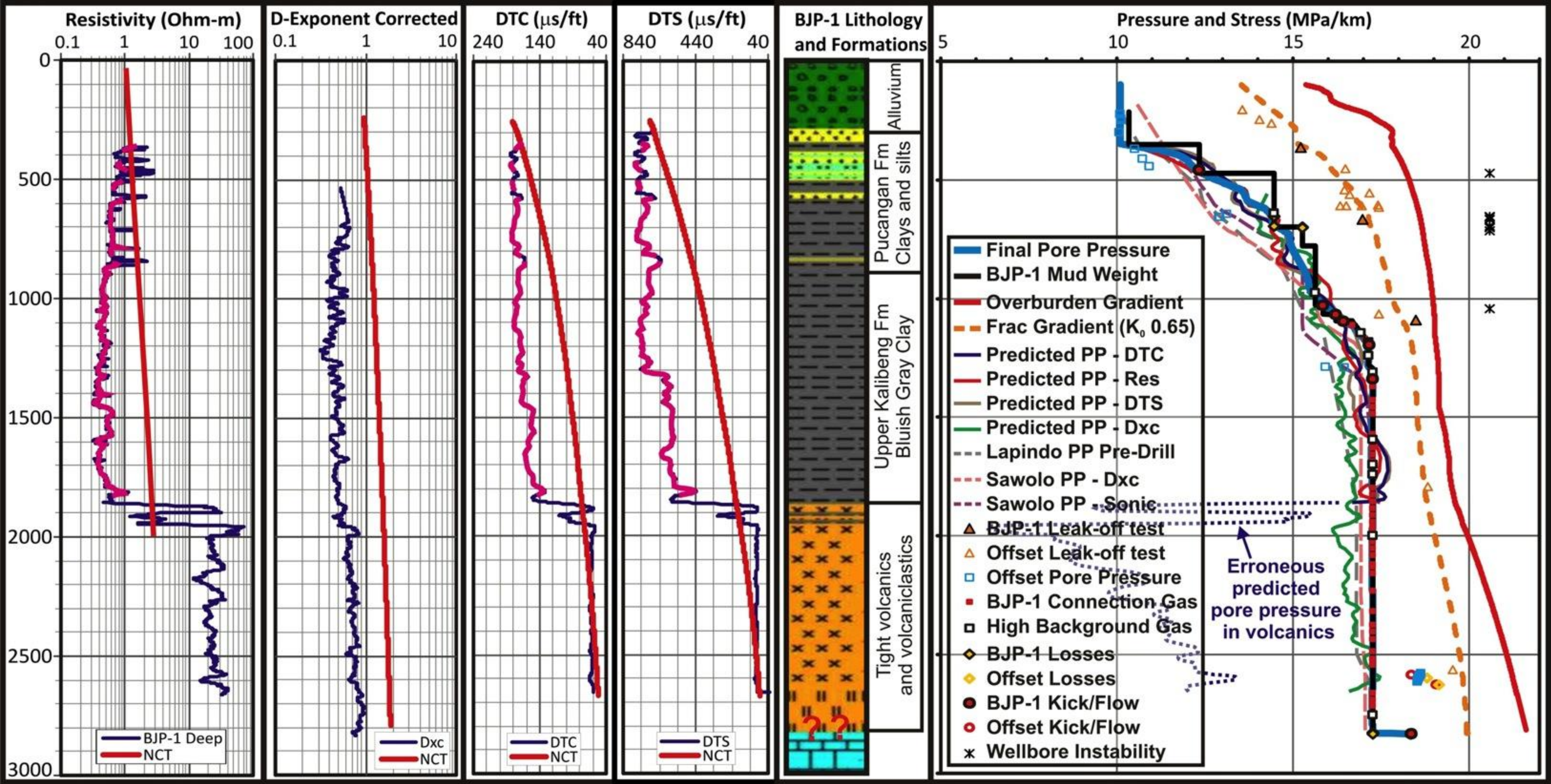
Interpretation / February 2015 SE33

Pore Pressure Prediction: Final PP Model



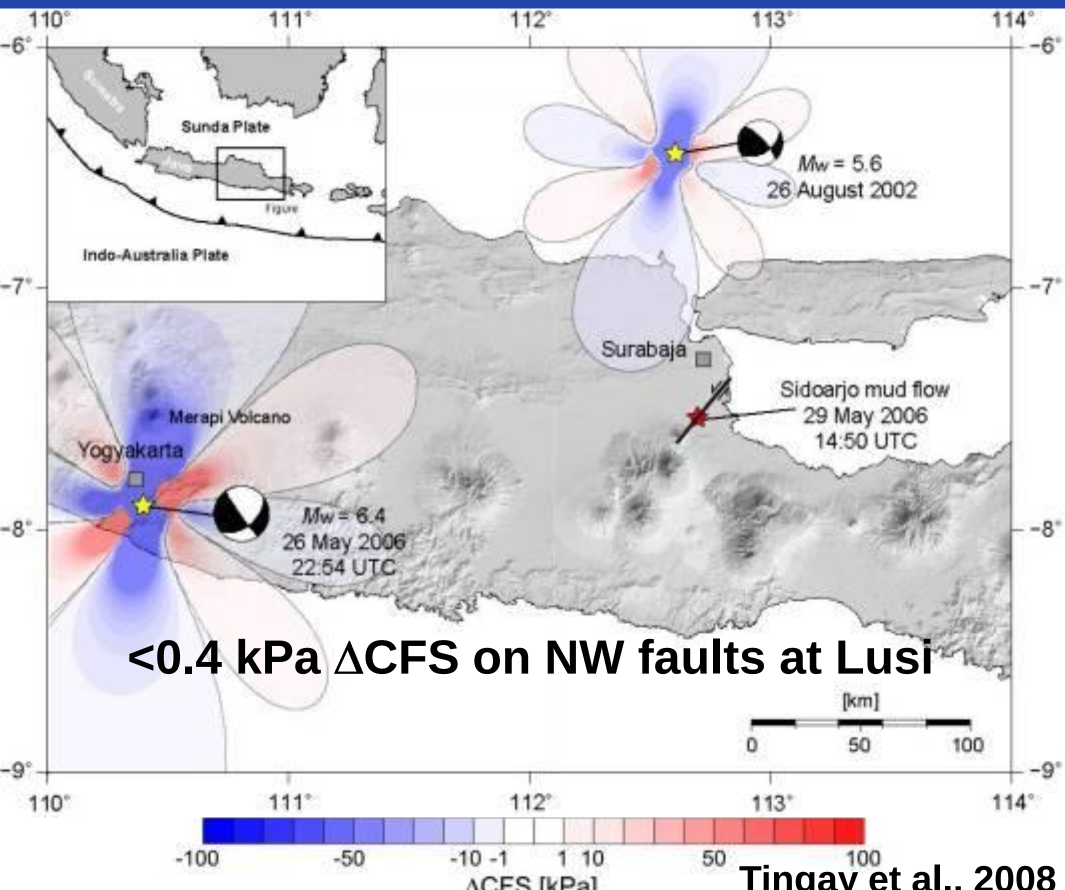
PP predictions using standard Eaton exponents and approximately consistent NCTs for DTC, DTS, Res, Dxc

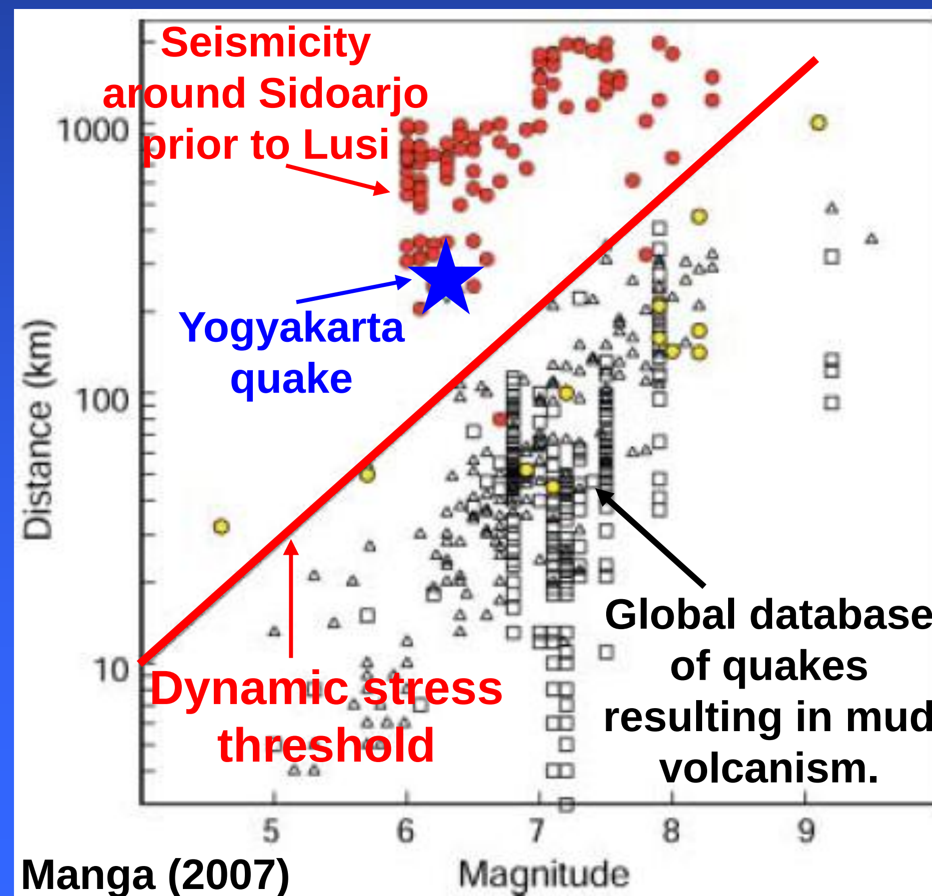
Source: Tingay, 2015

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:

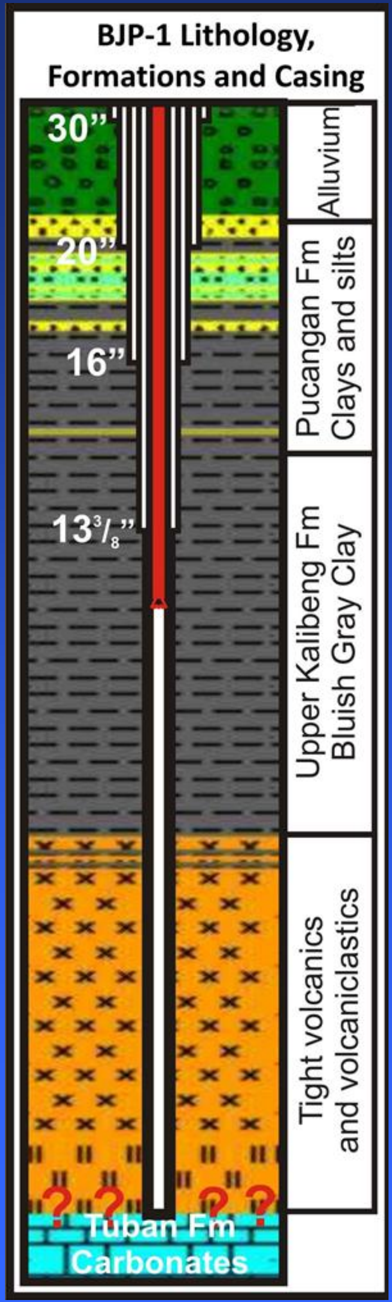
- co-seismically induced stress changes (e.g. ΔCFS); — Too small / far away (<0.4 kPa)
- post-seismic relaxation of static stress changes; } Too far away & too slow
- poroelastic rebound effects, and; } Too far away & too slow
- dynamic stress changes due to seismic shaking. — Too small / far away (max 33 kPa)





<u>Total Losses at TD</u>: 12:50 27/5/06, 2833.7m

- Sawalo et al. (2009) report 130 bbls lost. Daily mud report indicates up to 462 bbls lost at TD.
- 1300-2200hrs: Spotted 60 bbl LCM, POOH to 2663m. <u>Check well – static</u>. 600bbls new mud made and transferred to trip tank.
- 2200–0625hrs: POOH, pumping 4-7 stands.
- Sawolo et al. (2009) report “losses stabilized”, “no losses” on POOH, “no apparent drag. Unlikely to swab”.
- Yet, reports note pipe worked from 2652-2591m. “Overpull increasing”; “50% returns at 2469m”; “unable to keep hole full” at 1981m; “total volume displacement hard to counter”.
- **<u>Total losses at TD, and numerous indications that losses were ongoing throughout POOH.</u>**



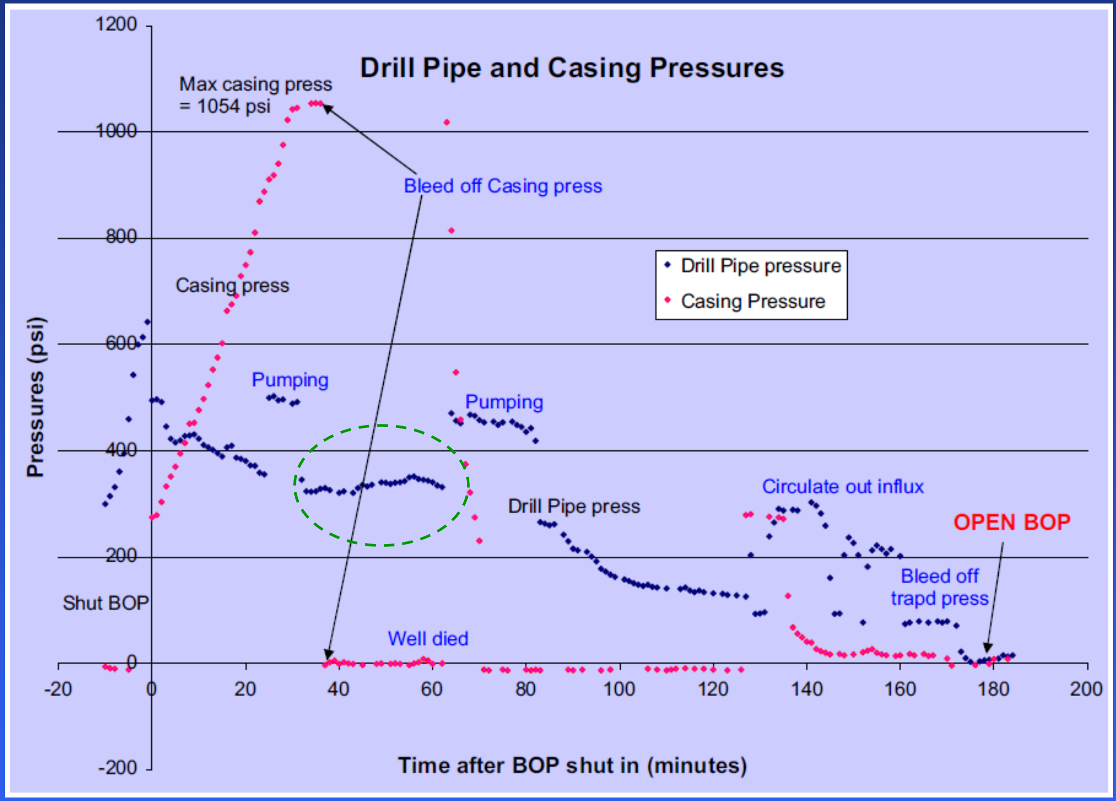
<u>Major Kick</u>: 06:25 28/5/06, ~1275m

- Well flowing 0625hrs. Pumped and pulled two stands. Well kicked 730hrs. >365bbls to surface, 500ppm H_2S, 20% gas. Well shut-in 753hrs.

- Well control. 350psi stabilized DP pressure, max 1054 psi casing pressure, bled through choke. Volumetric method, three periods pumping 15.5 ppg mud to circulate influx.

- Sawolo et al. claim “Well dead” at 805hrs (~60 mins).

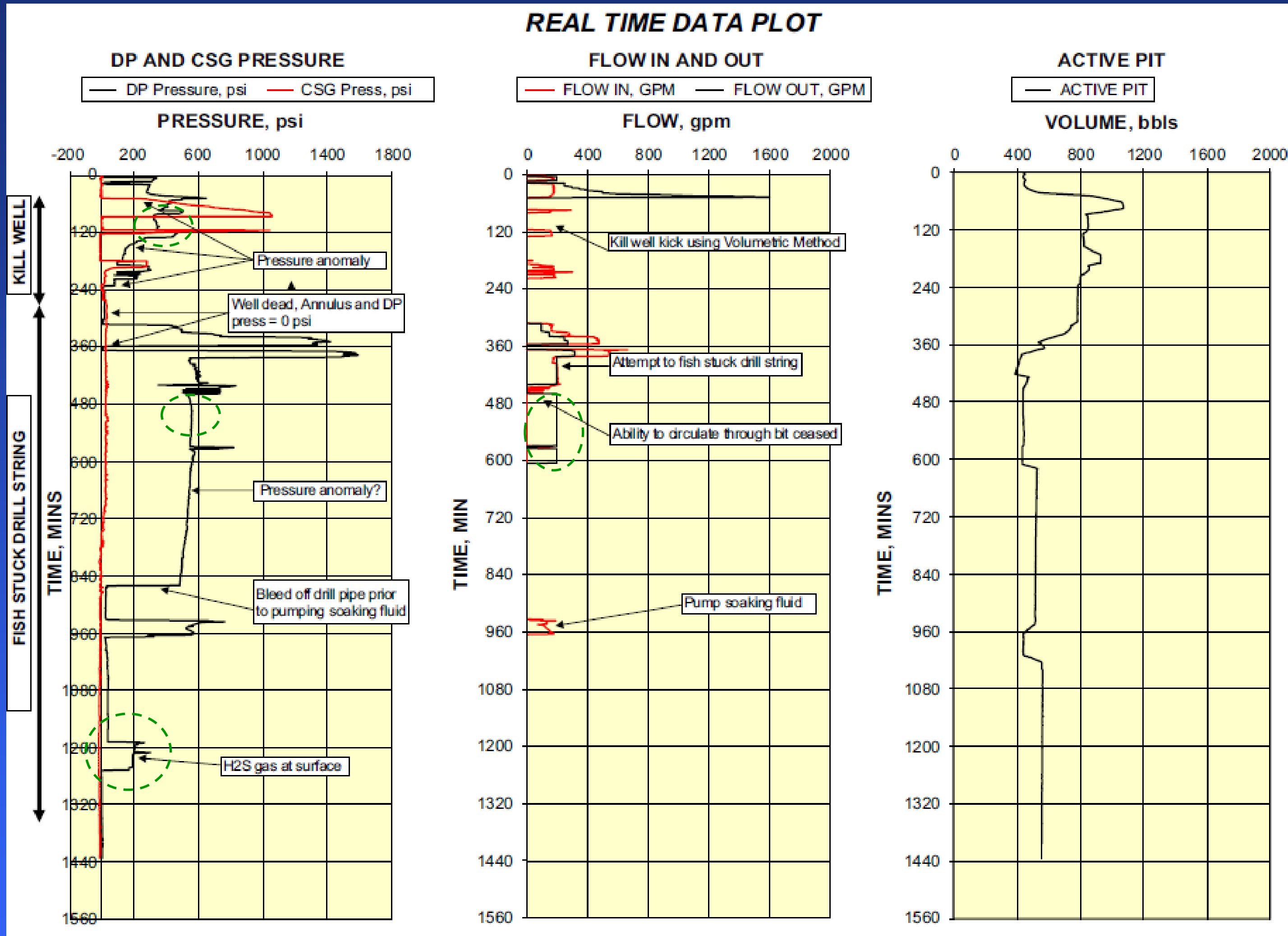
- **<u>BOP opened and well static for ~1hr (1030 – 1130 hrs).</u>**



DP and Csg pressures for 3 hrs after shut-in until BOP opened (Sawolo et al., 2009). Reports that well dead, DP still fluctuating.

Was the kick really killed?

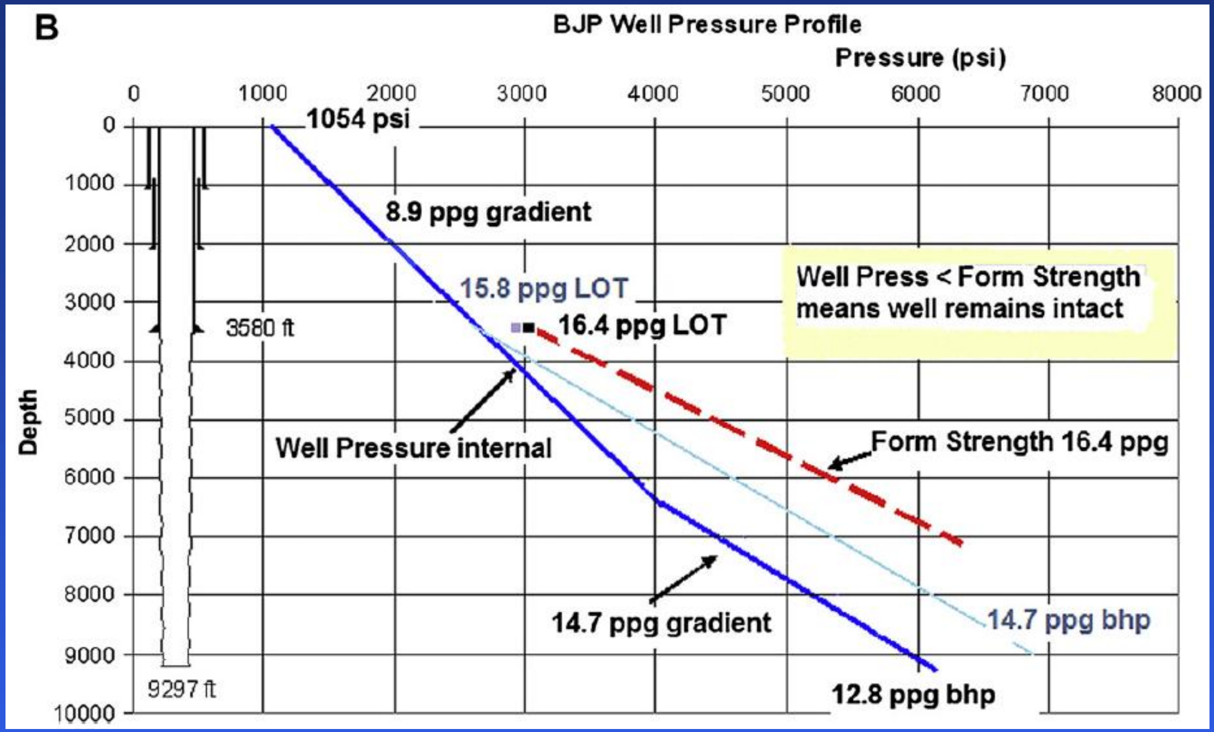
- Several instances of DP pressure and trip tank increases while shut-in, not pumping.
- Evidence for both influxes and losses occurring over 24 hour period.
- ~0200-0300hrs 29/5/06: Sharp increase in DP, "*bubbling around surface*", 35ppm H_2S. **Lusi reported at sunrise ~0500hrs**.



DP and casing pressures and active pit volume for 24 hrs after shut-in (Sawolo et al., 2009). Note several periods where pressures and volumes indicate influx after "well killed".

Underground blowout: Was well integrity lost in kick?

- Sawolo et al. state that "casing shoe was intact and not breached" and indicate no evidence for any losses during kick or connection with Lusi.
- Used max casing pressure, assumed fluid densities and estimated bottom-hole pressure of 12.8 ppg (fill-up method, Dxc, resistivity).
- Argued well pressures below LOP.
- Argued DP pressure unreliable due to float valve.



Pressure profile during BJP-1 kick using surface casing pressure (Sawolo et al., 2009).

Underground blowout: Evidence for Fracturing in Kick?

- Well control 0730-1130hrs 28/5: Casing pressure spikes then drops while pumping when shut-in, indicating losses. Mud engineer reports 300bbl mud loss during well control.

- Attempt to free stuck pipe 1130-1340hrs 28/5: Partial circulation, 50-60% returns. Indications of both losses and influx in this period.

- Stuck and packed off 1430-2100 hrs 28/5: Lost ability to circulate at 1430hrs, no further returns from BJP-1. DP pressures fluctuating, indicating ongoing losses with occasional influxes.

- Pumping effort to stop Lusi ~0630hrs 29/5: pumped 185-230bbls 14.7 ppg mud down DP. "*bubble intensity reduced and elapse time between each bubble is longer*". Bubbling bursts reduced from 8m high at 5min intervals to 2.5m high at 30min intervals.

- Further pumping to try and stop Lusi 2300hrs 29/5 – 1000hrs 30/5: 200bbl 16 ppg LCM, 50bbl 15.8ppg cement slurry, 100bbl 16ppg mud: "bubbles activity decreased since night".

- Injection test 0330hrs 31/5: Pumped 100bbl 15.8 ppg cement slurry to isolate BHA from open hole below. Wait on cement. Injection tests at 2.5bbl/min indicate no further communication between BJP-1 and Lusi.

Sawolo et al., 2009; Tingay, 2015