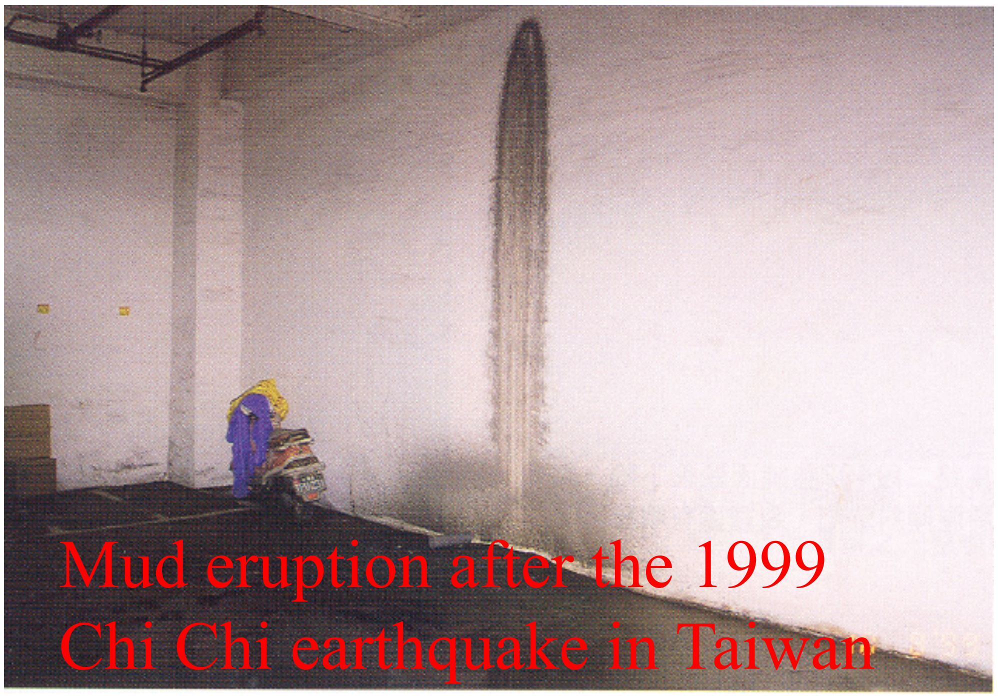
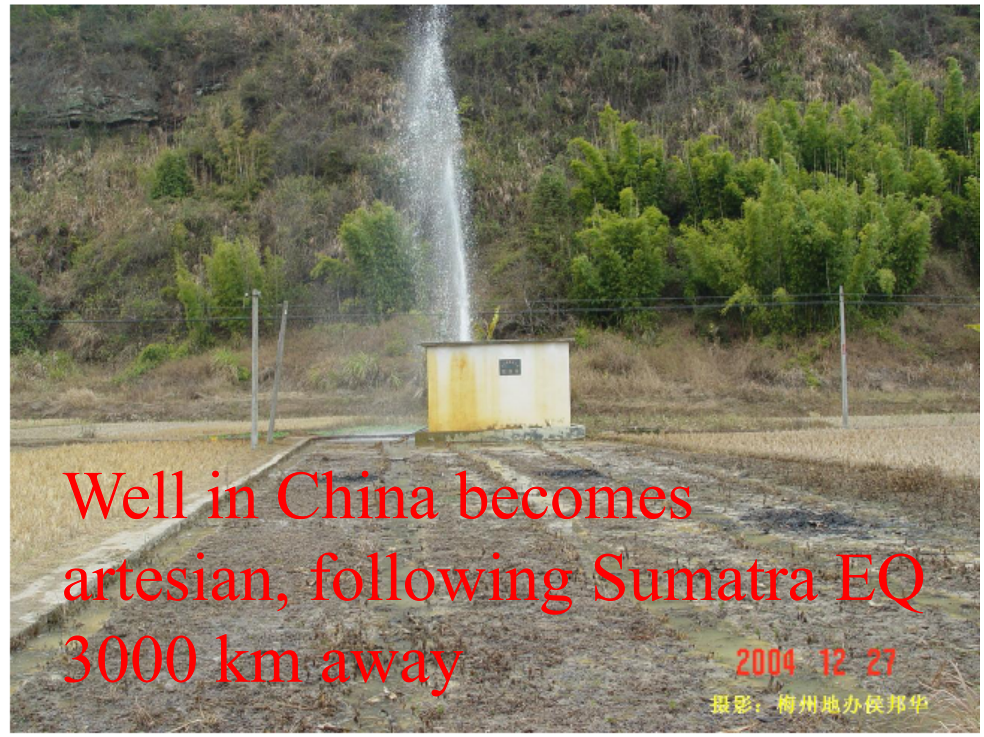
Earthquakes and water

(and why the LUSI eruption was not triggered by an Earthquake)





Michael Manga, University of California, Berkeley

Interrupt and ask questions at any time

Why?

"It's one of those curiosities of nature that has preoccupied people for years"

Stuart Rojstaczer, *Nature*, 2003

Hope to obtain new insight into interactions between stress and subsurface fluid flow, transport and the evolution of hydrogeologic properties

Long history of study (e.g., Pliny, 77 AD) but still not understood

Formerly dry stream that starts to flow after the earthquake (video by Mike Hendry of Hendry winery)

San Francisco Chronicle, Sunday Sept 8, 2014 cover story:
"Surprise bonanza since Napa quake: dry creeks now flowing"

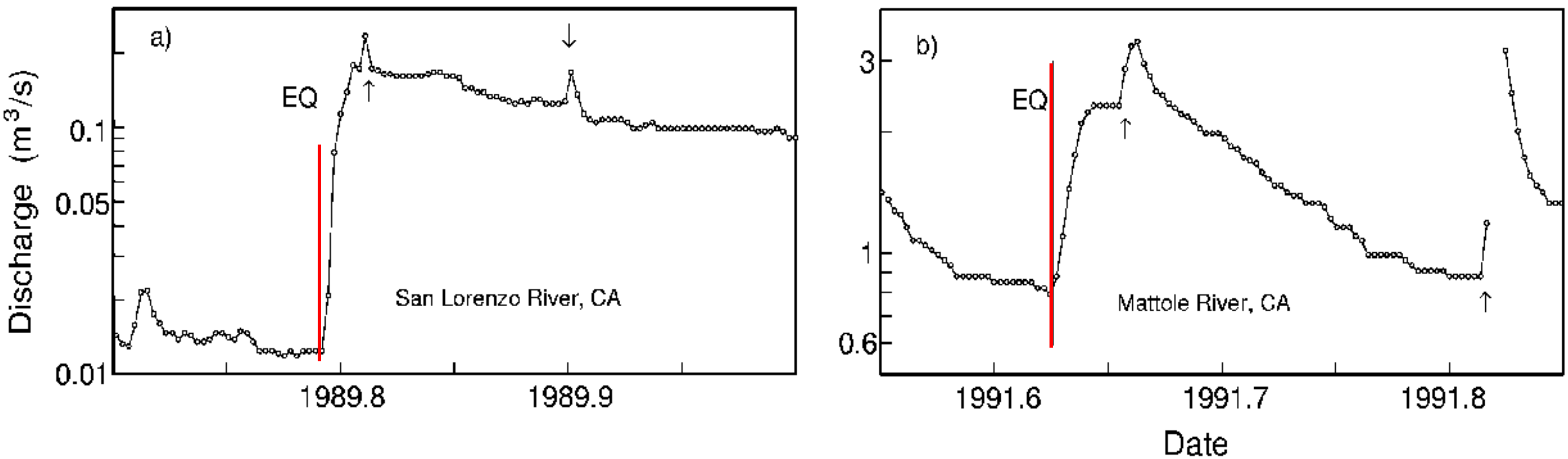
Earthquakes and water

(and why the LUSI eruption was not triggered by an Earthquake)

Examples of hydrological responses to earthquakes

- Liquefaction
- Mud volcanoes (and magmatic ones)
- Stream flow
- Wells (level, temperature, geochemistry)
- Geysers
- Earthquakes
- Precursors

Why does streamflow increase after (distant) earthquakes?



Observed and documented for thousands of years

Distant: more than 1 fault length away from ruptured fault

Origin of excess flow

$$q = -AK\partial h/\partial x$$

Discharge

Hydraulic conductivity

Head gradient

1) Hydraulic conductivity (permeability) increased
2) Head gradient increased (water released from storage)

Five hypotheses

1) Static compression

(e.g., Muir-Wood and King, 1993)

2) Breaching barriers or seals

(e.g., Sibson 1994; Brodsky et al. 2003)

3) Consolidation and liquefaction

(e.g., Manga, 2001; Montgomery et al., 2003)

4) Shaken from the unsaturated zone

(Mohr, Manga et al., 2015)

5) Permeability enhancement

(e.g., Rojstaczer et al., 1995; Tokunaga, 1999; Sato et al., 2000)

Static stress: permanent changes in stress caused by displacement along the fault

Dynamic stress: temporary stresses created by passage of seismic waves

Five hypotheses

1) Static compression
(e.g., Muir-Wood and King, 1993)

2) Breaching barriers or seals
(e.g., Sibson 1994; Brodsky et al. 2003)

3) Consolidation and liquefaction
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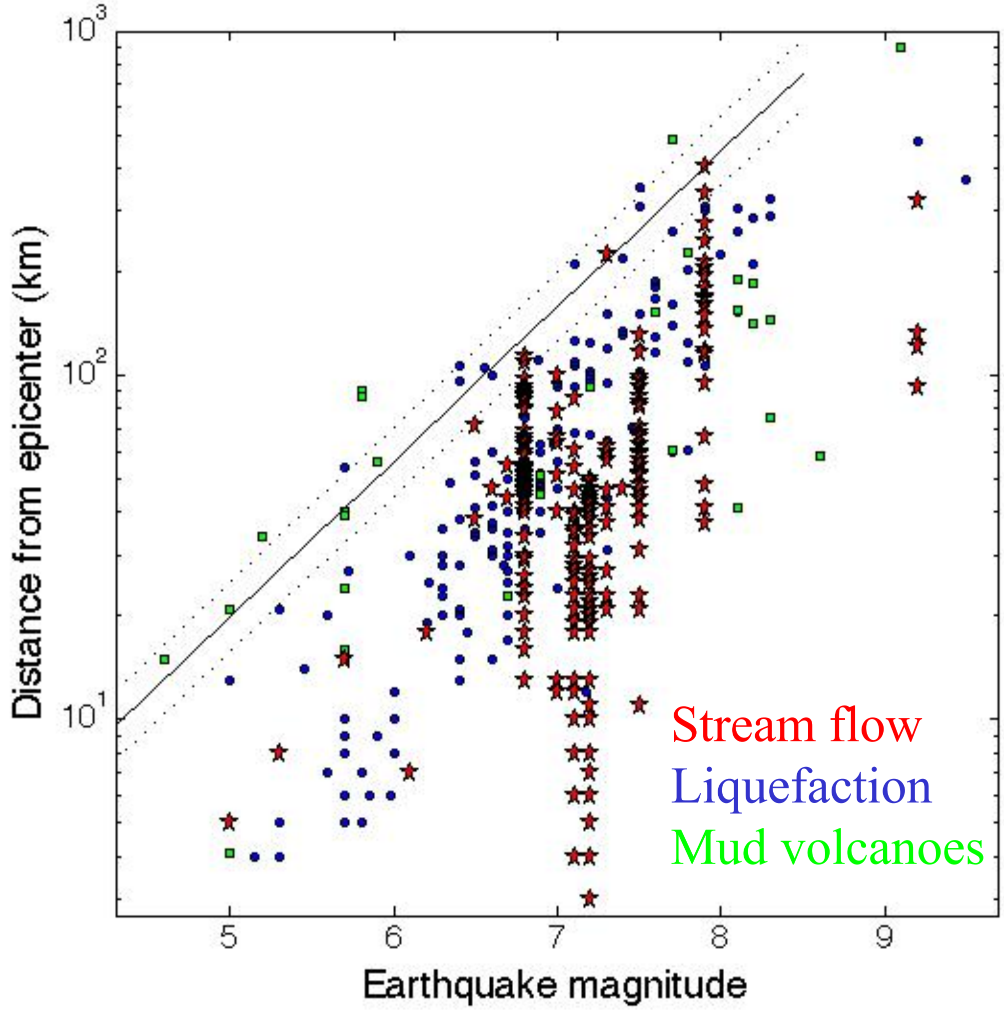
(Mohr, Manga et al., 2015)

5) Permeability enhancement
(e.g., Rojstaczer et al., 1995; Tokunaga, 1999; Sato et al., 2000)

Why consolidation or liquefaction?

Similar magnitude-distance relationships



Where is the excess water coming from?

Five hypotheses

1) Static compression
(e.g., Muir-Wood and King, 1993)

2) Breaching barriers or seals
(e.g., Sibson 1994; Brodsky et al. 2003)

3) Consolidation and liquefaction
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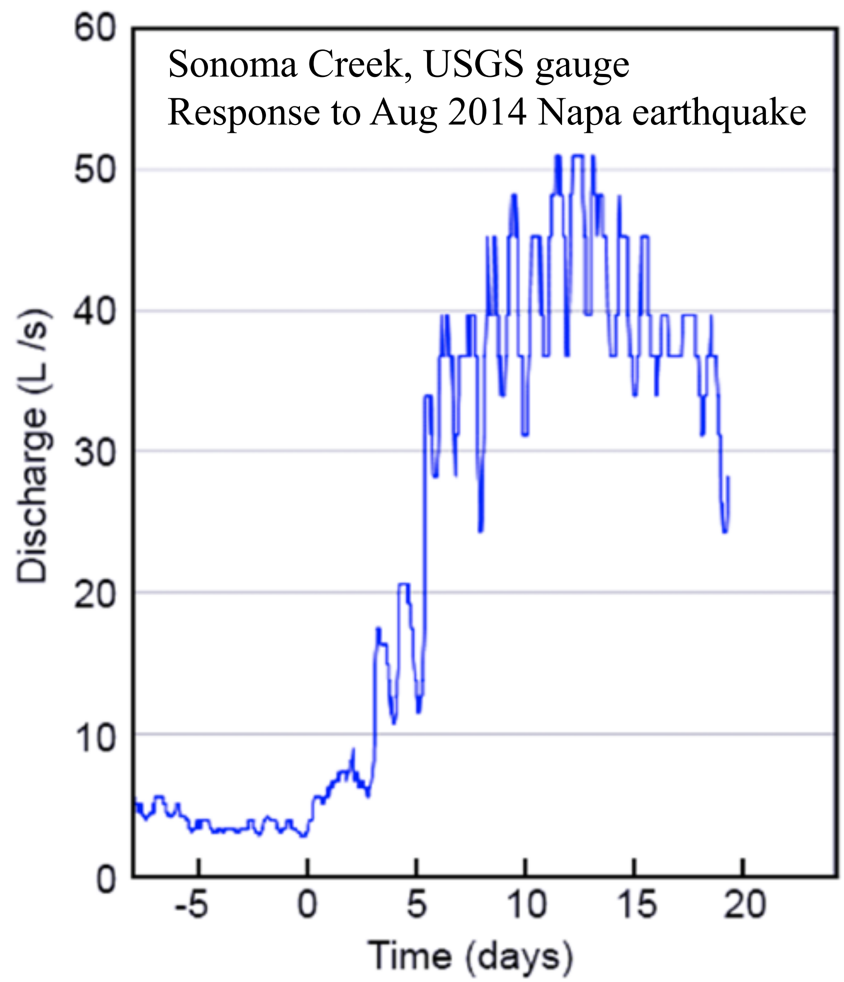
5) Permeability enhancement
(e.g., Rojstaczer et al., 1995; Tokunaga, 1999; Sato et al., 2000)

New streams and springs after the 2014 M6 South Napa earthquake

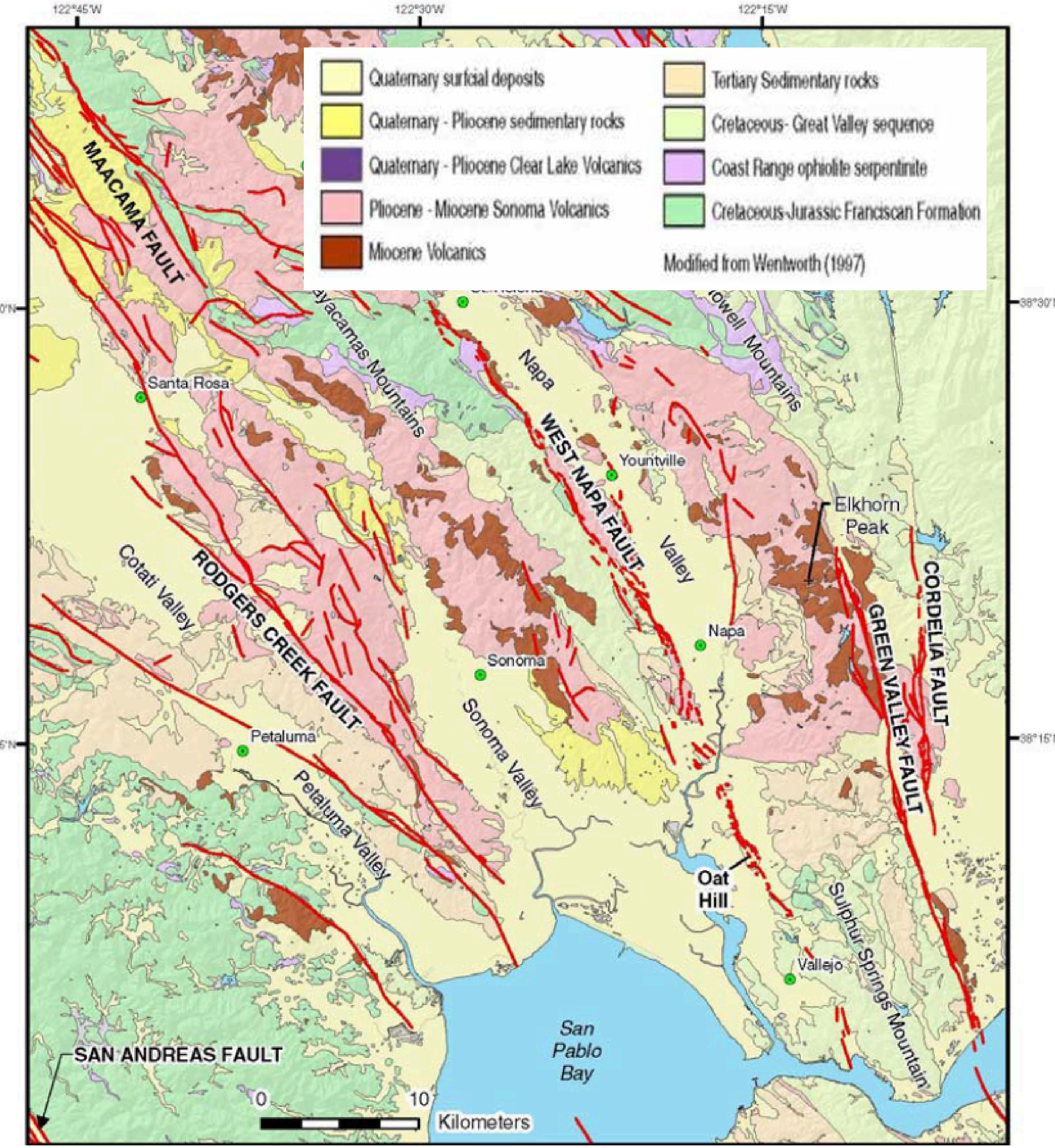


Key: streams were dry before earthquake
No significant rain for ~ 2 months after earthquake

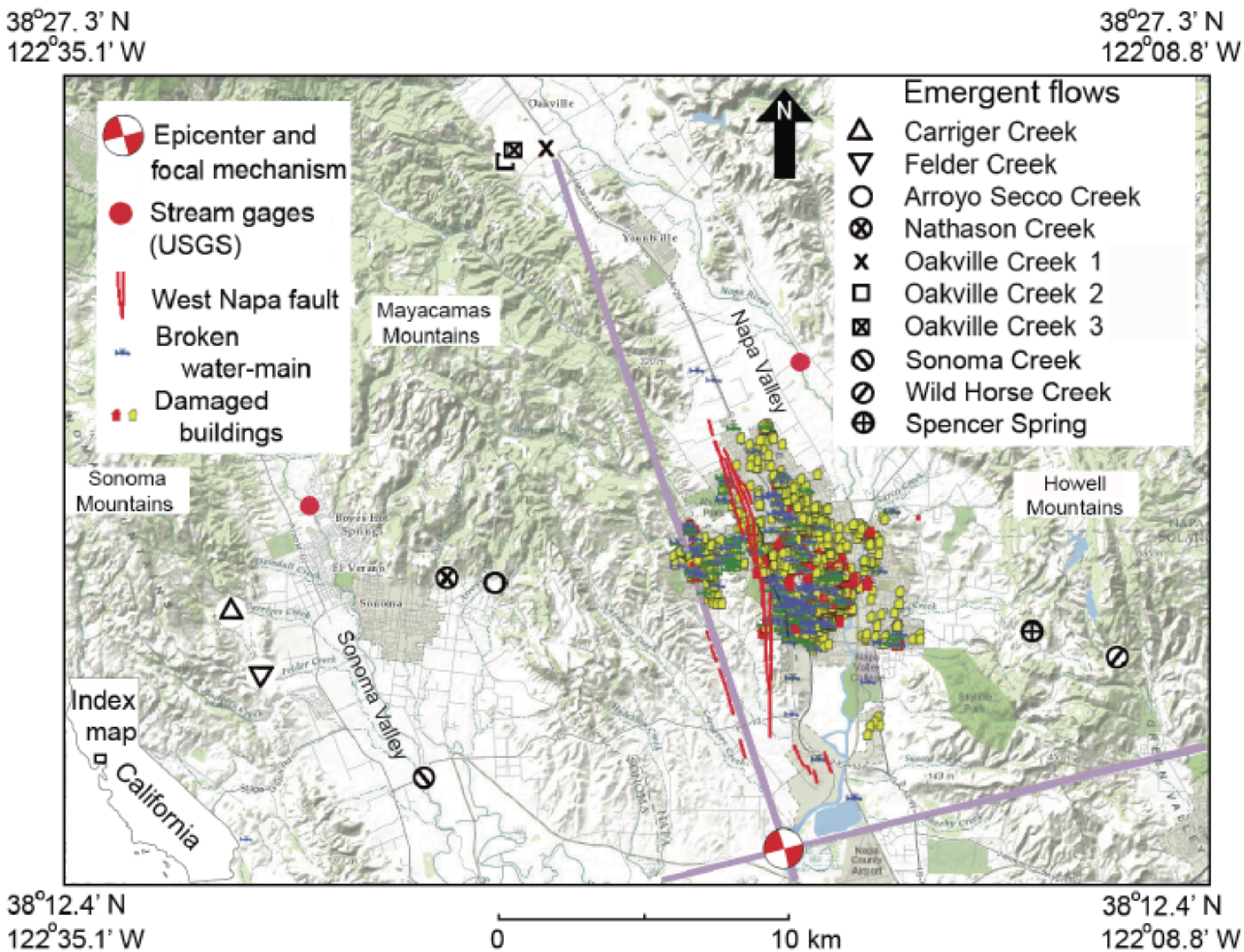
Geologic setting

The Napa-Sonoma Valleys are structural troughs between the Coast Ranges north of San Francisco Bay

Valleys are filled with Quaternary alluvial deposits that overlie Plio-Pleistocene sedimentary rocks, which in turn overlie Miocene to Pliocene Sonoma volcanics of uncertain thickness.
Mountains consist mostly of the Sonoma volcanics, with soil cover rarely exceeding a meter in thickness.



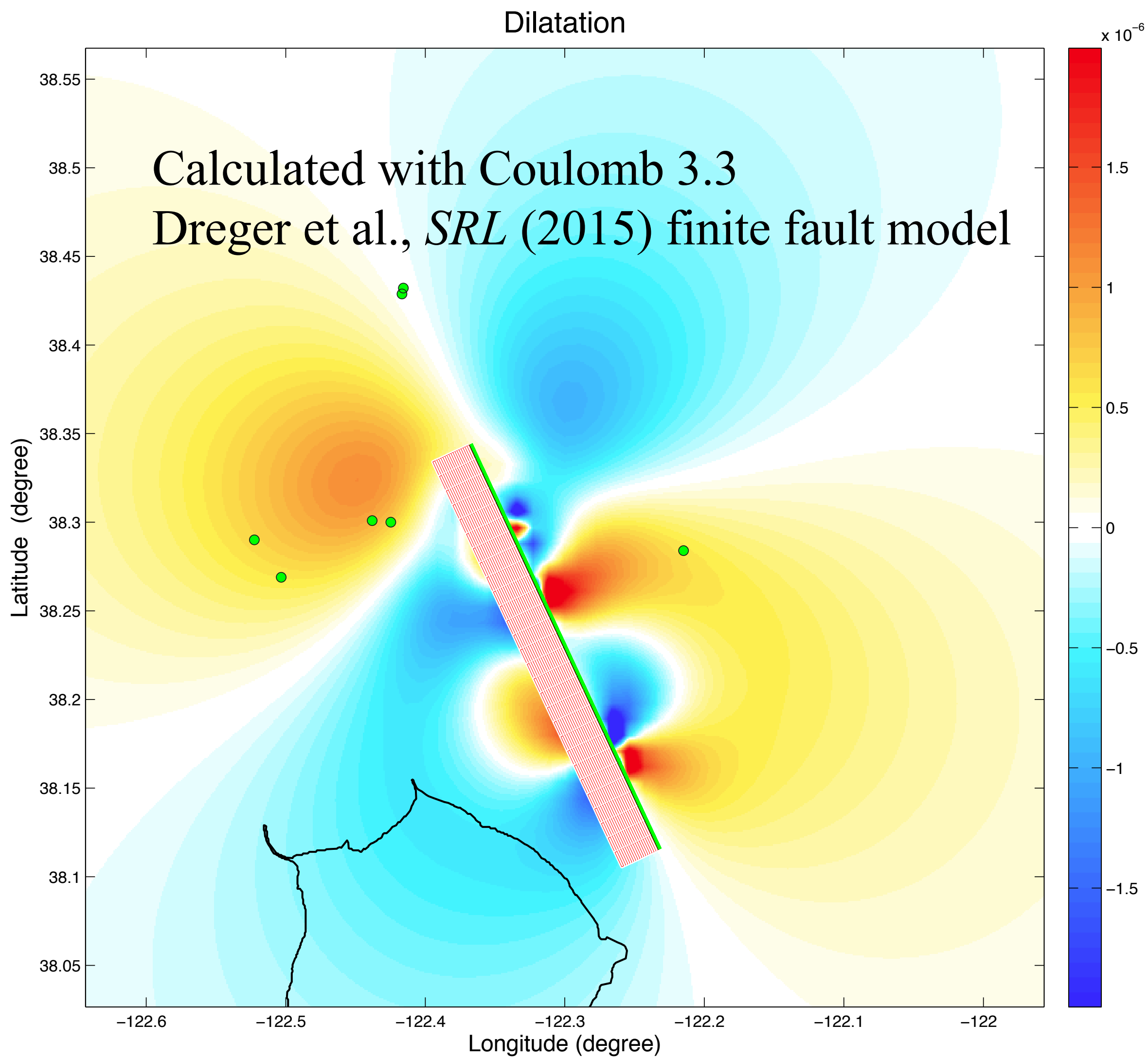
0. Where is water coming from?



Wang and Manga, *Nature Communications* (2015)

Water emerges at base of mountains, not in the alluvial deposits

1. Static strain?



Flow ALWAYS increased, even for small or negative volume strain

(implication, if correct: given a few mm of new flow and strains, water must be expelled from >10 km of crust!)

2. New (hydrothermal) water?

Concentrations of B and Li in the new streams are much more similar to the regional groundwater than to hydrothermal fluids

3. Liquefaction?

Only a few instances of ground failure or liquefaction (Brocher et al., 2015) and excess water is from the mountains

4. Unsaturated zone?

Sampled waters for O and H isotopes, and find no signature of evaporation in new flows

details and data in Wang and Manga, *Nature Communications* (2015)

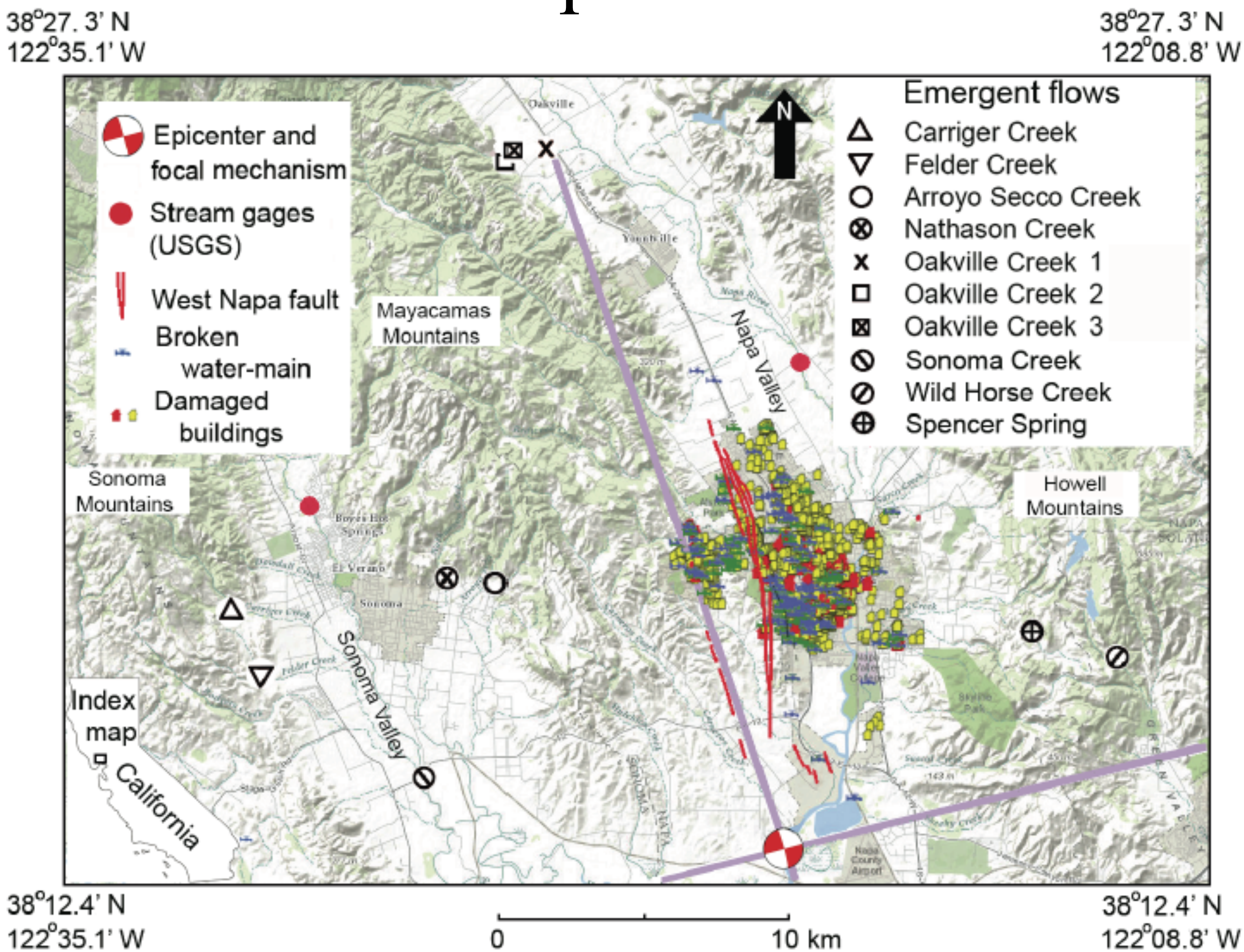
2. New (hydrothermal) water?

Sample	Date	Li (ppb)	B (ppb)
Oakville 1	10/1/14	27.1	431
	10/11/14	27.8	447
Oakville 2	10/1/14	32.6	587
	10/11/14	38.1	467
Oakville 3	10/1/14	9.7	537
	10/11/14	27.5	574
Felder	10/1/14	27.7	92
	10/11/14	28.4	96
Arroyo Seco	10/1/14	8.3	43
	10/11/14	9.1	48
Carriger	10/1/14	3.6	18
	10/11/14	3.7	19
Nathanson	10/1/14	1.8	18
	10/11/14	1.8	18
Spencer Spring	10/11/14	79.4	739
*Hydrothermal fluid		1633	10723
*Groundwater		15.5	211

* Forrest et al., Applied Geochemistry (2013)
Measurements by Ben Thurhoffer and Jim Bishop

Concentrations of B and Li in the new streams are much more similar to the regional groundwater than to hydrothermal fluids (except the warm spring)

3. Liquefaction?



Only a few instances of ground failure or liquefaction (Brocher et al., 2015)

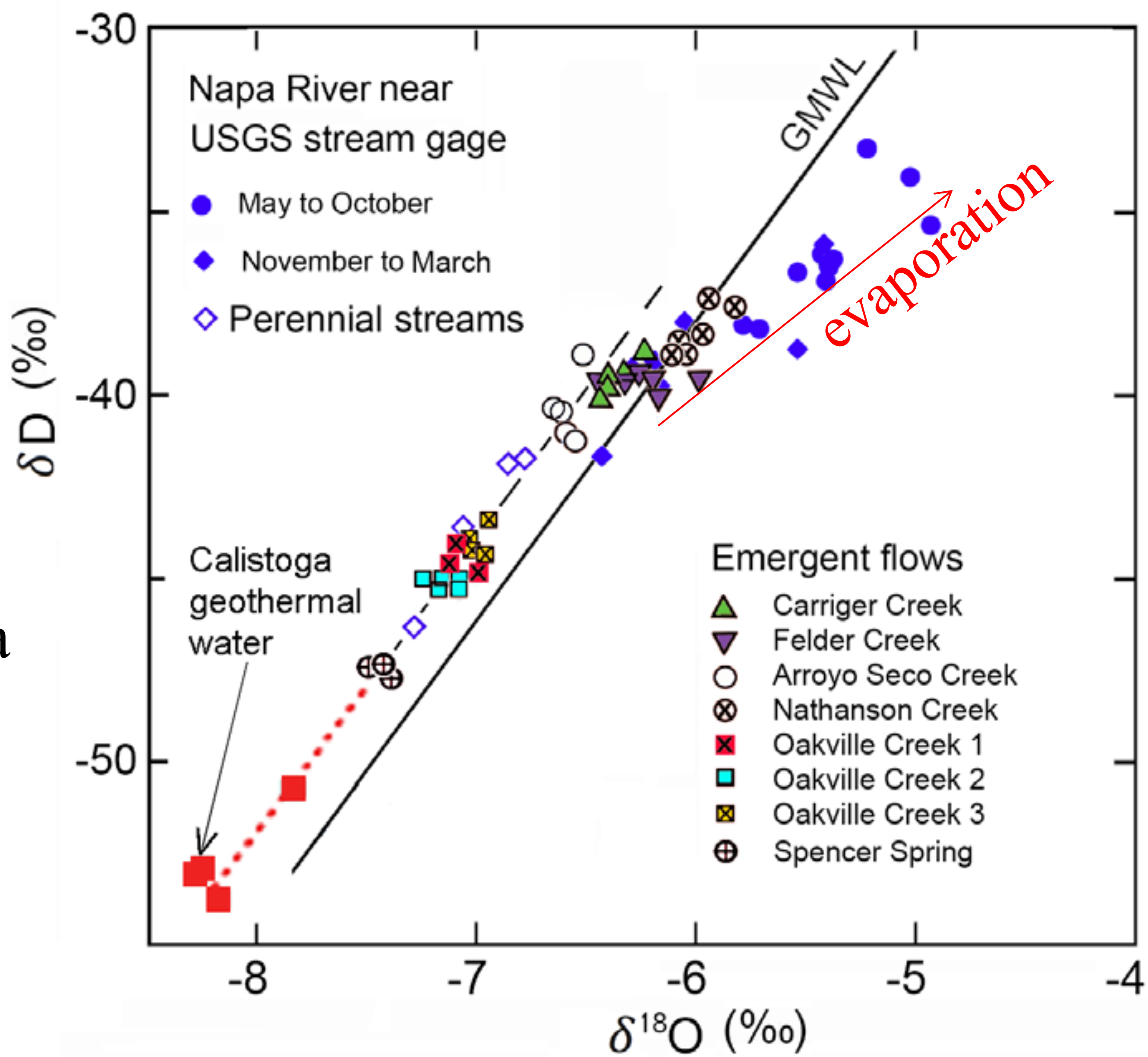
excess water from the mountains

4. Unsaturated zone?

first few months of data

No signature of evaporation in new flows

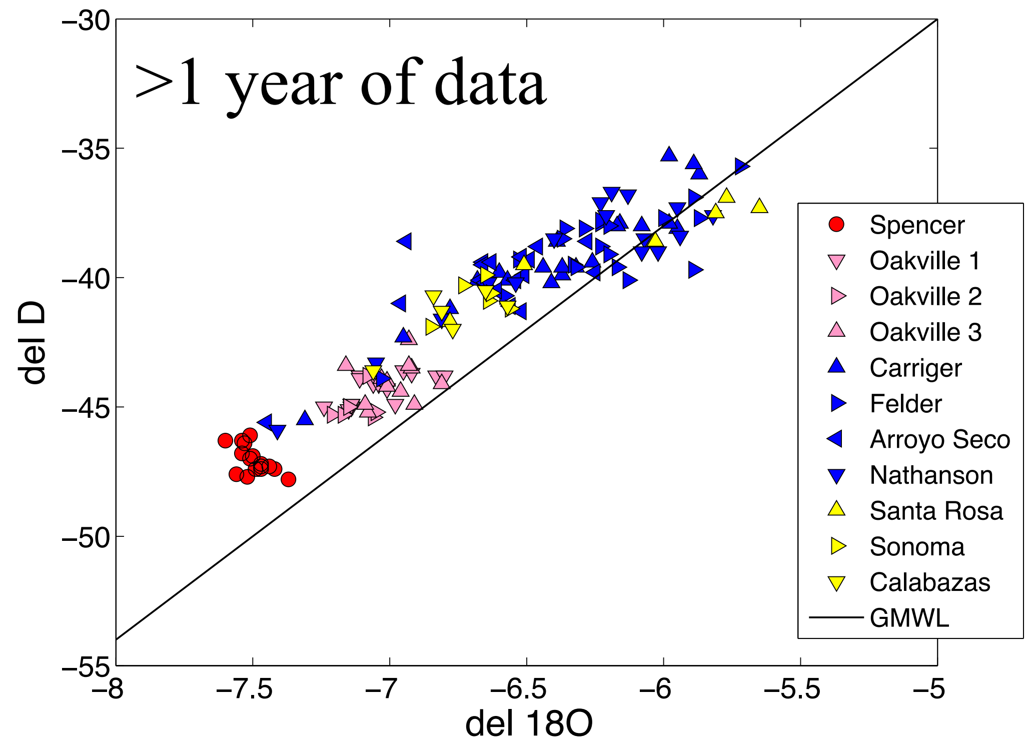
Cannot rule out geothermal water as a source for the excess water.

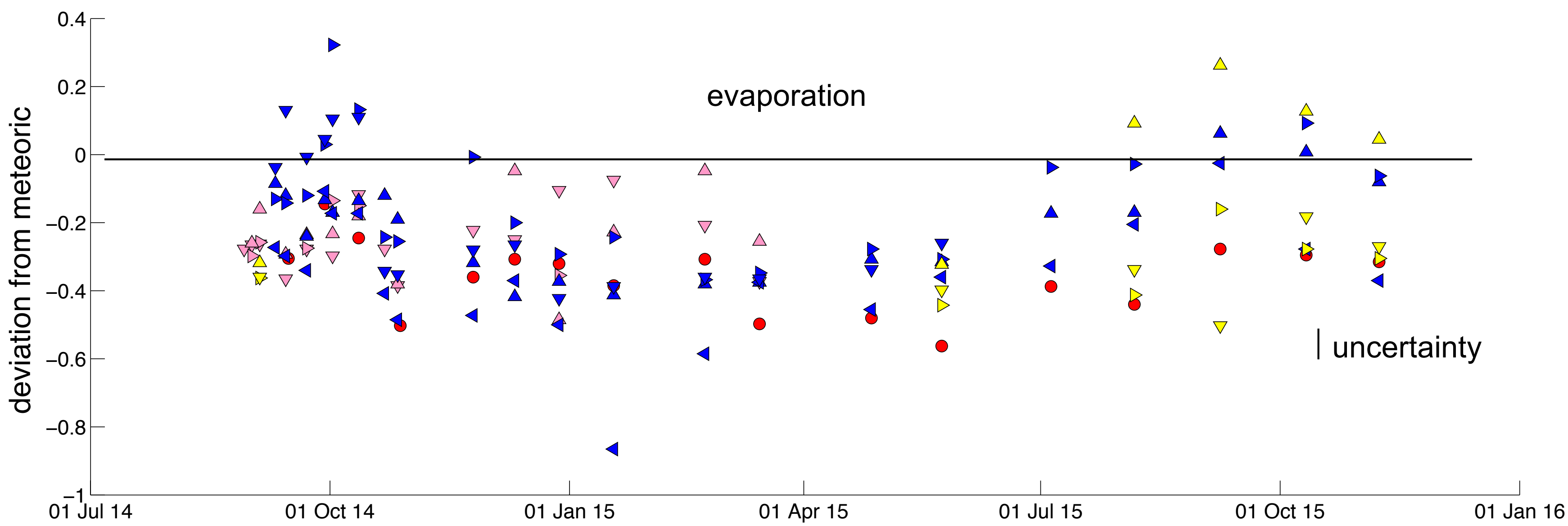


Wang and Manga, *Nature Communications* (2015)

4. Unsaturated zone?

Small seasonal changes in perennial streams; no strong evidence for an evaporation signal



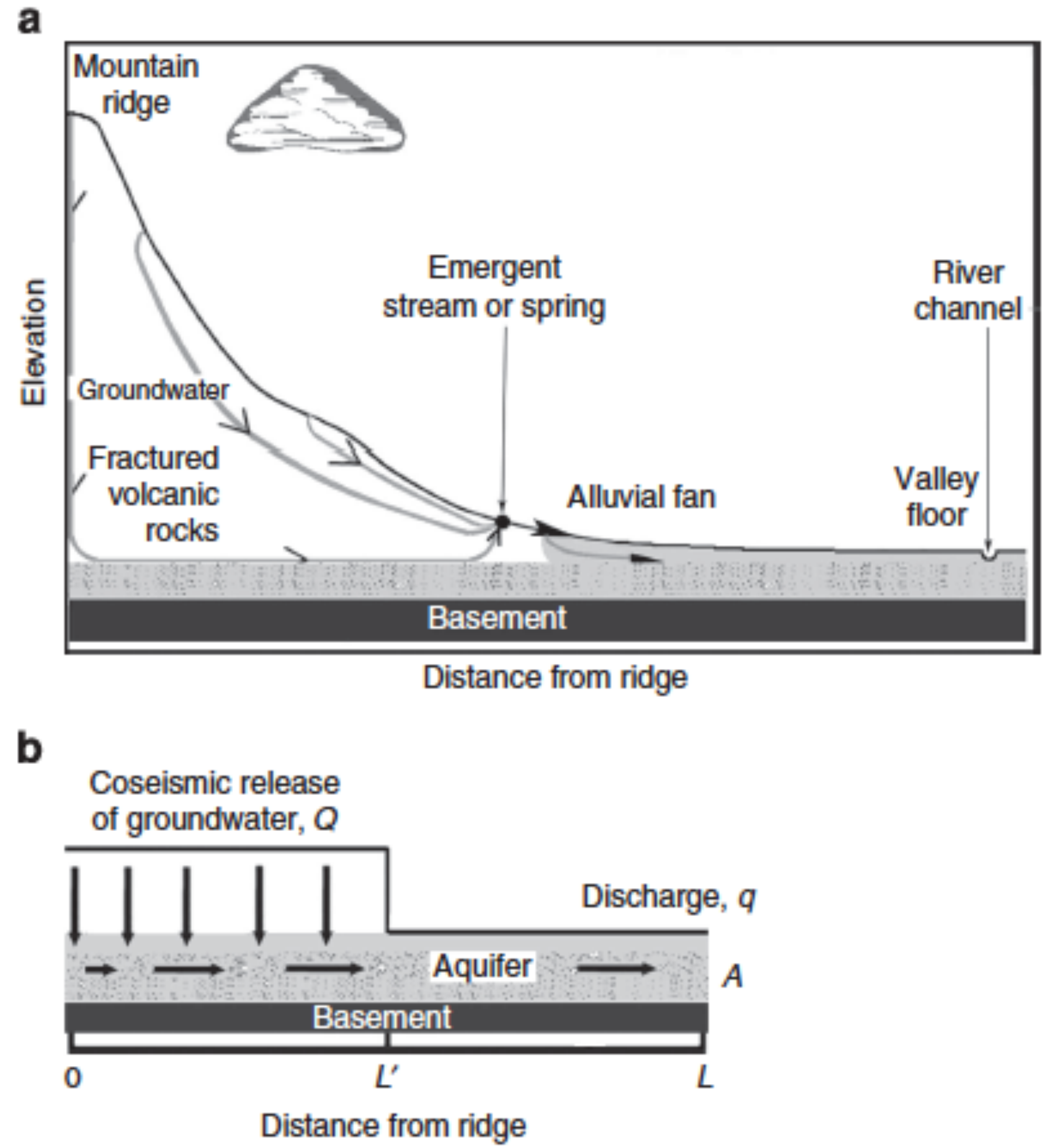


5. Permeability enhancement?

Solve groundwater flow equations analytically

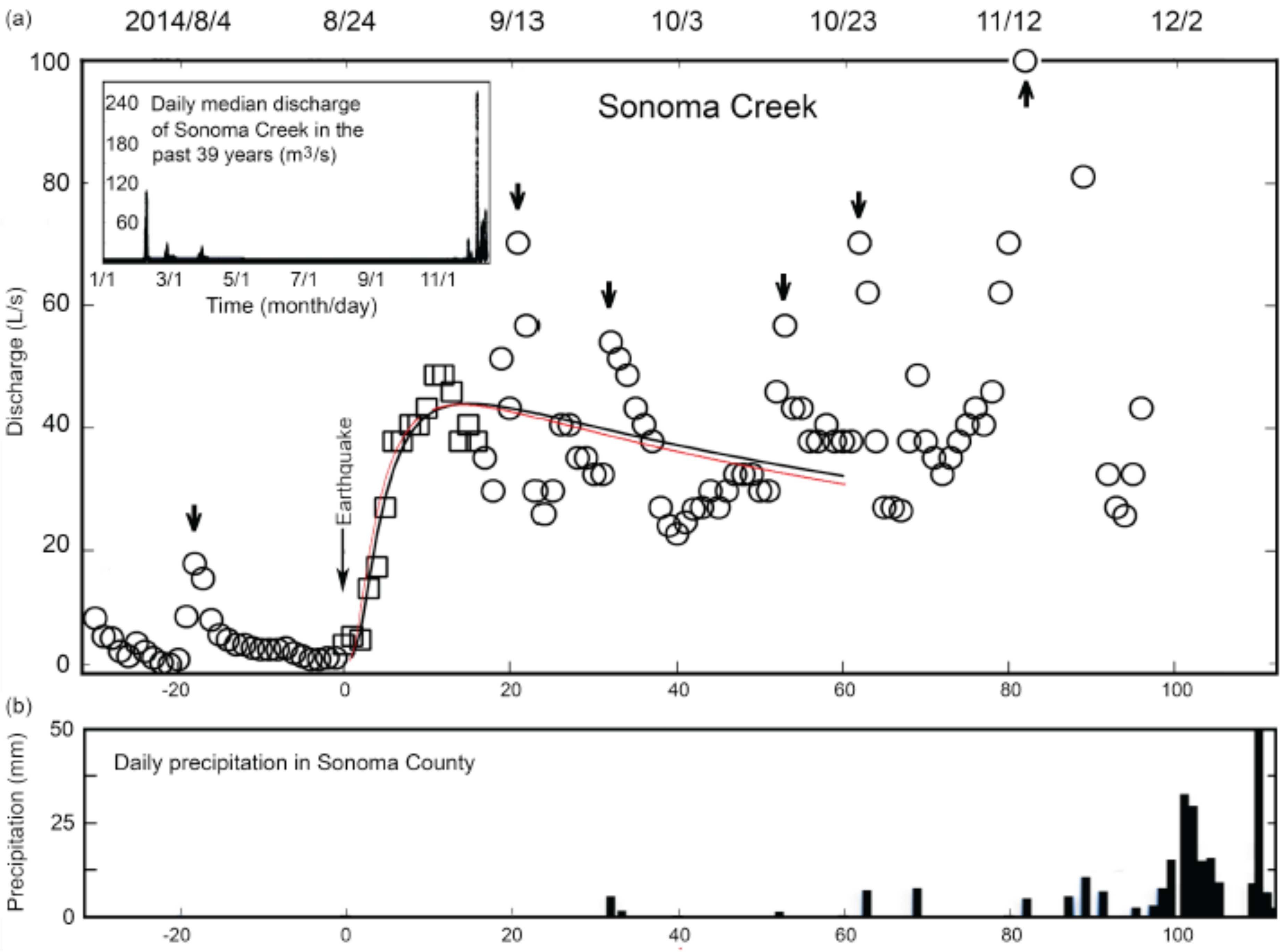
Fit model to data (obtain hydraulic diffusivity and total excess discharge)

Vertical permeability enhancement model of Wang et al., *Geology* (2004)



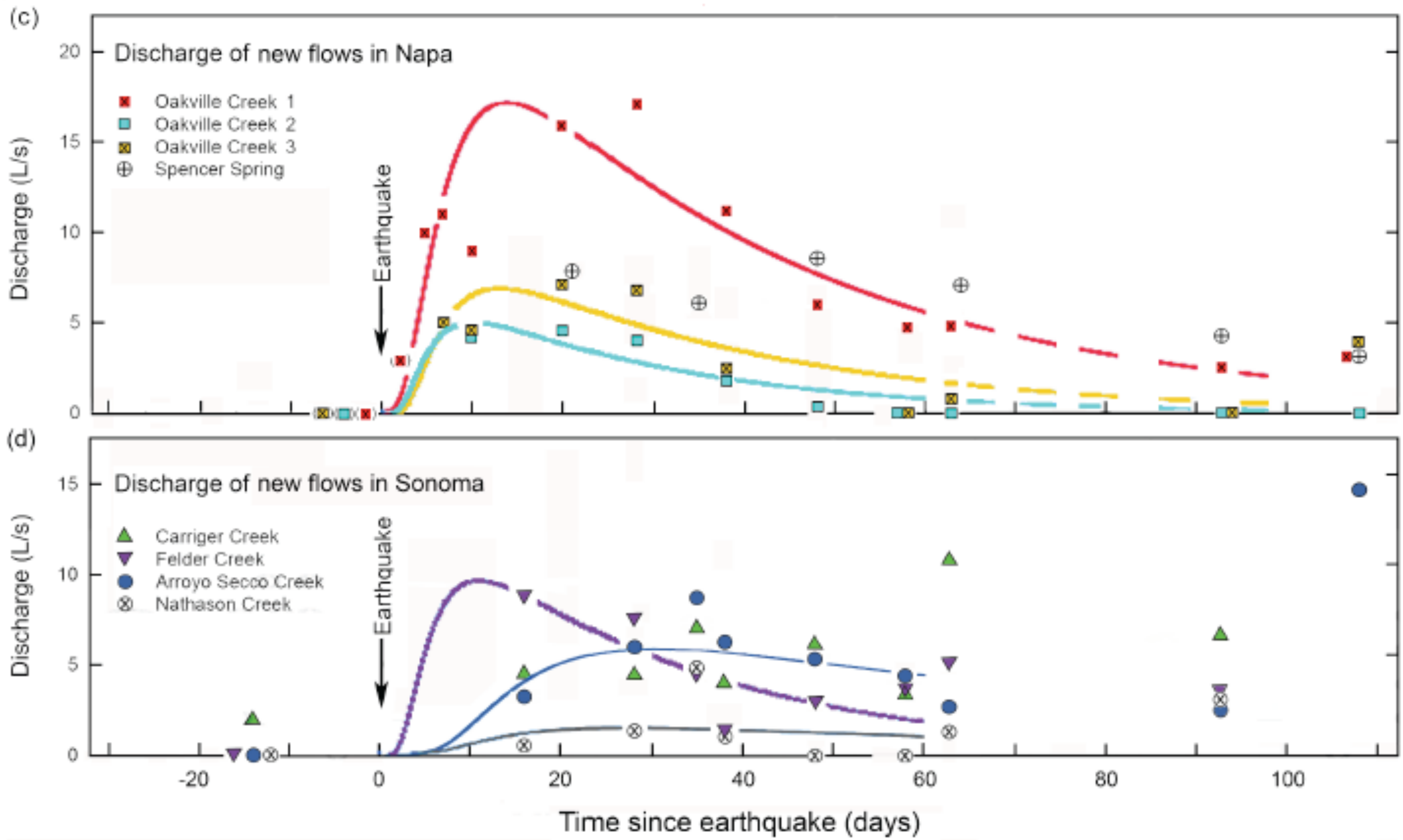
Wang and Manga, *Nature Communications* (2015)

5. Permeability enhancement?



Wang and Manga, *Nature Communications* (2015)

5. Permeability enhancement?

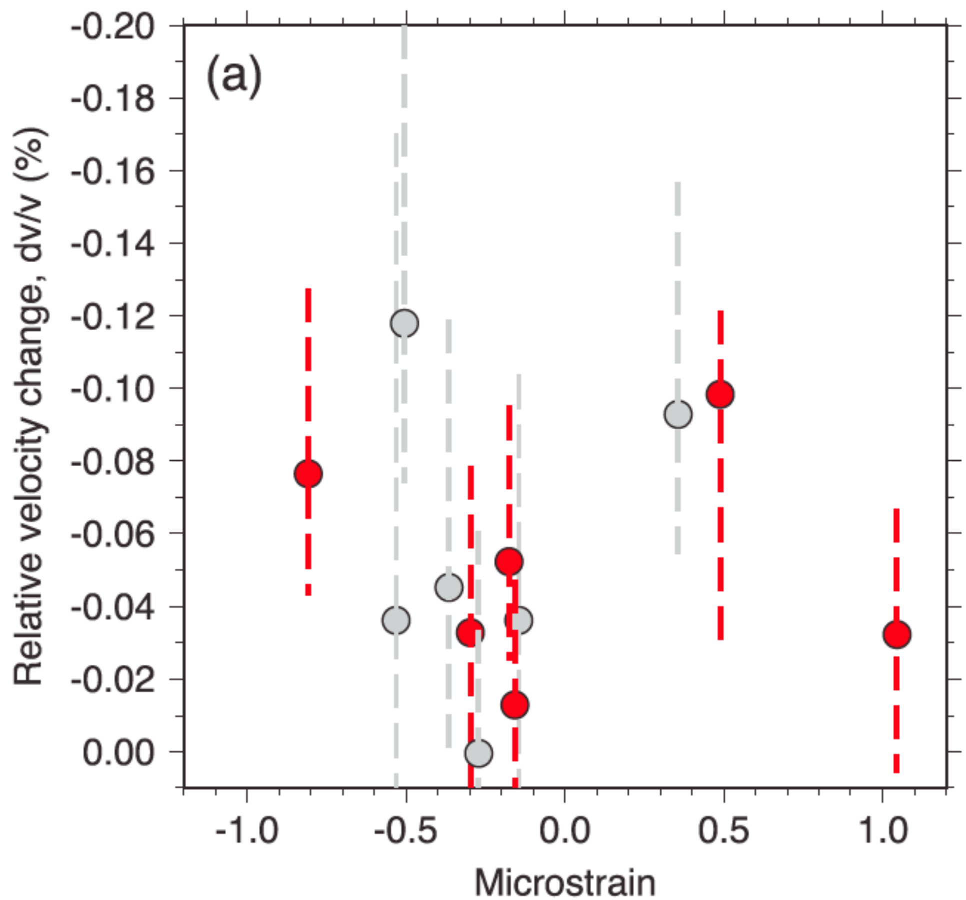


Wang and Manga, *Nature Communications* (2015)

Total excess discharge ~10^6 m^3

5. Permeability enhancement?

Drainage of water would make crust more compressible and lower seismic velocity of shallow crust

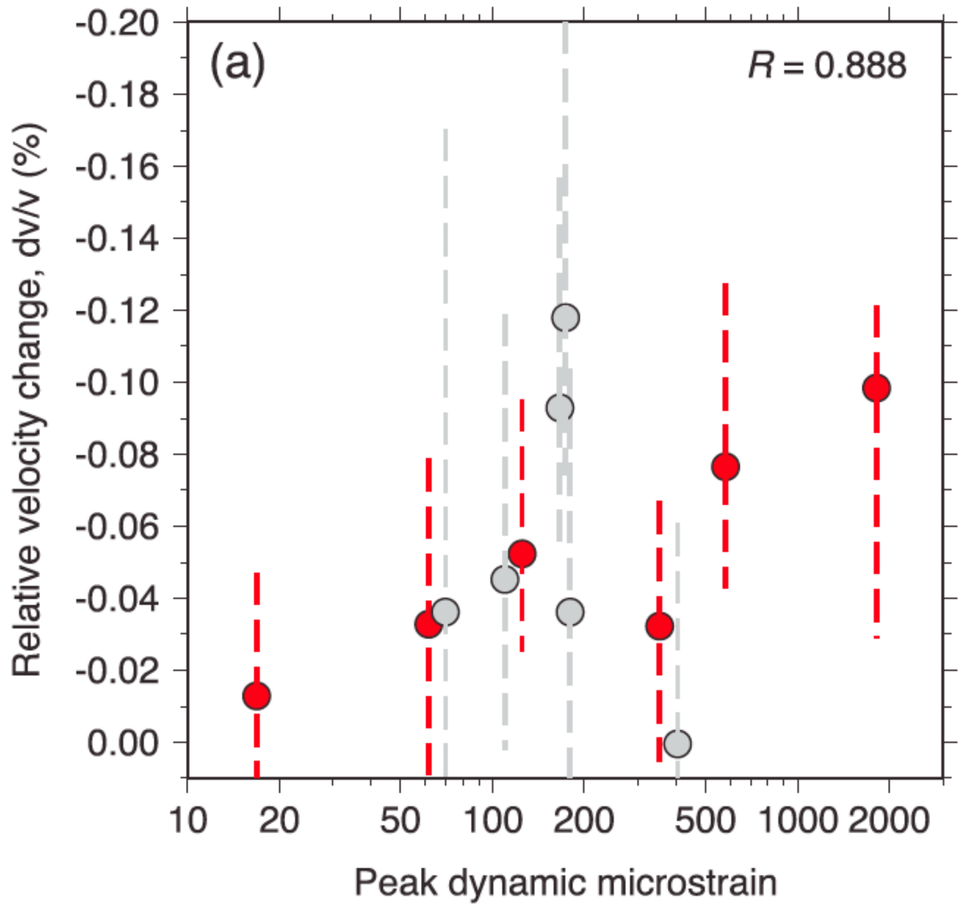


Taira et al., *GRL* (2015) document a velocity decrease

Not correlated with static strain

5. Permeability enhancement?

Drainage of water would make crust more compressible and lower seismic velocity of shallow crust

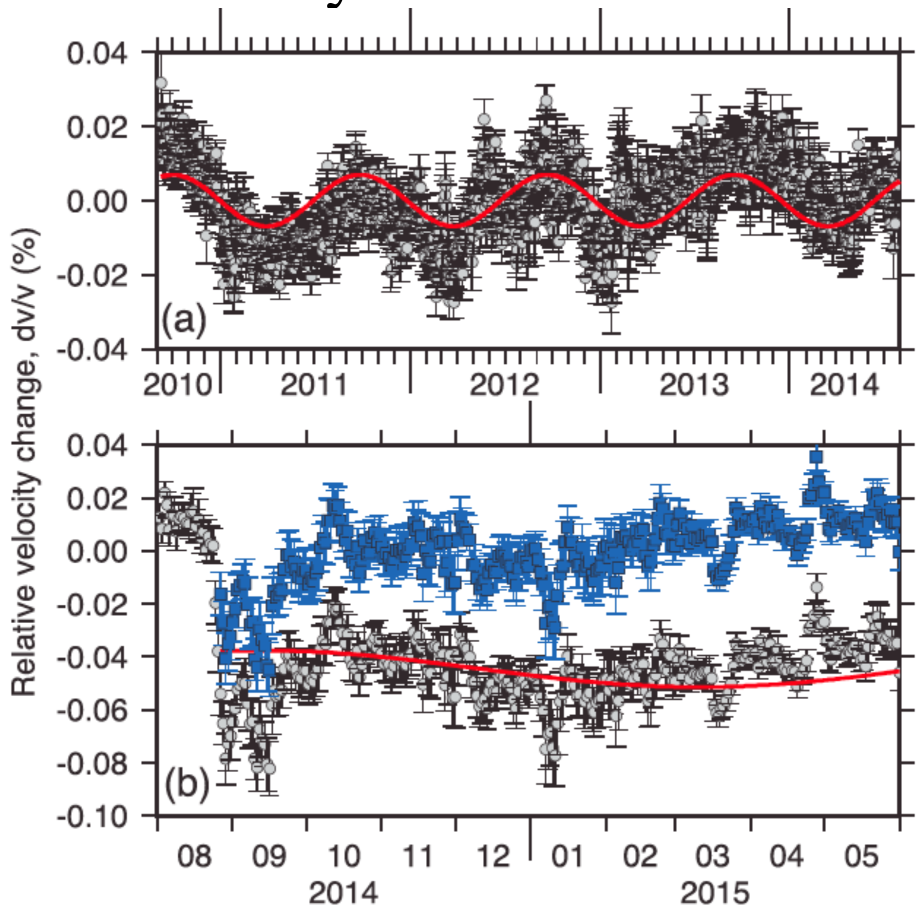


Taira et al., *GRL* (2015) document a velocity decrease

There IS a correlation with dynamic strain

5. Permeability enhancement?

Drainage of water would make crust more compressible and lower seismic velocity of shallow crust



Taira et al., *GRL* (2015) document a velocity decrease

Recovery time scales ~ time with excess discharge

Conclusions

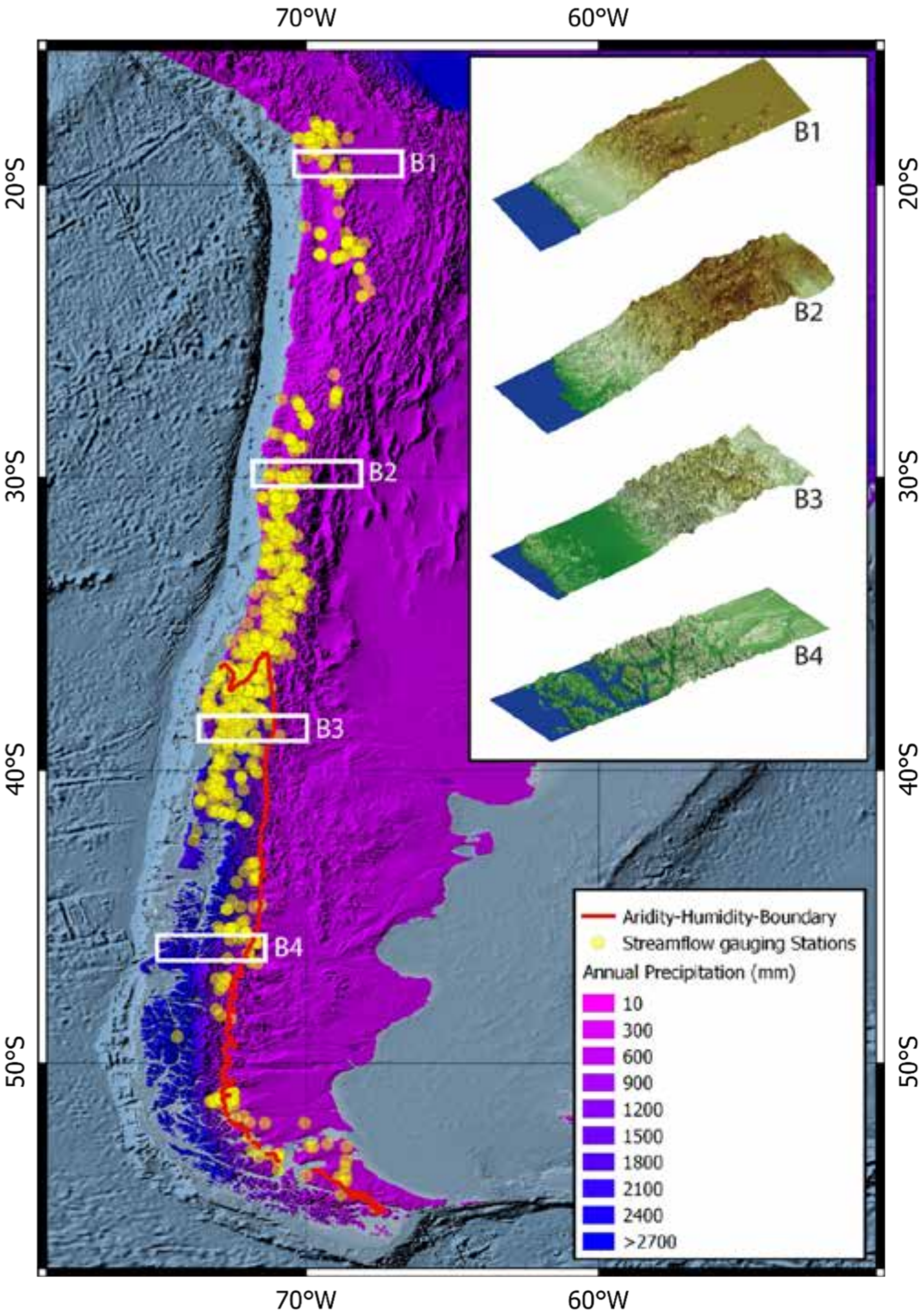
1) Static compression
(e.g., Muir-Wood and King, 1993)

2) Breaching barriers or seals
(e.g., Sibson 1994; Brodsky et al. 2003)

3) Consolidation and liquefaction
(e.g., Manga, 2001; Montgomery et al., 2003)

4) Shaken from the unsaturated zone
(Mohr et al., 2015)

5) Permeability enhancement by dynamic strain
(e.g., Rojstaczer et al., 1995; Tokunaga, 1999; Sato et al., 2000)



Why Chile?

- Strong climatic gradients
- High seismicity
- Steep topography gradients
- Diverse geology
- Long time series of hydrometeorological data

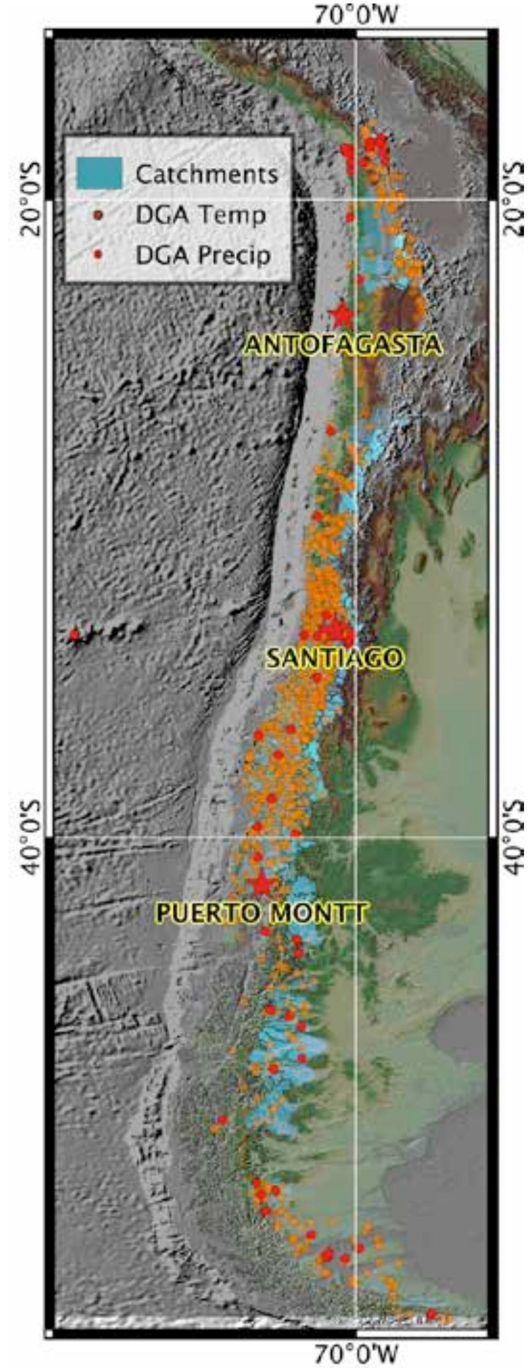
Details in Mohr et al., EPSL (2017)

Data available:

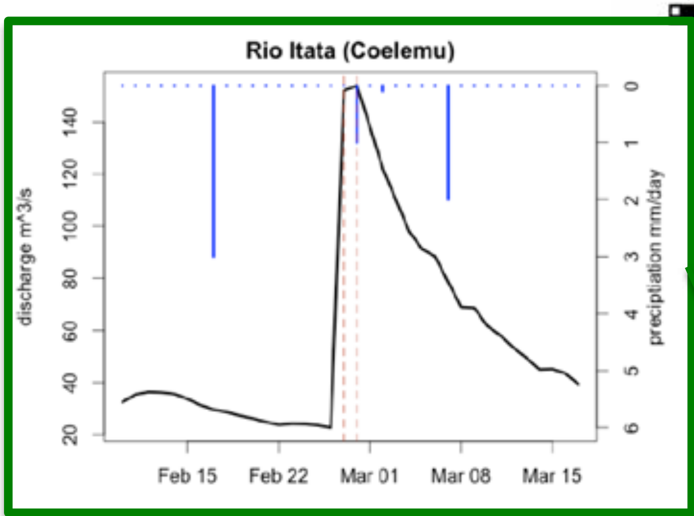
- 716 catchments monitored (1940 -)
- 802 rainfall gauges (1940 -)
- 75 Air temperature stations (1960 -)

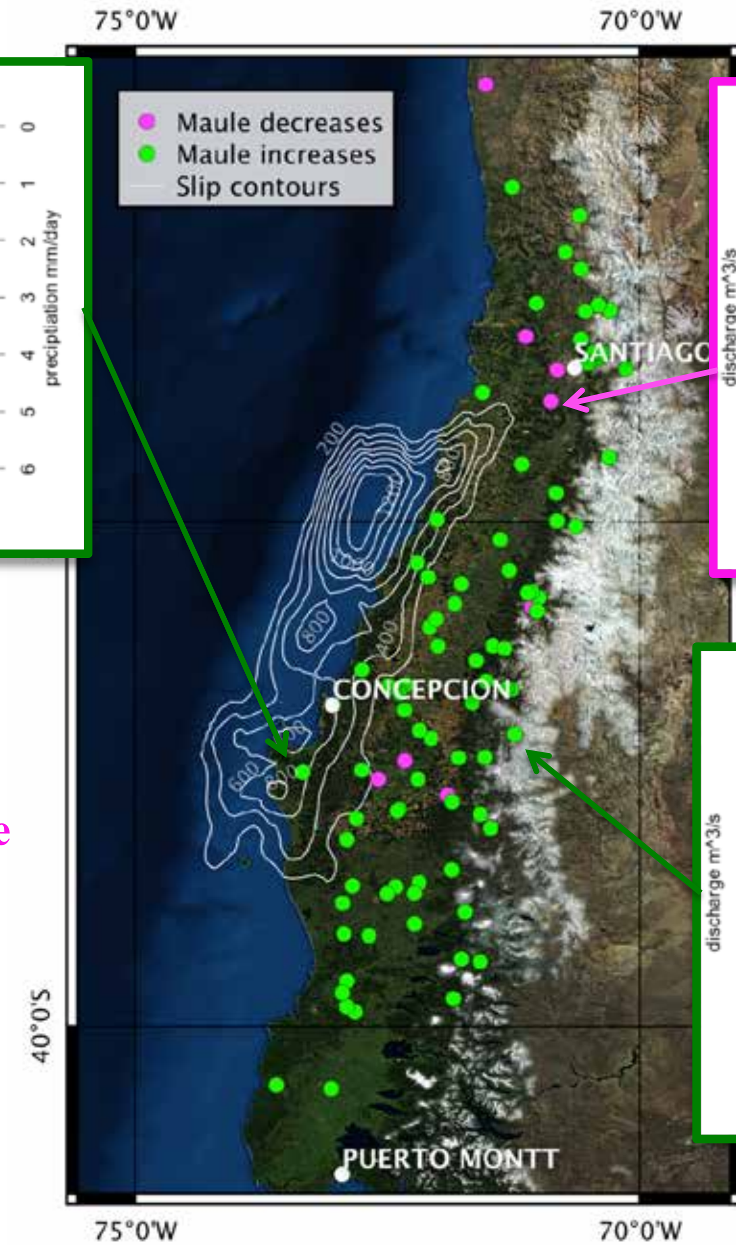
Earthquakes covered:

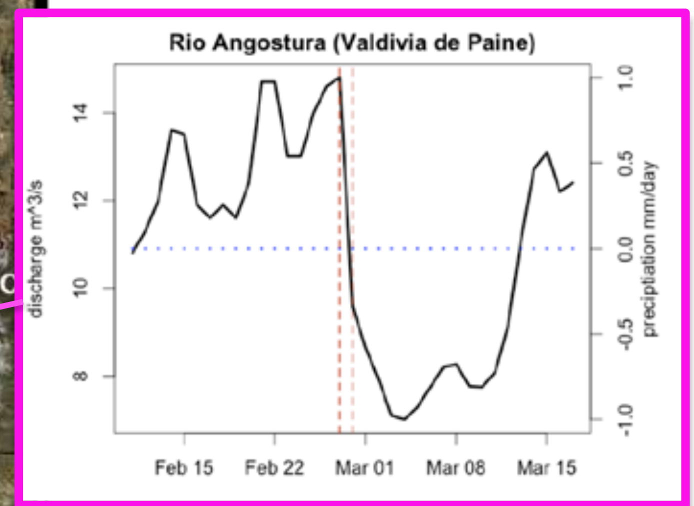
- M8.1 Coquimbo 1943
- M8.2 Antofagasta 1950
- M9.5 Valdivia 1960
- M8.0 Valparaiso 1985
- M8.0 Antofagasta 1995
- M8.8 Maule 2010
- M8.2 Iquique 2014

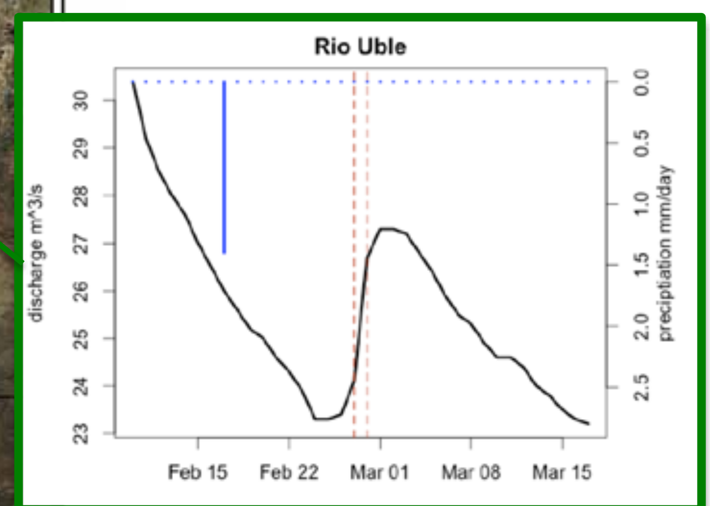


Streamflow responses to M8.8 Maule earthquake 2010



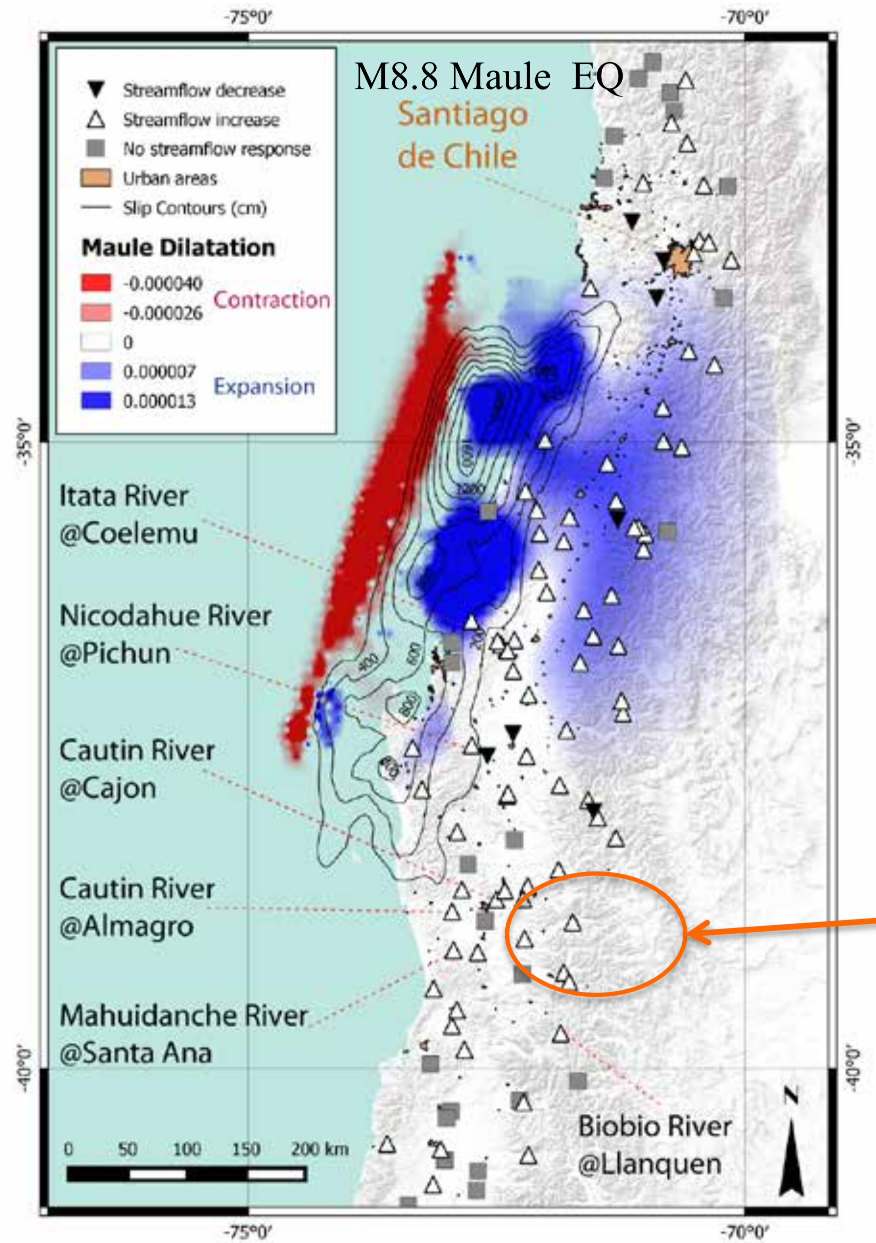






- $n_{Increase} >> n_{decrease}$
- Responses in Andes, Cental Valley and Coastal Range

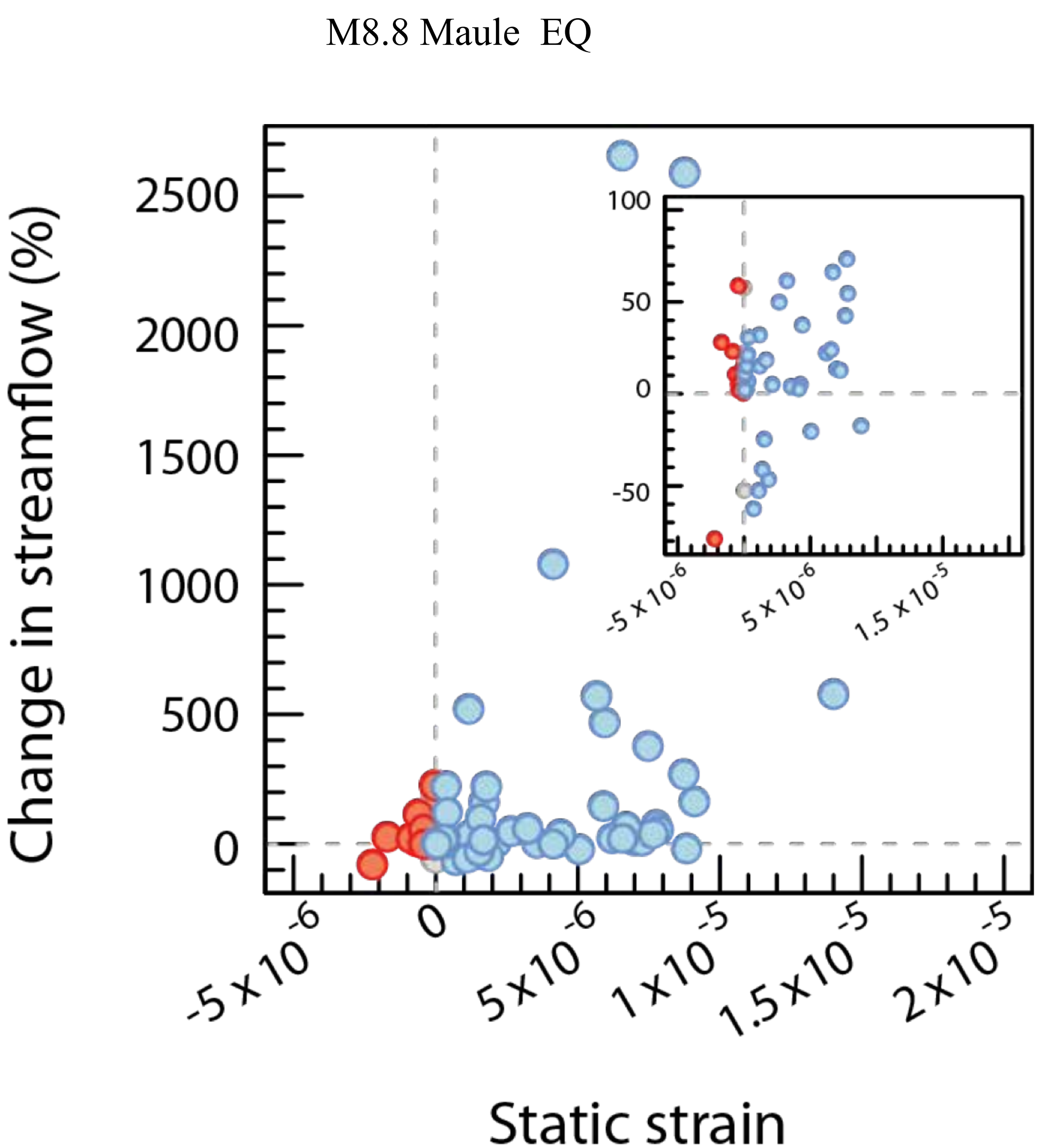
1. Volumetric strain?



- **Volumetric strain uncorrelated with sign of responses**
- **Flow decreased for positive volumetric strains**
- Potential effects of hydropower excluded

https://file.ejatlas.org/docs/ralco_chile2.jpg, 12/07/2015

1. Volumetric strain?



- **Volumetric strain uncorrelated with sign of responses**
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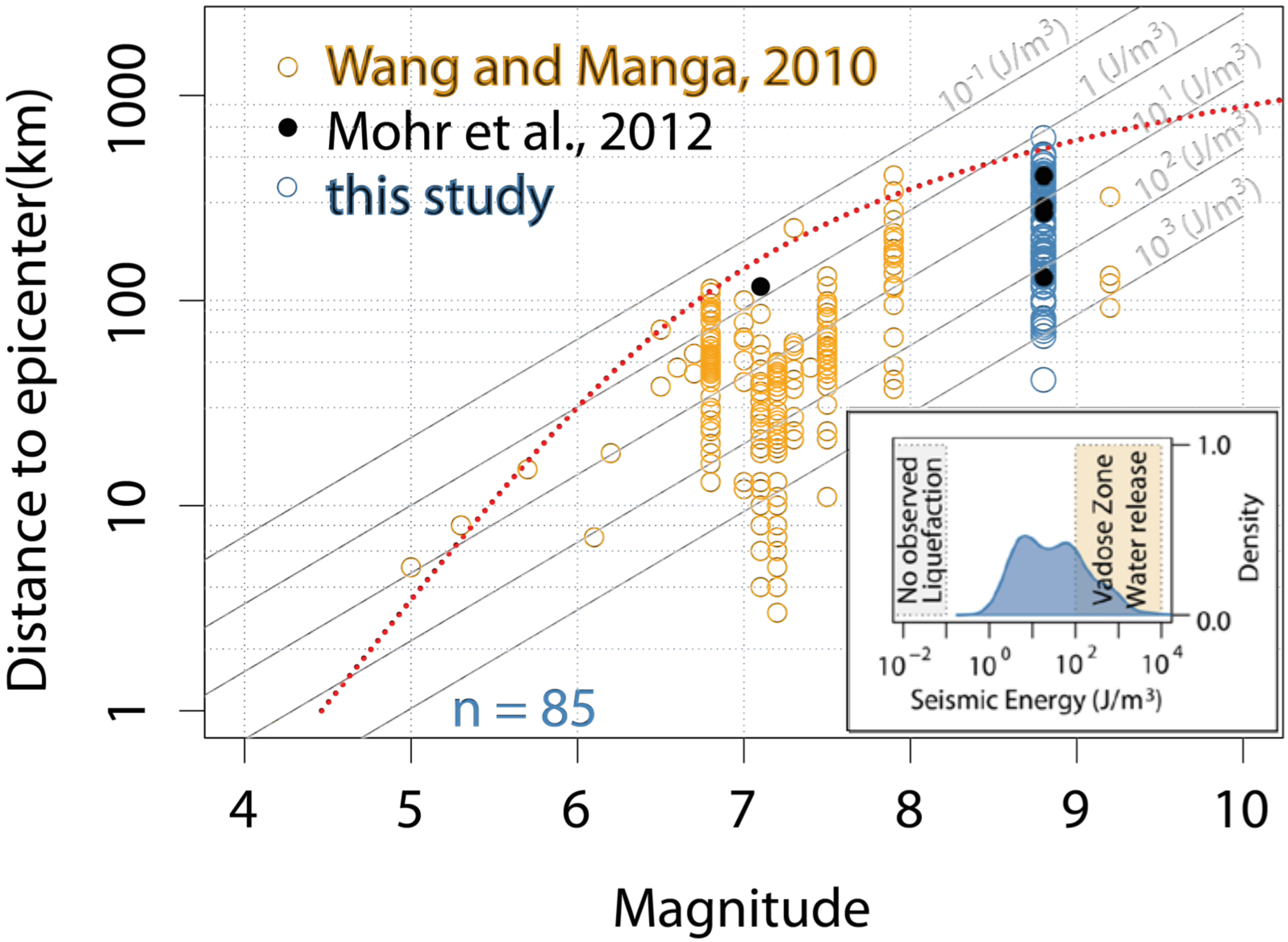
https://file.ejatlas.org/docs/ralco_chile2.jpg, 12/07/2015

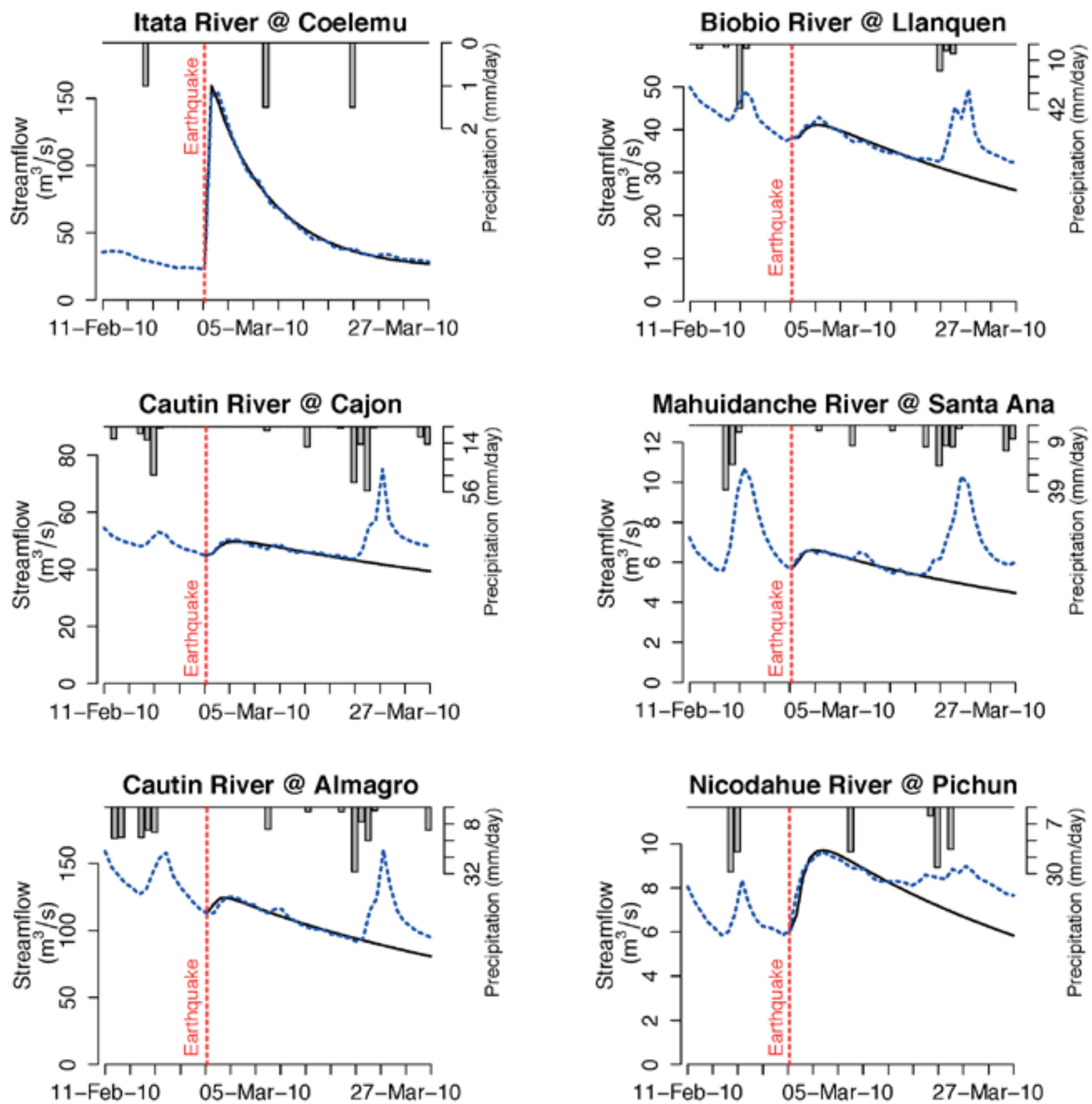
3+5. **Liquefaction from dynamic strain? Vadose zone?**

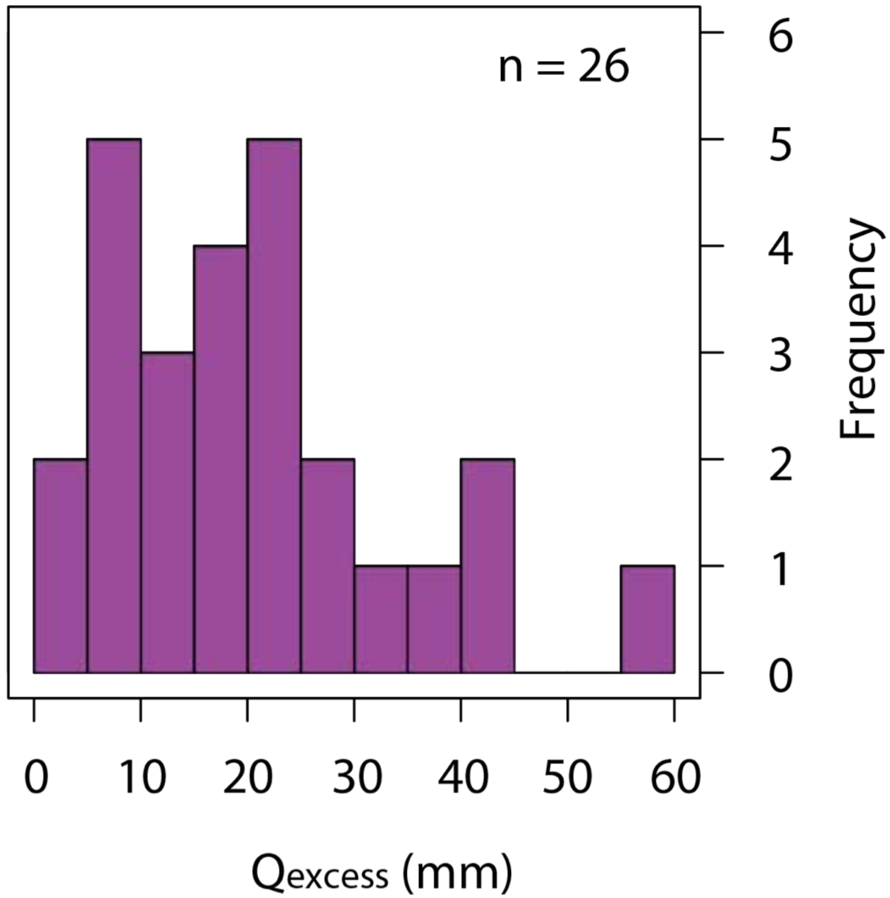


- Seismic energy sufficient to trigger streamflow responses
- Undrained consolidation possible, but no field evidence
- Excess water also in mountains

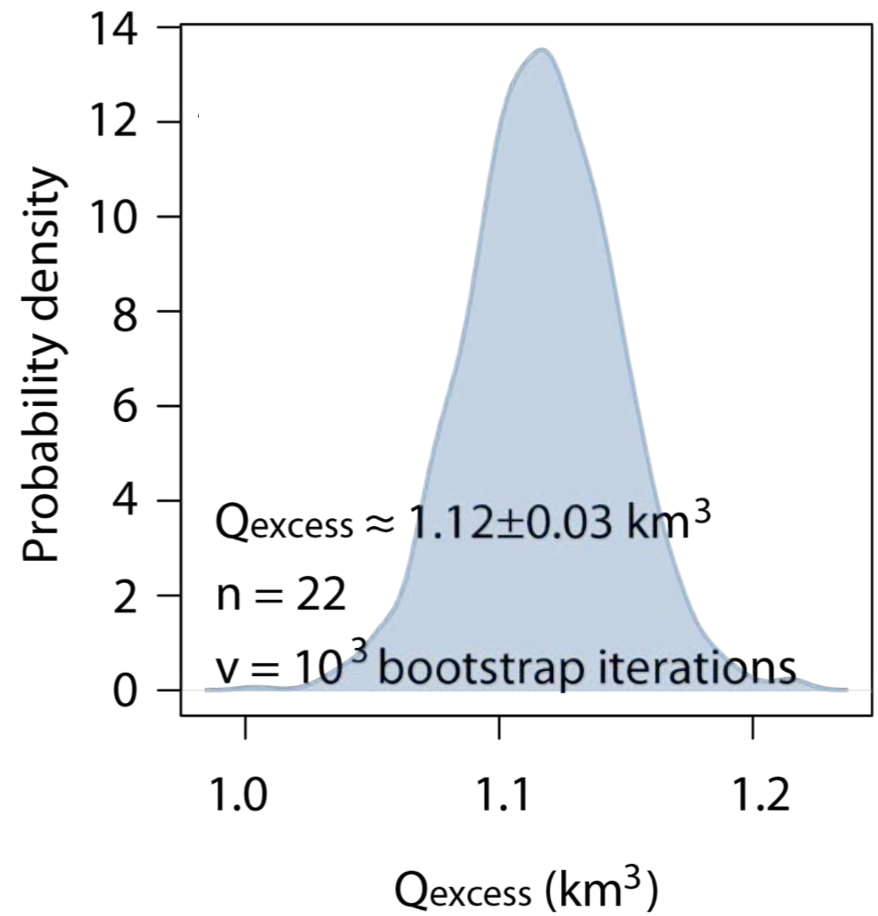
Papadopoulos and Lefkopoulos (1993)

5. Enhanced permeability?

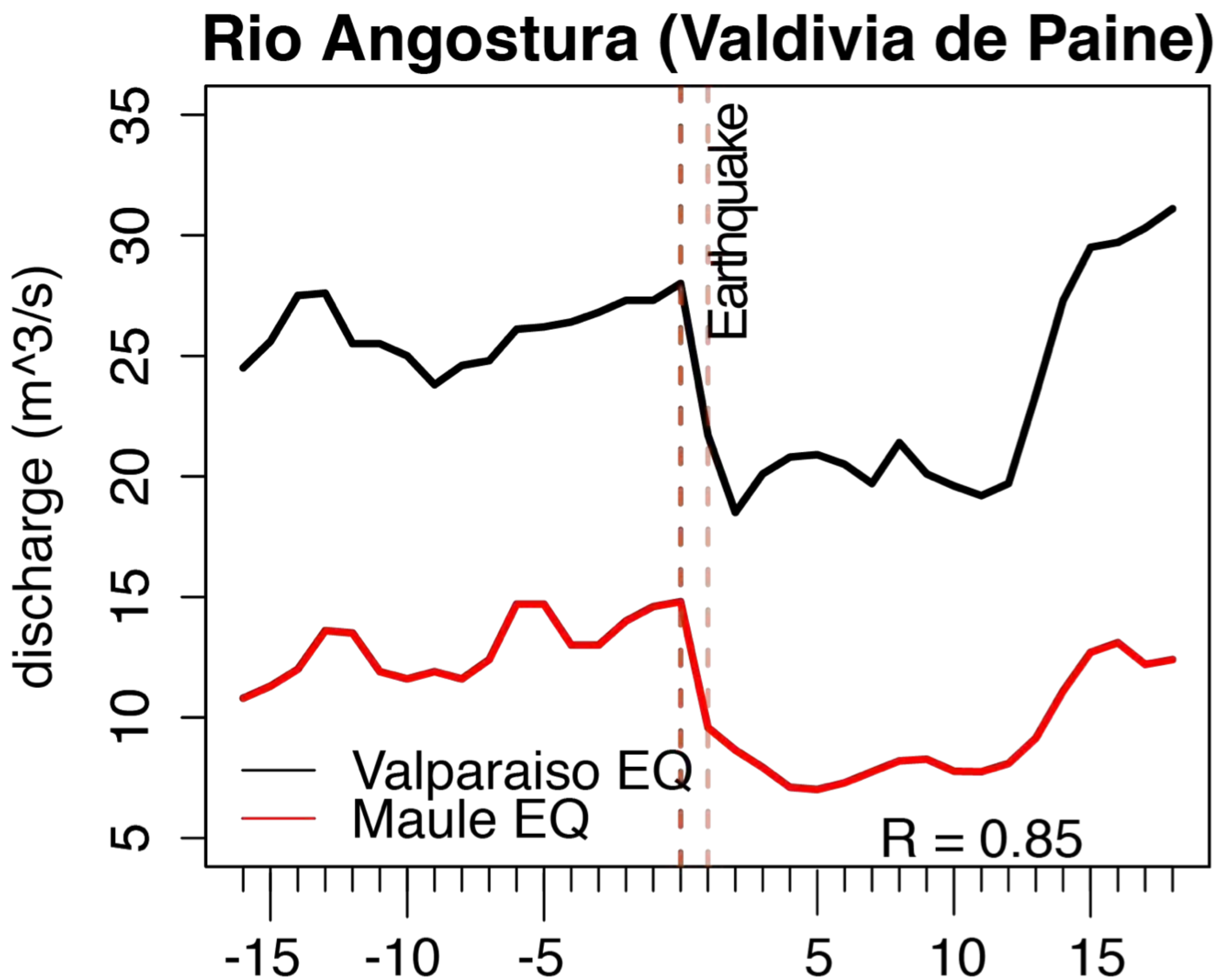




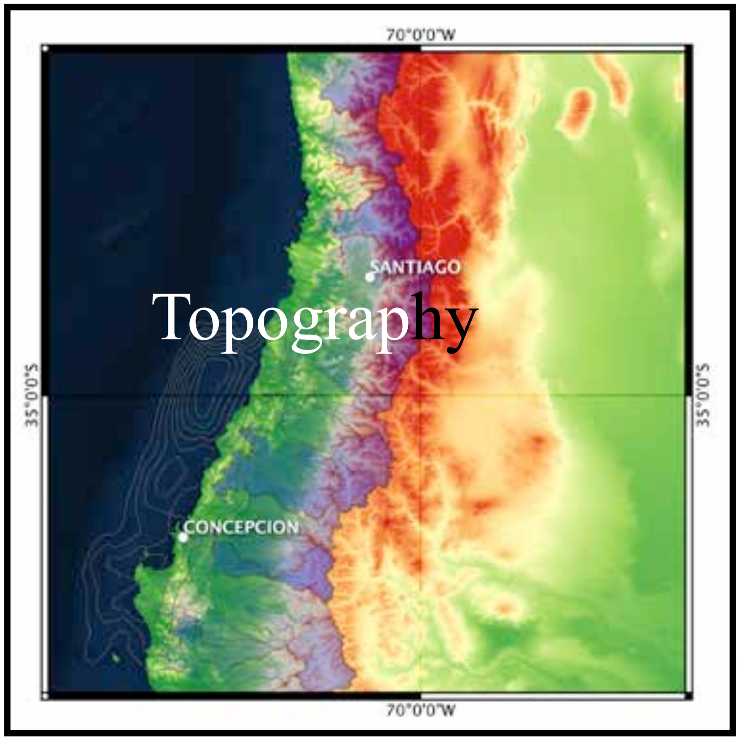
Leaves out 2
(very interesting)
outliers

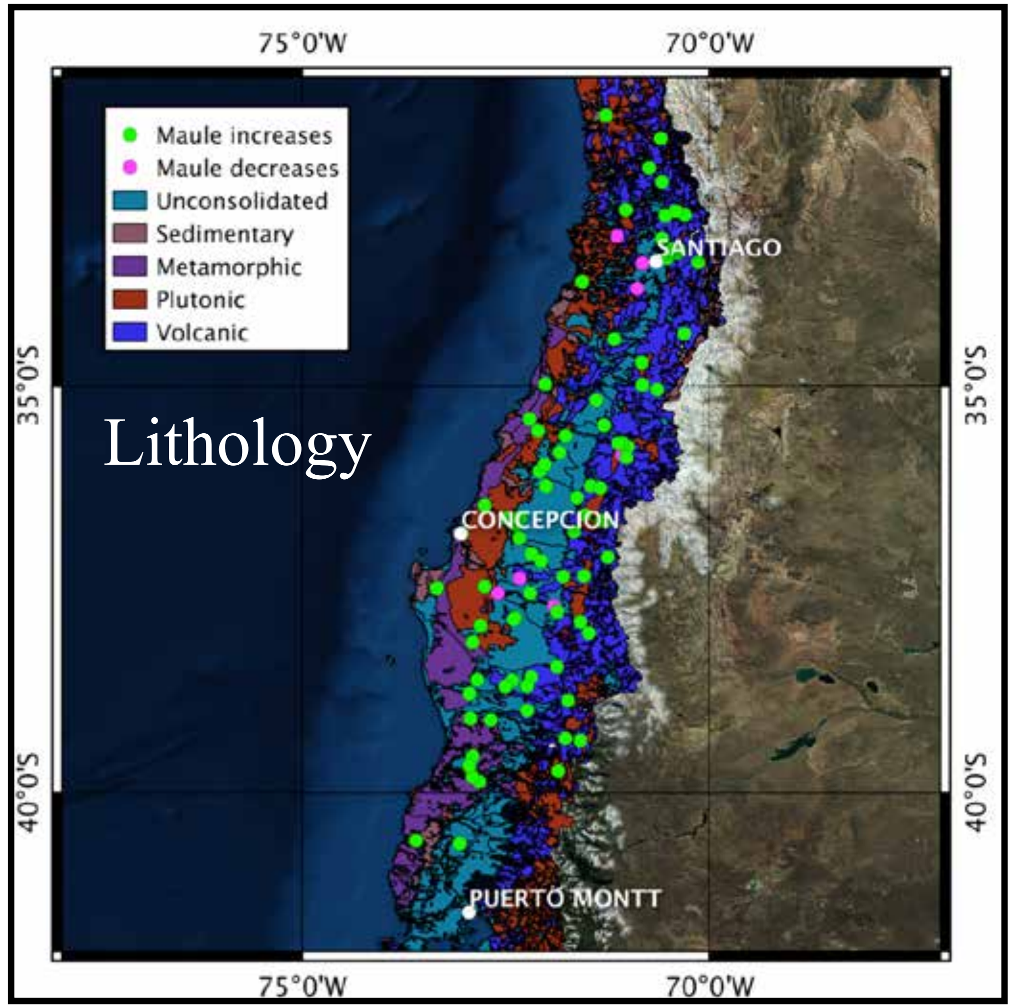


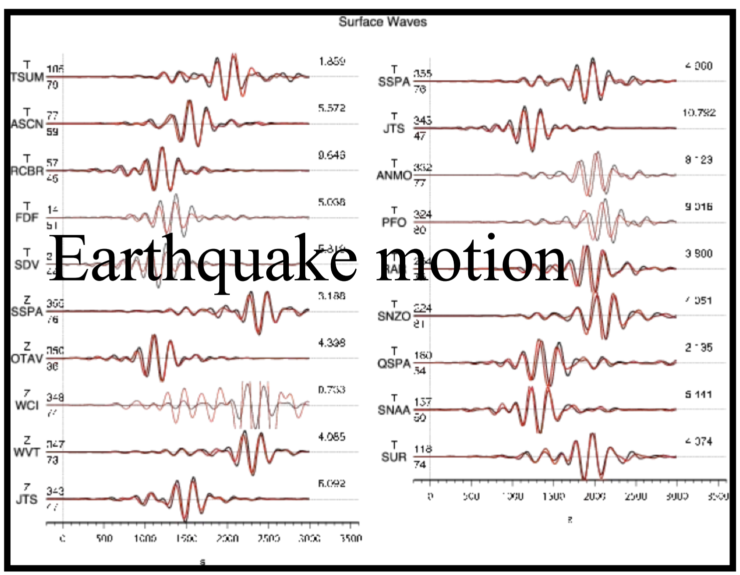
But the model may not explain all the observations...



(Days)

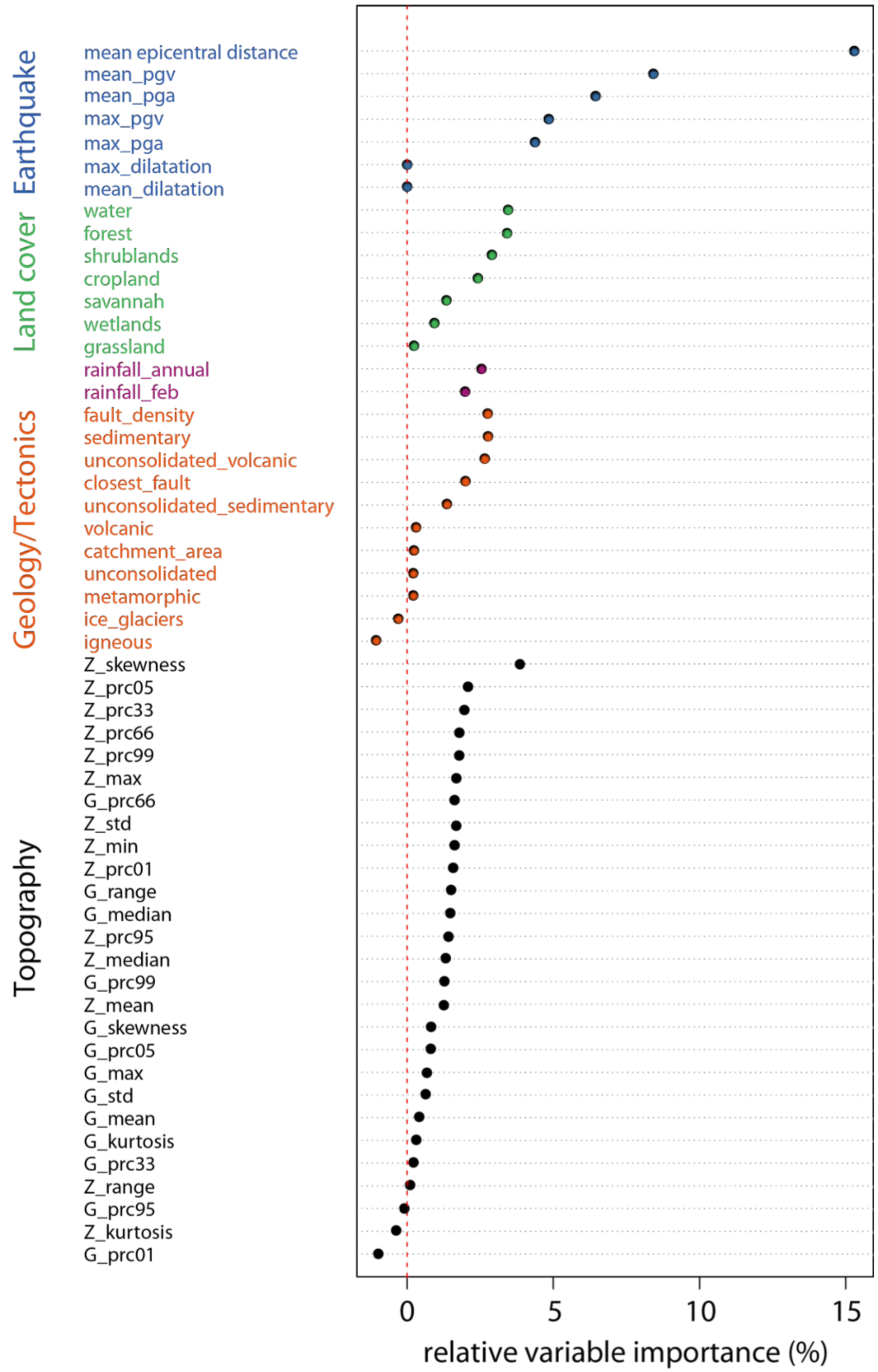






Random Forest

Details in Mohr et al., *EPSL* (2017)



Earthquake
Land cover
Geology/Tectonics
Topography
mean epicentral distance
mean_pgv
mean_pga
max_pgv
max_pga
max_dilatation
mean_dilatation
water
forest
shrublands
cropland
savannah
wetlands
grassland
rainfall_annual
rainfall_feb
fault_density
sedimentary
unconsolidated_volcanic
closest_fault
unconsolidated_sedimentary
volcanic
catchment_area
unconsolidated
metamorphic
ice_glaciers
igneous
Z_skewness
Z_prc05
Z_prc33
Z_prc66
Z_prc99
Z_max
G_prc66
Z_std
Z_min
Z_prc01
G_range
G_median
Z_prc95
Z_median
G_prc99
Z_mean
G_skewness
G_prc05
G_max
G_std
G_mean
G_kurtosis
G_prc33
Z_range
G_prc95
Z_kurtosis
G_prc01
0
5
10
15
relative variable importance (%)

Conclusions from Chile

1) Static compression

(e.g., Muir-Wood and King, 1993)

2) Breaching barriers or seals

(e.g., Sibson 1994; Brodsky et al. 2003)

3) Consolidation and liquefaction

(e.g., Manga, 2001; Montgomery et al., 2003)

4) Shaken from the unsaturated zone

(Mohr et al., 2015)

5) Permeability enhancement by dynamic strain

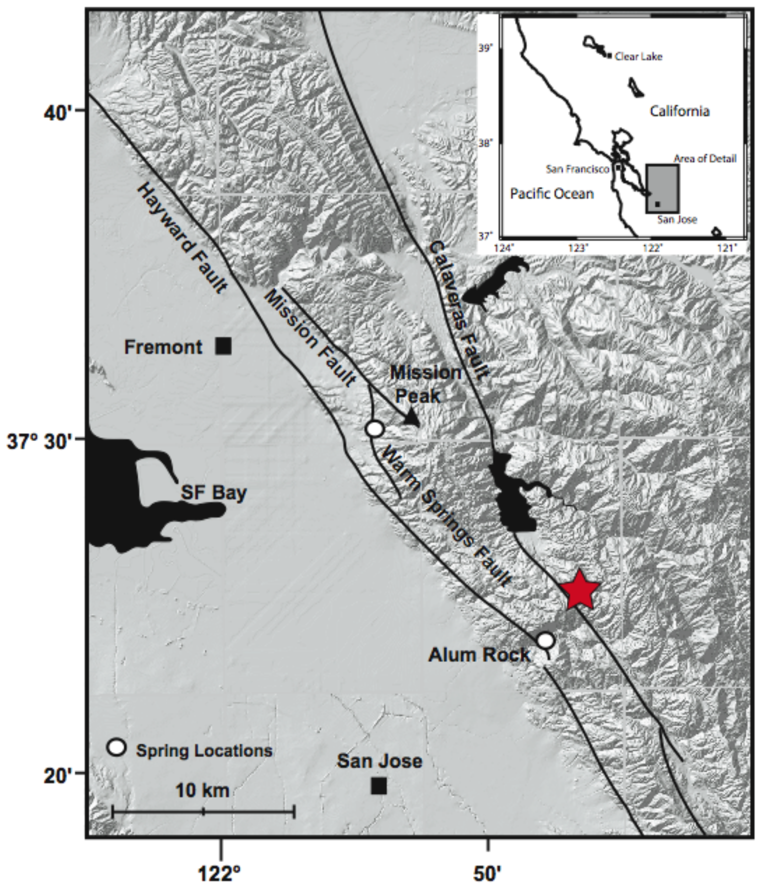
(e.g., Rojstaczer et al., 1995; Tokunaga, 1999; Sato et al., 2000)

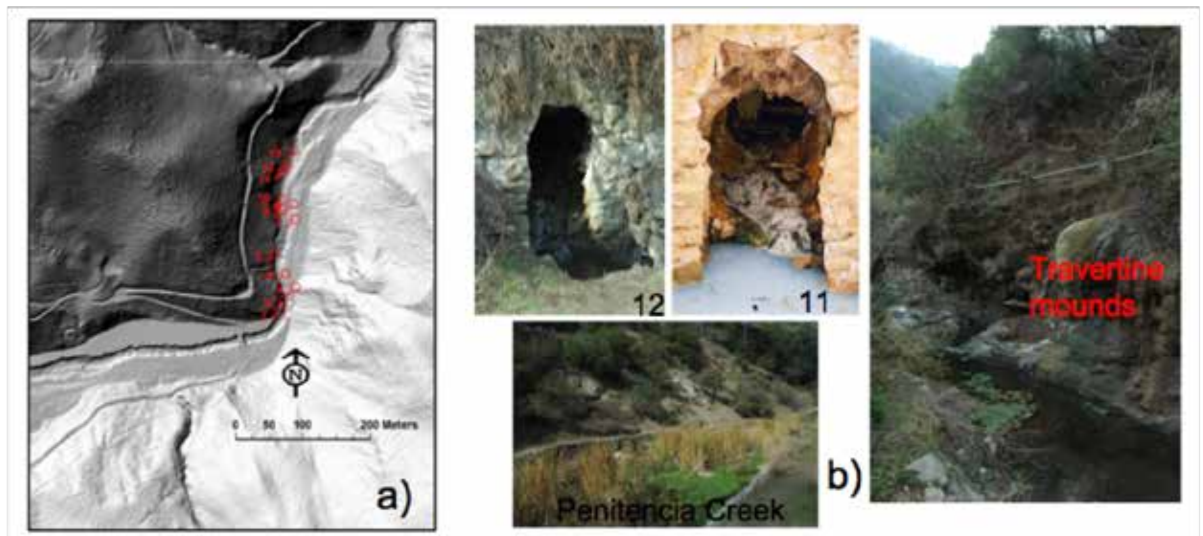
Supported by a variety of lab experiments and field measurements

e.g., Candela et al., *EPSL* (2014), Elkhoury et al., *JGR* (2011), Liu and Manga, *GRL* (2009) Roberts and Abdel-Fattah, *EPSL* (2009)

Are changes only shallow?

Response of springs along a fault

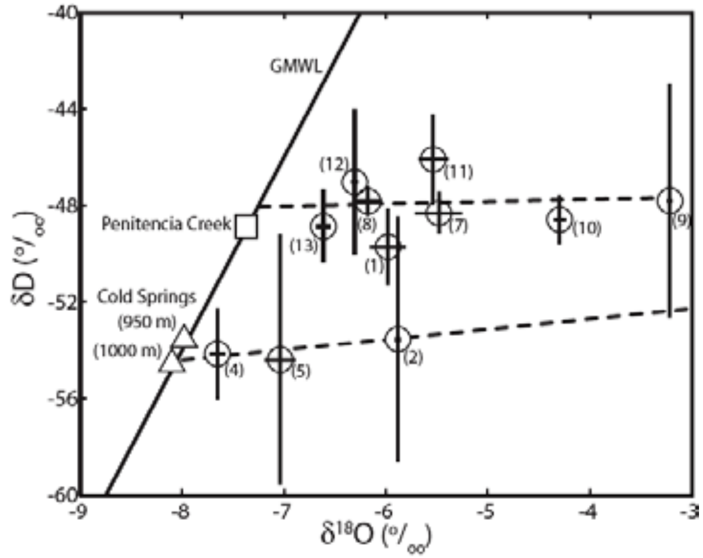


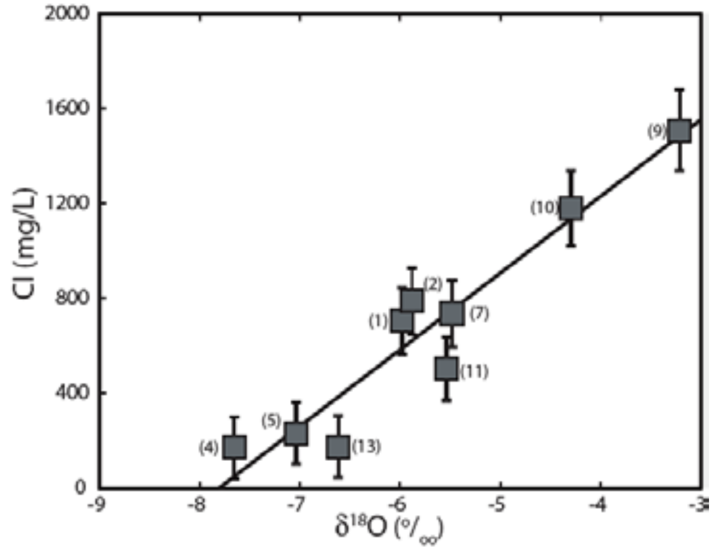


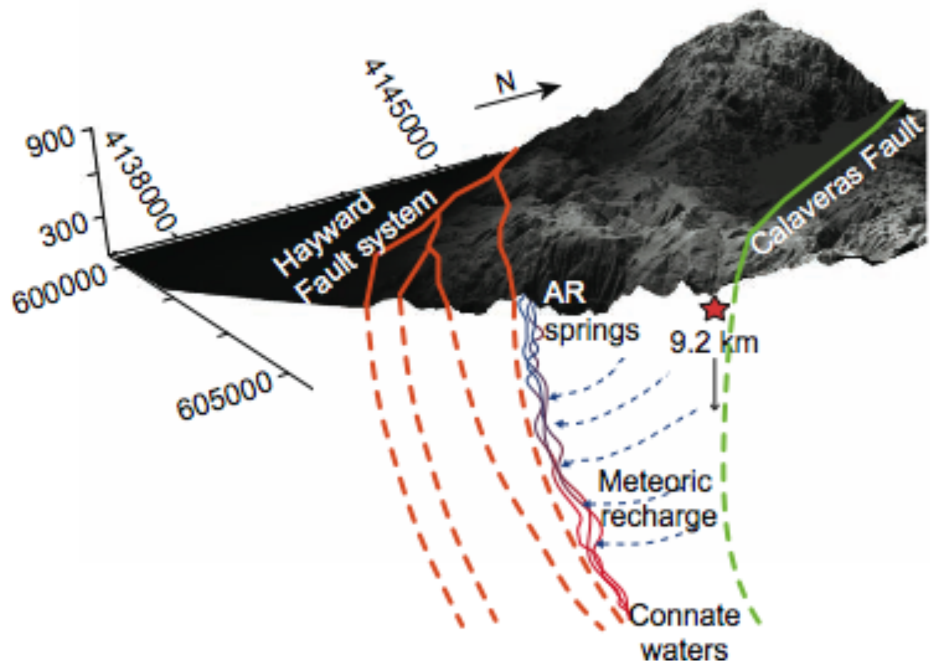
Response to M 5.5 Alum Rock event on October 30, 2007

King et al. (1994) documented response to 5 previous events

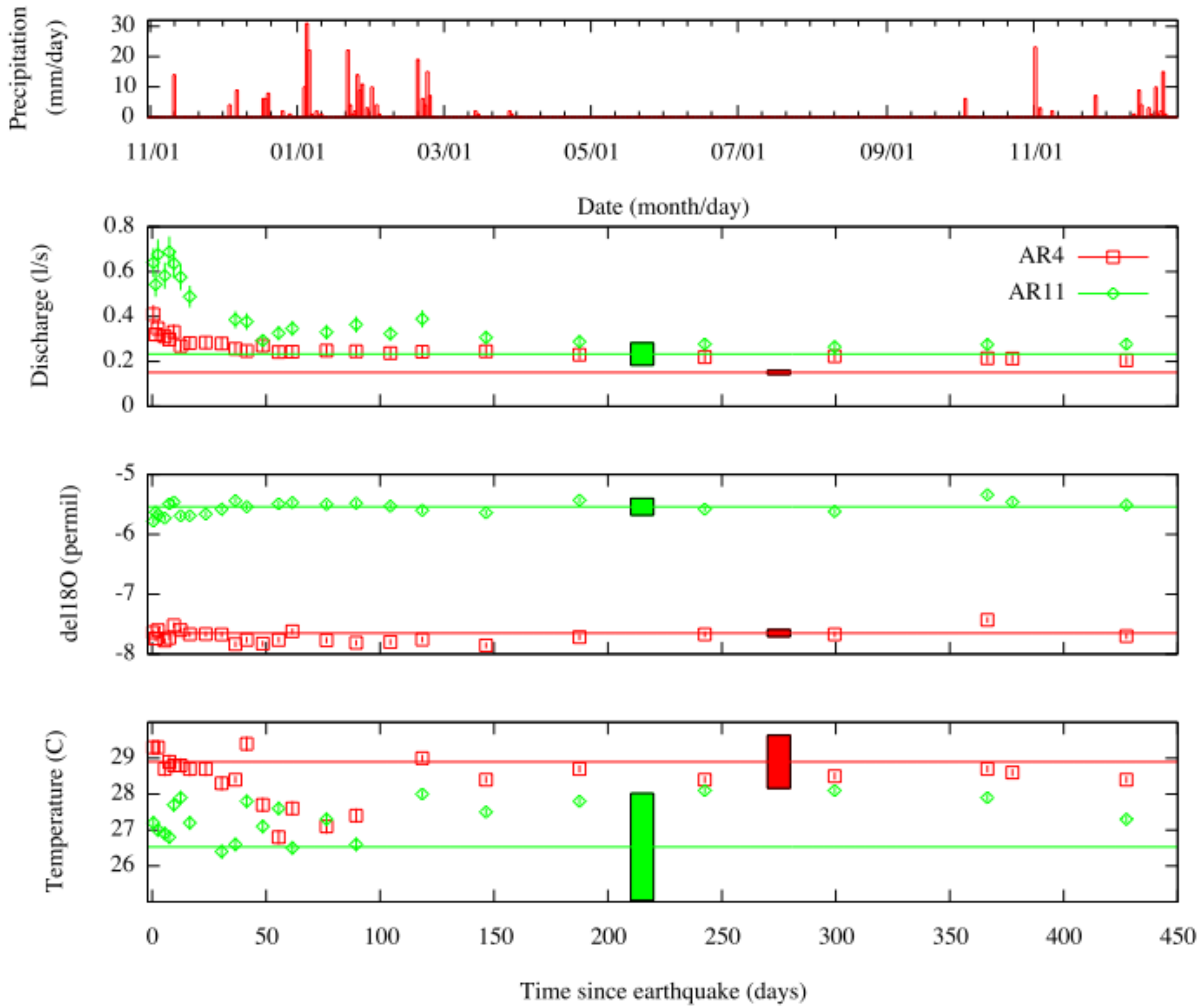
Mixture of “shallow” and “deep” water







Example of changes



Features

- Flow always increases
- Peak discharge within days
- After 2 years, discharge was still elevated
- No clear temperature change
- No to very small shift towards meteoric water
- No correlation with static strains
- Clear magnitude-distance relation for response

Static strain?

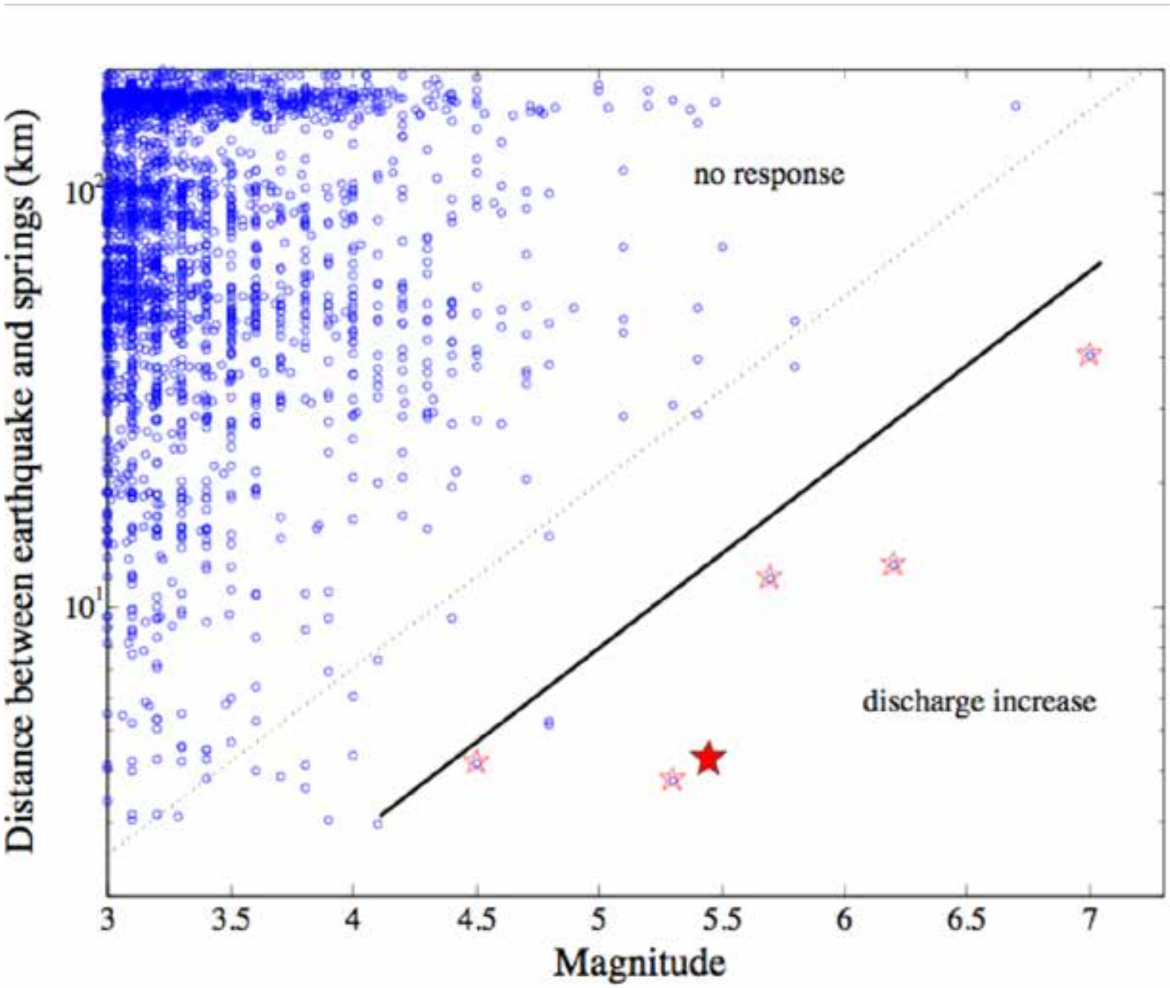
Earthquakes followed by flow increases

Event		M	Epicentral distance	Volumtric strain	Reference
4/18/1906?	San Francisco	7.8	70 km	D	Lawson (1908)?
4/24/1984	Morgan Hill	6.2	18 km	C	King et al. (1994)
3/31/1986	Mount Lewis	5.7	15 km	C	King et al. (1994)
6/13/1988	Alum Rock	5.3	8 km	C	King et al. (1994)
4/3/1989	Alum Rock	5.0	5 km	-	King et al. (1994)
10/18/1989	Loma Prieta	7.1	40 km	D	King et al. (1994)
10/30/2007	Alum Rock	5.6	4 km	-	This study

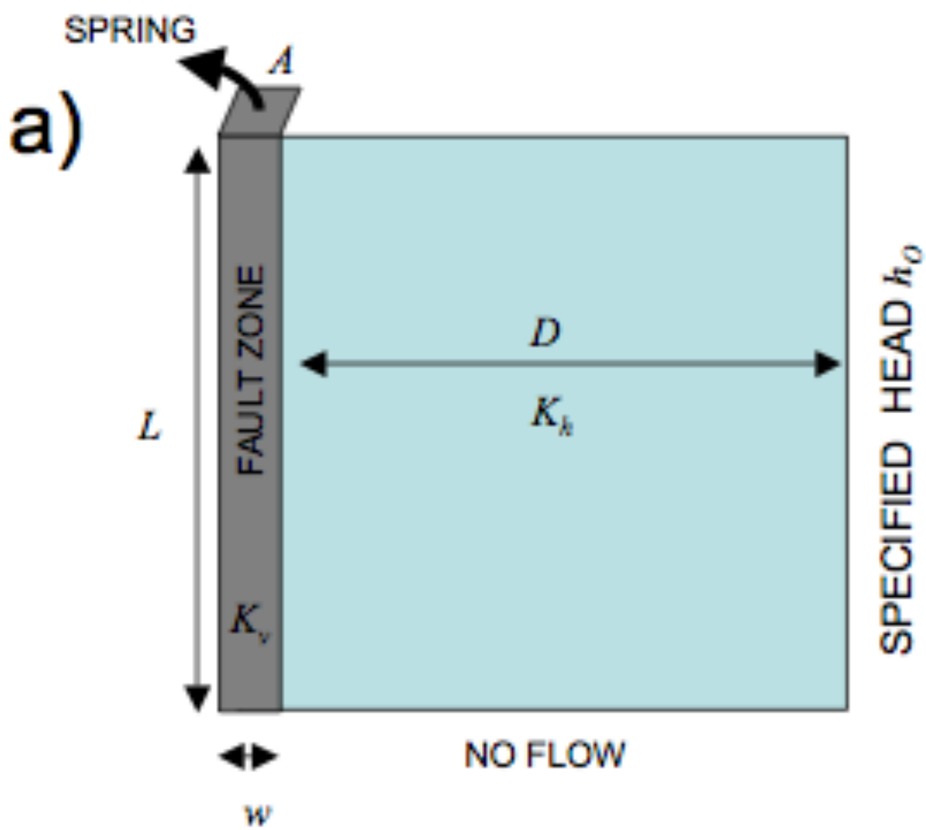
Springs not consistently in compressional or dilatational quadrant

Pore pressure changes < 10^3 Pa

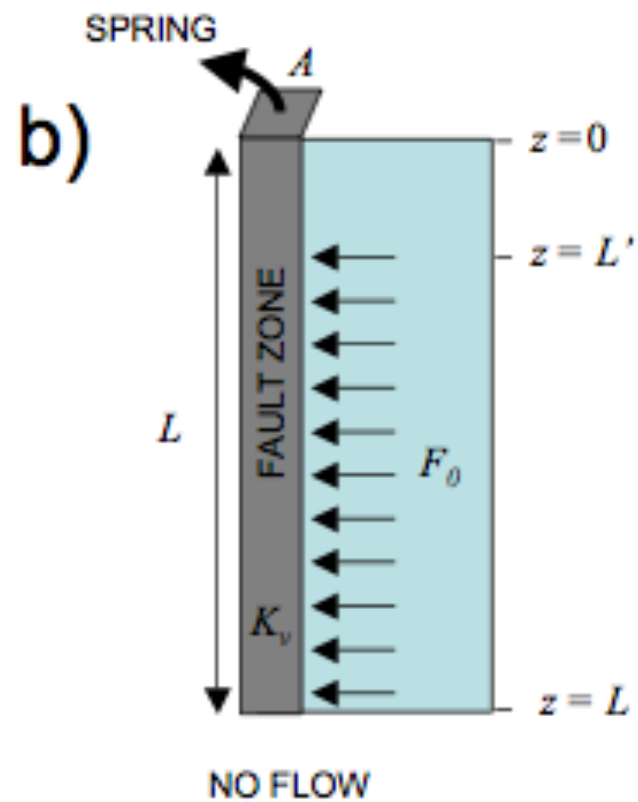
Magnitude-distance relationship



Models (cartoon form)



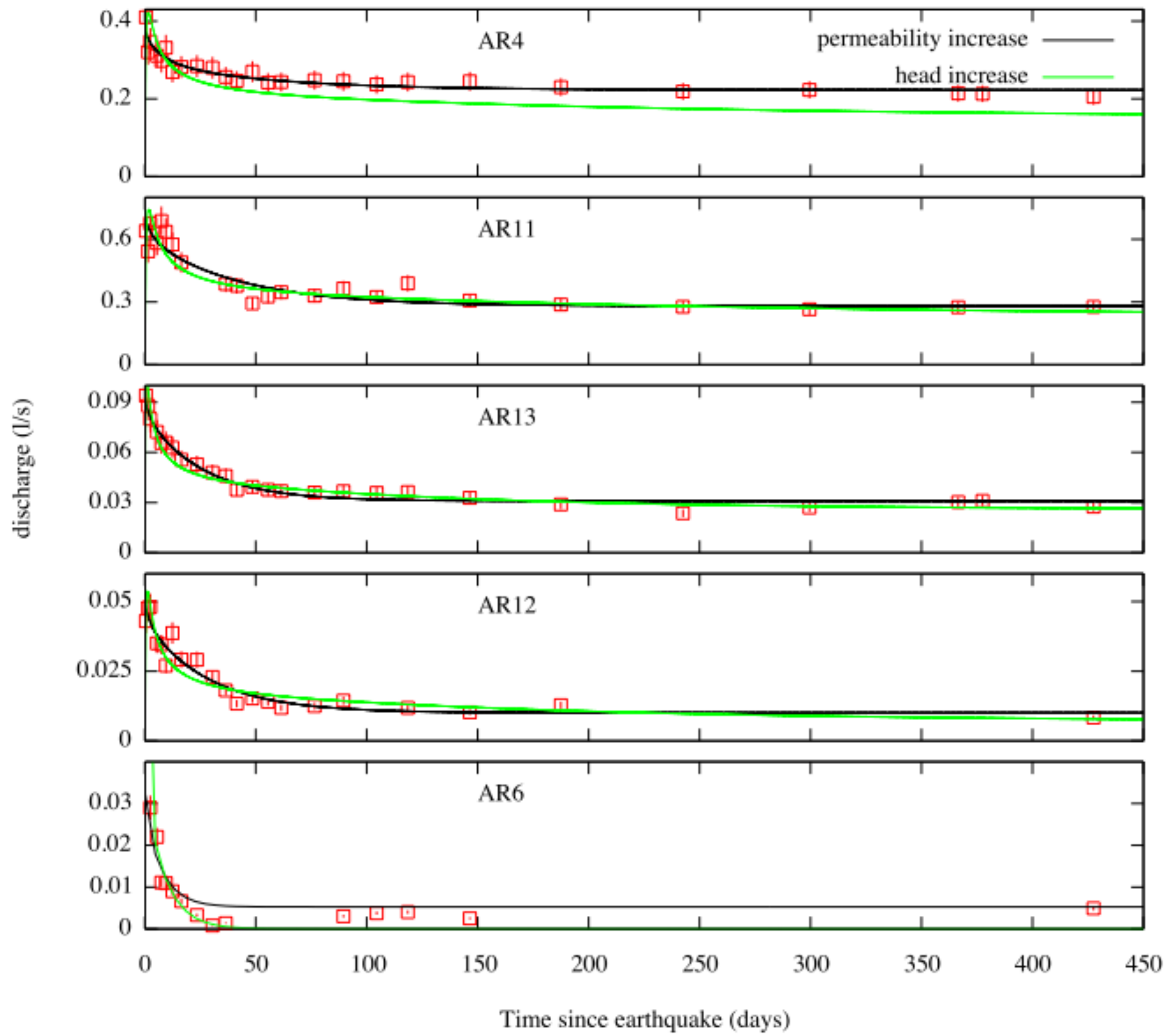
Increased permeability



Increased head

Analytical solutions in Manga and Rowland (2009)

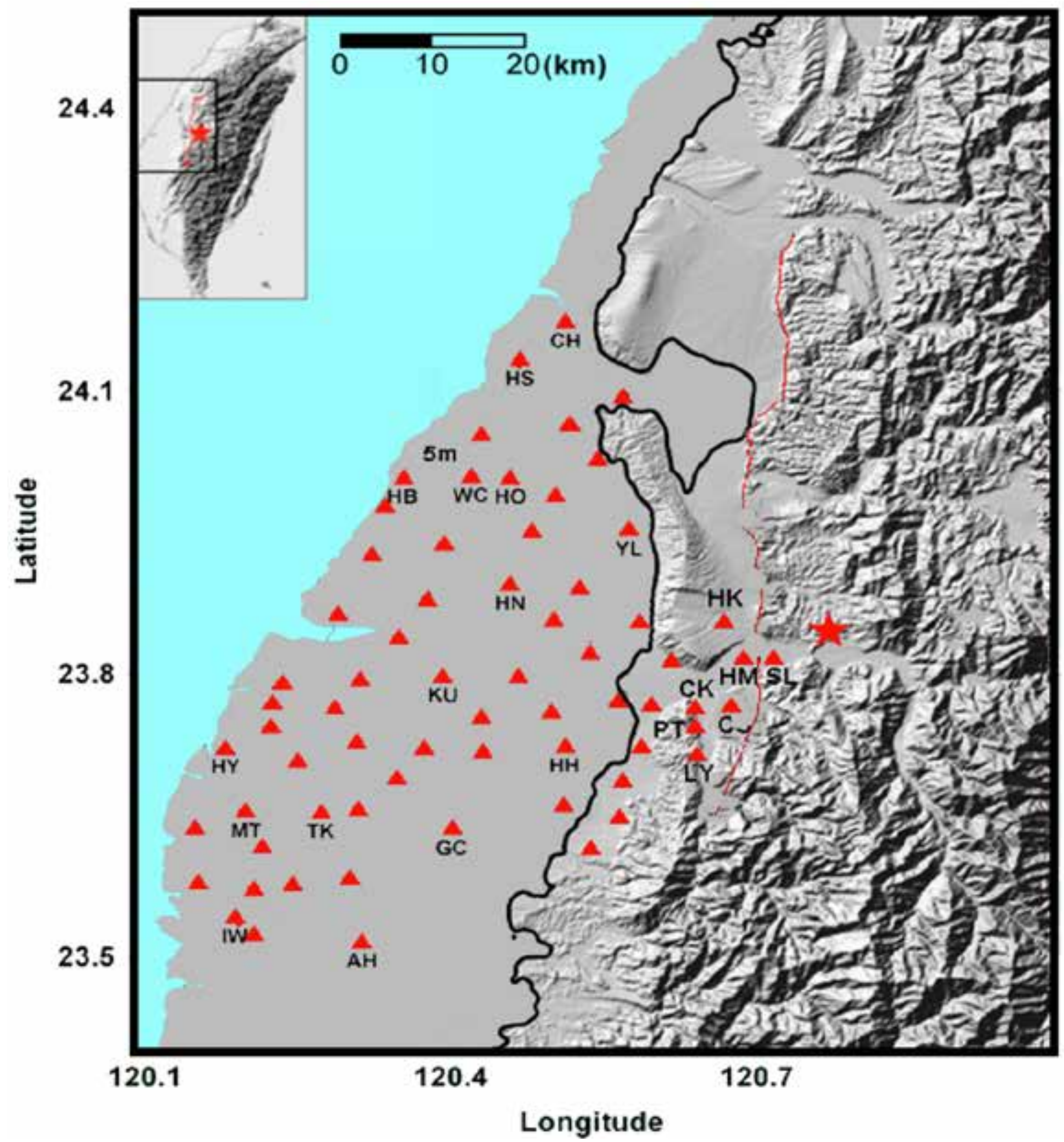
Best-fit models



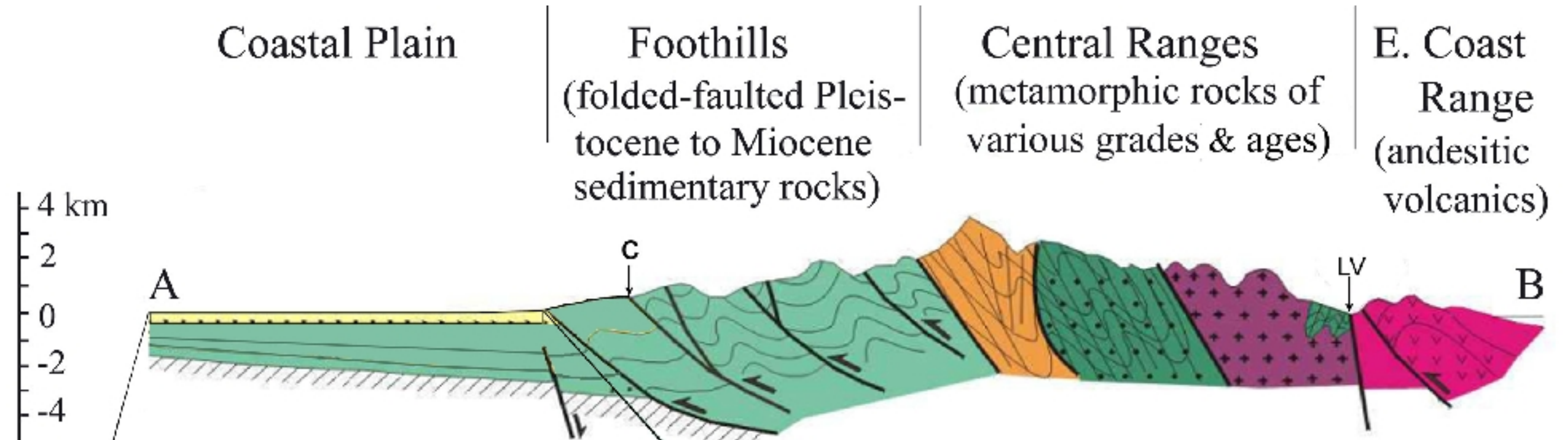
Are changes large? Widespread? Significant?

Groundwater temperature in wells

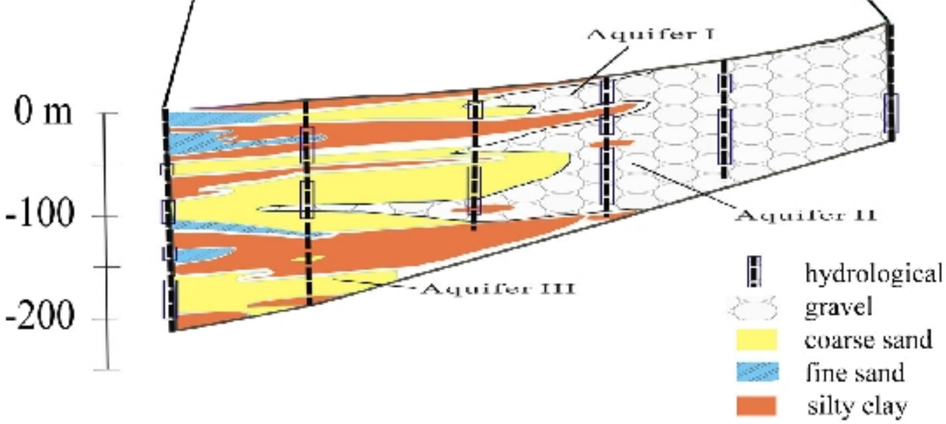
Well locations with temperature data before and after the 1999 Chi-Chi earthquake



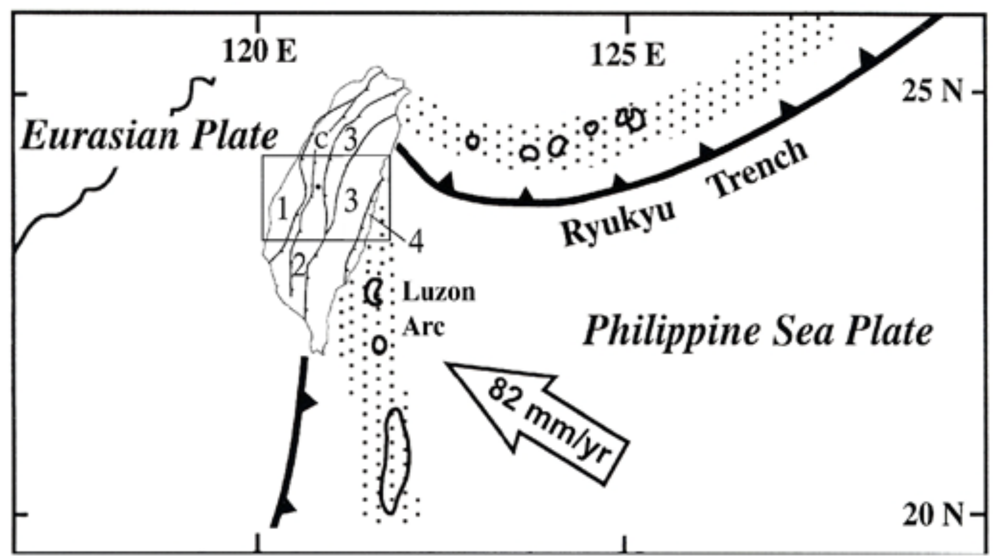
Taiwan



Coastal Plain
Foothills
(folded-faulted Pleis-
tocene to Miocene
sedimentary rocks)
Central Ranges
(metamorphic rocks of
various grades & ages)
E. Coast
Range
(andesitic
volcanics)
4 km
2
0
-2
-4
A
B
C
LV

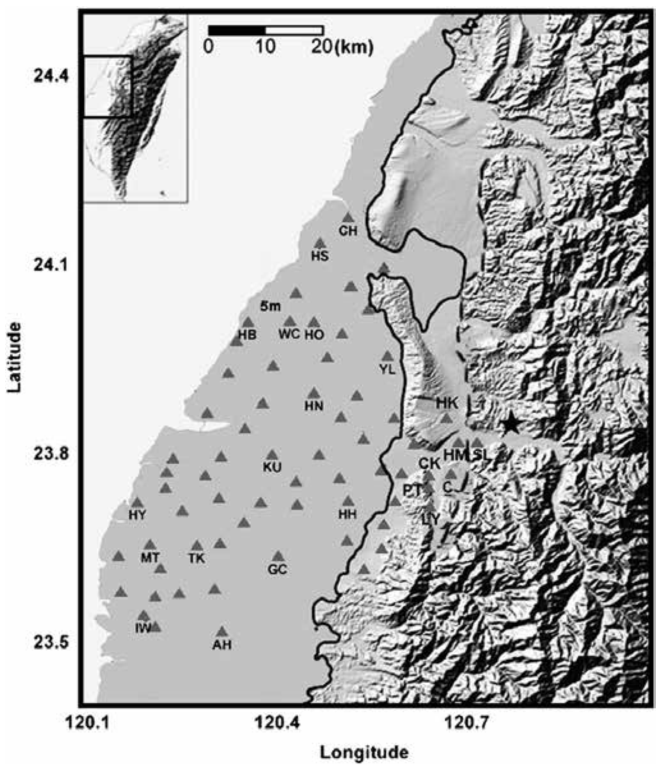


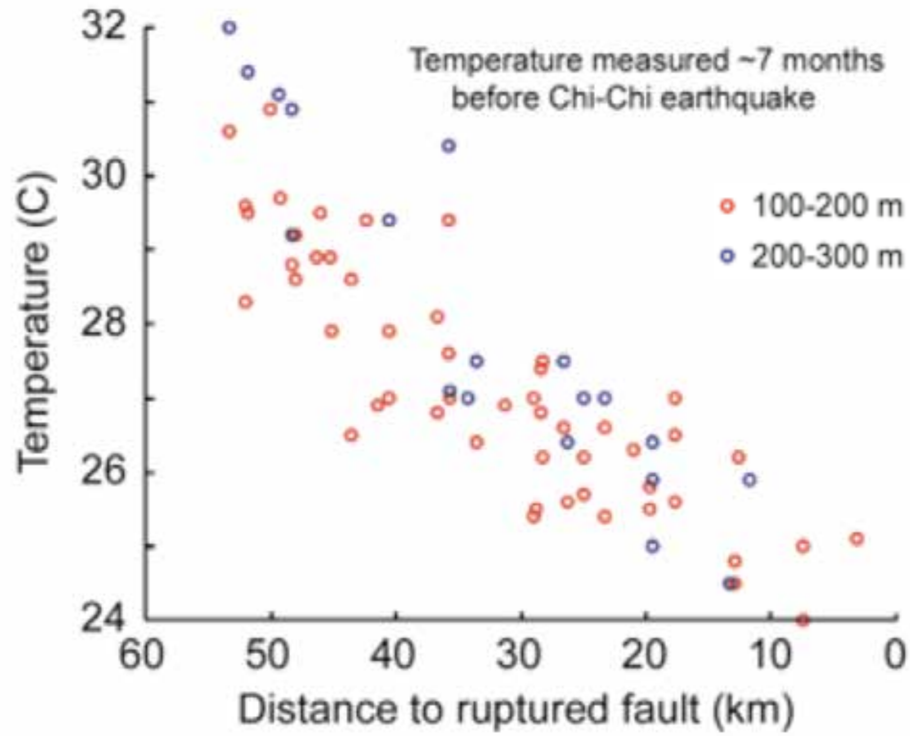
0 m
-100
-200
Aquifer I
Aquifer II
Aquifer III
hydrological
gravel
coarse sand
fine sand
silty clay



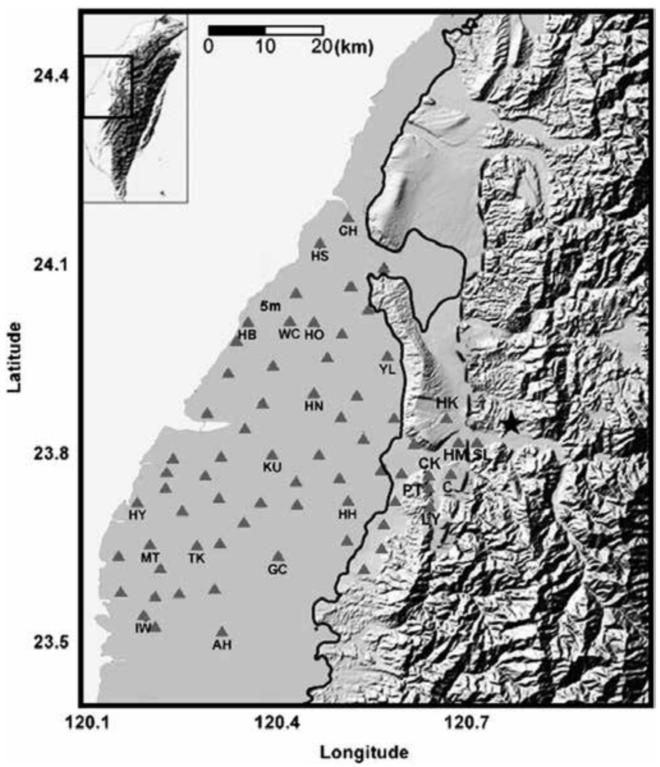
120 E
125 E
25 N
20 N
Eurasian Plate
Philippine Sea Plate
Ryukyu
Trench
Luzon
Arc
82 mm/yr
c
1
2
3
3
4

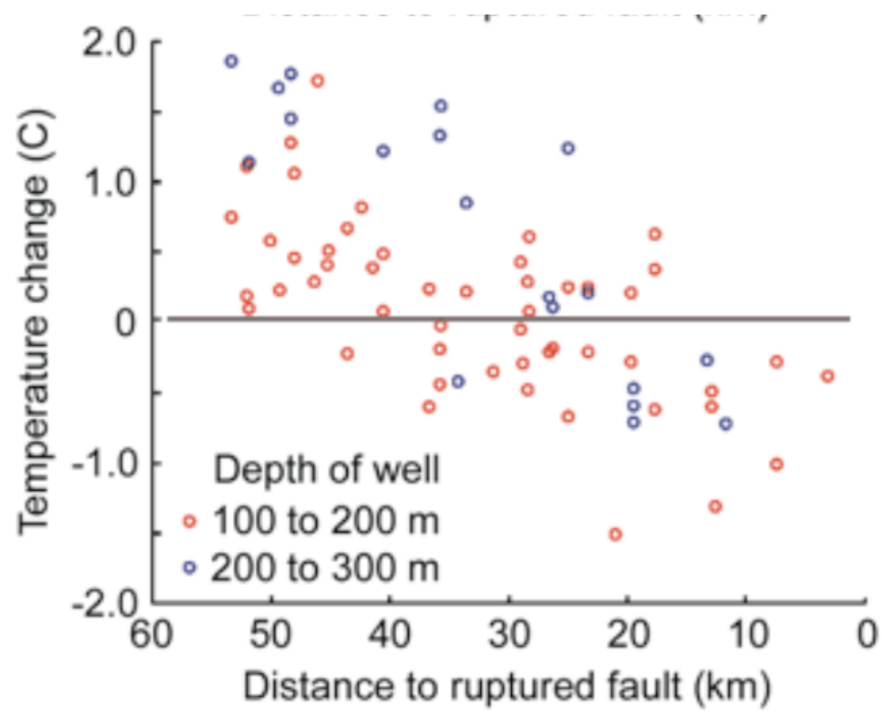
Pre-earthquake



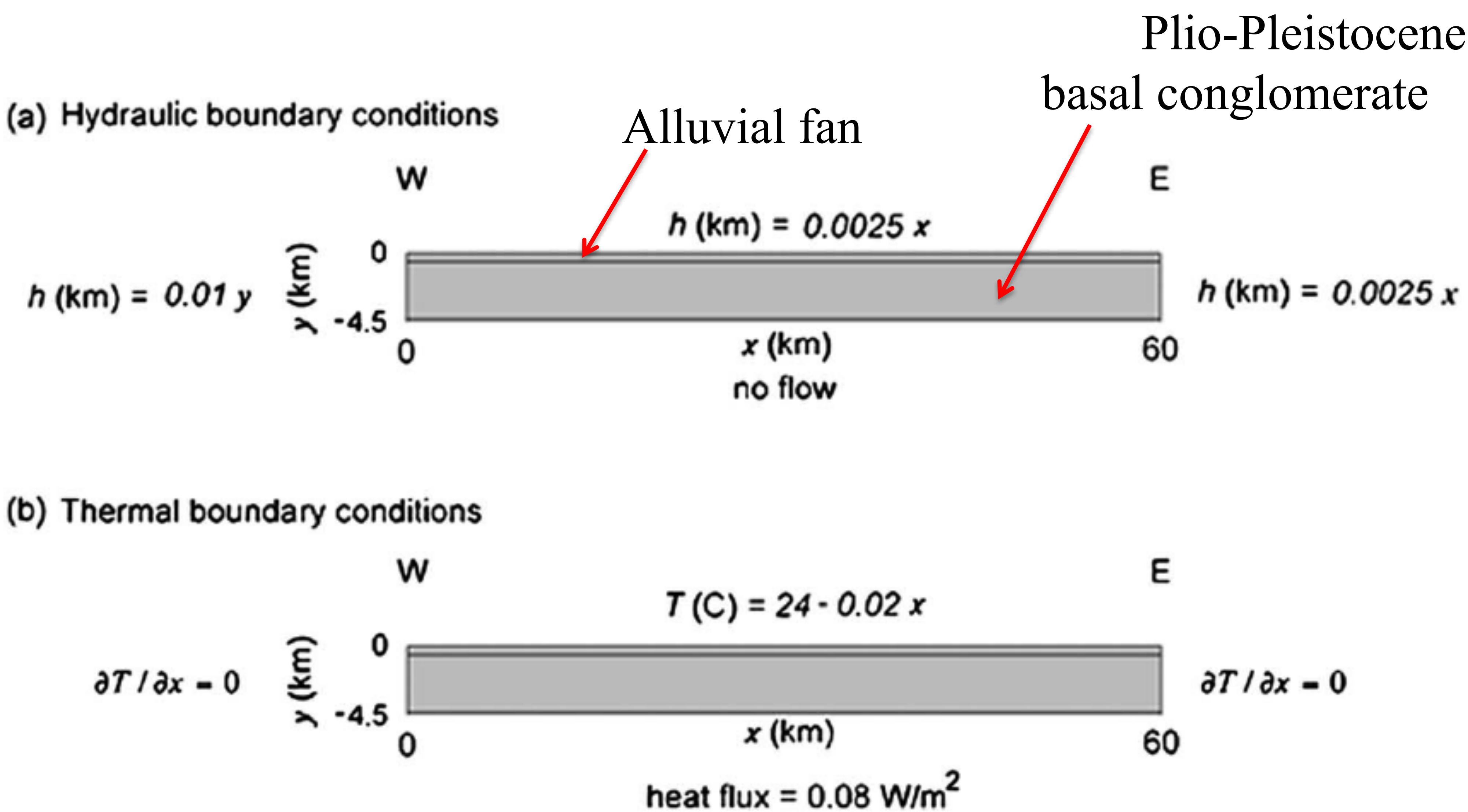


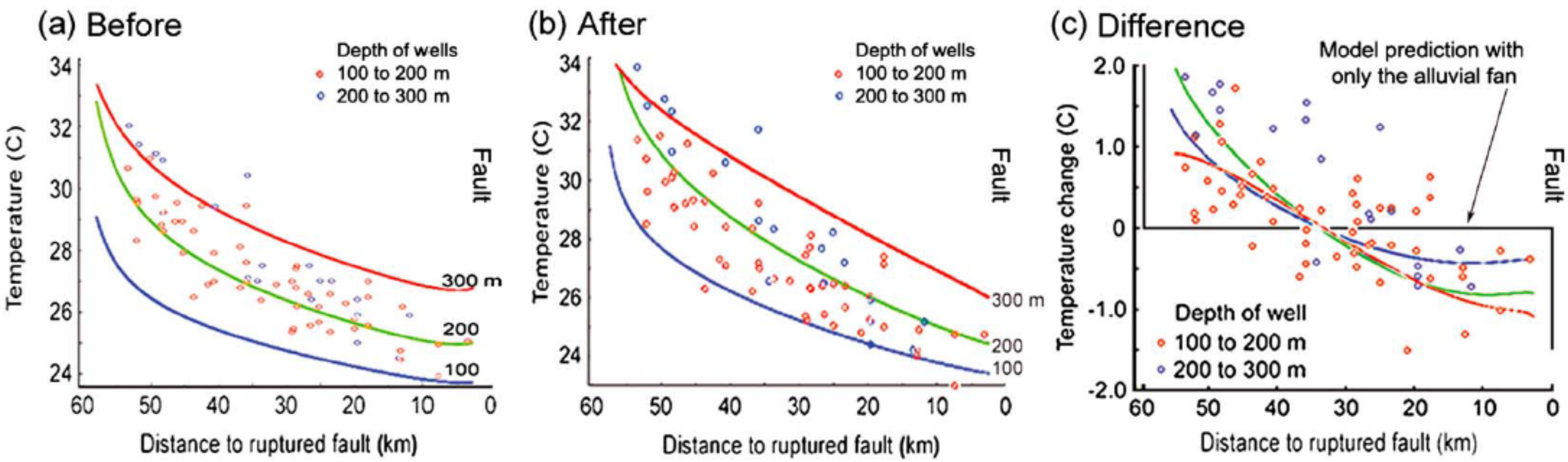
Post-earthquake





Idealized problem





Permeability increases factor of 100
Returns to “normal” over a few months

Permeability is not a static quantity

½ the transport occur over short period with enhanced permeability

Summary

Earthquake-generated time-varying strains can change (increase) permeability for amplitudes as small at 10^{-6}

Permeability changes in the intermediate- to far-field (a few to many fault lengths from the earthquake), and may dominate responses even in the near-field

Permeability changes can be modest, but up to 2 orders of magnitude and over regional scales

Changes persist for months to years

Did an Earthquake Trigger the Sidoarjo (“Lusi”) Mud eruption?

Photo courtesy Arif Hidayat

What's Special About Lusi?

- Observe the birth of a large mud eruption
- Well next to main vent

Human and environmental effects

- ~100,000 m^3/day (will last another 10-50 years?)
- >40,000 people displaced; 11 deaths
- Rice fields and shrimp ponds destroyed
- Highways, rail and power transmission disrupted
- Mud diverted to river (10 km upstream of a delta)

- Lapindo asked to pay $280M to victims and $140M to stop flow
- Damage estimates up to $4.9B
- Sept 2009, House of Representatives decided event was a natural disaster

The Yogyakarta Earthquake

- Two days before the eruption
- Mw 6.3
- 250 km away

- Earthquakes trigger other mud "volcanoes" (e.g., Pliny; Manga and Brodsky, 2006; Mellors et al., 2007; Bonini, 2009)

Coincidence or a Trigger?

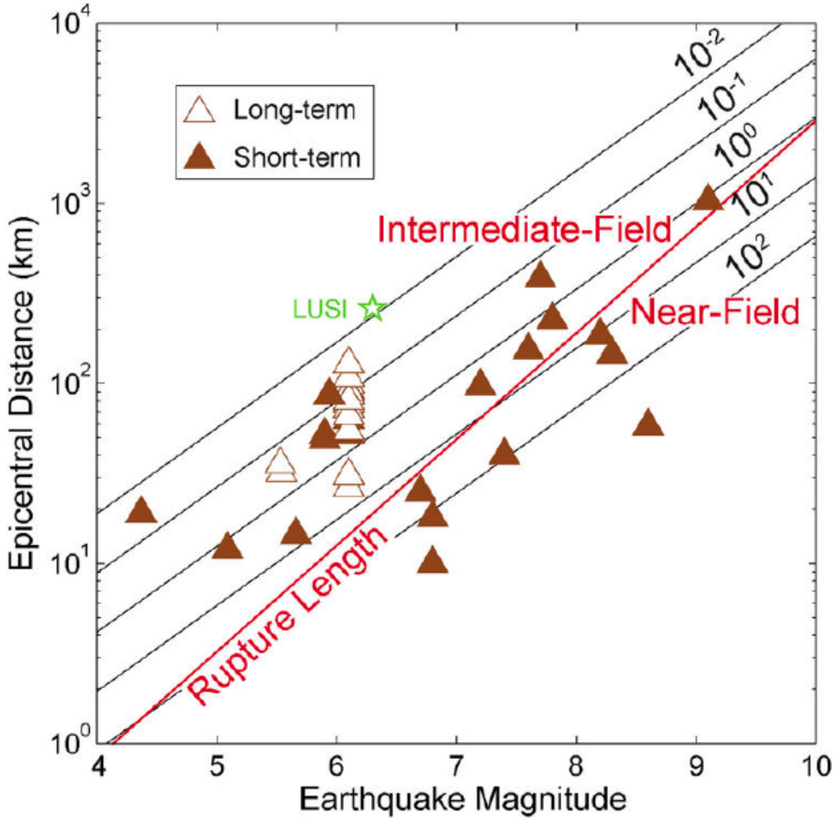
Approach

1. Compare to other triggered mud volcanoes
2. Compare static stress changes to other stresses
3. Compare ground shaking to earthquakes that did not trigger an eruption
4. Did other earthquakes prime Lusi?
5. Consider the chance of fault reactivation

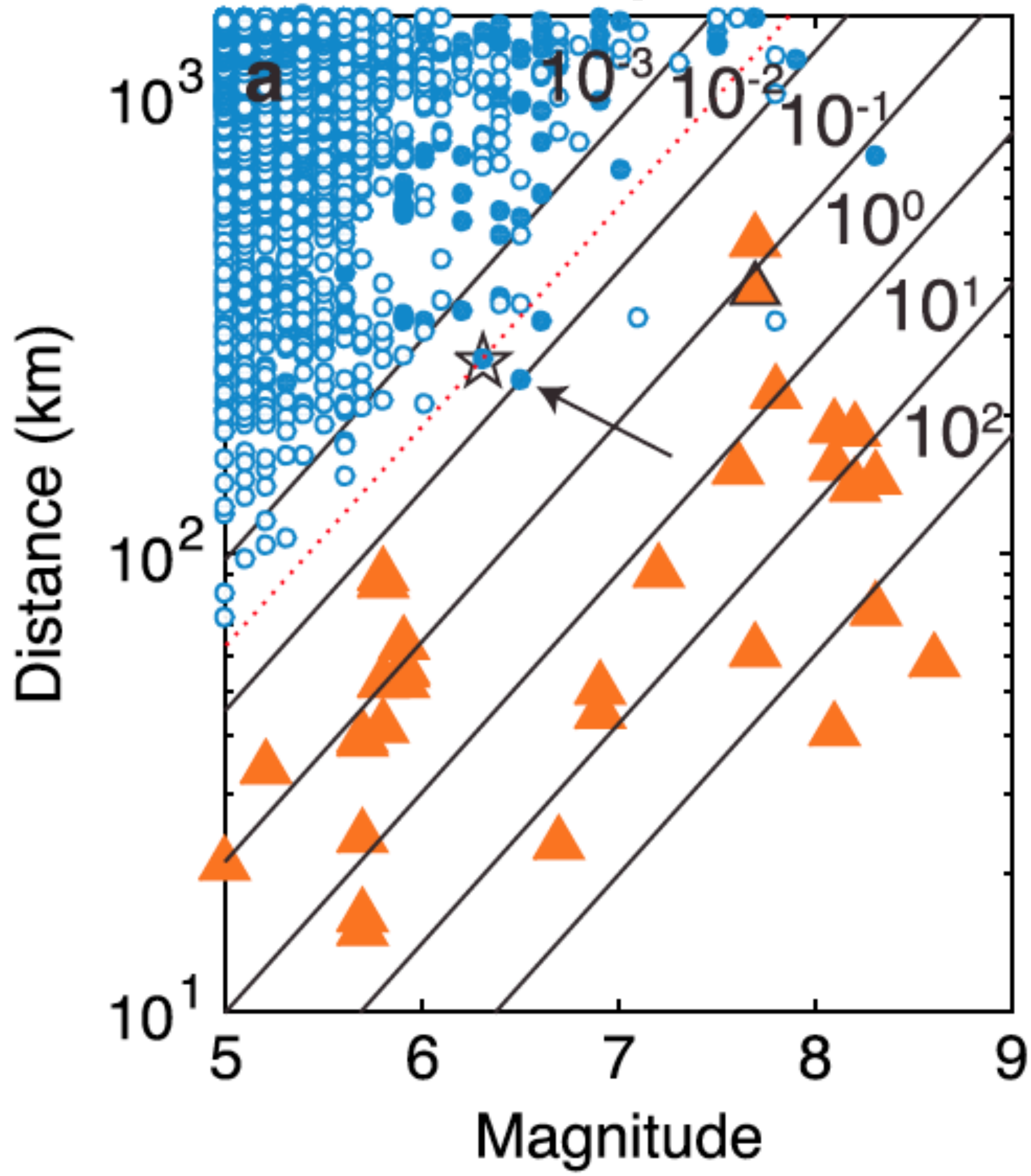
(Mazzini et al., *EPSL* 2007)

Response Threshold

Bonini, Rudolph and Manga (2016)



Rudolph et al. *GRL* (2015)



Conclusions

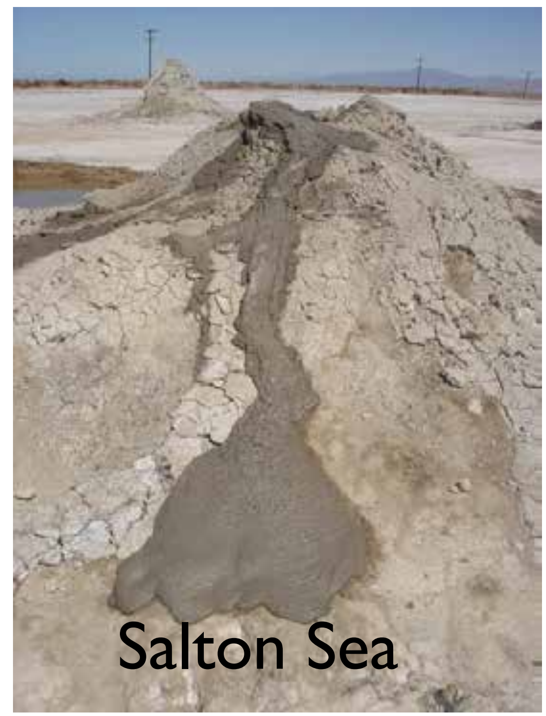
1. **Larger, closer earthquakes**
2. Static stress changes too small to trigger
3. > 20 earthquakes caused more shaking
4. No unusual seismicity in months before eruption
5. Coulomb stresses too small and have wrong sign to reactivate fault

Nothing “special” about Yogyakarta earthquake

Mechanism for triggering?

Use observations from Azerbaijan, Taiwan, Imperial Valley, northern Japan, Indonesia, Pakistan, Italy, Romania (Bonini et al., 2016)

- Triggered by dynamic, not static, strains
- Repose time of ~ years for triggering
- More sensitive to long period waves
- Triggering strain amplitudes too small to weaken mud or initiate undrained consolidation (our own lab experiments)
- Bubble nucleation or growth unlikely
- Favoured: increasing permeability and/or breaching hydraulic barrier



A Drilling Trigger?

- Well control issues prior to the erution
- Well was temporarily sealed
- Pressure in well, with weight of drilling mud, was enough to cause hydrofracturing or reactivate existing faults

2018 in press

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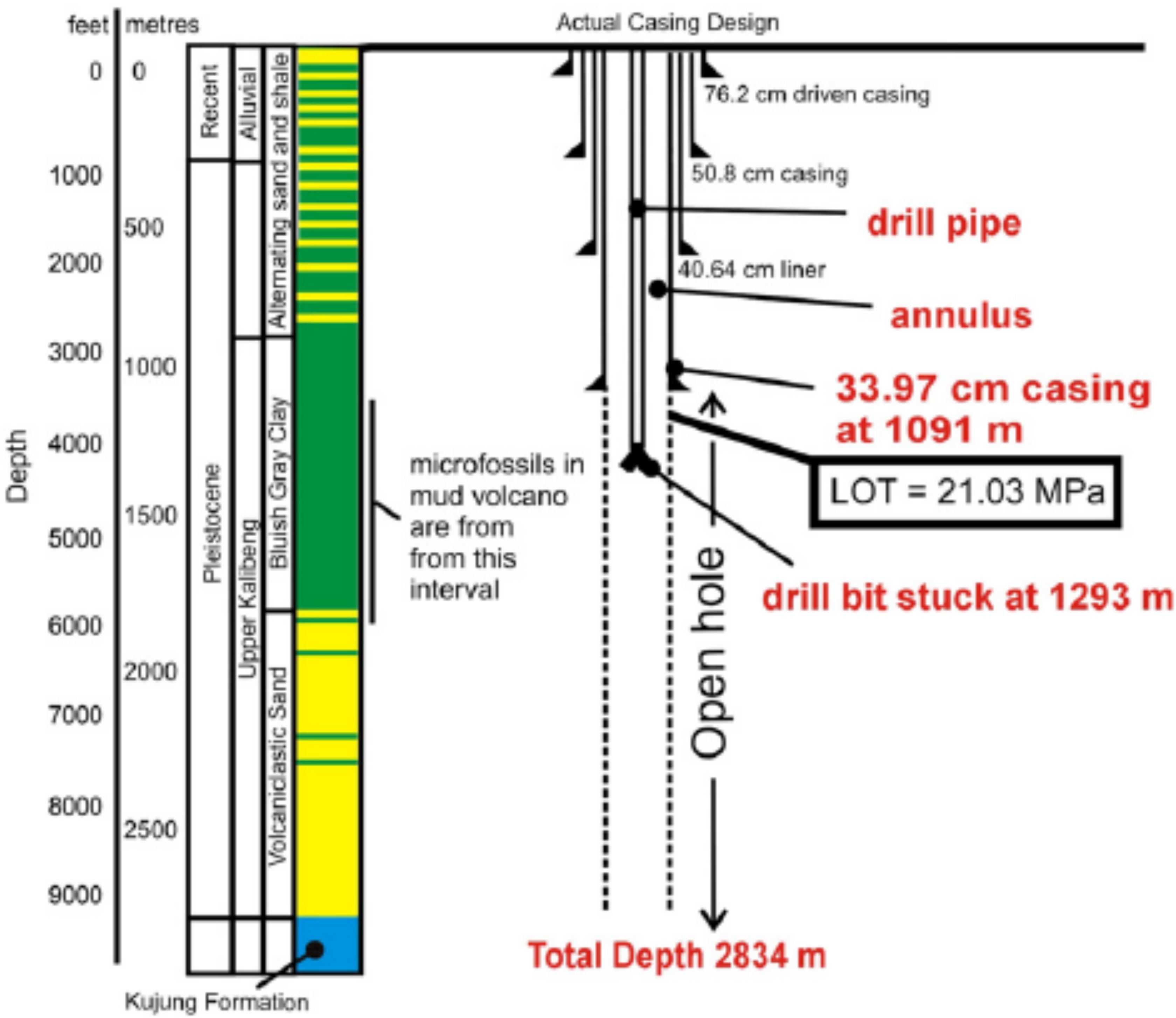
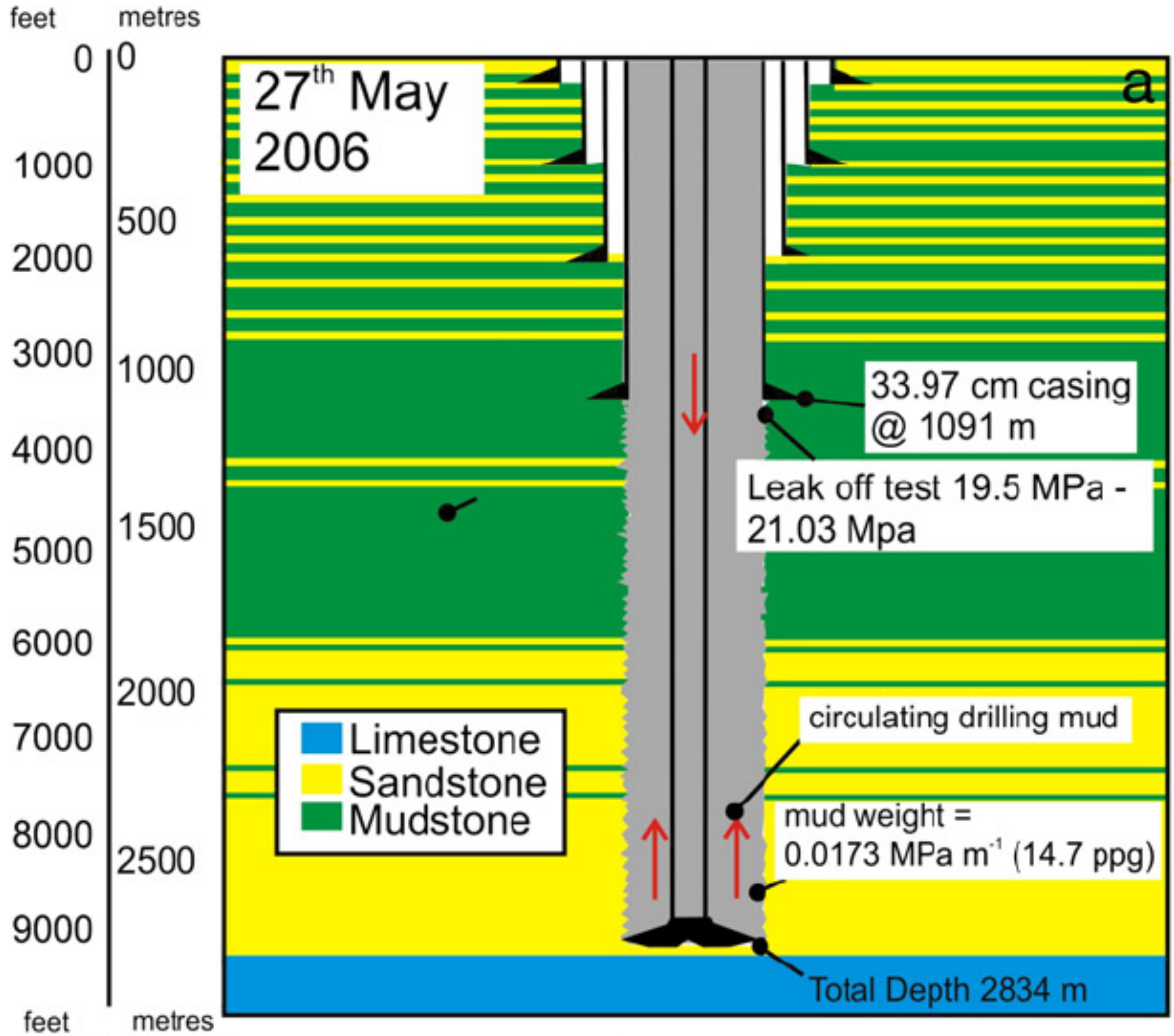
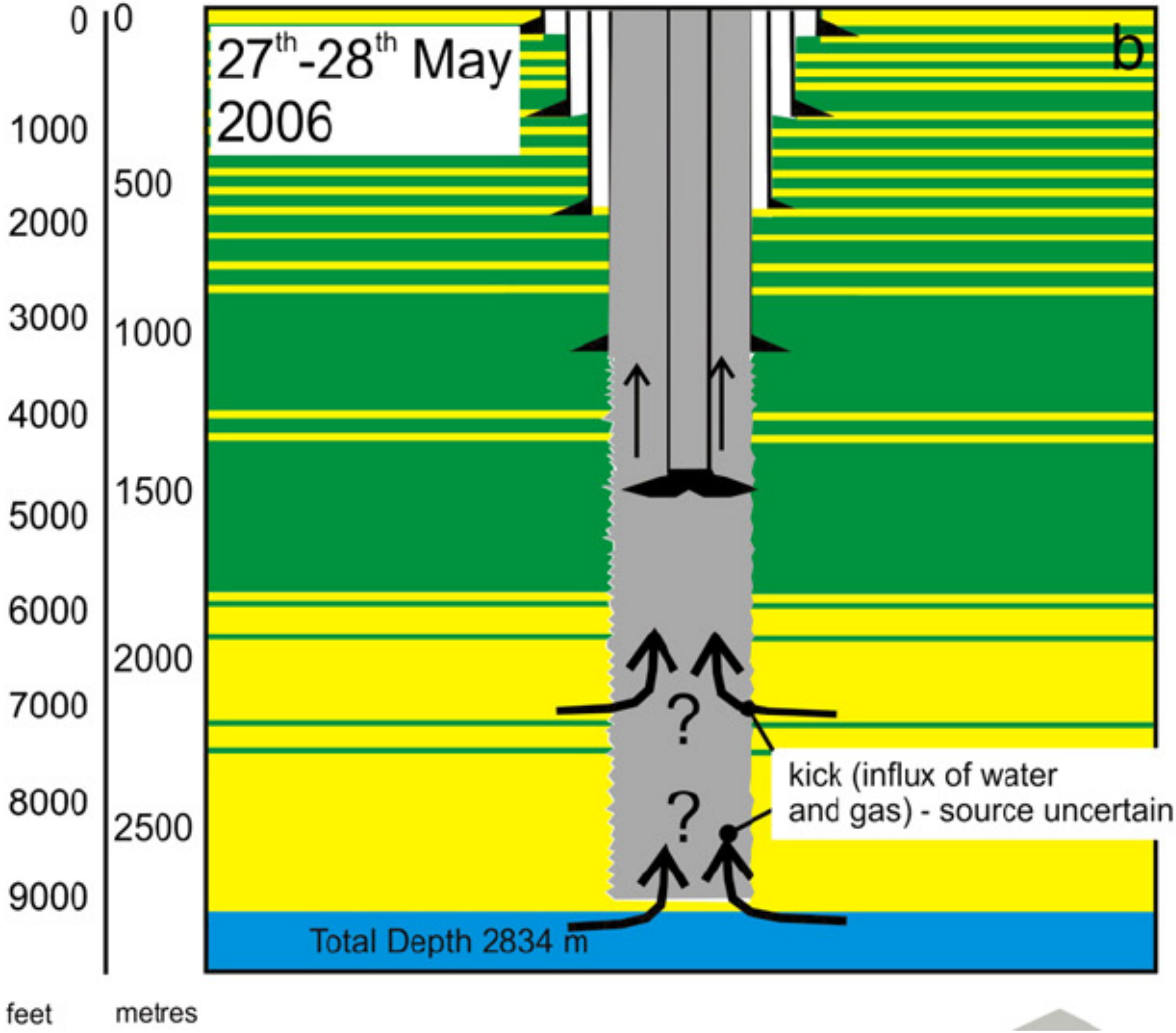
Discussion

An alternative review of facts, coincidences and past and future studies of the Lusi eruption

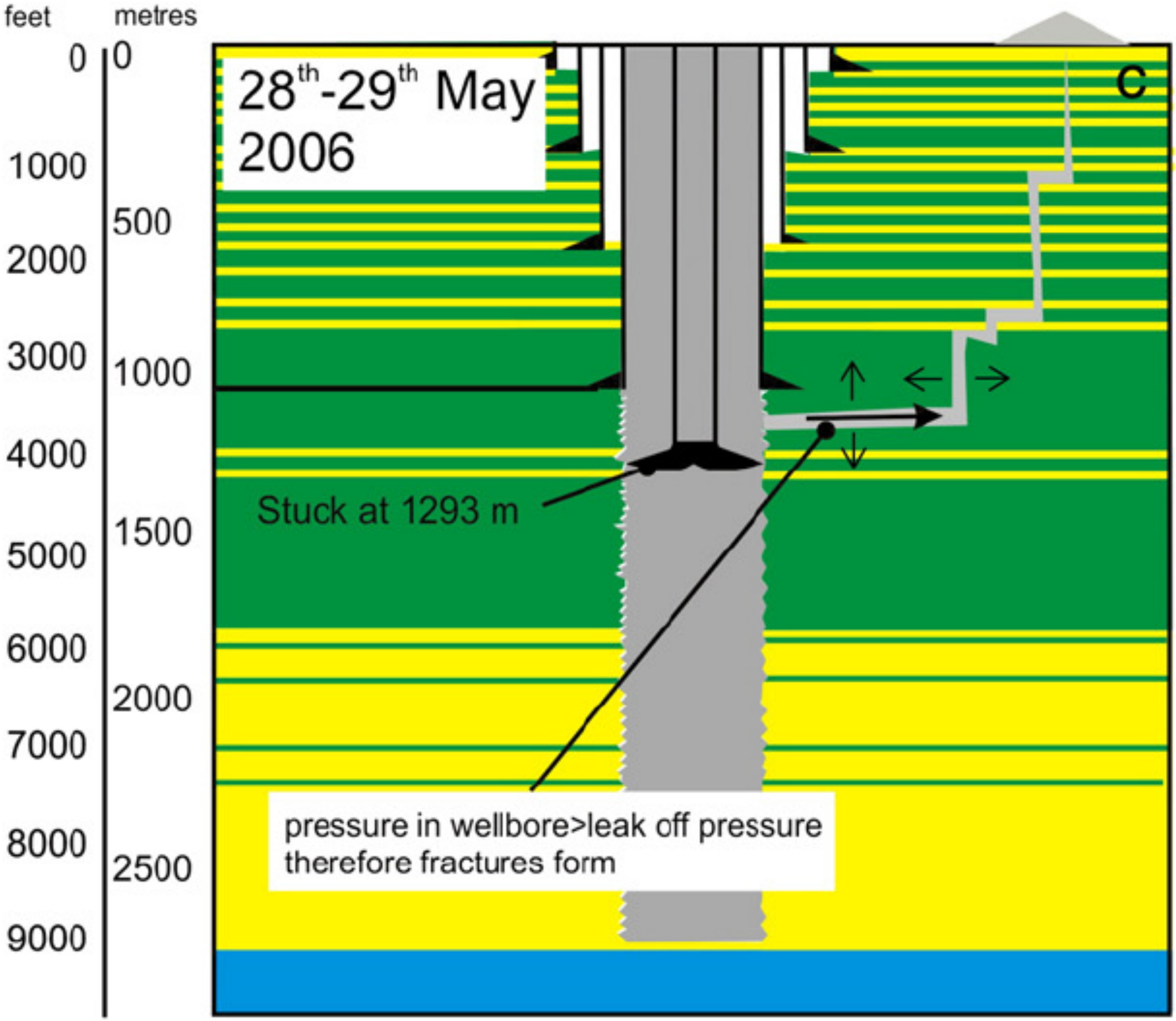
Mark Tingay[a], Michael Manga[b,*], Maxwell L. Rudolph[c], Richard Davies[d]


feet
metres
Depth
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
0
500
1000
1500
2000
2500
Recent
Pleistocene
Alluvial
Upper Kalibeng
Alternating sand and shale
Bluish Gray Clay
Volcaniclastic Sand
Kujung Formation
microfossils in
mud volcano
are from
from this
interval
Actual Casing Design
76.2 cm driven casing
50.8 cm casing
drill pipe
40.64 cm liner
annulus
33.97 cm casing
at 1091 m
LOT = 21.03 MPa
drill bit stuck at 1293 m
Open hole
Total Depth 2834 m


feet
metres
0
0
1000
500
2000
3000
1000
4000
1500
5000
6000
2000
7000
8000
2500
9000
feet
metres
27th May 2006
a
33.97 cm casing @ 1091 m
Leak off test 19.5 MPa - 21.03 Mpa
circulating drilling mud
mud weight = 0.0173 MPa m-1 (14.7 ppg)
Total Depth 2834 m
Limestone
Sandstone
Mudstone



27th-28th May 2006
b
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
feet
0
500
1000
1500
2000
2500
metres
?
?
kick (influx of water and gas) - source uncertain
Total Depth 2834 m

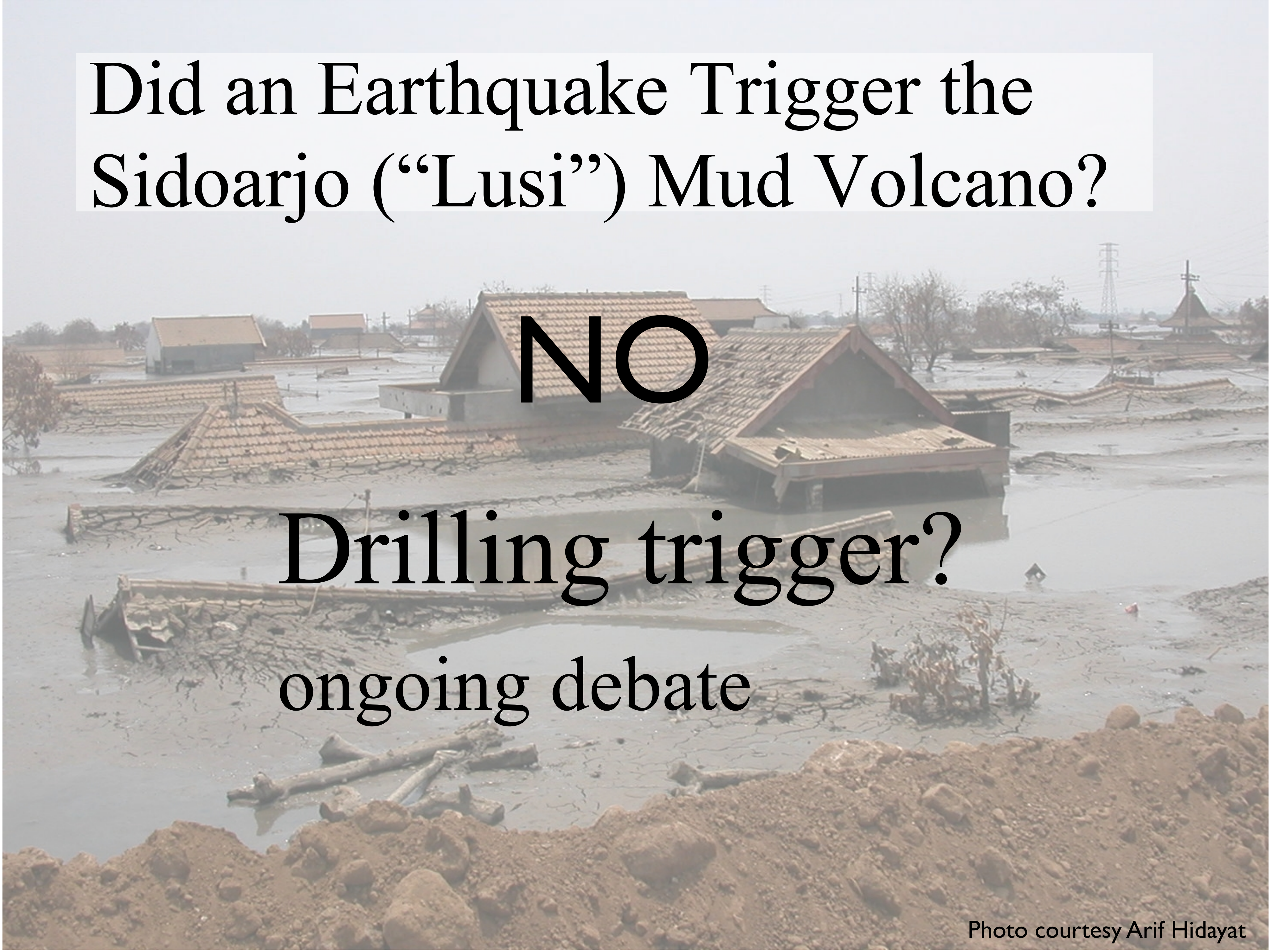


feet
metres
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
0
500
1000
1500
2000
2500
28th-29th May 2006
C
Stuck at 1293 m
pressure in wellbore>leak off pressure therefore fractures form

Did an Earthquake Trigger the Sidoarjo (“Lusi”) Mud Volcano?

NO

Photo courtesy Arif Hidayat


Did an Earthquake Trigger the
Sidoarjo ("Lusi") Mud Volcano?
NO
Drilling trigger?
ongoing debate
Photo courtesy Arif Hidayat

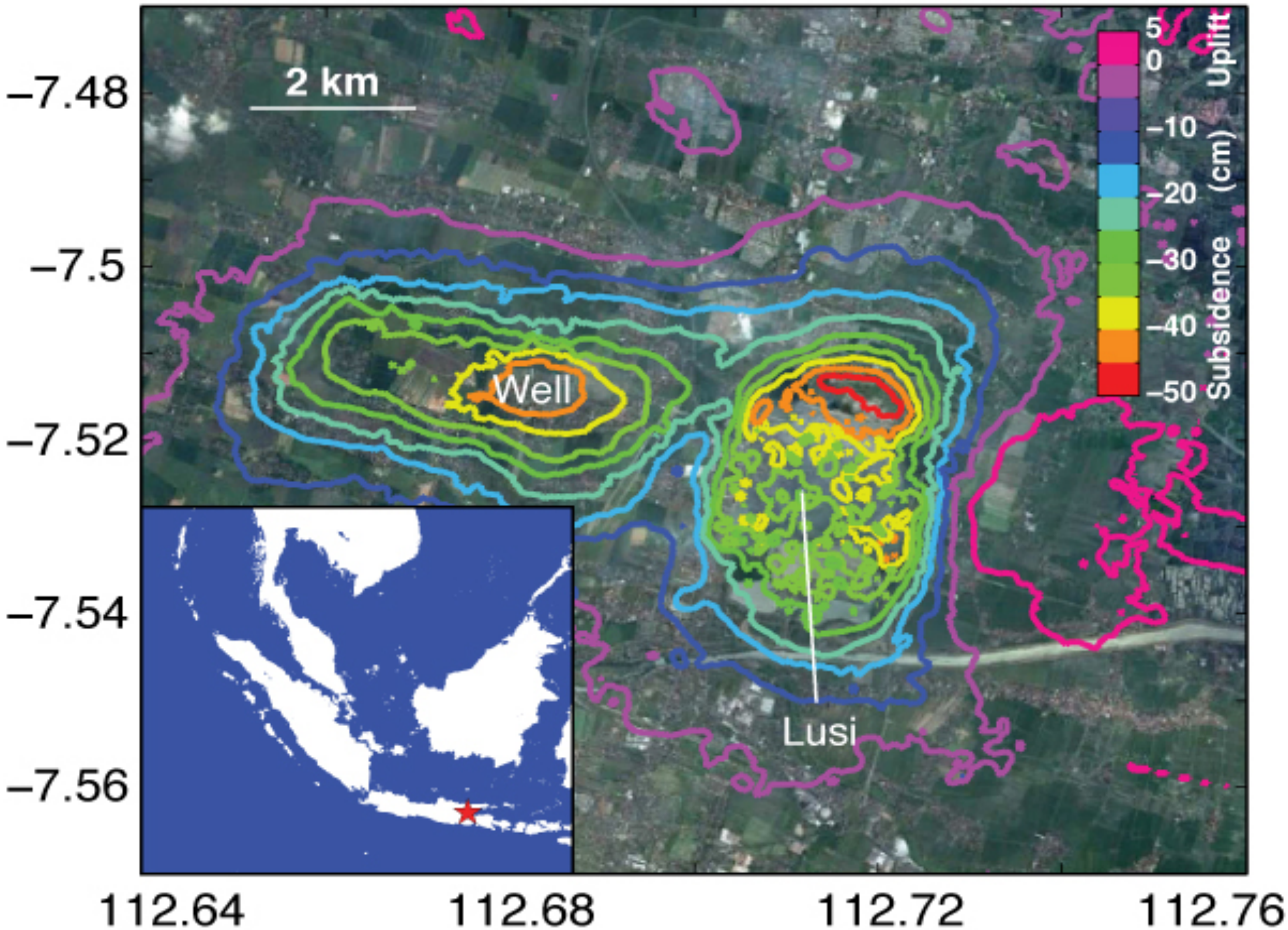
Did an Earthquake Trigger the Sidoarjo (“Lusi”) Mud Volcano?

NO

When will it end?

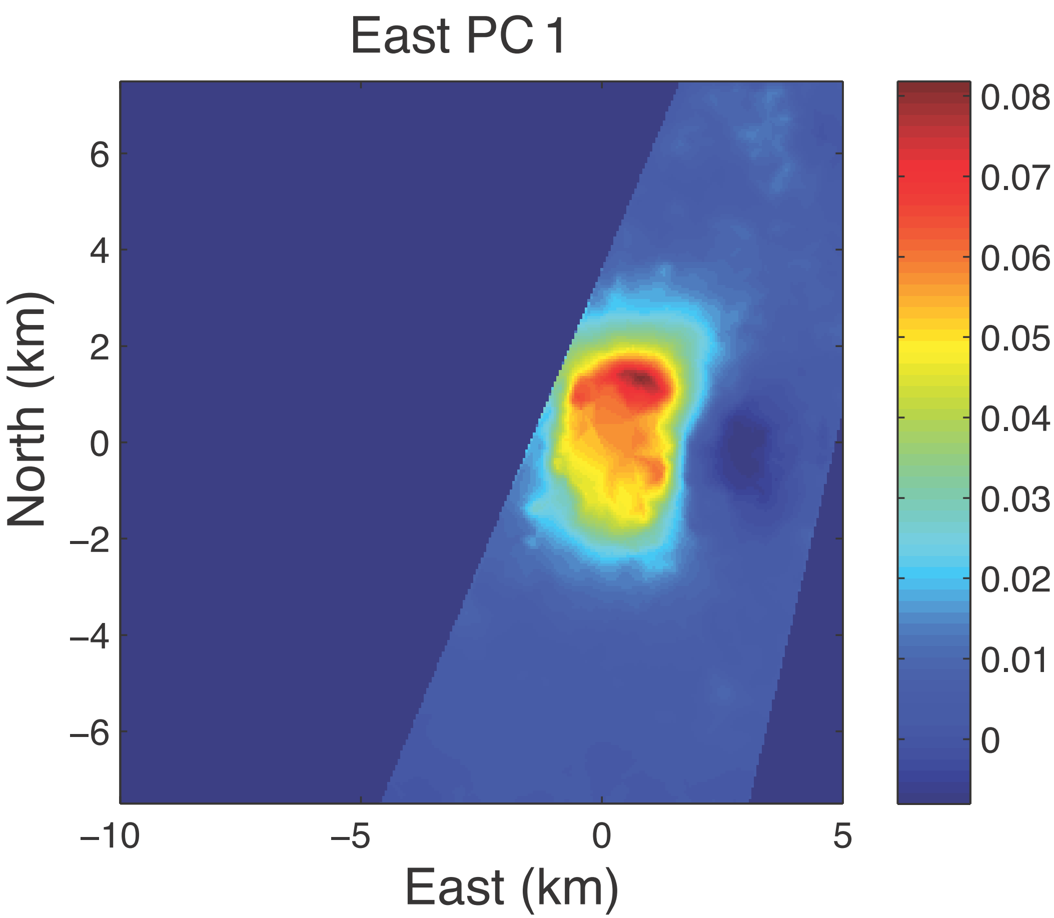
Photo courtesy Arif Hidayat

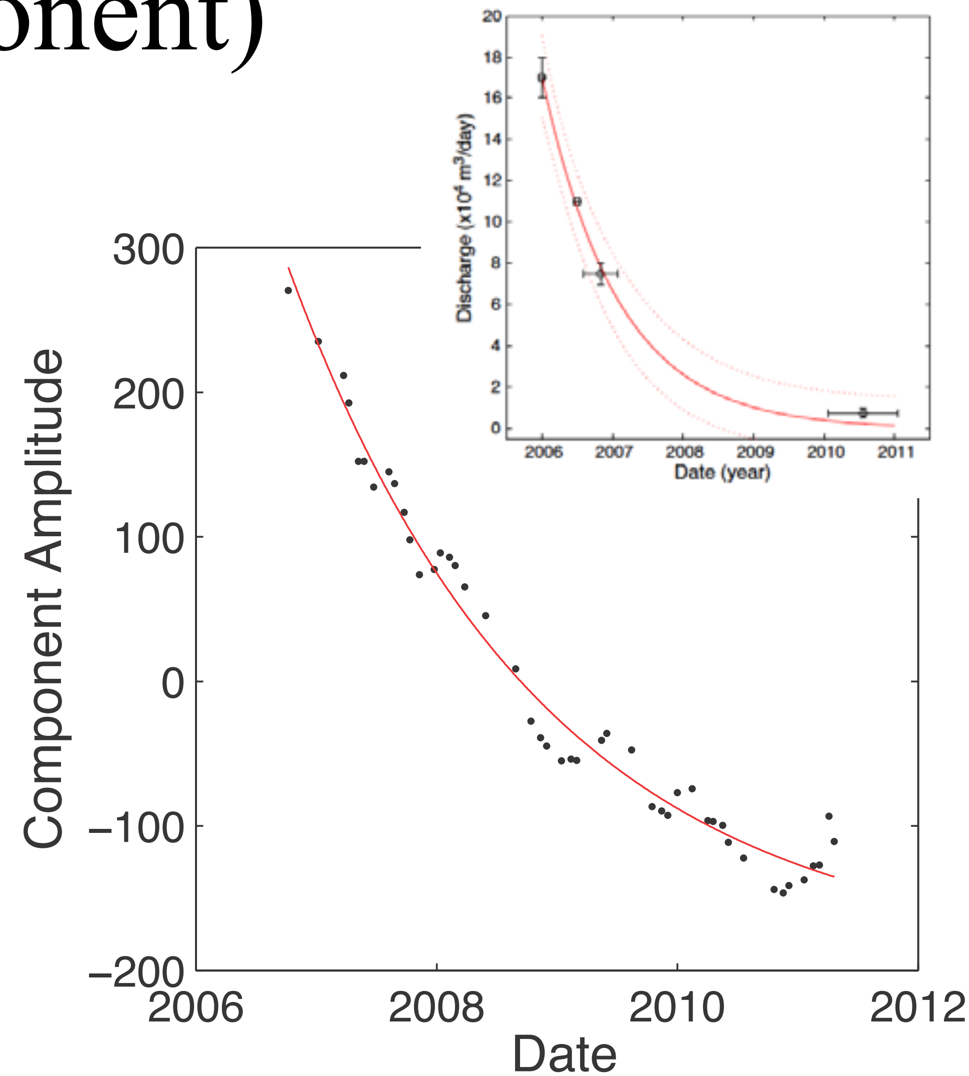
Observed Ground Deformation



Cumulative ground deformation October 2006 - April 2011
46 L-band ALOS radar images

PCA Result
(1st Principal Component)



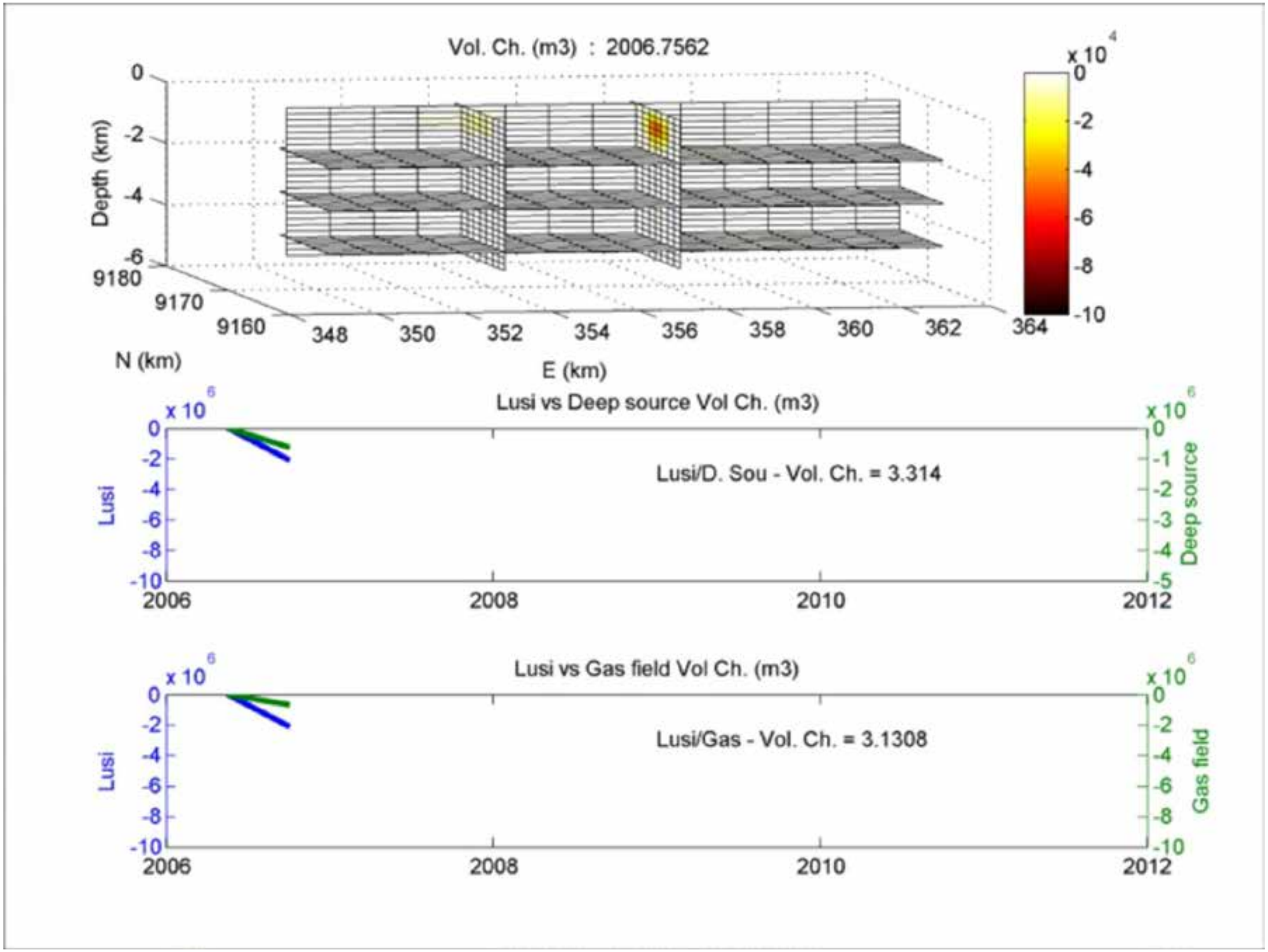


Exponential fit, *e*-folding time $2.1^{+0.5}_{-0.3}$ years

Shorter than our mechanical model predictions (Rudolph et al., 2011)

Both a deep and more shallow source

Shirzaei et al. *GRL* (2015)

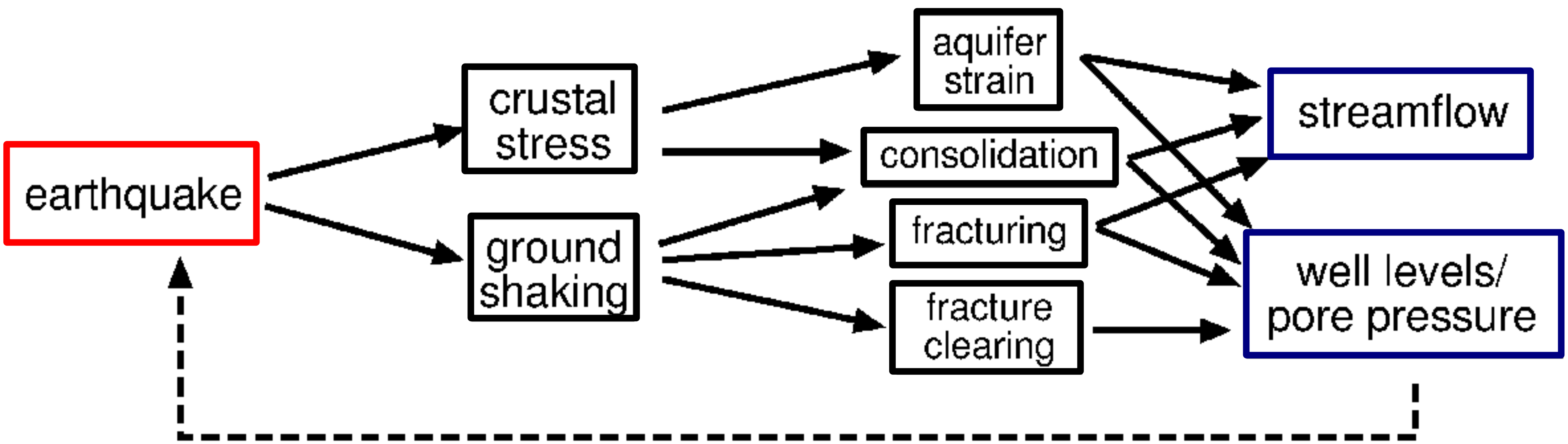


Confirmed from gas geochemistry (Tingay et al. *Nat Geo* 2015)

Collaborators

Chi Wang, Joel Rowland, Emily Brodsky, Max Rudolph, Leif Karlstrom, Maria Brumm, Richard Davies, Mark Tingay, Marco Bonini, Manoo Shirzaei

Summary



Montgomery and Manga, *Science* (2003)

Why?

"It's one of those curiosities of nature that has preoccupied people for years"

Stuart Rojstaczer, *Nature*, 2003

- Affects water supply and water quality
- Hydrocarbon migration and recovery
- May affect underground waste repositories (Carrigan et al., 1991; Roeloffs, 1998)
- Affects engineering structures

New insight into

Controls on hydrologic properties

Evolution of hydrologic cycle

Triggered seismicity and eruptions