Hydrogeologic Transients and Fault Mechanics

Clues, Connections, and Open Questions

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Why Fluids Matter in Fault Mechanics

$\sigma' = \sigma - P$

- fluid pressure lowers effective stress

$\tau_f = \mu\sigma_n'$

- Lower effective stress → weaker faults

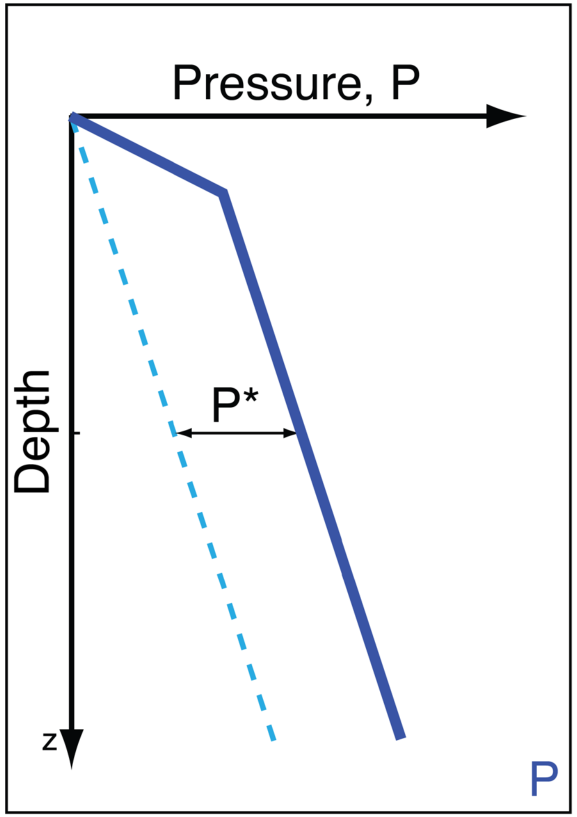
- Lower effective stress can also promote fault slip and alter slip style

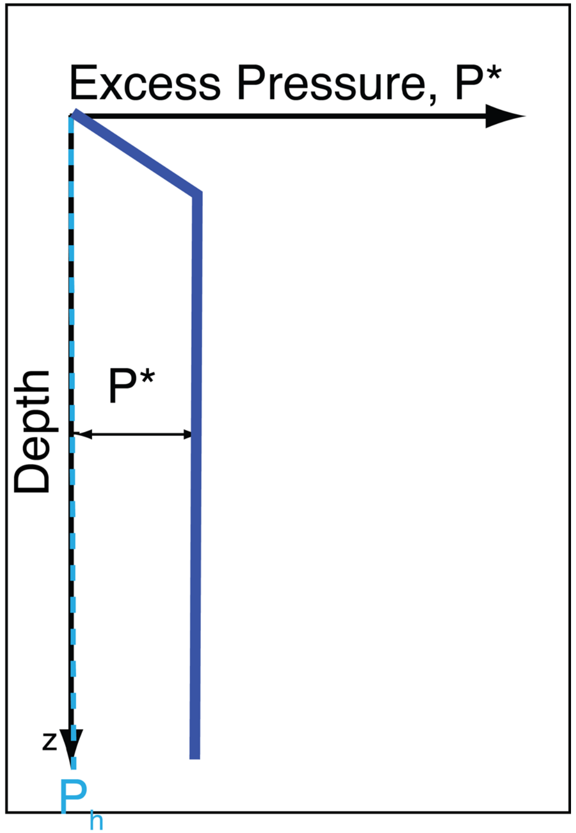
Darcy's Law and Excess Pressure

$$q = -(k/\eta)\, \nabla P^*$$

- Fluids flow due to gradients in excess pressure $P^* = P - P_{hydrostatic}$

- Not all pressure gradients cause flow





When Do Overpressures Form?
Neuzil Number

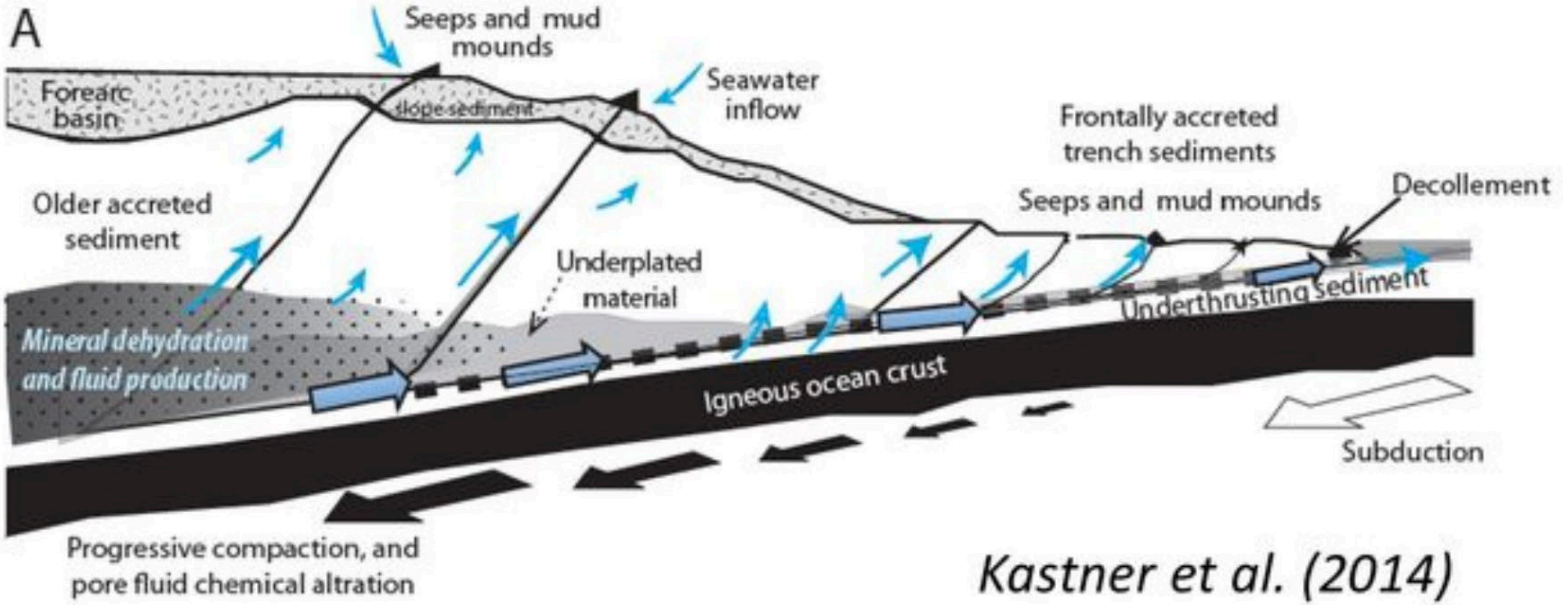
Overpressures maintained when:

$$\Gamma \cdot L / K > 1$$ (Neuzil, 1995)

- Γ : geologic forcing
  (e.g. compaction or fluid source (Vwater/Vrock per time) [s^{-1}]
- L : drainage distance [m]
- K : hydraulic conductivity [m/s]

Drainage vs Entrapment

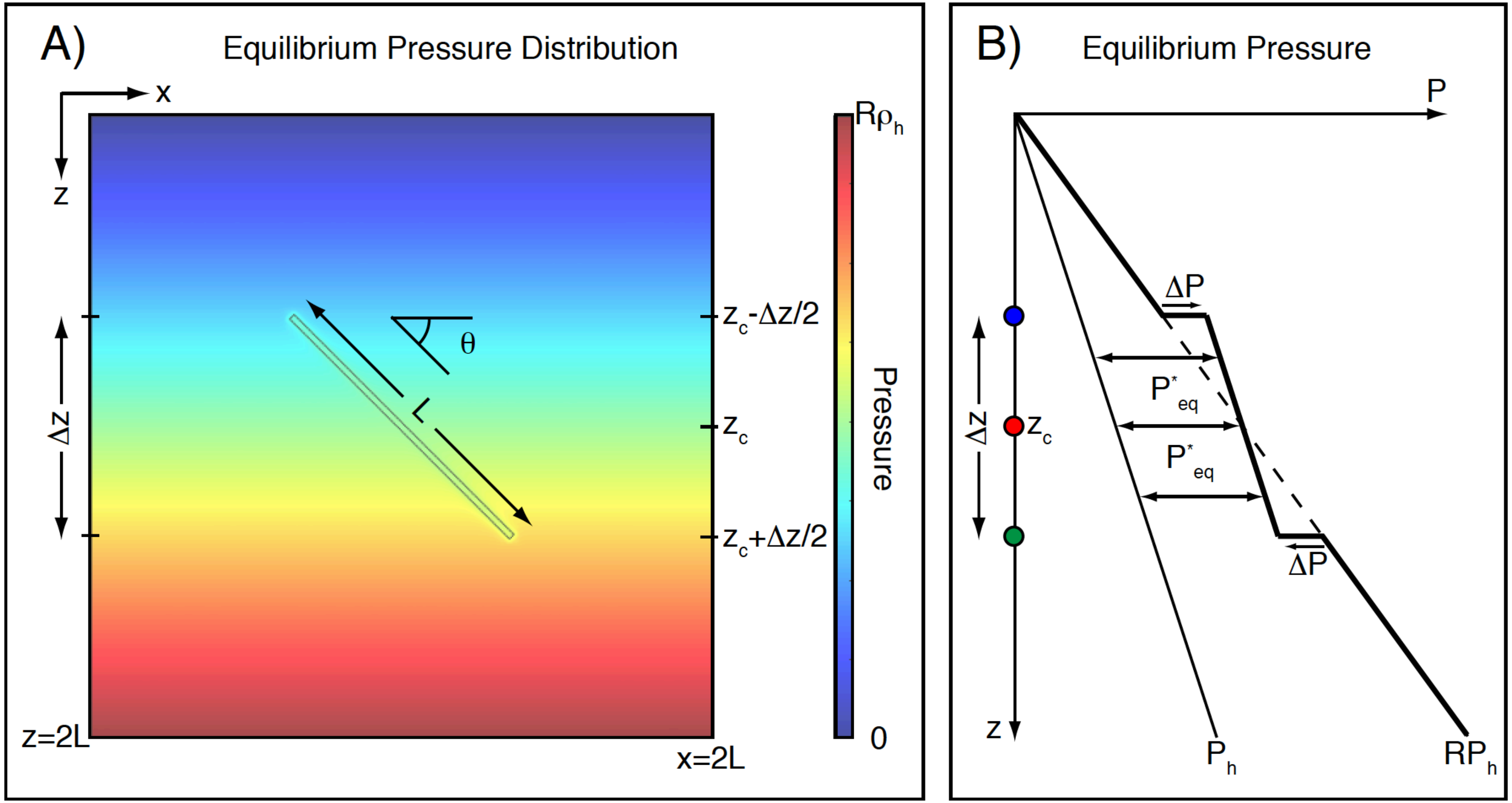
- Permeable faults can drain fluids to seafloor
- Bounded faults redistribute pressure internally
- Flow focusing and heterogeneous stress may result



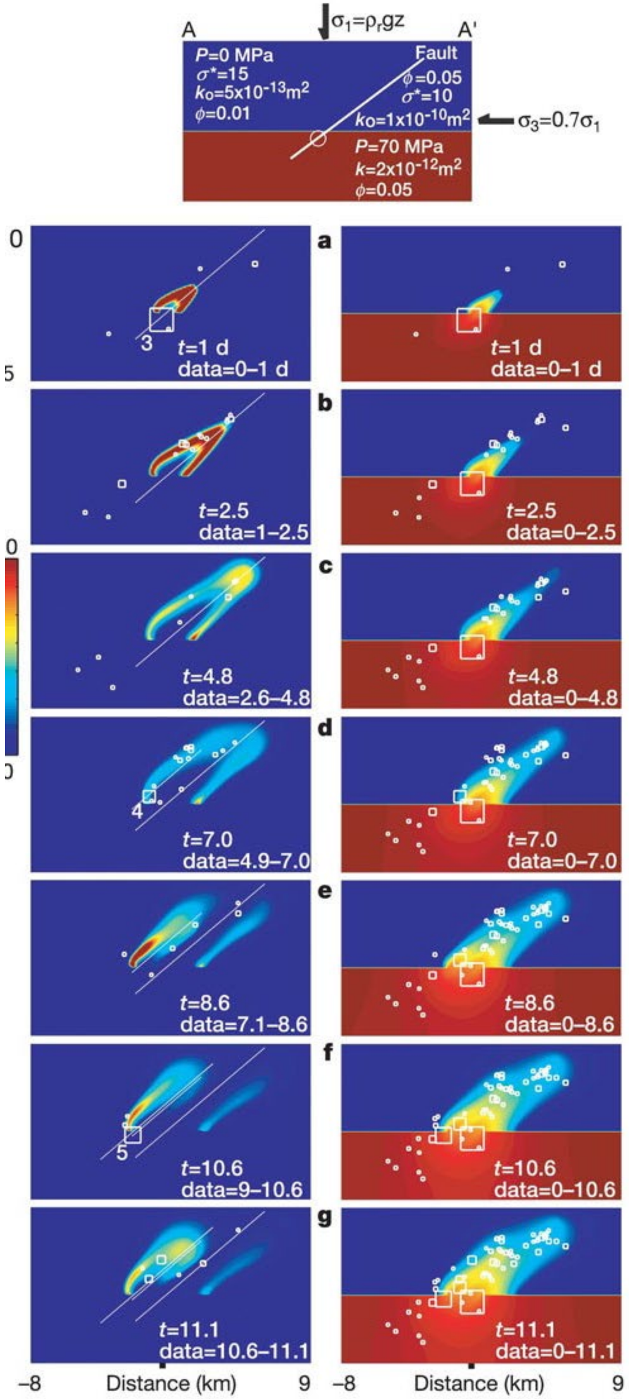
Kastner et al. (2014)

Flow Focusing

- Pressure drawn down at depth
- Pressure builds at shallower levels
- Promotes localized failure and slip migration



Model results following upon Flemings et al., *Am. J. Science*, 2002



Fault valving

Sibson (1992) introduced the *fault-valve model*:

- Faults behave like intermittent seals: impermeable under high stress
- Slip or rupture temporarily opens the fault → fluid discharge
- Healing or mineralization reseals the fault, starting the cycle again

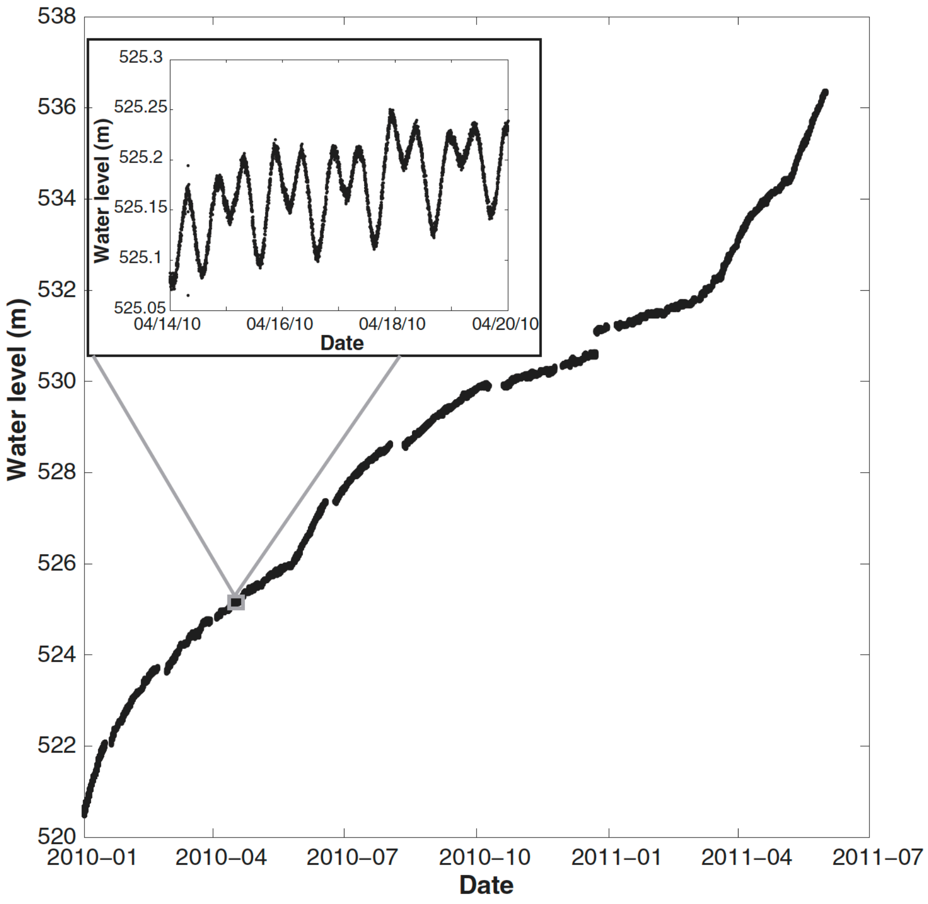
Miller et al. (2004, Nature):

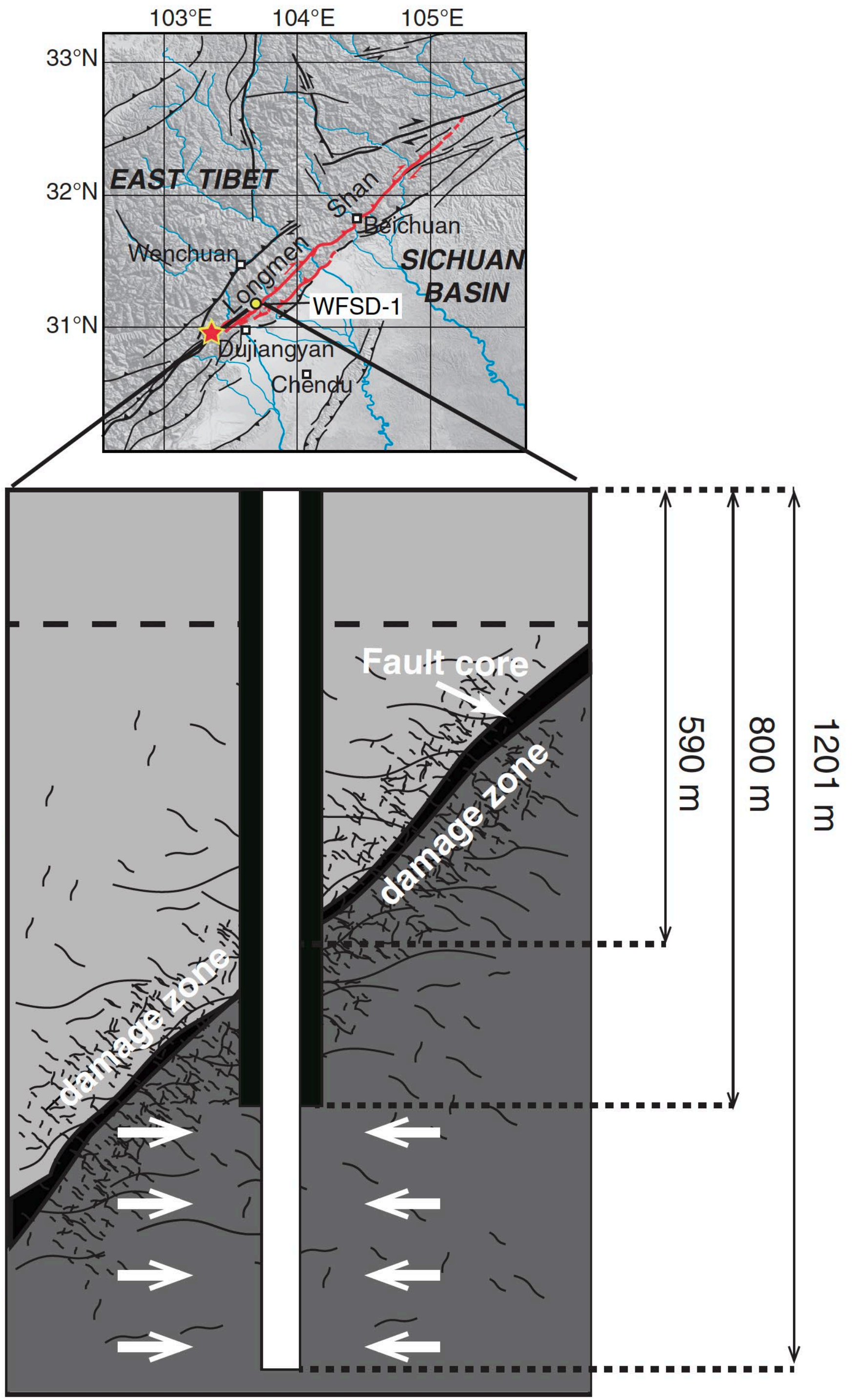
- Observed an aftershock sequence in the Dolomites that migrated upward along a fault
- Interpreted as evidence an upward migration traced along a permeable fault segment, suggesting a transient increase in permeability

Is Permeability Constant?

- Earthquakes and fault slip can change the permeability
- Transient opening or sealing alters fluid pathways
- **However, it’s not just shearing that can cause permeability increases**

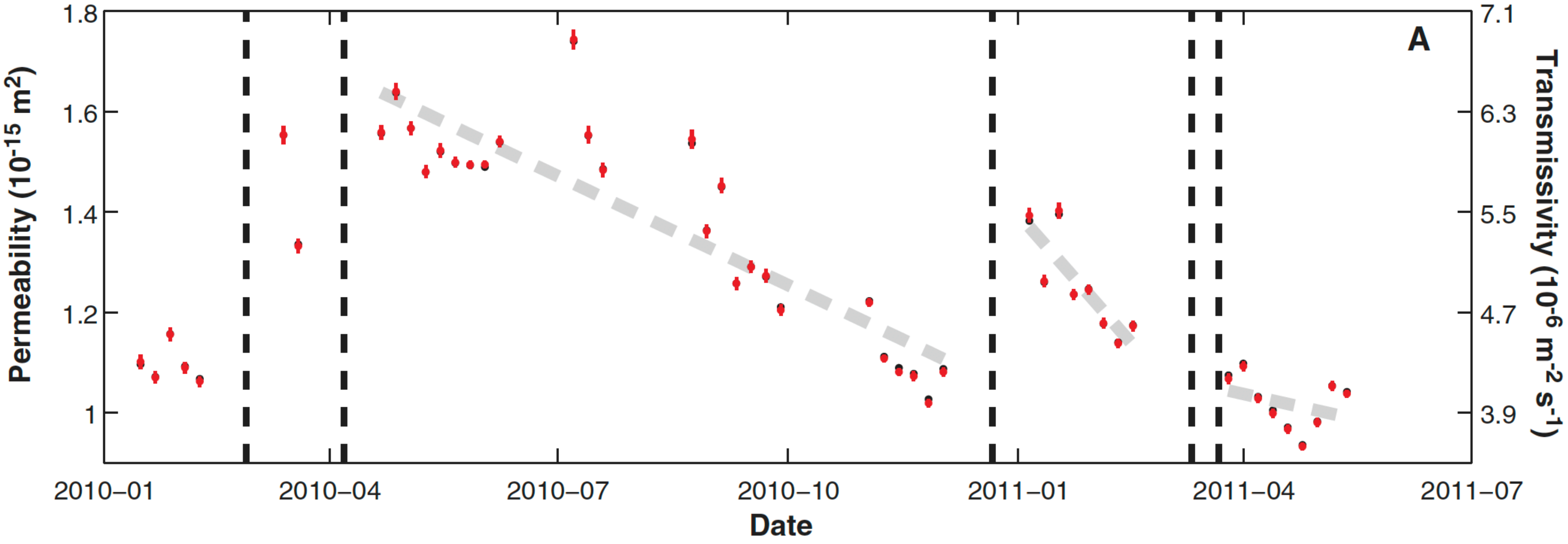
Xue et al. (2013): Damage and Healing





Xue et al. (2013): Damage and Healing

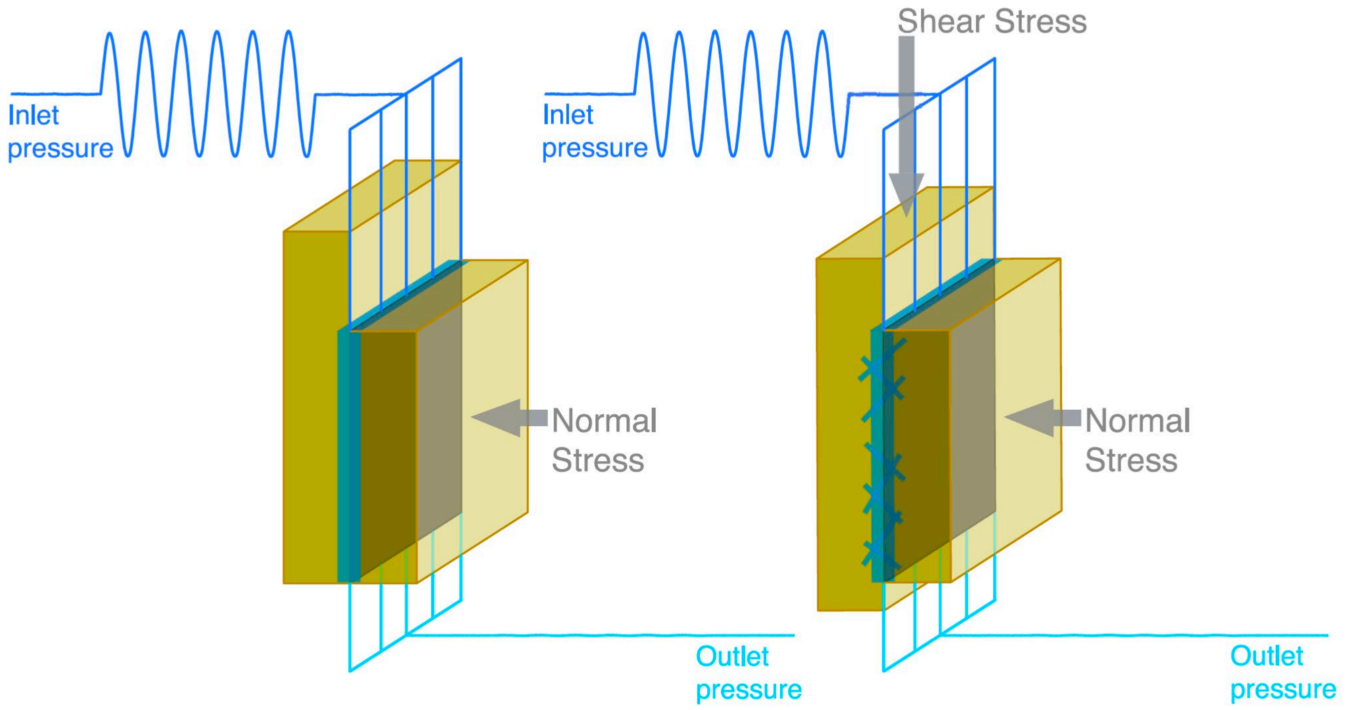
- Fault zone permeability increases after distant earthquakes
- Gradual healing over time



Xue et al., *Science*, 2013

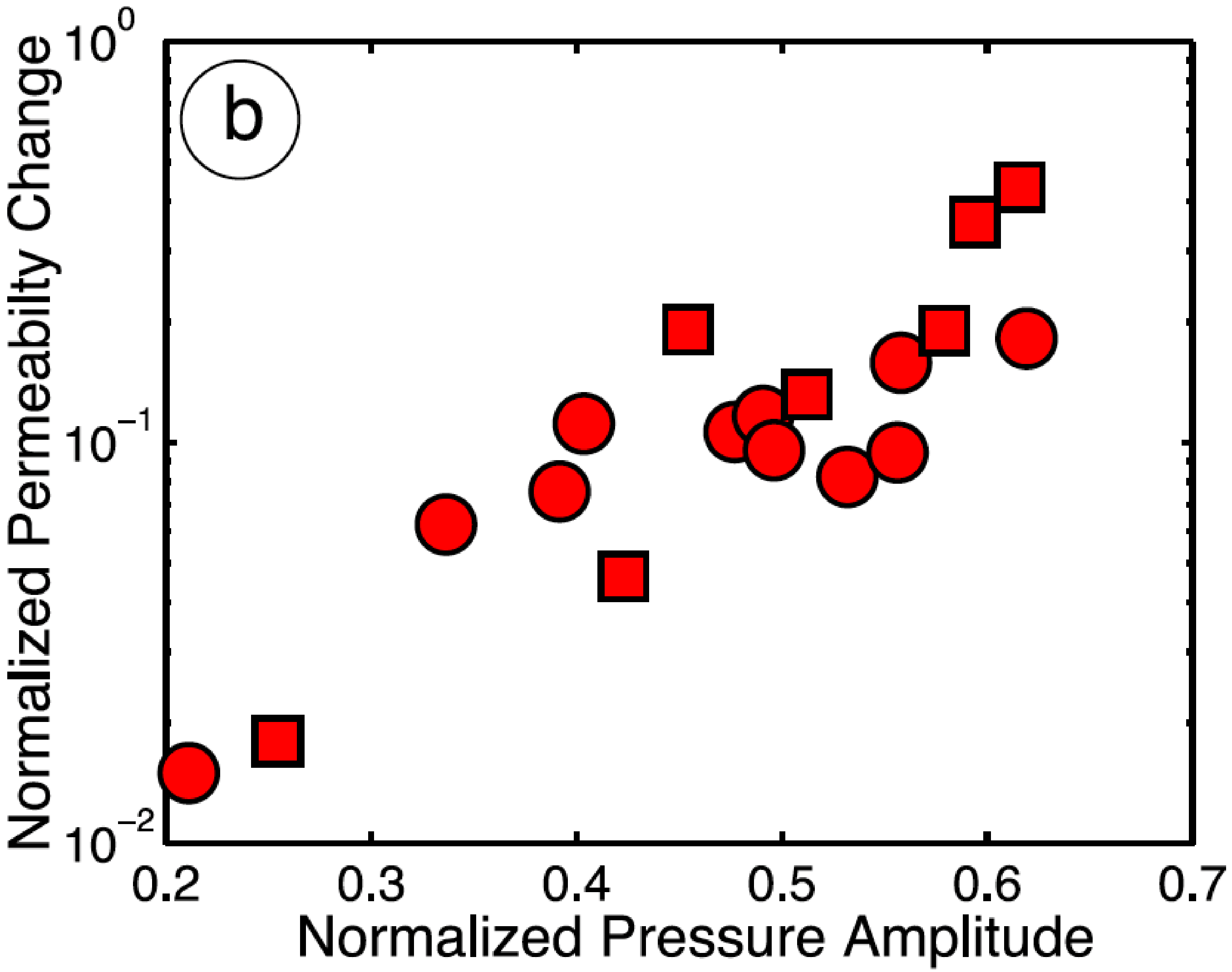
Candela et al. 2014: Lab Evidence

- Shaking can open pore throats
- Fluid chemistry affects clay mobilization
- Lab confirms effects of damage and healing on permeability

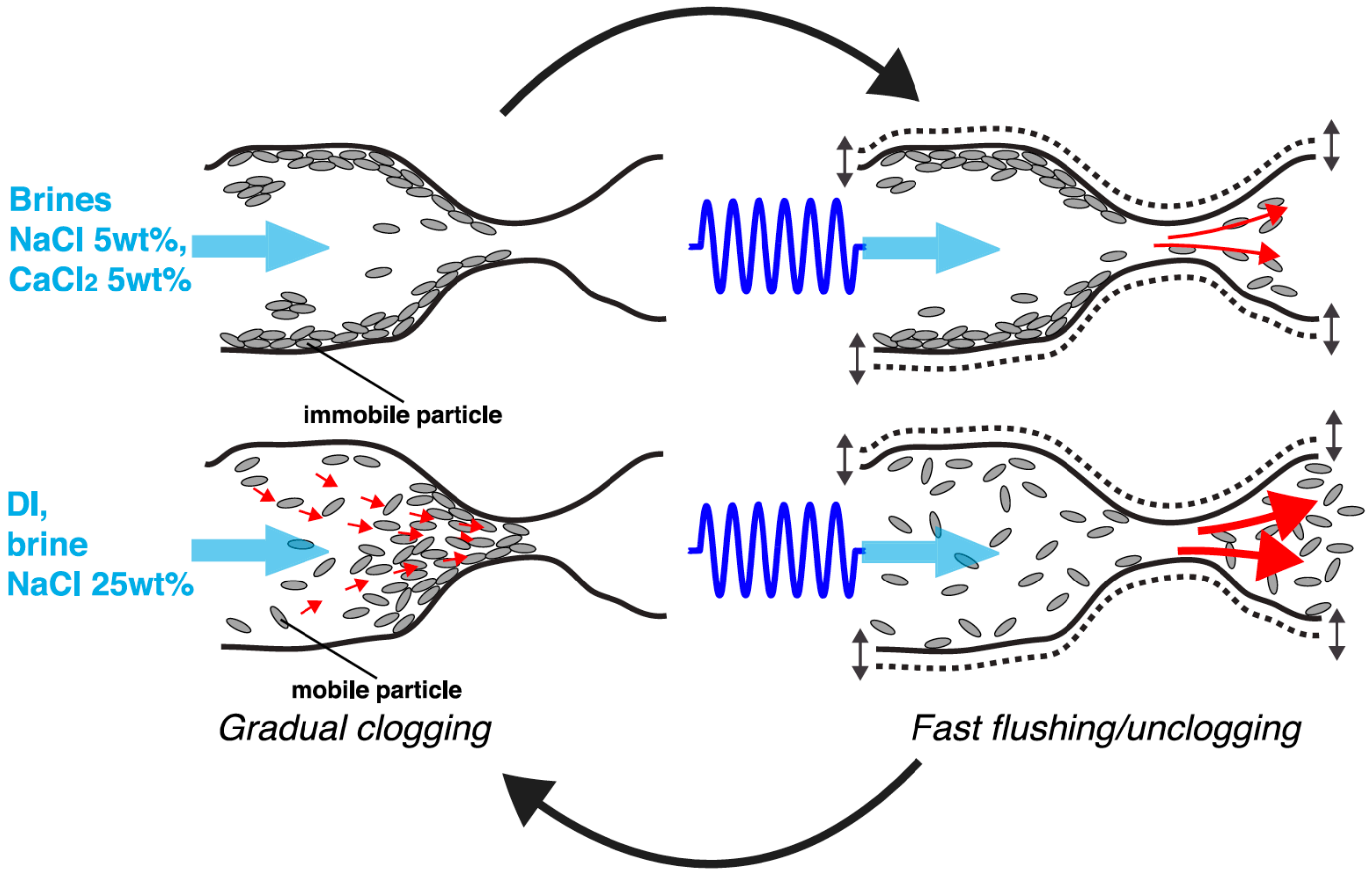


Candela et al. 2014: Lab Evidence

- • Shearing can open or clog pore throats
- • Fluid chemistry affects clay mobilization
- • Lab confirms permeability is reactive

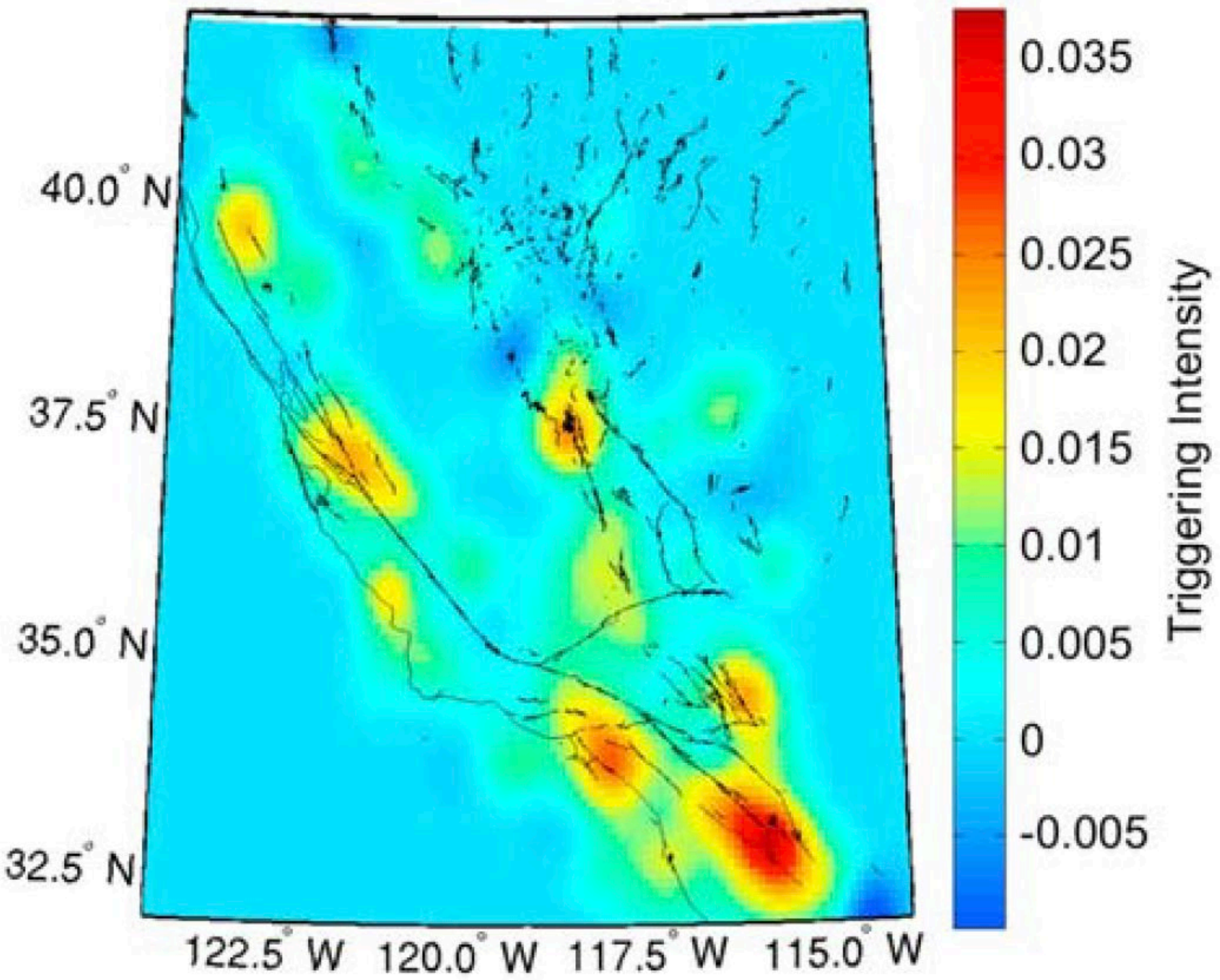


Candela et al. 2014: Lab Evidence



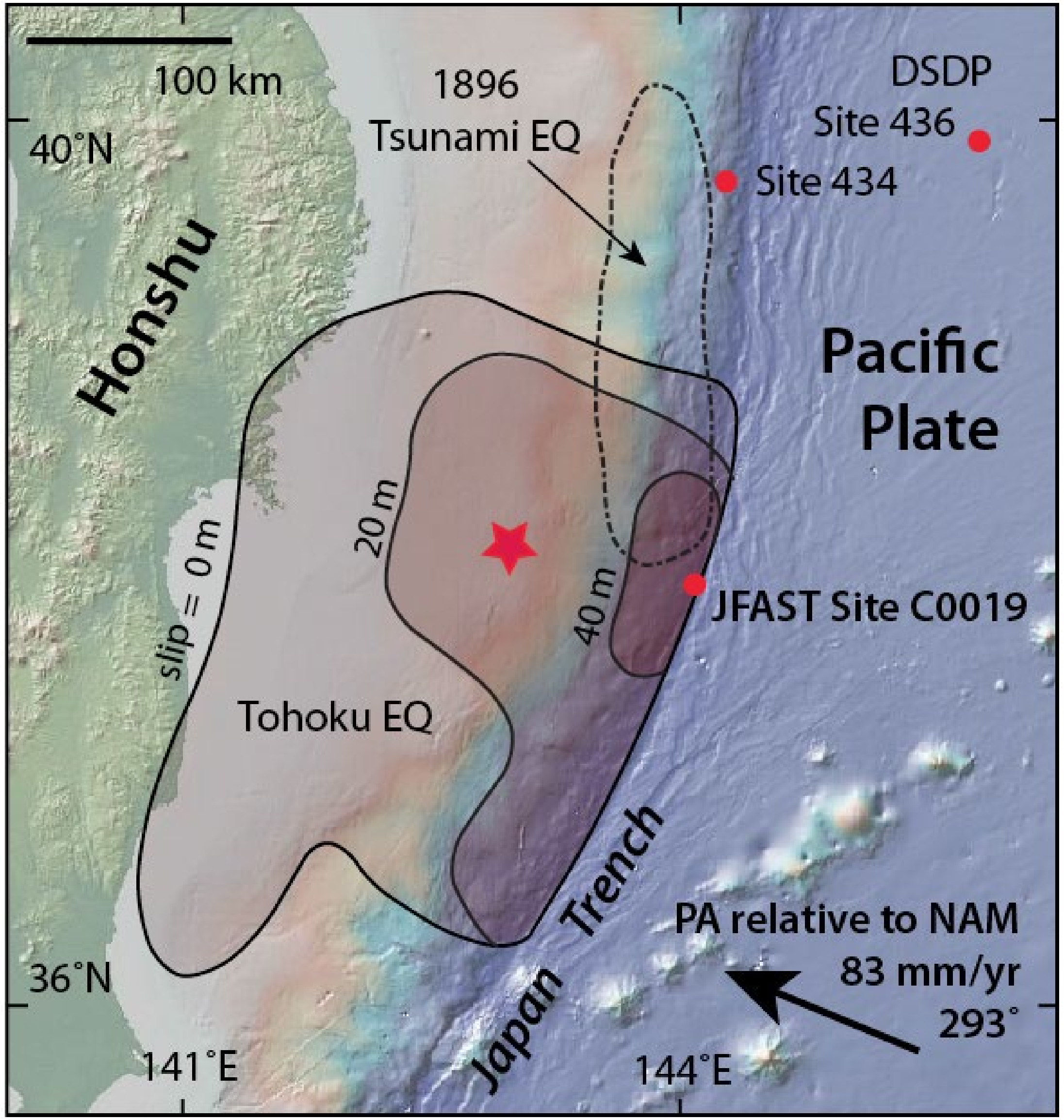
Van der Elst & Brodsky, 2010: Delayed EQ triggering

- Delayed triggering in geothermal regions and potentially fluid rich regions
- Could transient fluid flow be involved?



JFAST Observations

- Fluid pulses observed post-Tohoku
- Fault sensitivity to shaking changed over time
- Suggests permeability evolution

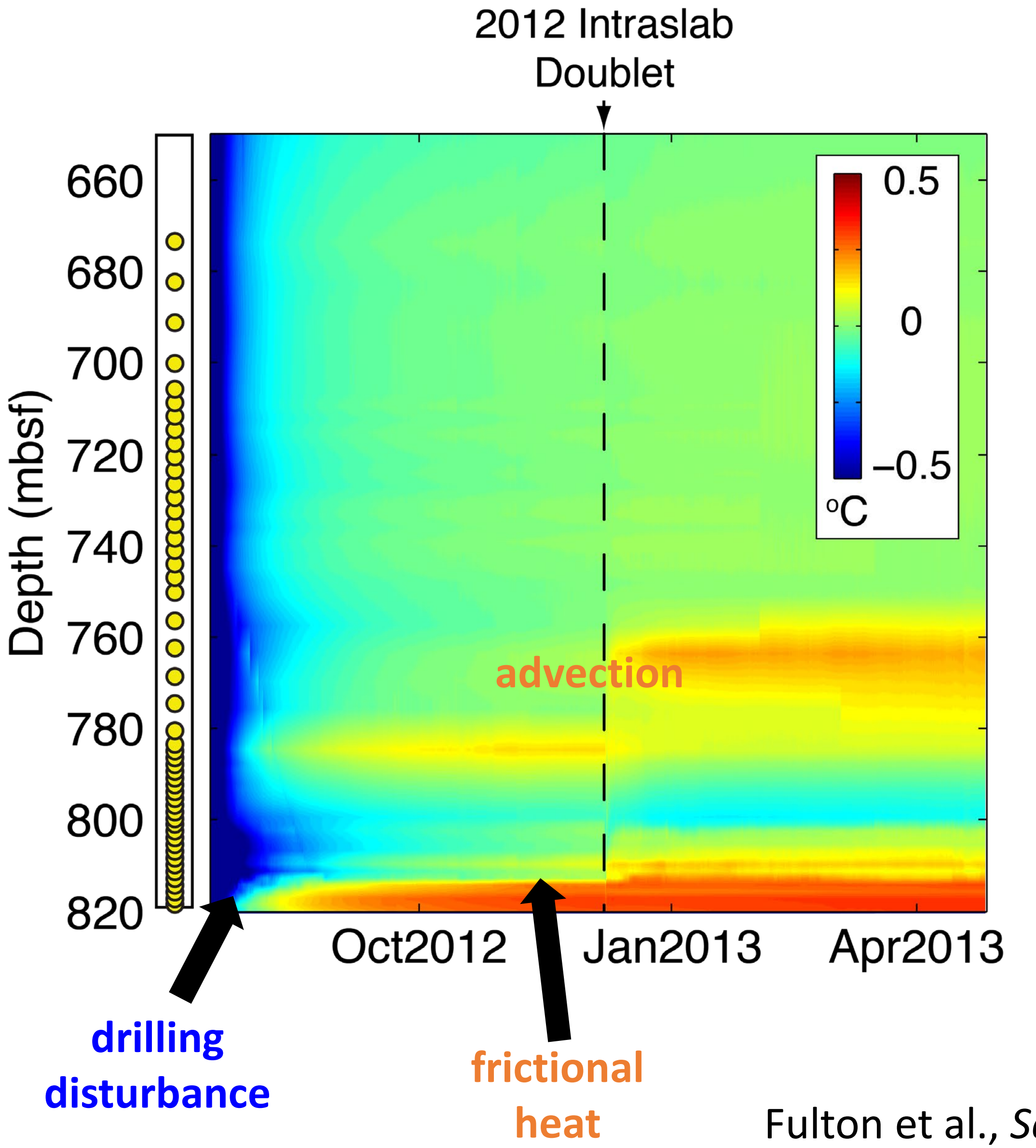


Chester et al. , *Science 2013*

Residual temperature (geotherm removed)

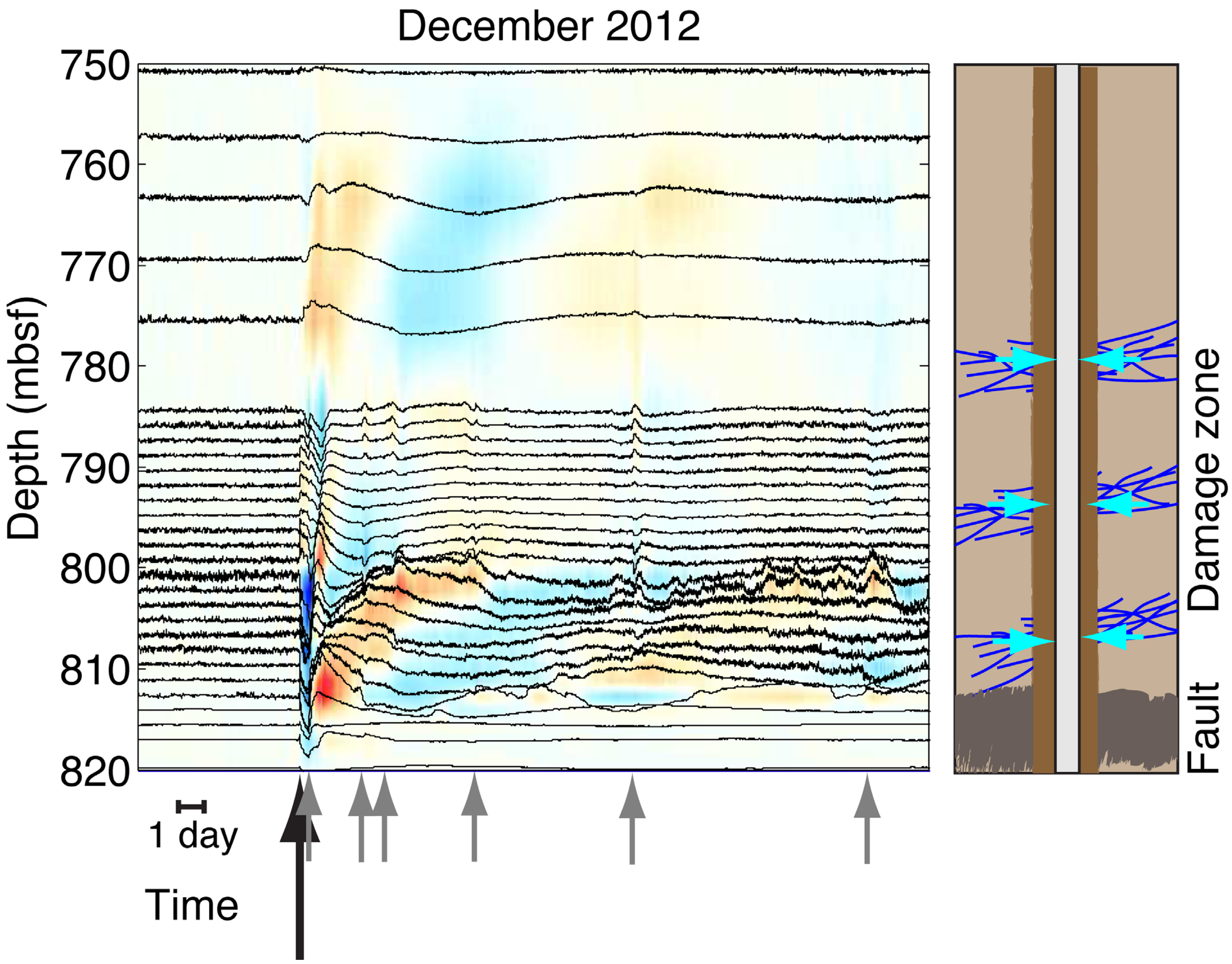
Japan Trench
2011 Mw 9.0
Earthquake Fault

820 m below
seafloor
in 7 km water depth



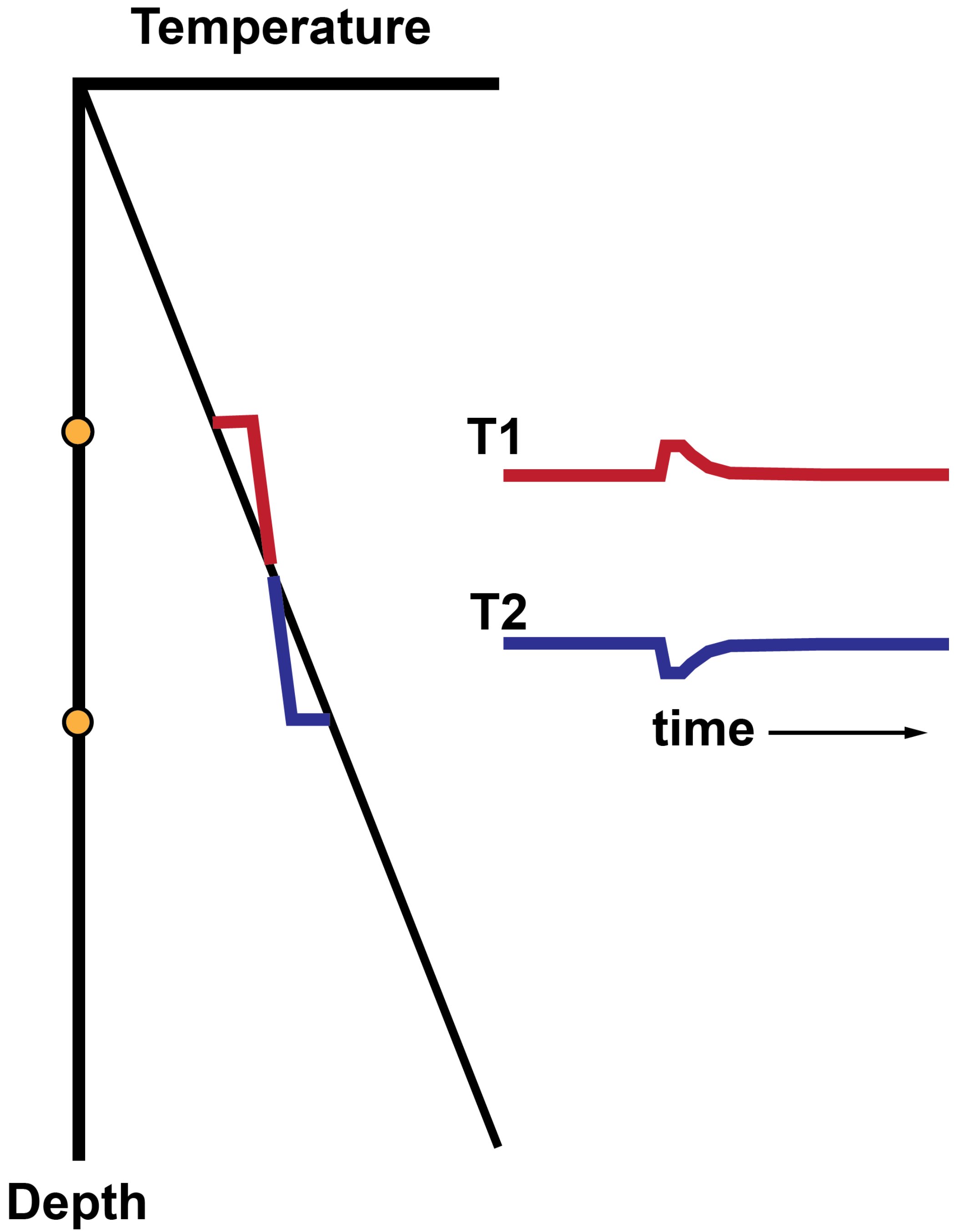
Fulton et al., *Science 2013*

High-pass filtered temperature

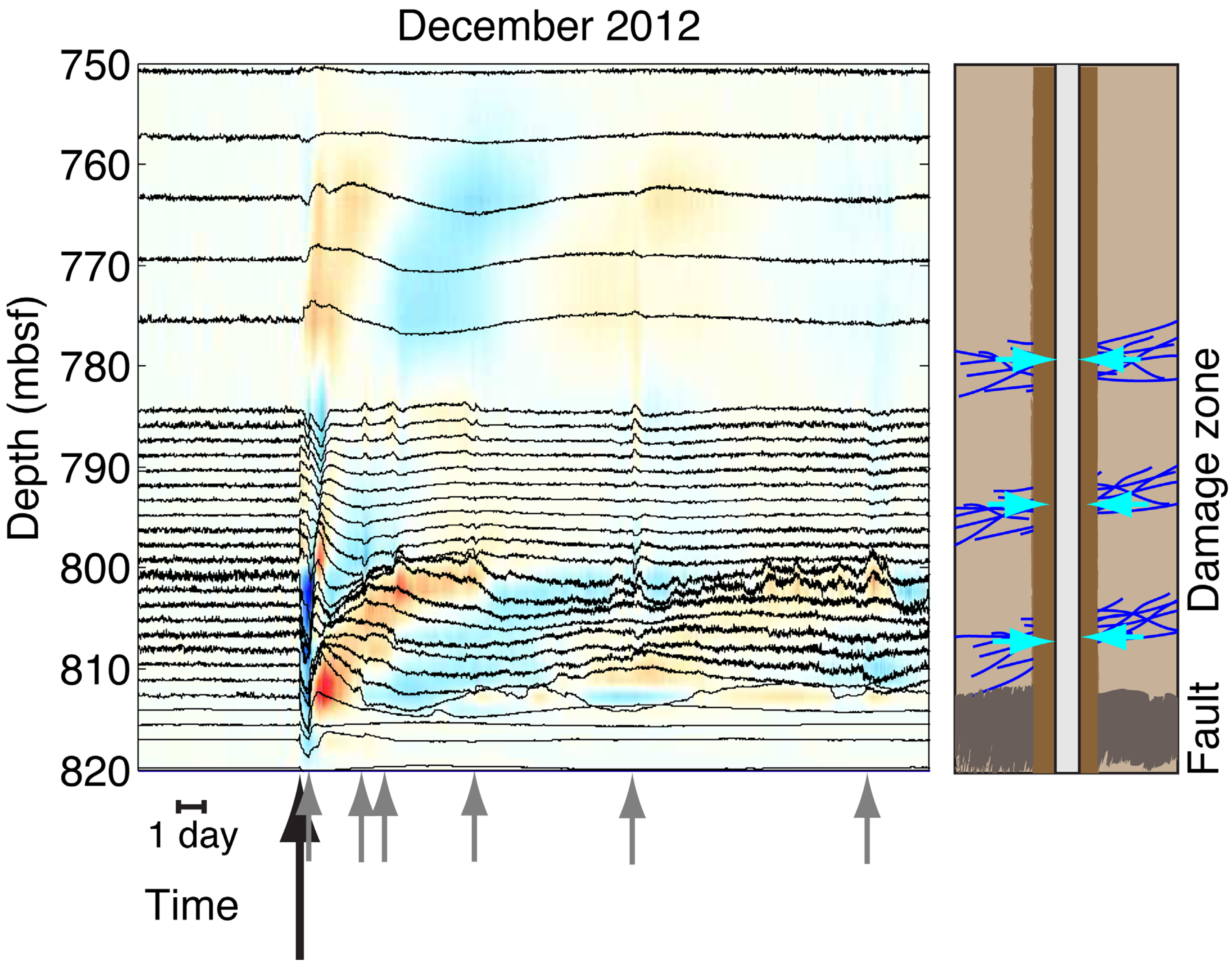


Bandwidth:
10 minute – 20 day

Fulton & Brodsky, *Geology, 2016*


Temperature
T1
T2
time
Depth

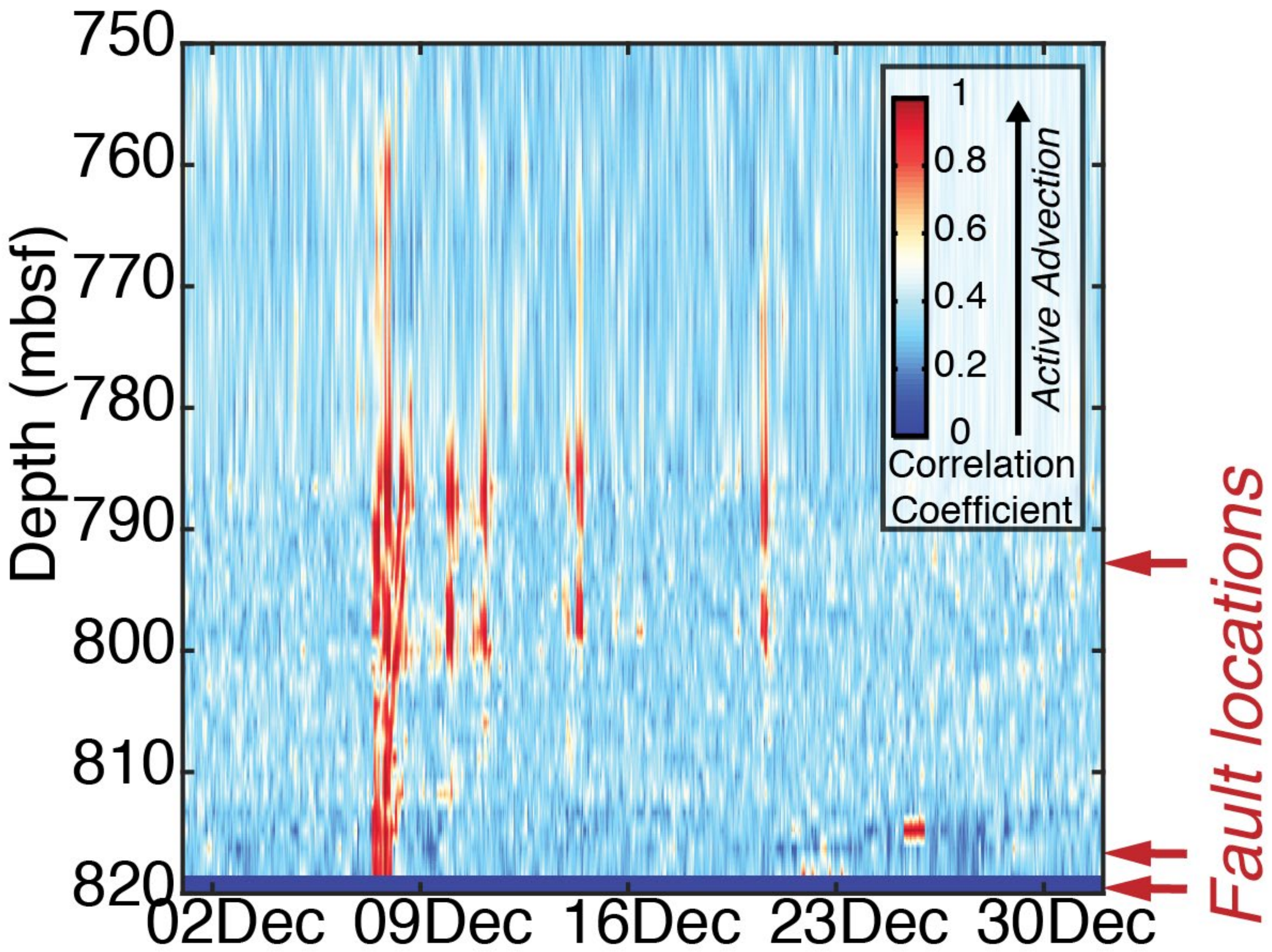
High-pass filtered temperature



Bandwidth:
10 minute – 20 day

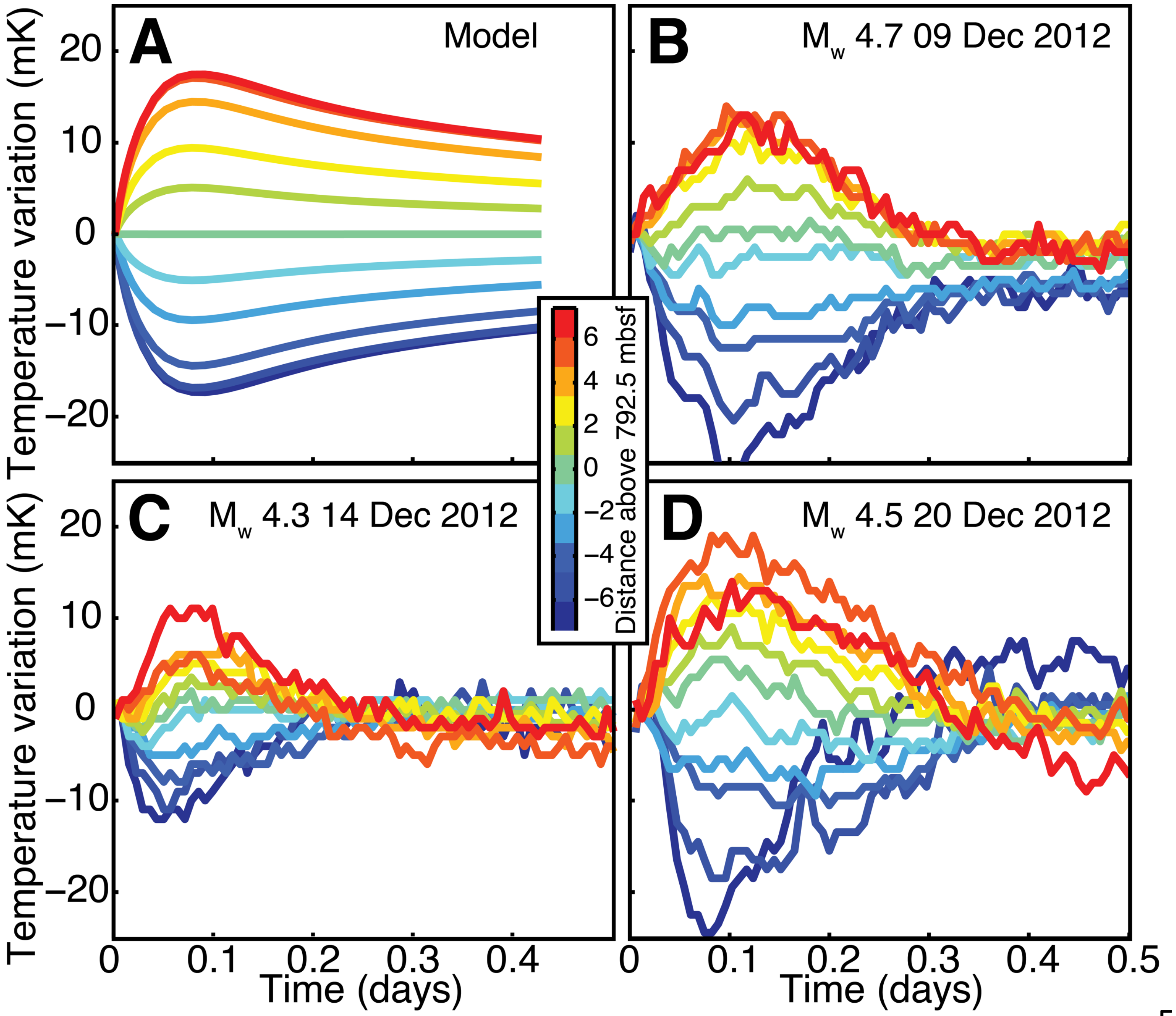
Fulton & Brodsky, *Geology, 2016*

Correlation coefficient shows where and when advection is occurring



6-hour overlapping windows

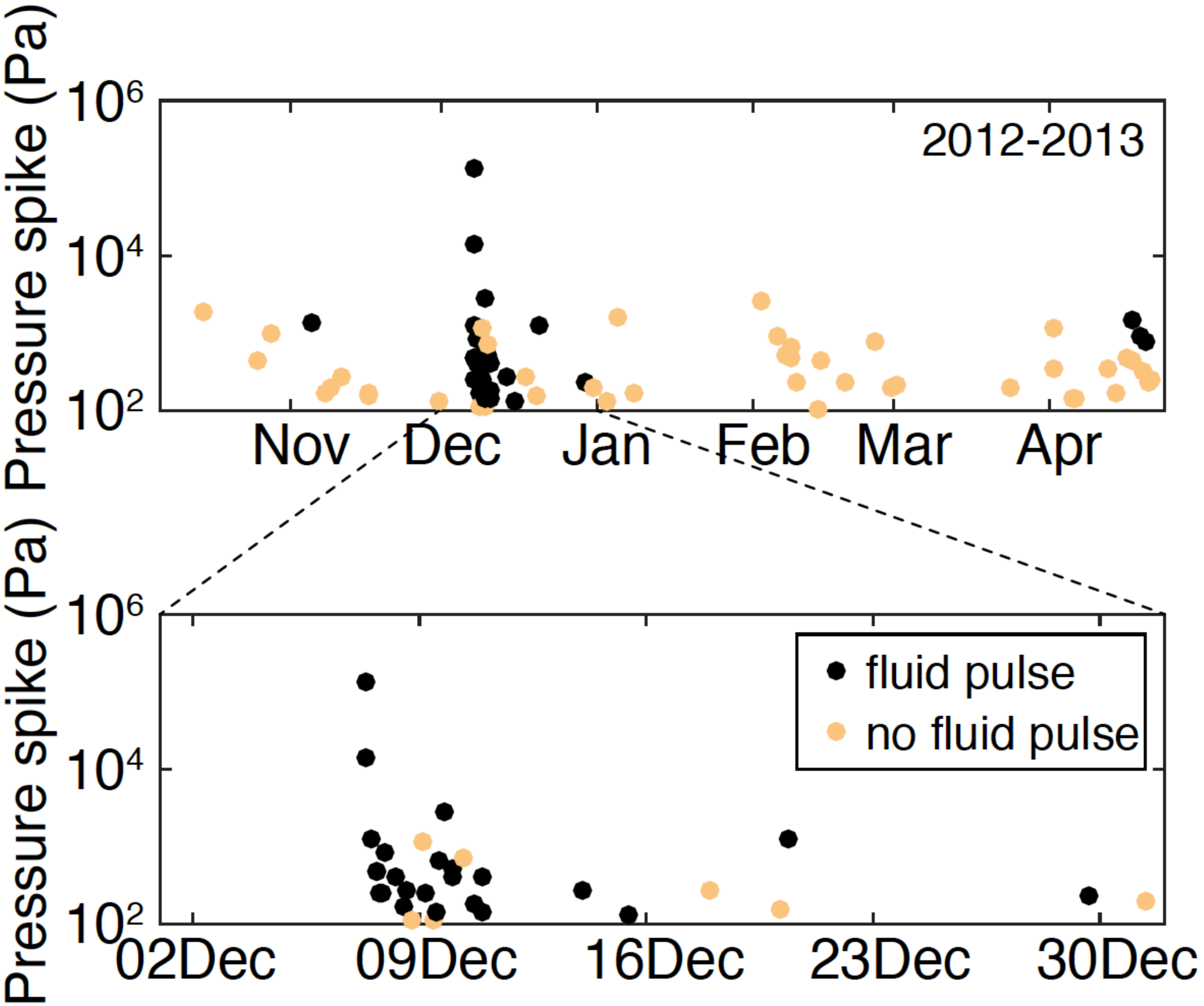
Fulton & Brodsky, *Geology, 2016*



Transient pulses of vertical fluid advection

Fulton & Brodsky, *Geology, 2016*

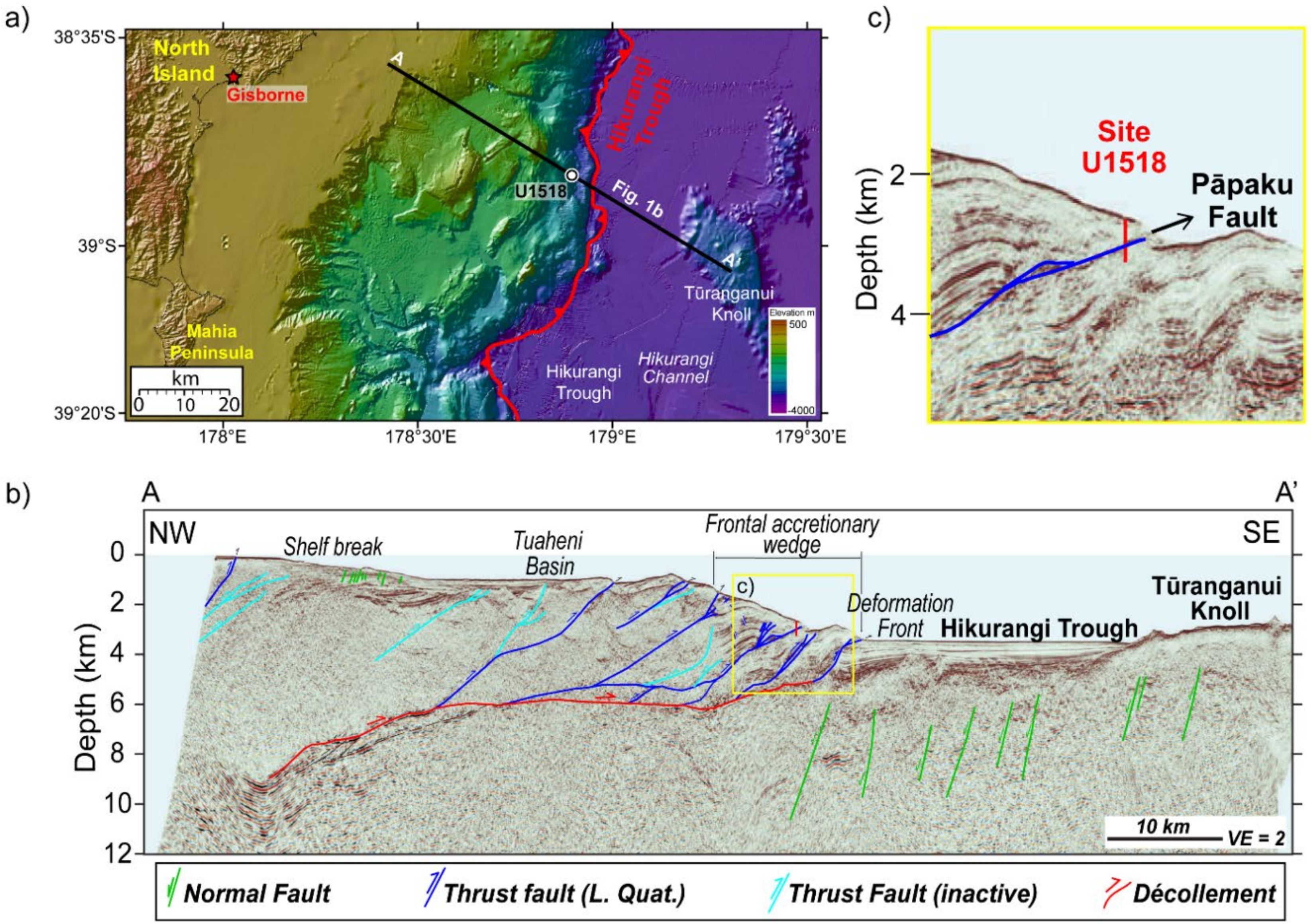
Seafloor seismic wave amplitude



Sensitivity of fluid pulses change over time suggesting a damage and healing process

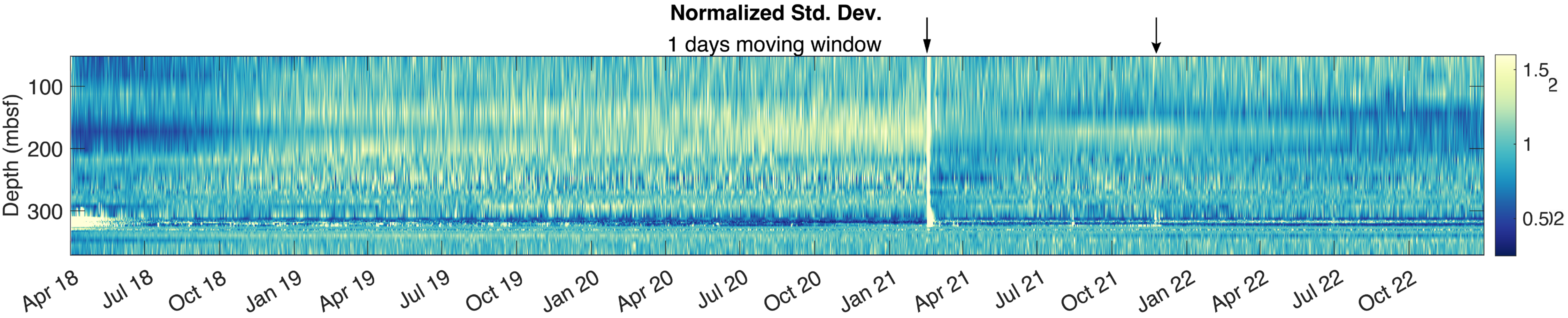
Fulton & Brodsky, *Geology, 2016*

Hikurangi Observatory Observations:



Hikurangi: Flow Switching

- Fluid flow turns on/off with slow slip and shaking
- Subseafloor temperature observatories capture these transients

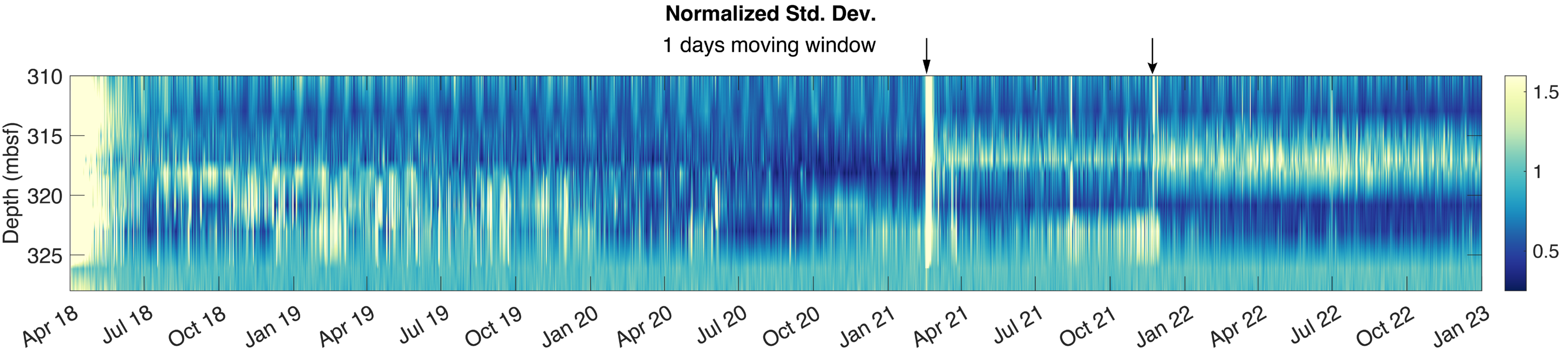


Clairmont and Fulton, in prep.

Hikurangi: Flow Switching

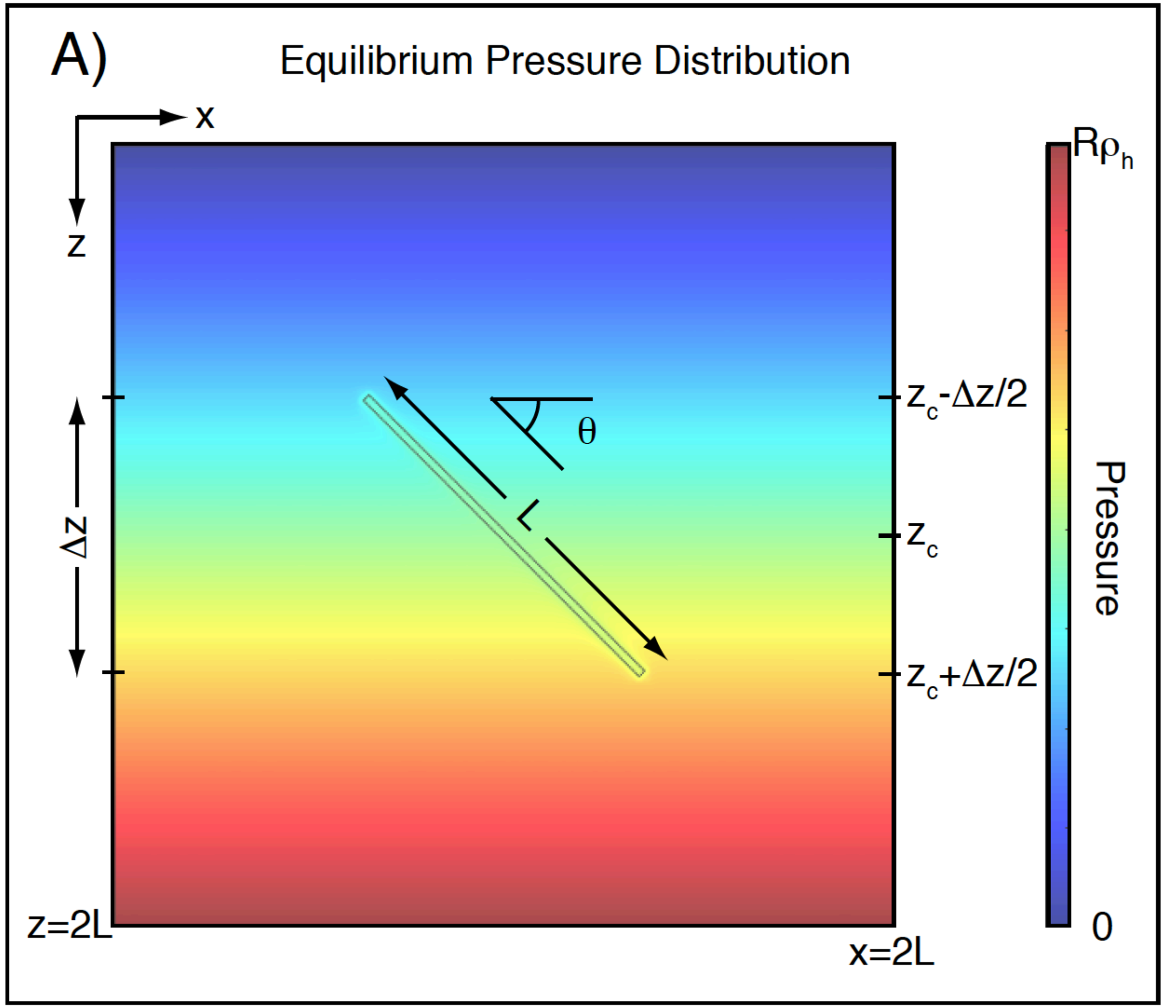
Zoom in on fault ~318 mbsf:

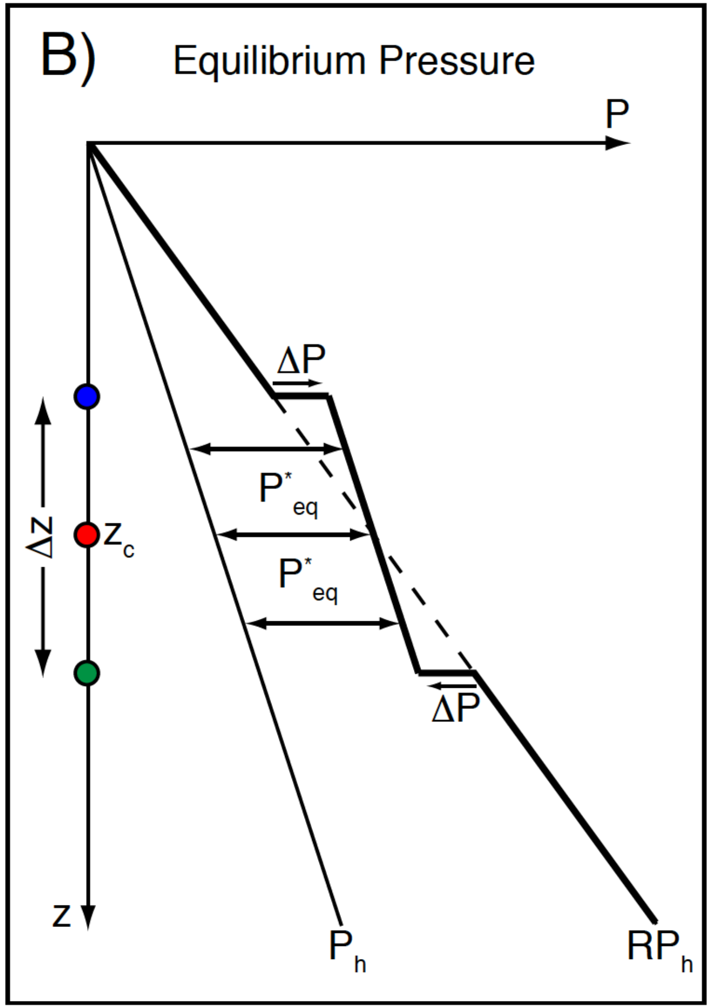
- Fault zone fluid flow starts and increases in response to large ground motion from regional earthquakes



Clairmont and Fulton, in prep.

Transient Flow Focusing



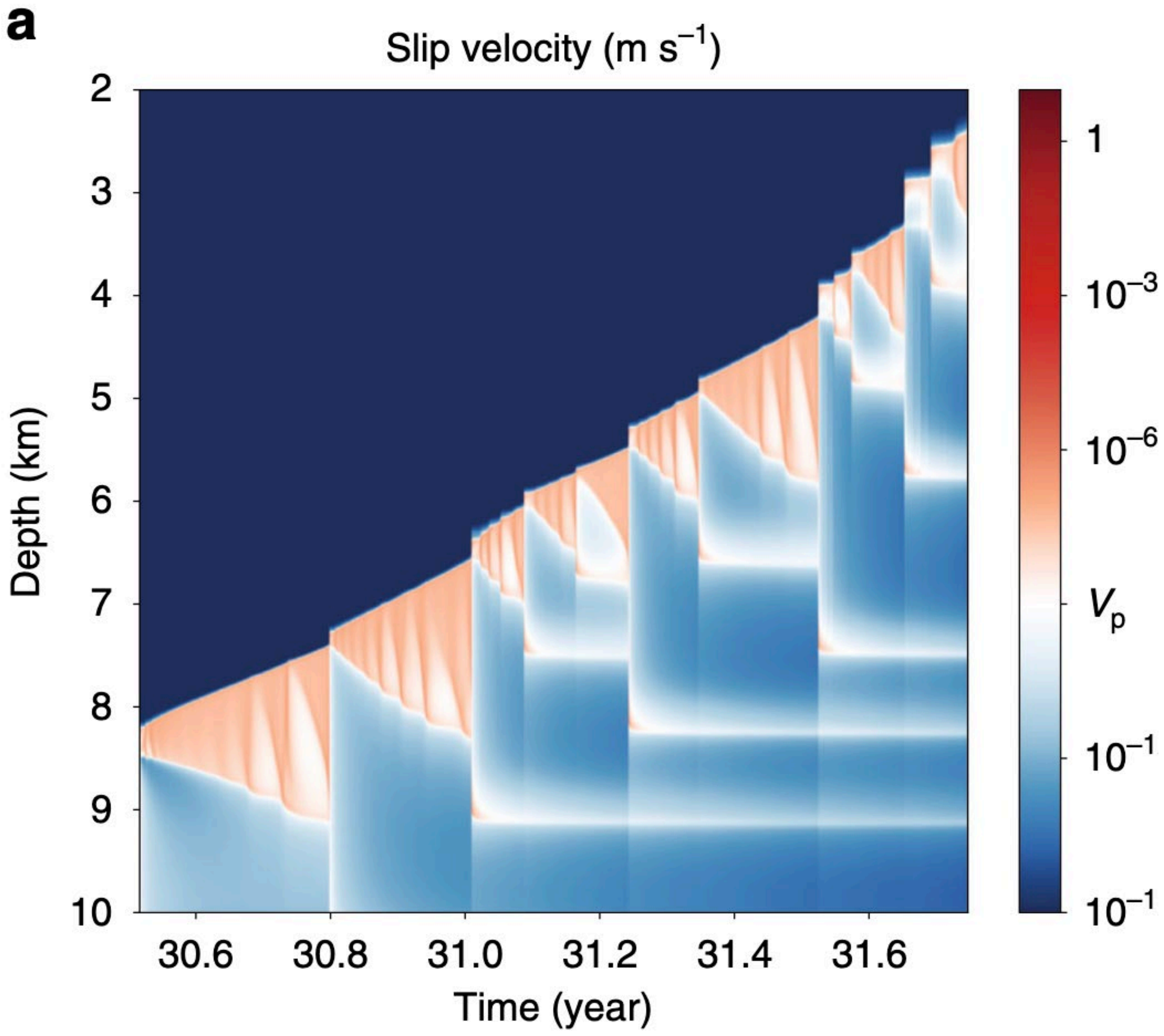


Stress Heterogeneity Matters

- Transient changes in permeability AND fluid flow → pressure redistribution
- Extreme pressure variations → heterogeneous stress → fault slip behavior

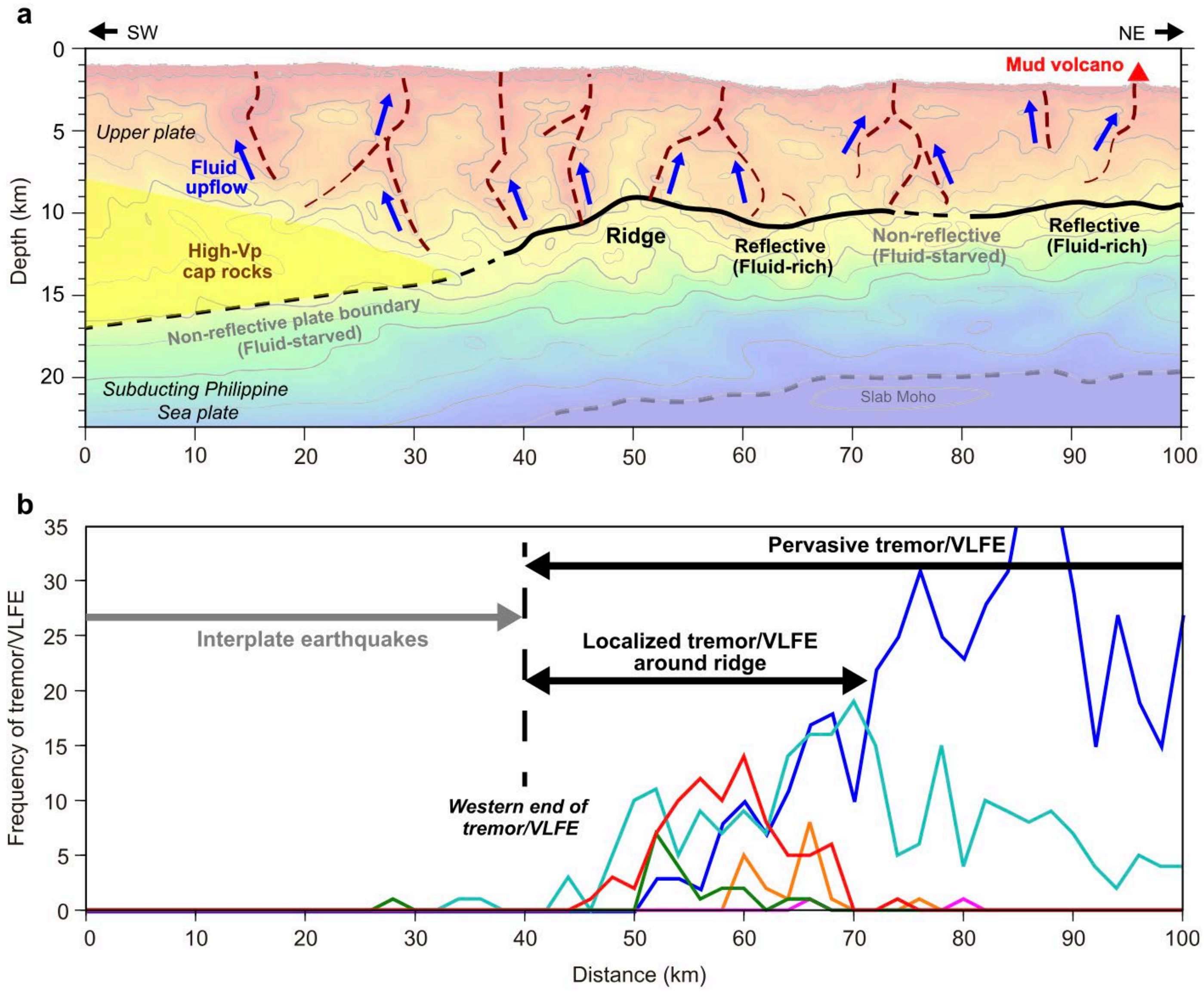
Zhu et al., Nat. Comm., 2020

Damage and healing / fault valving associated with slow slip can trigger swarms of seismicity



Arai et al. (2023): fluid drainage and slip behavior

- **Fault slip behavior spatially correlated with hydrogeologic structure**



Part 1 Summary

- Permeability is dynamic
- Transient flow causes stress heterogeneity
- Feedbacks between fluids and fault slip

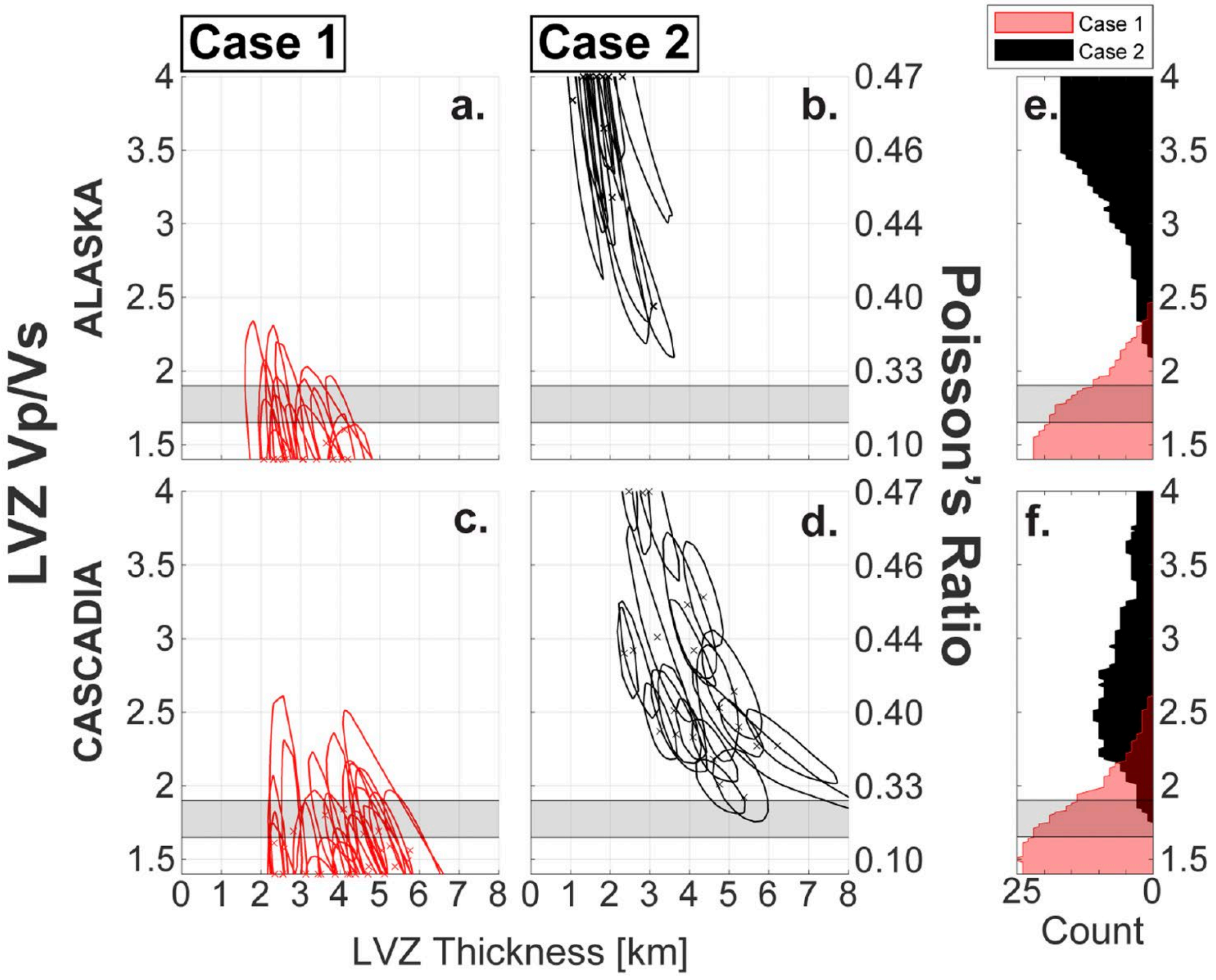
Transition to Depth

- Do fluids still affect faults at deep seismogenic depths?
  - Hard to interpret what's going on hydrogeologically at 10s of km depth.
- Rocks are lithified and porosity is low
- Many reactions that promote sealing things up
- Sensitivity to fluid pressures may be low

Caution: Geophysical Indicators

- Geophysical proxies need caution
- What assumptions are made between observation and hydrologic interpretation? Are there other interpretations? Do they make sense?

Mann et al., EPSL 2024: unusually high Vp/Vs in low velocity zones may be artifact of using band-limited signals or scattered-phase interference. Disappear upon higher resolution analysis.



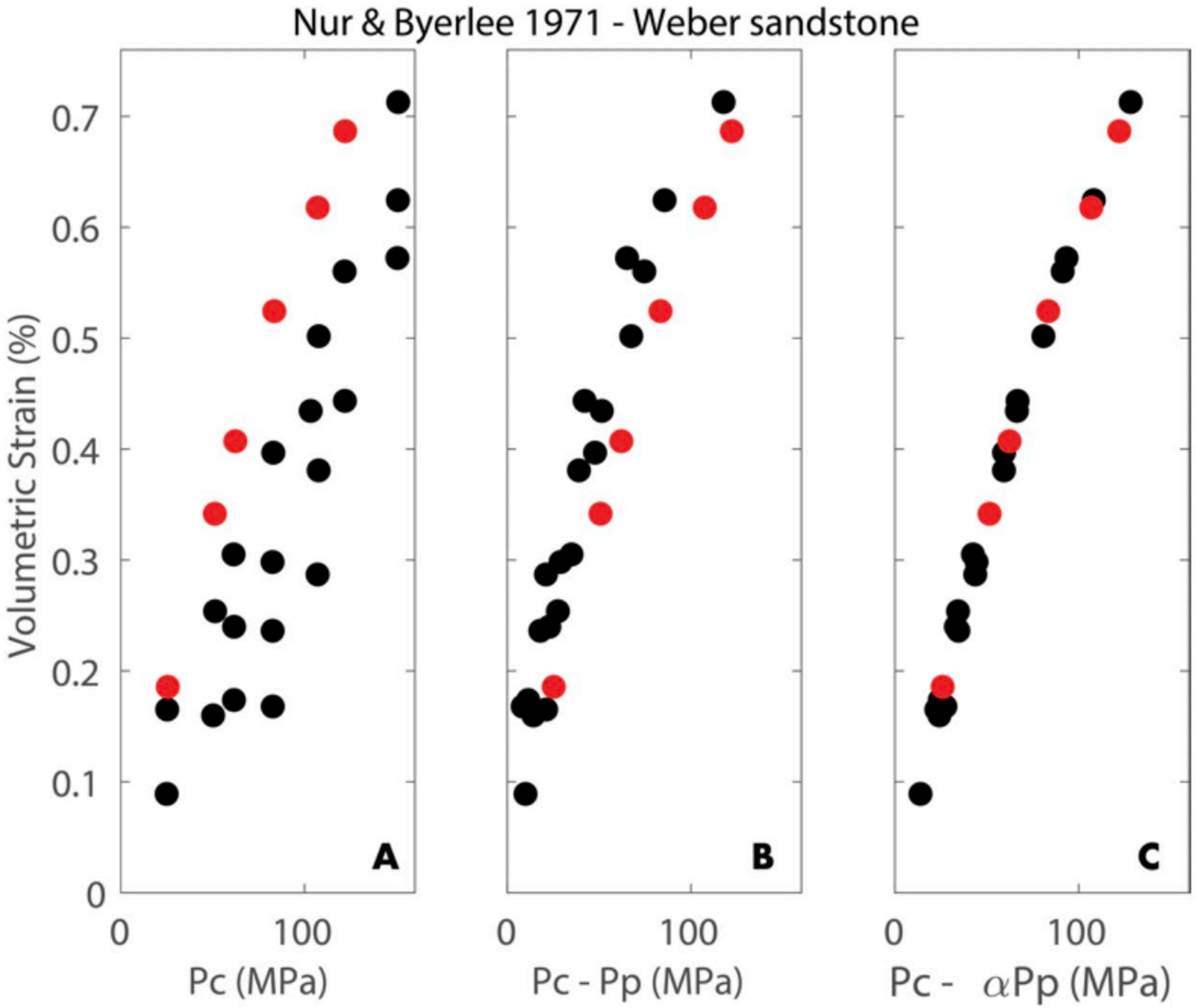
Effective Stress Revisited

$$\sigma' = \sigma - \alpha \cdot P$$

- Biot coefficient α modulates the sensitivity to fluid pressure
- α ≈ 1 in loose sediments; but can be << 1 in lithified rock

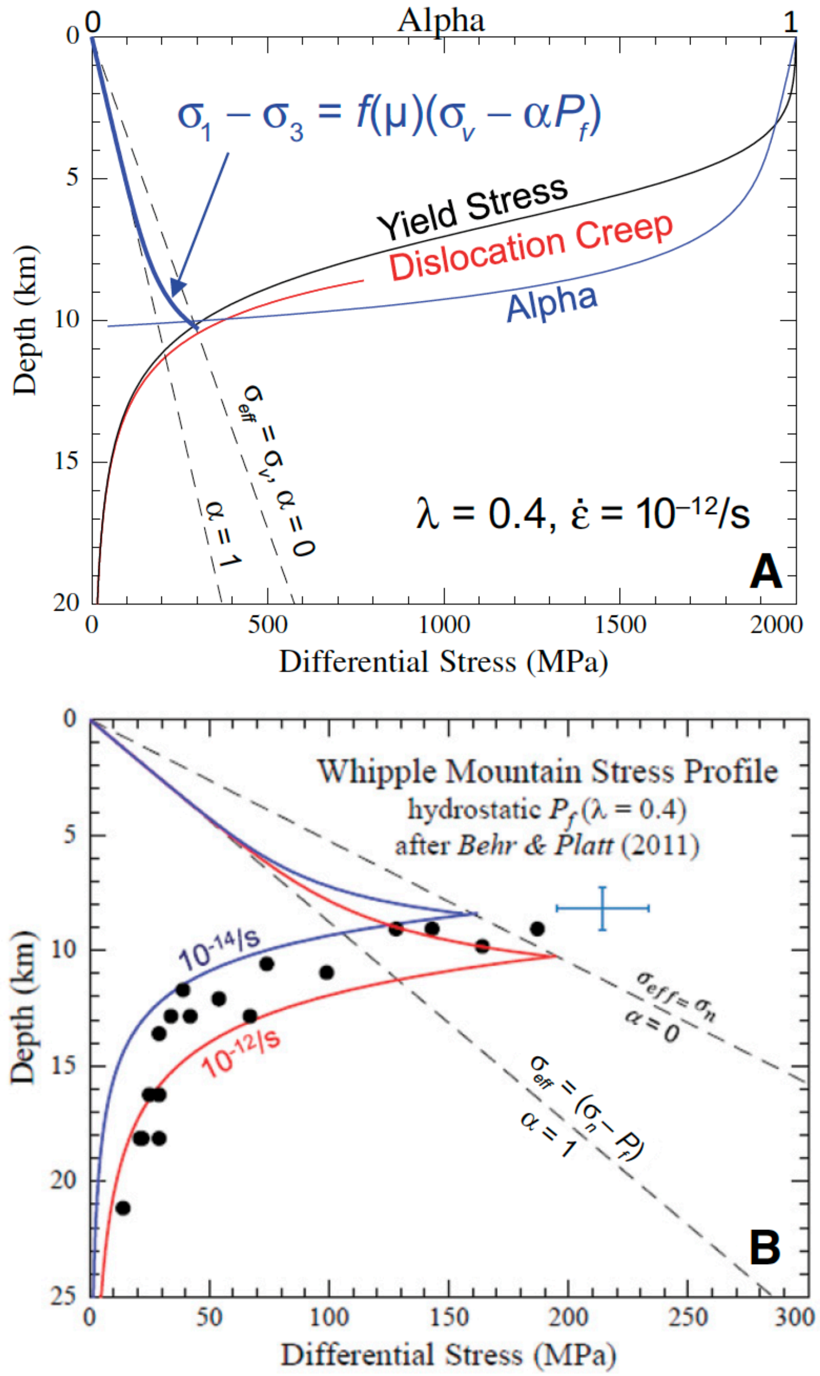
What Controls α?

- $\alpha = 1 - K\_rock/K\_matrix$
- Depends on stiffness and porosity
- Lower α → pressure has less effect



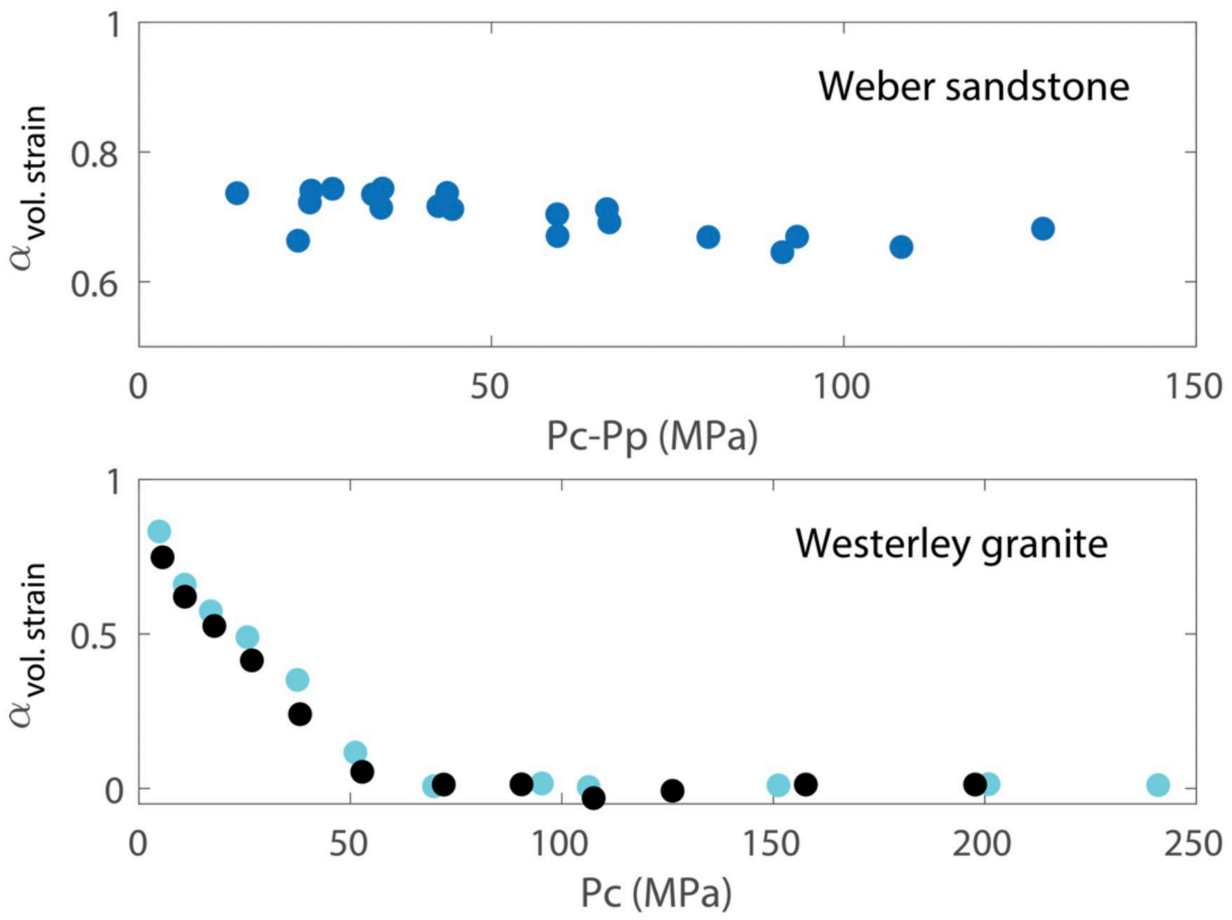
Hirth & Beeler (2015): Low α at Depth

- Exhumed rocks from brittle-ductile transition show low α
- Theoretical and observational support
- α drops across brittle-ductile transition



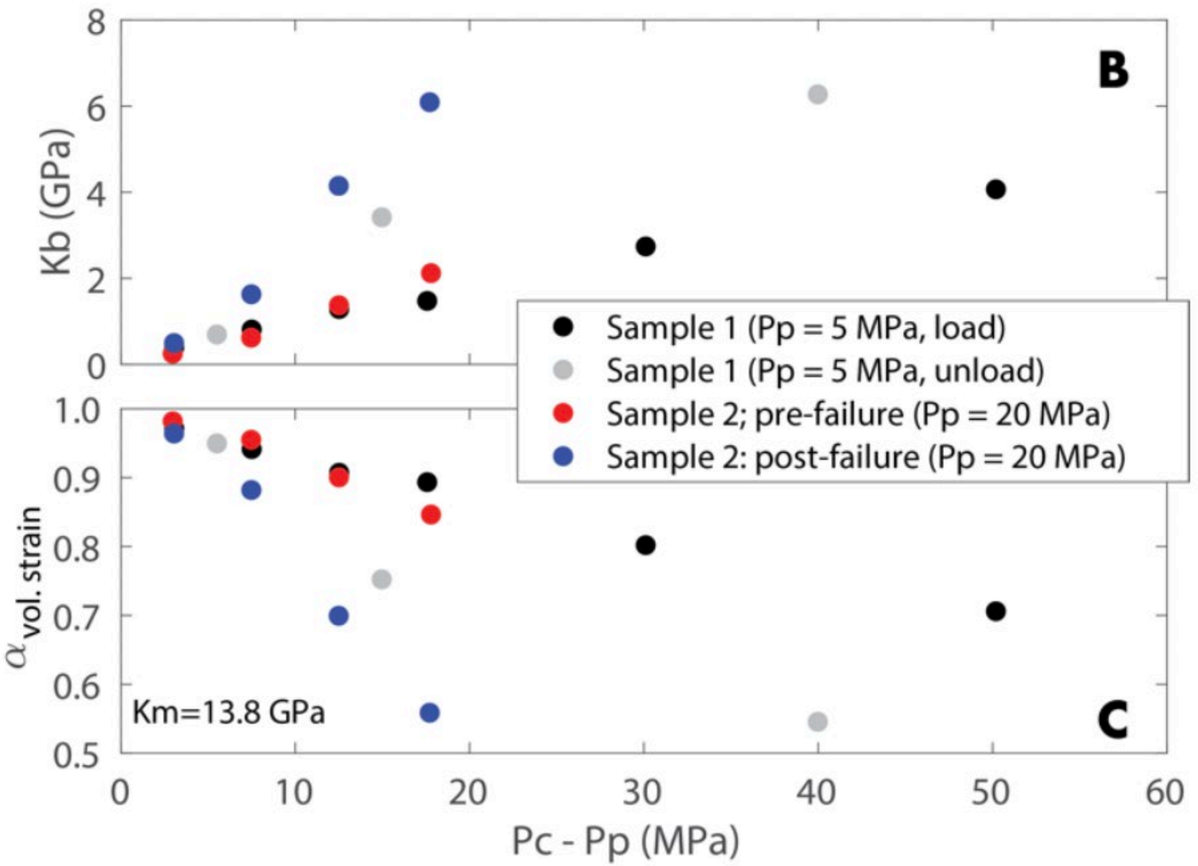
Fulton & Kitajima: Experimental α

- Reanalysis of Nur and Byerlee data
- α decreases with confining pressure



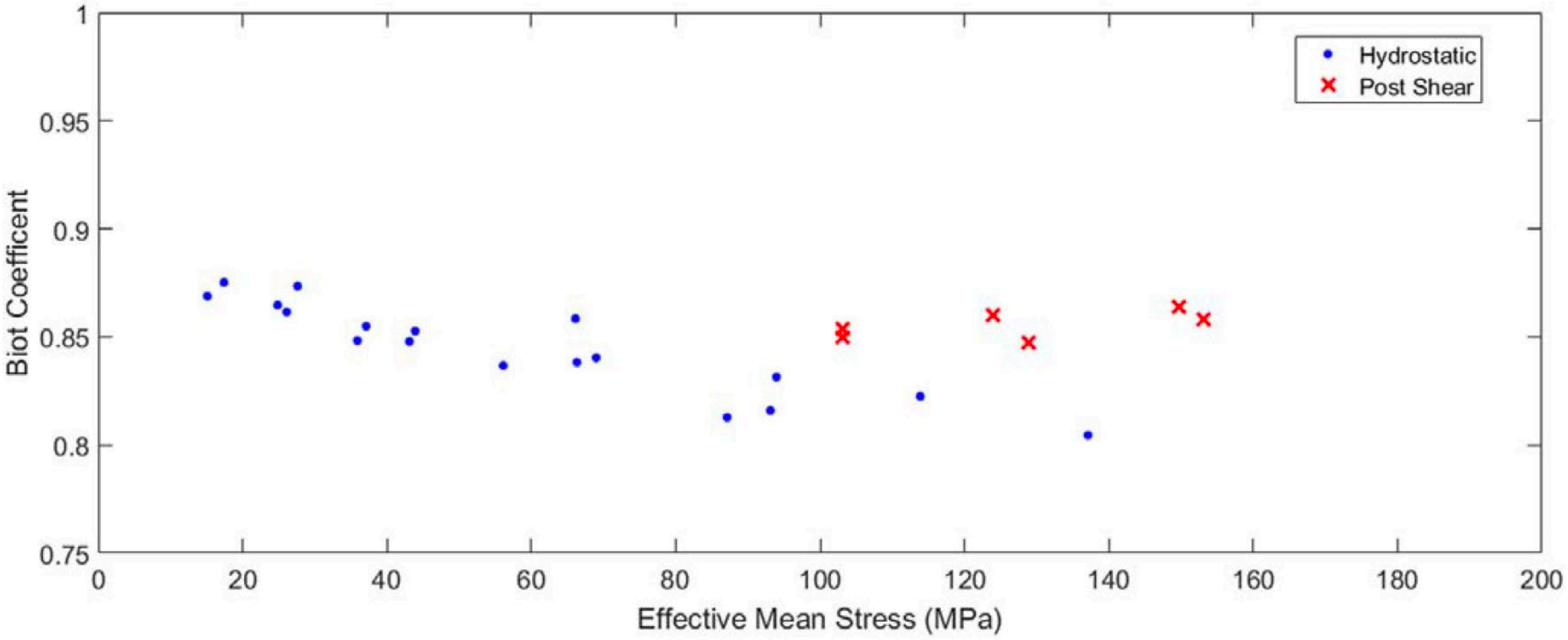
Fulton & Kitajima: Experimental α

- α decreases with confining pressure Weber sandstone
- In our experiment, α decreased post-failure (compaction)



Ingraham et al., 2017: Experimental α

- α decreases with confining pressure (Castlegate Sandstone)
- **α increases after shearing**



Hydrogeologic Processes and Fault Slip: A Deeper Look

- At deep seismogenic depths, rocks are lithified and low-porosity
  → Their sensitivity to fluid pressure (α) is often much lower than in shallow sediments

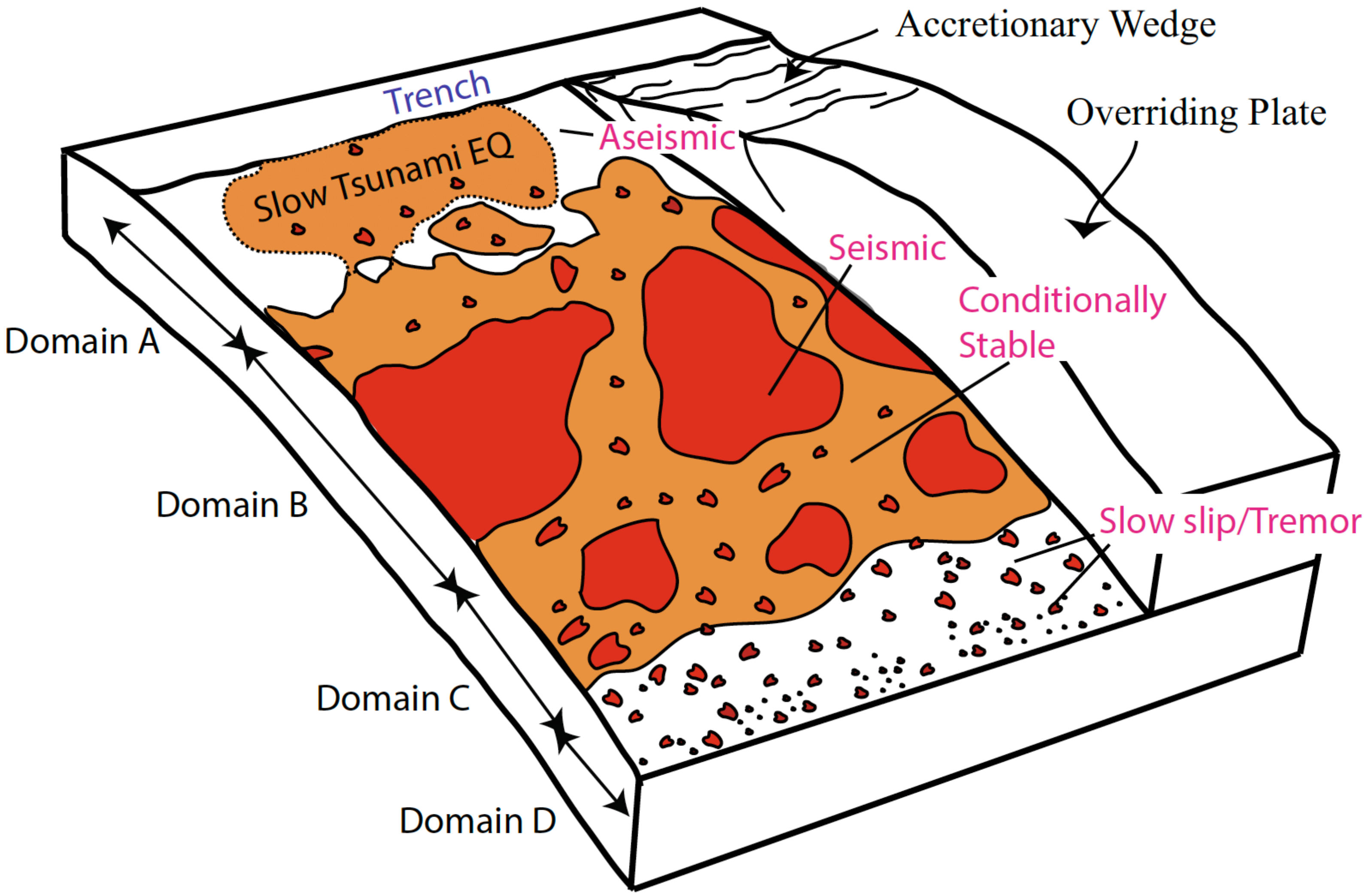
- Faults and fractures are the main conduits controlling:
  - Fluid flow
  - Pressure distribution
  - Localized stress fields

- Flow focusing along permeable zones produces spatially heterogeneous effective stress

- In addition to shearing, dynamic stresses (e.g., from local and distant earthquakes) can:
  - Alter permeability
  - Change sensitivity to pore pressure
  - Drive transient deformation

- Healing processes (e.g., mineralization or sealing) make this cyclical and time-dependent

Stress Heterogeneity: A Key Driver?



Summary and Looking Forward

- The hydrogeology of fault zones is a dynamic system —one that superimposes spatially and temporally variable stress fields associated with fluid pressure on top of tectonic loading and slip history.

- Can we use these insights to better predict where and when hydrogeologic changes may occur — and how to detect and interpret them?

Thank You!

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