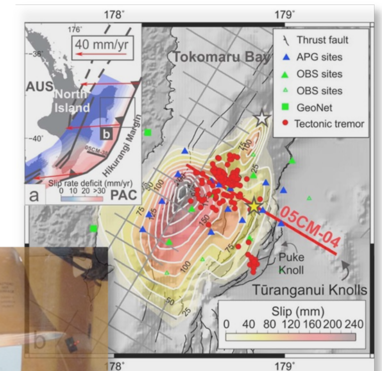
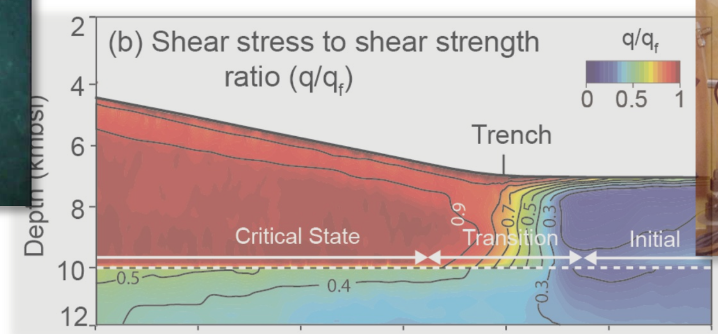
Hydrogeology of Subduction Forearcs: Fluids as Agents of Mechanical and Transport Processes

Demian Saffer
(*and many collaborators*)
CRESCENT

Fluids in Cascadia Workshop
April 23, 2025



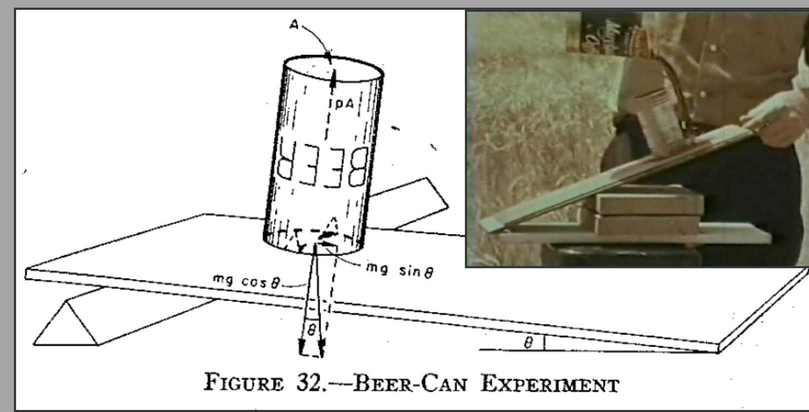


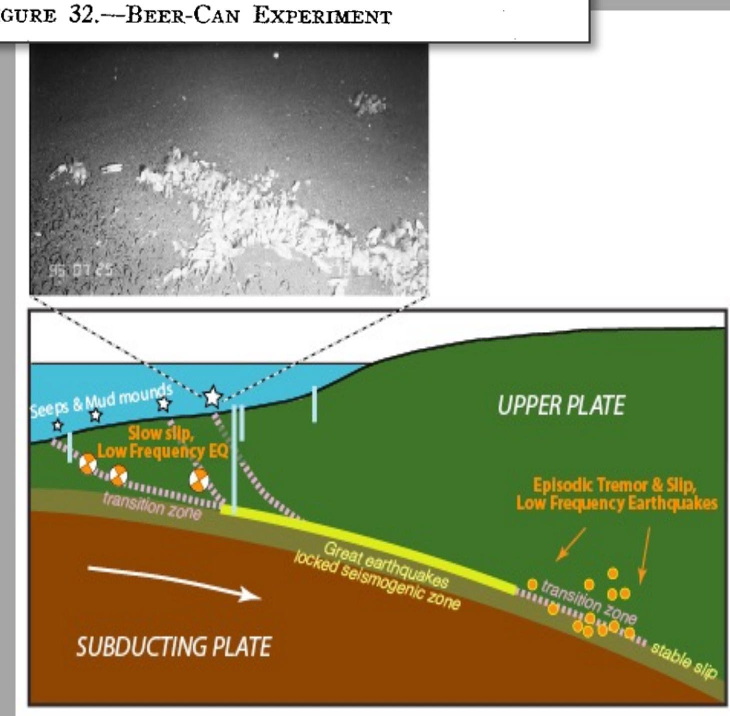
NSF

IODP
INTERNATIONAL OCEAN DISCOVERY PROGRAM

Fluid-mediated processes

- Effective stress controls fault and rock shear strength.
- Effective stress also modulates stability of slip - and frictional healing.
- Compaction state of fault and wall rocks are key to a host of physical properties.
- Pressure drives flow & transport of volatiles, heat, and solutes

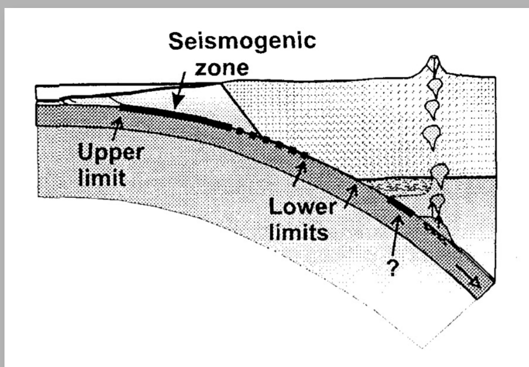




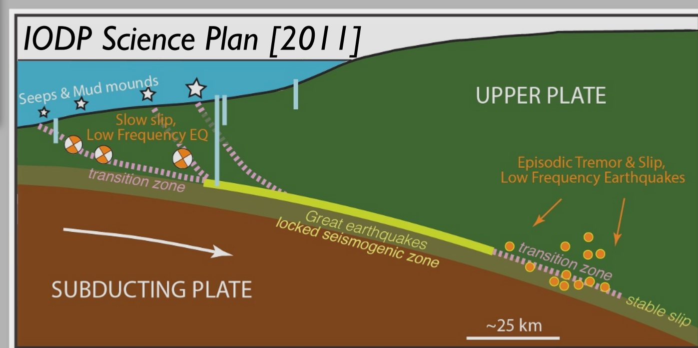
IODP Science Plan, 2012

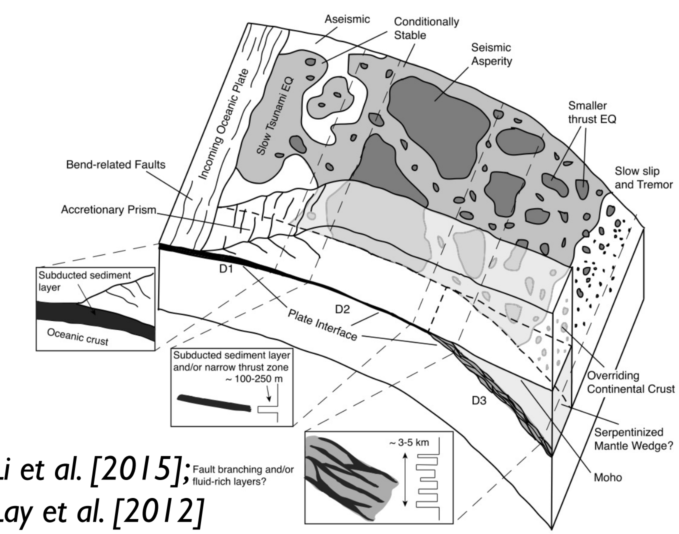
An Evolving View of the Subduction Megathrust

- A "spectrum" of fault slip behavior – discovered in the last two decades with increased monitoring and instrumentation.
- Recognition of spatiotemporal complexity & patchiness of slip behavior and locking within transition zones and seismogenic zone.



Hyndman et al., 1997



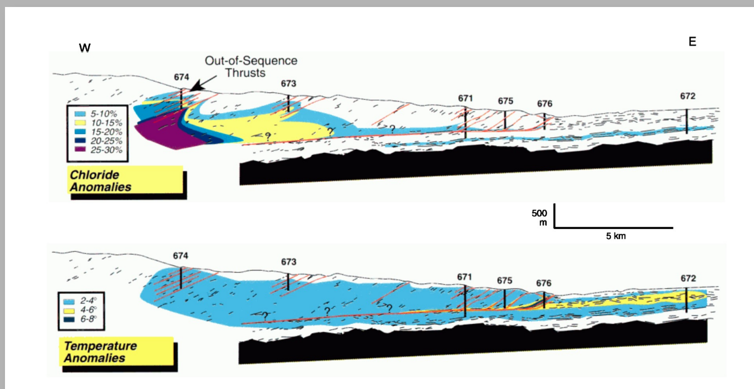


Li et al. [2015]; Lay et al. [2012]

Fundamental Questions:

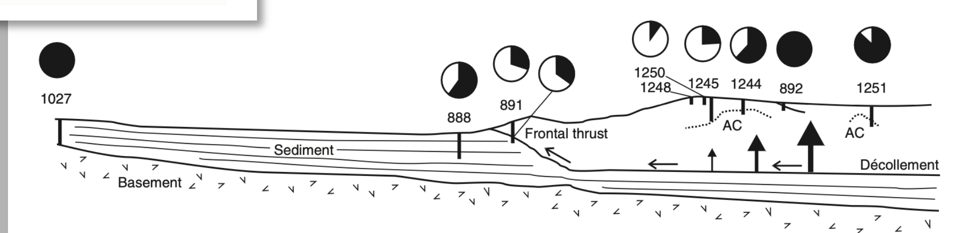
- What controls these behaviors globally?
- Are they predictable and persistent?
- What are the associated *in situ* rock properties and conditions?
- What role do fluids play?

Observations of transport and focused flow reveal a dynamic hydrological system



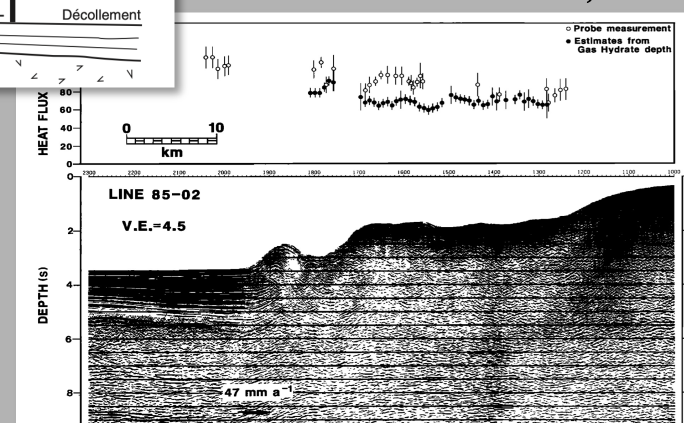
Moore & Vrolijk, 1992

- Focused flow, chemical, and heat transport – along primary faults and via mud volcanoes.
- Deeply-sourced fluids at seeps and in boreholes provide a window to processes and conditions atop the slab.



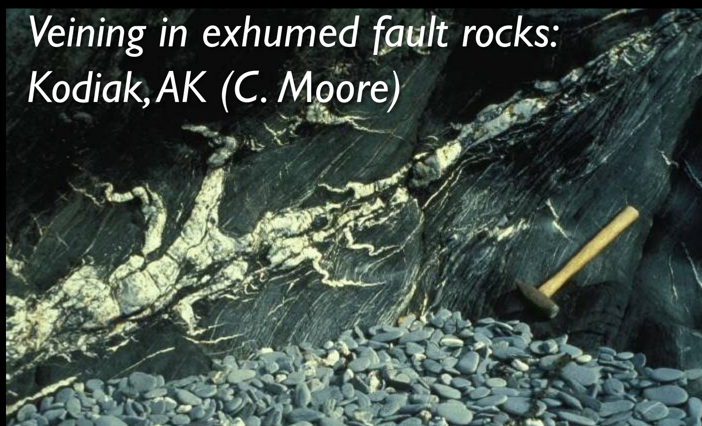
Teichert et al., 2006

Davis et al.,. 1994



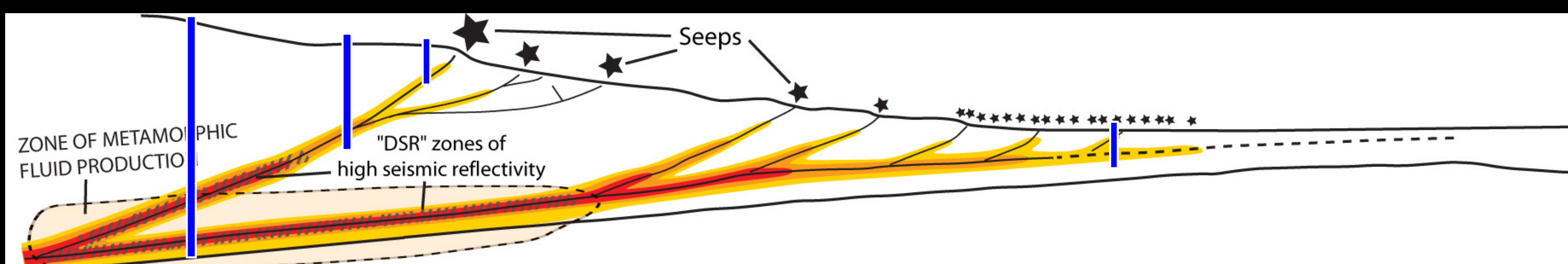
- Transient flow is required to explain many observations. The mechanisms/drivers are not well known.
- Fluid budgets include focused flow *and* diffuse dewatering through matrix.

Indirect & ancient evidence for elevated pore pressure and clues about plumbing and flow localization:


Veining in exhumed fault rocks: Kodiak, AK (C. Moore)


Carbonate & seepage at Middle America trench

But quantitative constraints on *in situ* pressure & flow paths are sparse!



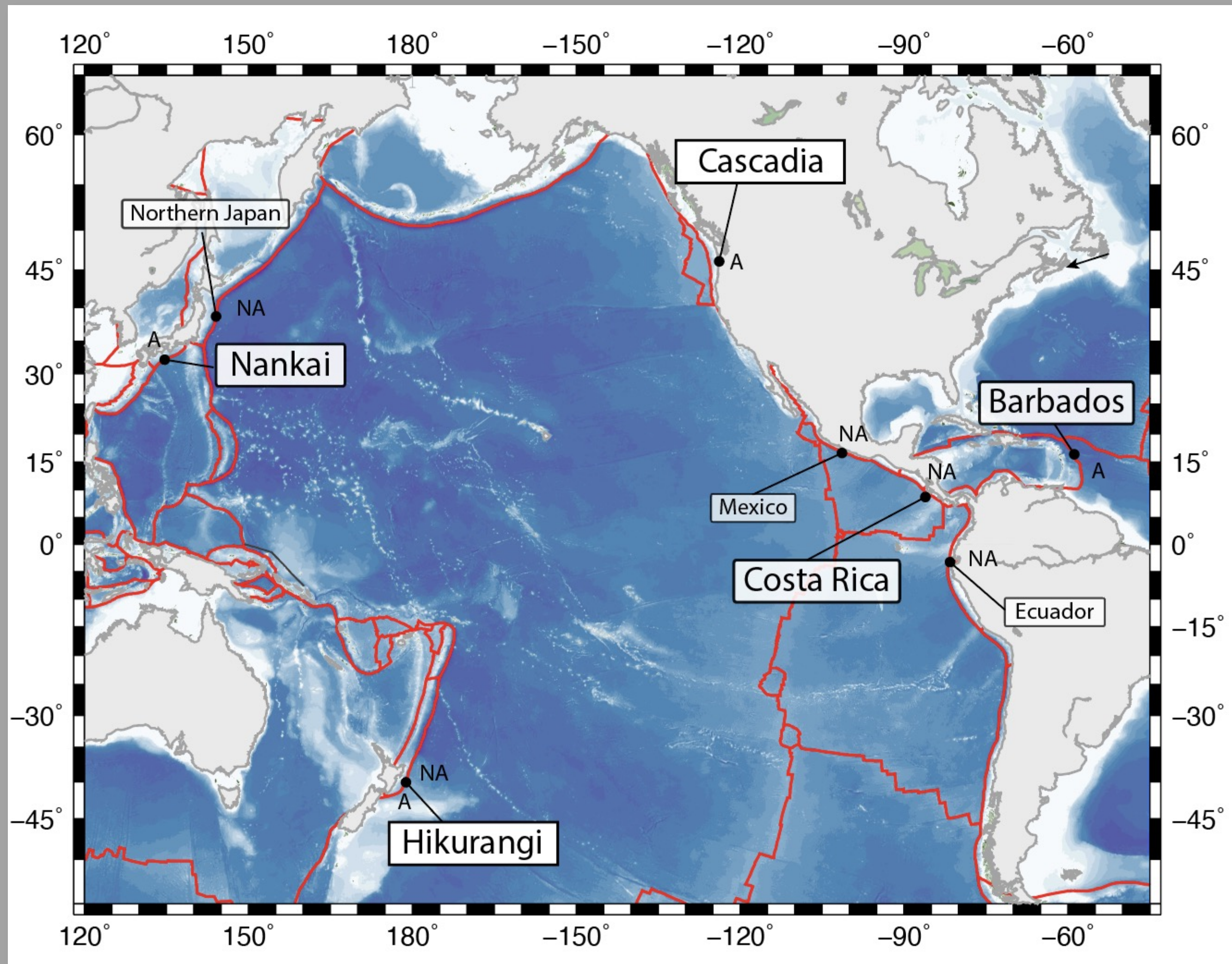
Outline

1. <u>What do we know about Pore Pressure and Effective Stress?</u>
   - Insights gained from the lab and drilling
   - Mapping regional geophysical observations to stress and pressure
   - What drives pressure? - Integration of numerical models and observations
   - Links to fault slip behavior

2. <u>Flow Pathways, Plumbing, and Localization of Flow</u>
   - Hydraulic architecture – observations and models
   - Flow rates, tapping deep fluids & volatiles
   - Evidence and mechanisms for transient flow

The Whirlwind Tour

- Draw upon several examples.
- Observations from drilling, coring, seeps, and seismic imaging.
- Insights from laboratory experiments.
- Modeling to investigate processes and feedbacks.



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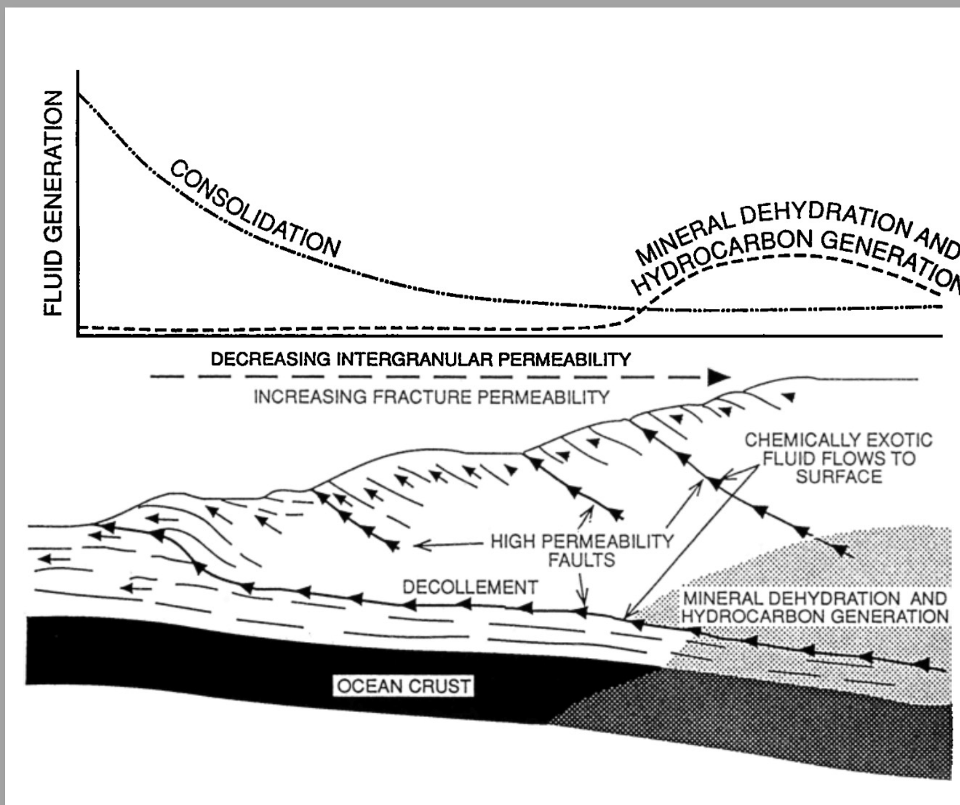
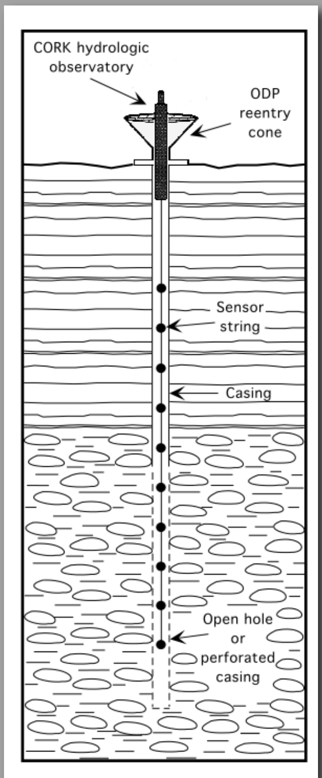
What Drives Pressure and Flow? Some Key Concepts



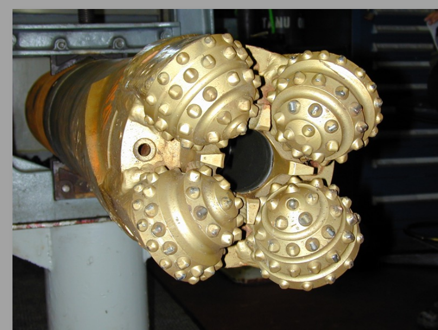
- Pore pressure is generated by compression of fluid. This can be driven *mechanically* or by *addition of fluid mass* to existing pore space.
- If consolidation takes place, this means there is *a degree* of drainage. "Compaction fluid sources" don't drive pressure. They are a result of dissipation.
- Pressure drives flow. Significant flow implies dissipation of pressure at the source.

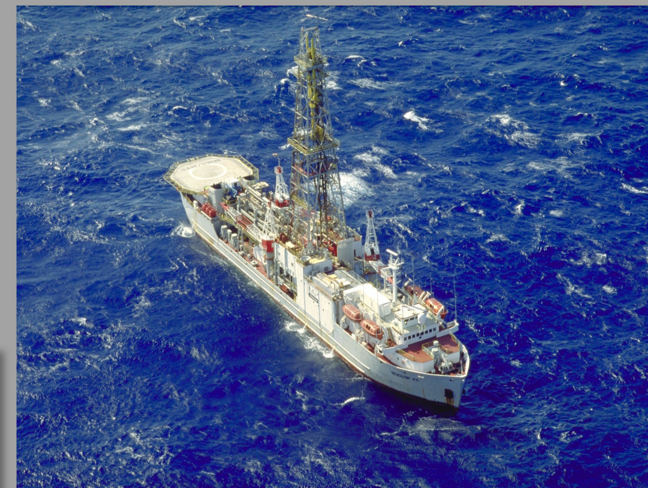
Direct Measurement of pore pressure:

CORKs: Long-Term Monitoring of pressure in subseafloor wells



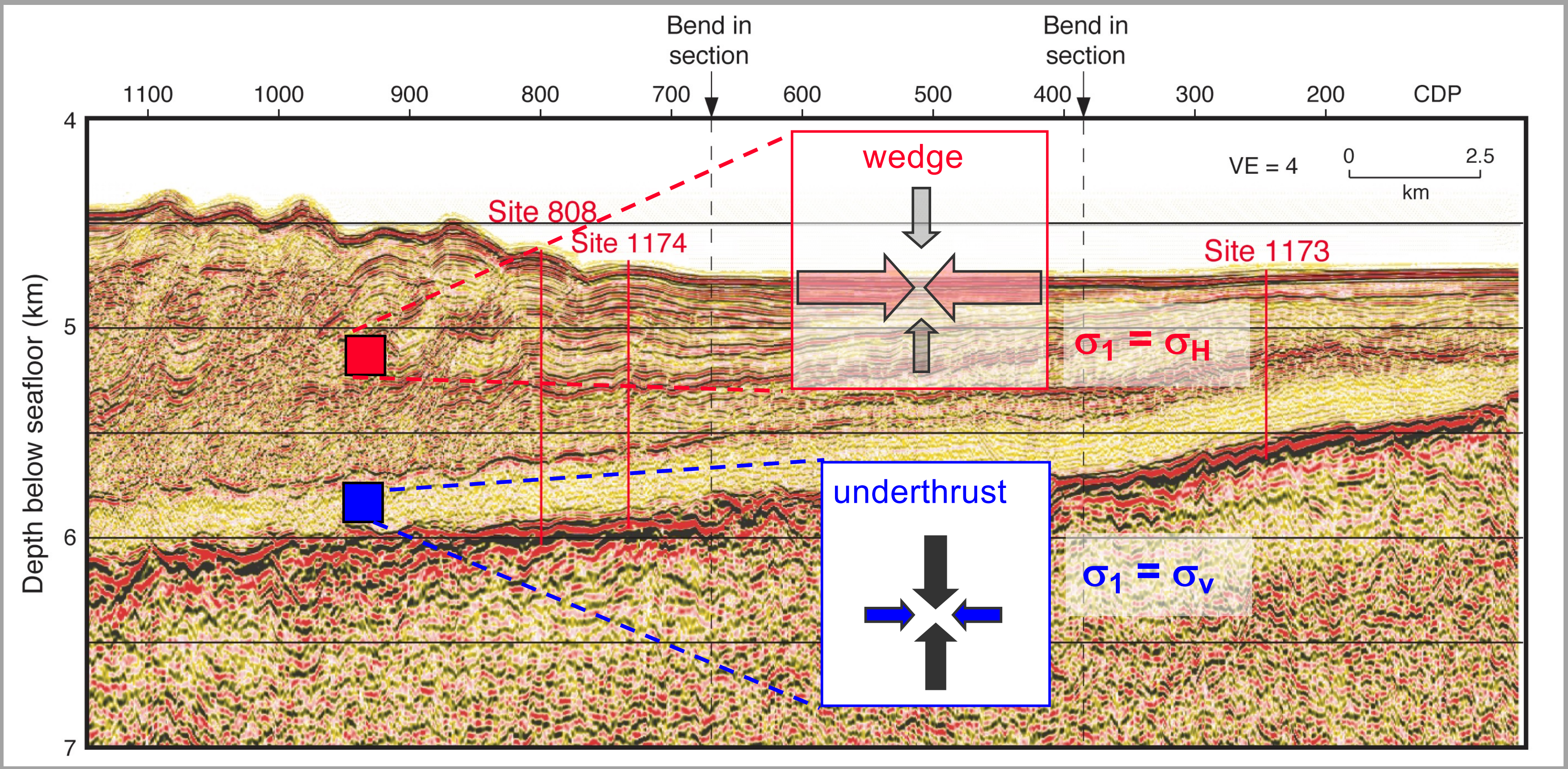
Laboratory Tests: Deformation, Permeability, and wavespeeds: Mapping from observations to state; parameterize models





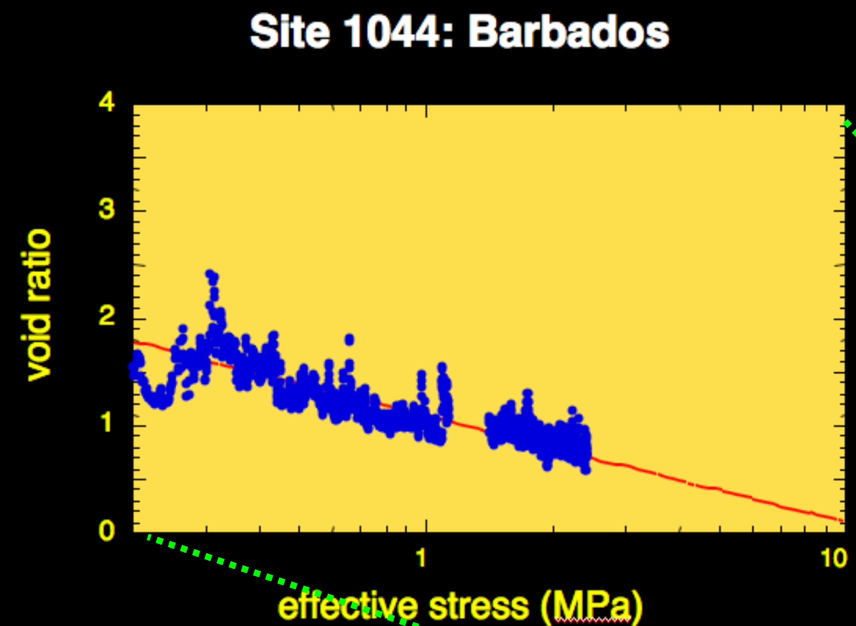
Data from drilling (sonic logs, porosity, density): Sediment constitutive behavior, stress indicators

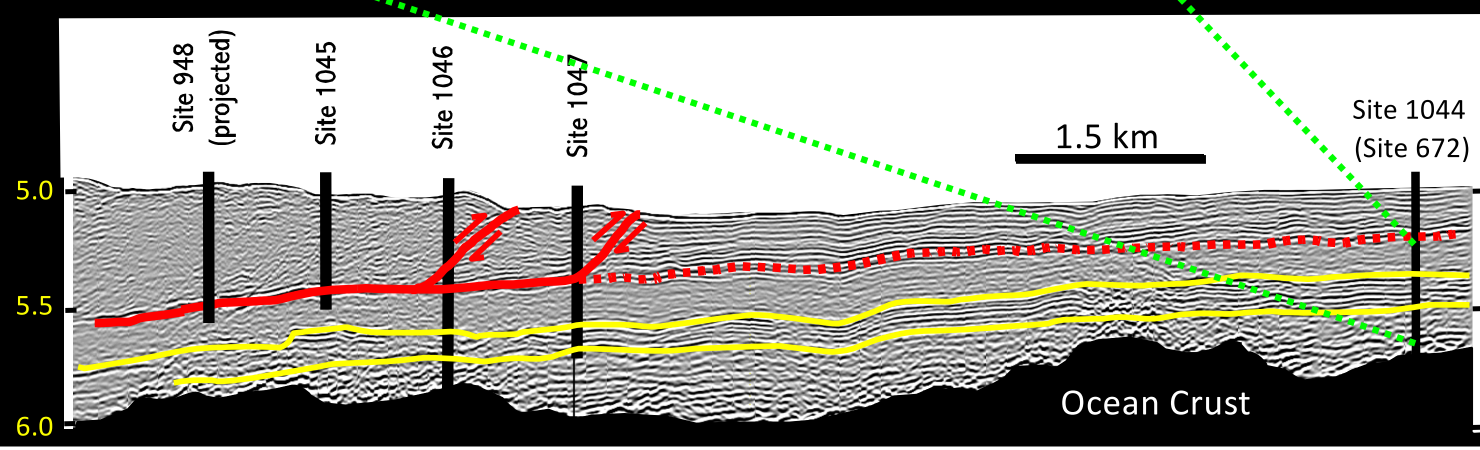
The outer-most forearc: Let's start beneath the décollement.



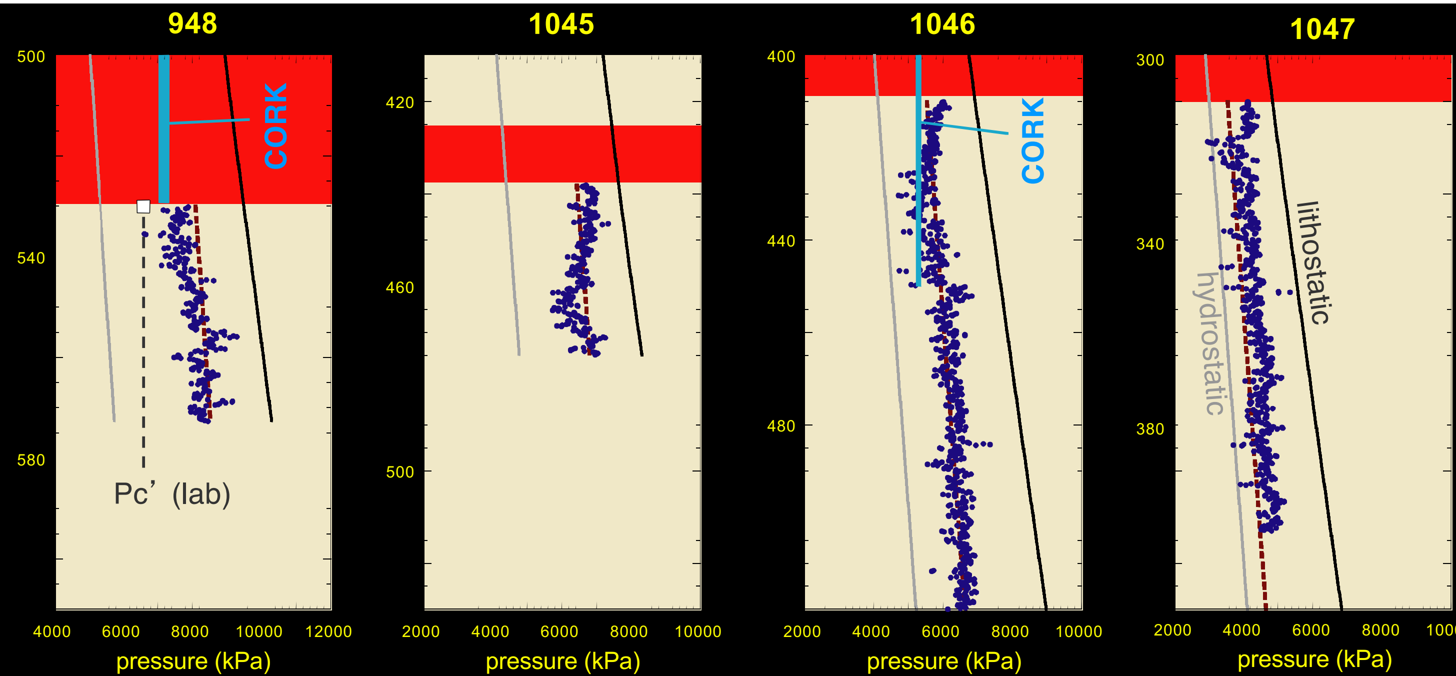
Barbados Example:

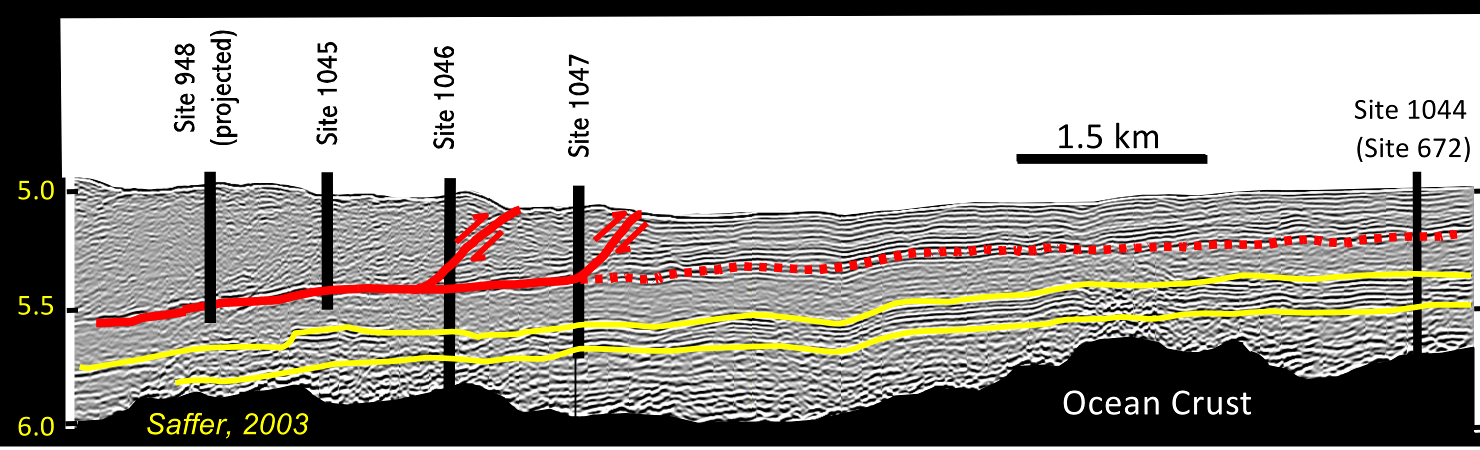
Define constitutive behavior using field data: porosity measurements from drilling at reference site 1044





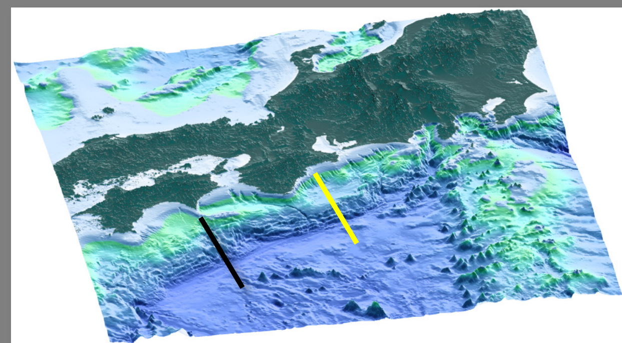
- Near undrained conditions.
- Consistent with lab and CORK observations.
- Despite slow conv. rate (~2.7 cm/yr), disequilibrium compaction is promoted by clays and low-perm.

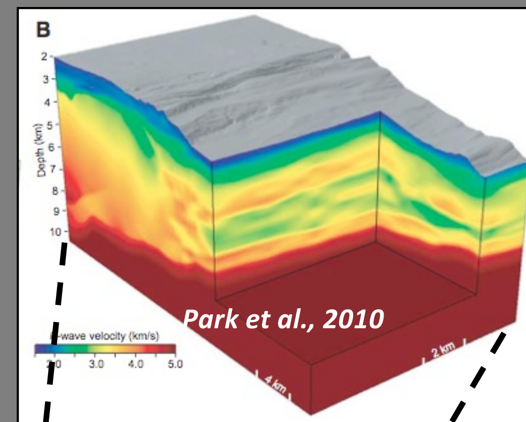


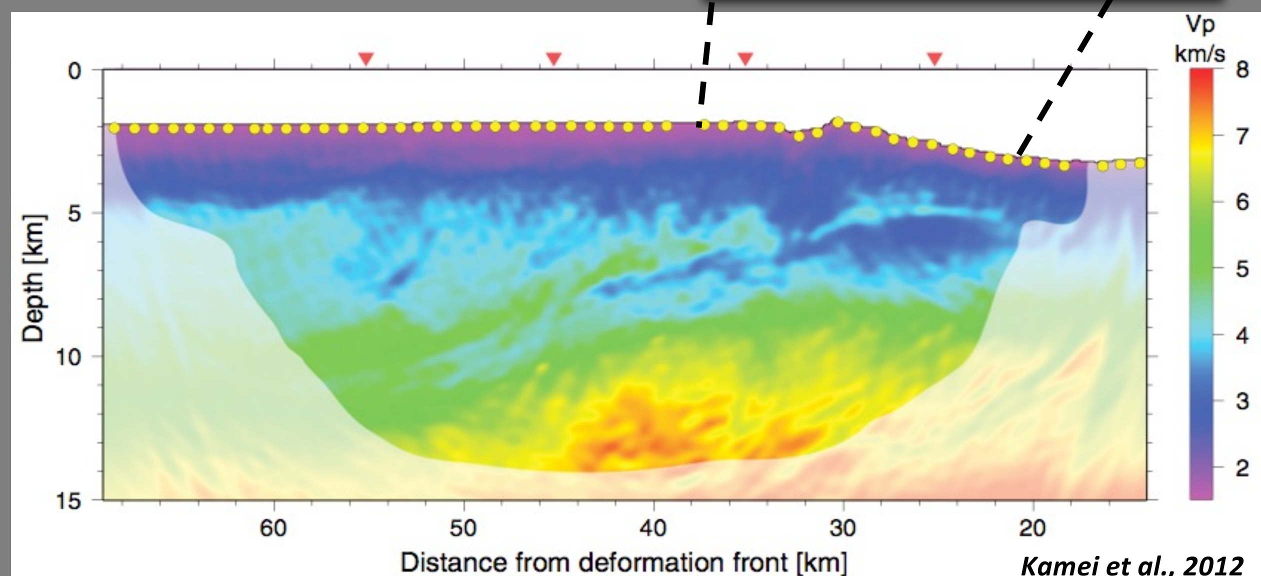


Nankai Example: Stress and Pressure from Geophysical Data

- Low Vp zones extend for > 100 km along-strike.
- Interpreted to reflect arrested consolidation and fluid overpressure.
- Map from Vp → porosity → effective stress state & pore pressure.
- Sediment constitutive behavior is the key to link the observations and state variables.

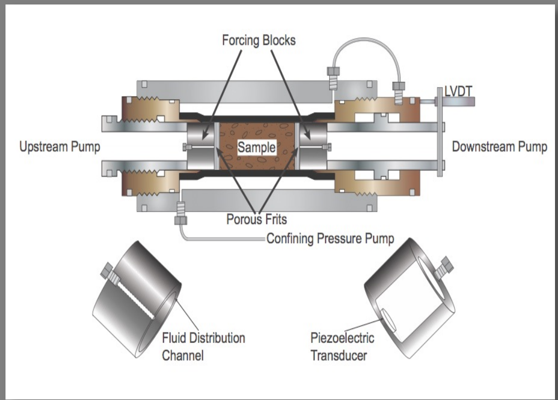


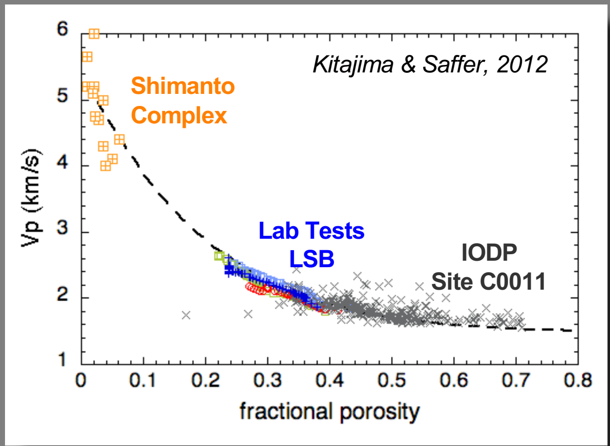


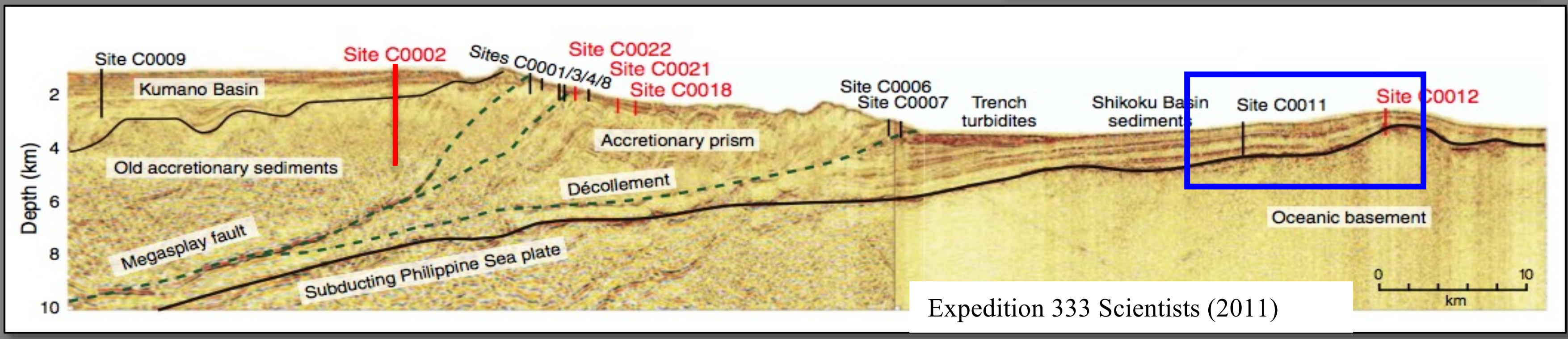


Triaxial Testing:

- Use core samples of subduction "inputs"
- Varied stress paths, including failure at critical state; concurrent P- and S-wavespeed measurements

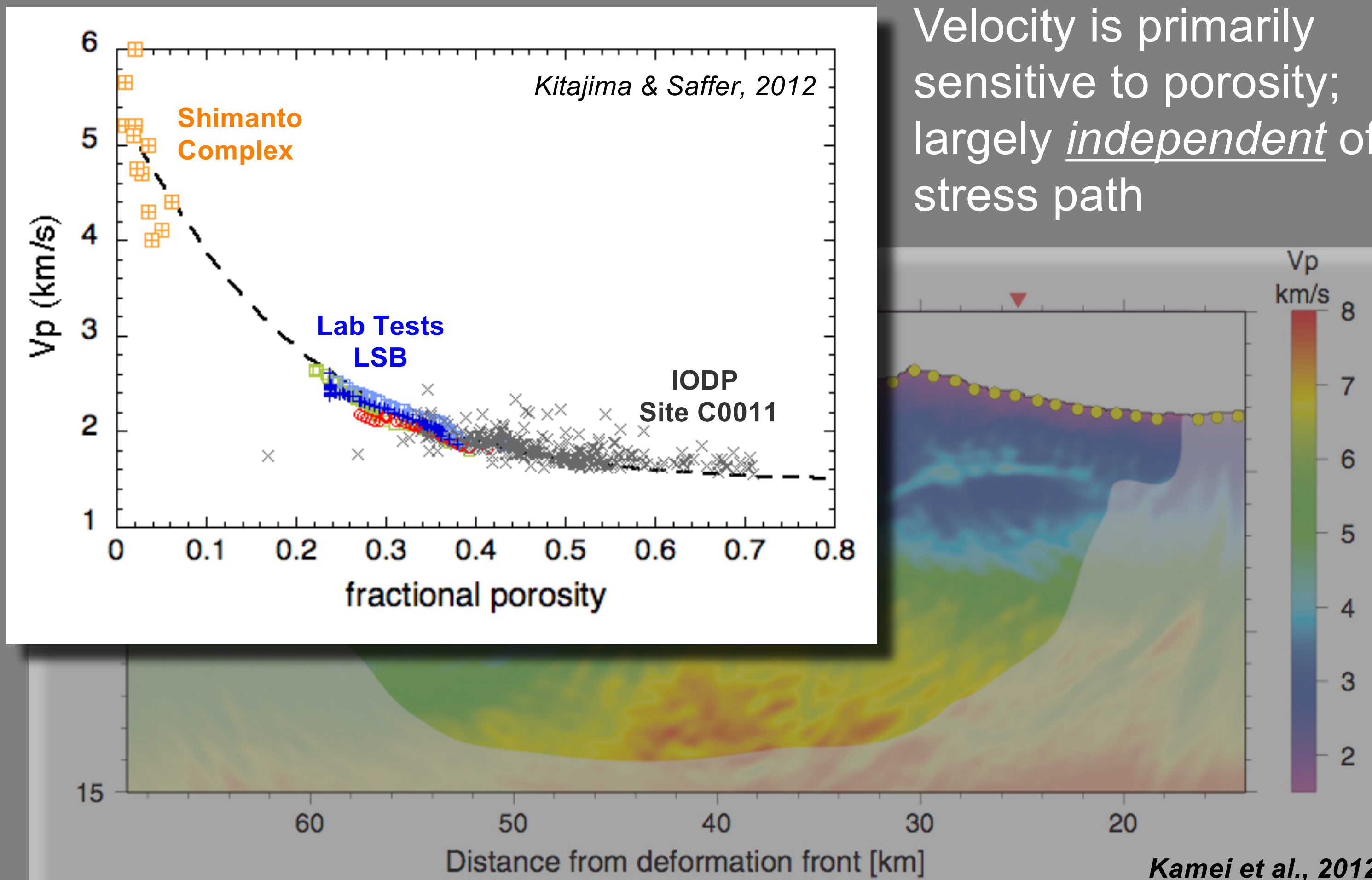






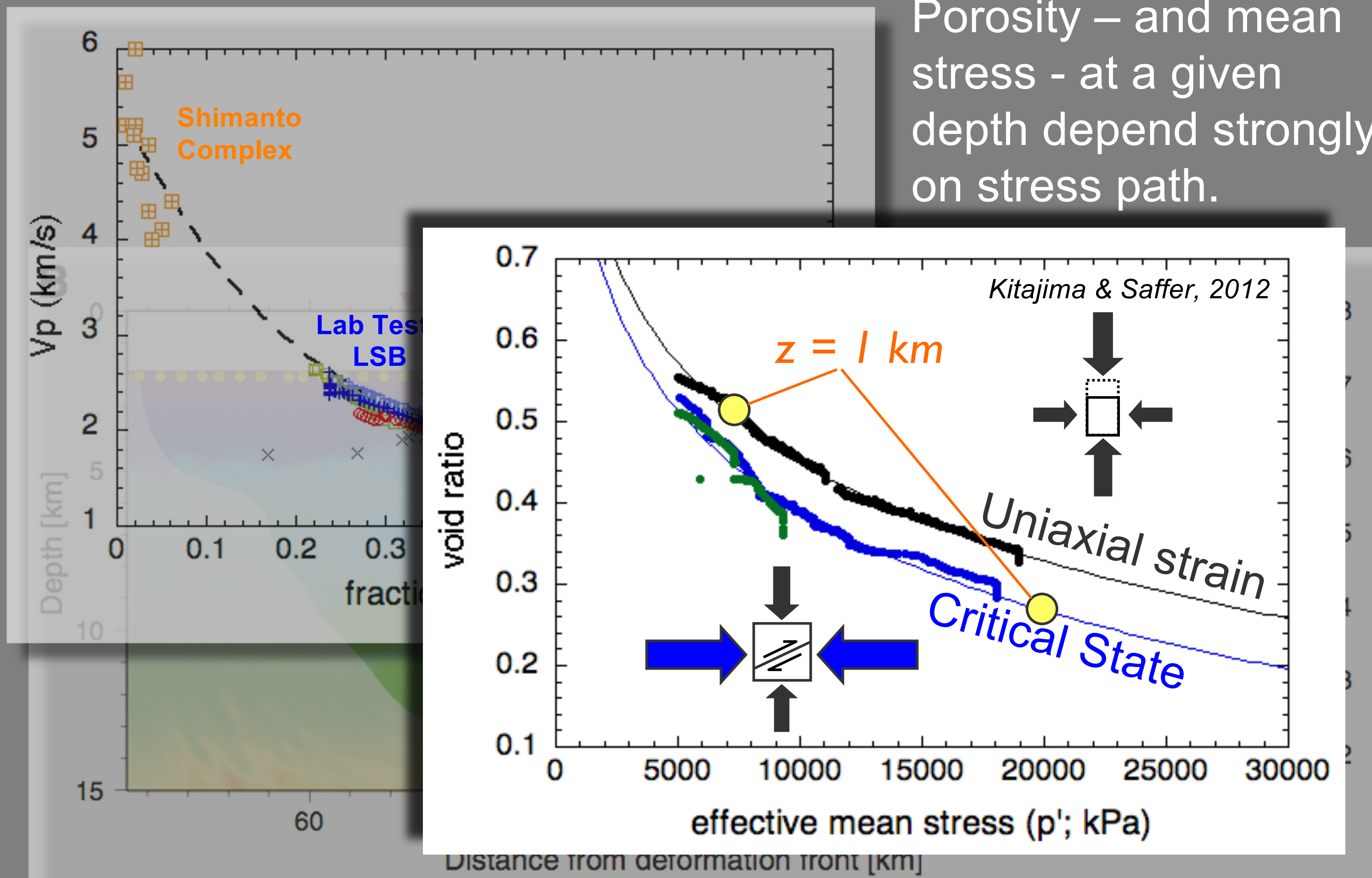
Compressional Velocity-Porosity Relation

Velocity is primarily sensitive to porosity; largely *independent* of stress path

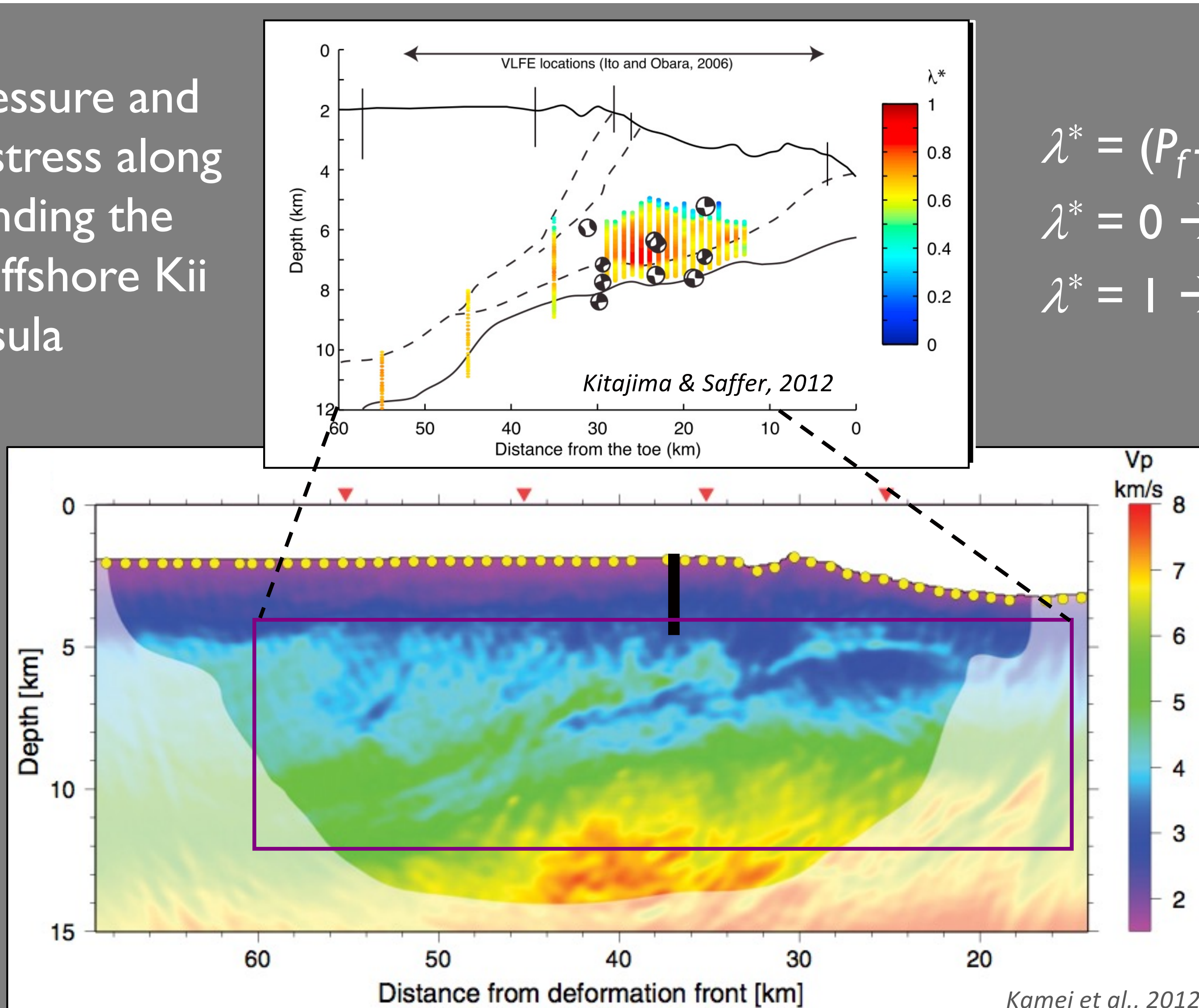


Constitutive behavior: Porosity-mean stress

Porosity – and mean stress - at a given depth depend strongly on stress path.



Fluid overpressure and low effective stress along and surrounding the megathrust offshore Kii Peninsula



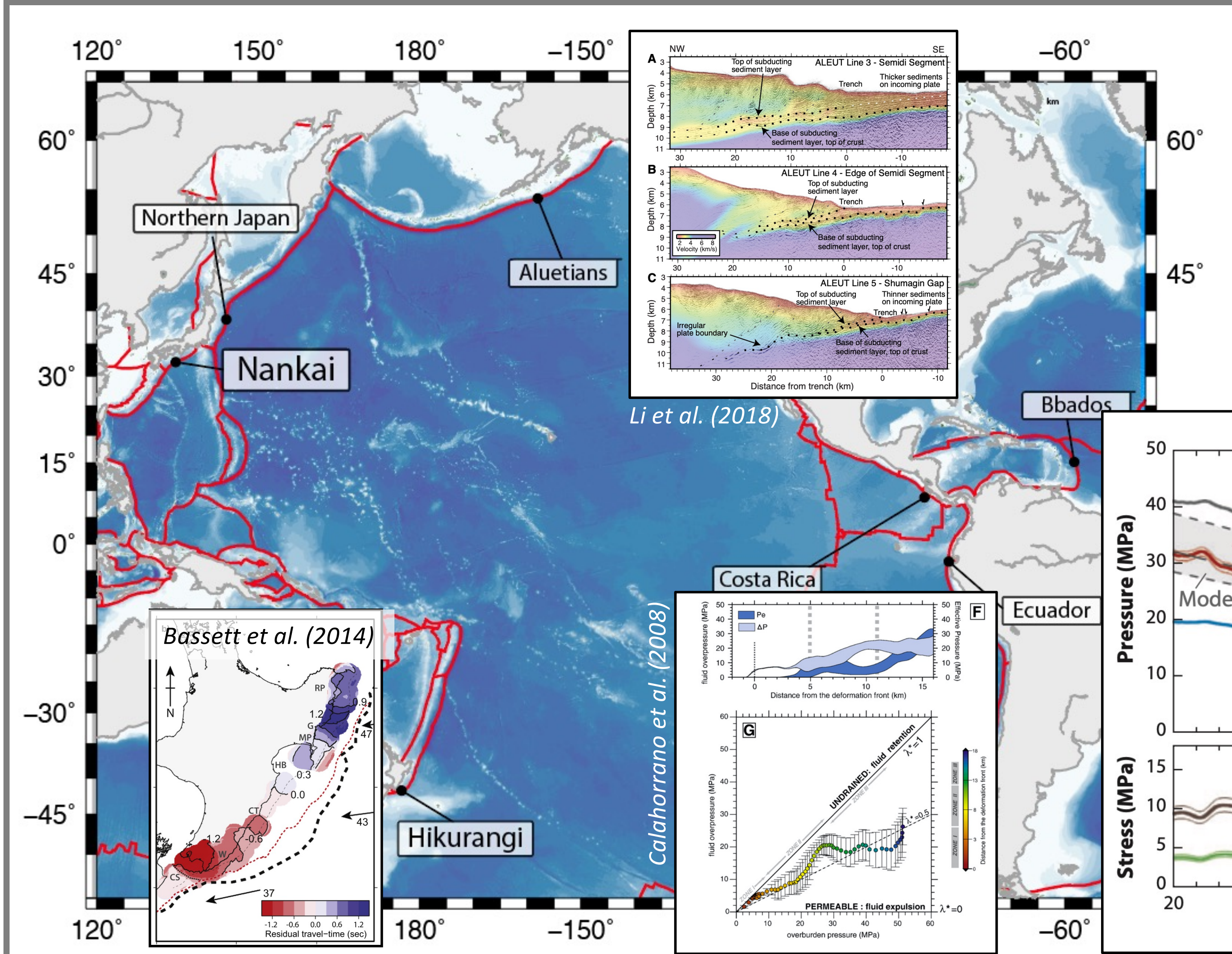
$\lambda^* = (P_f - P_h)/(P_l - P_h)$

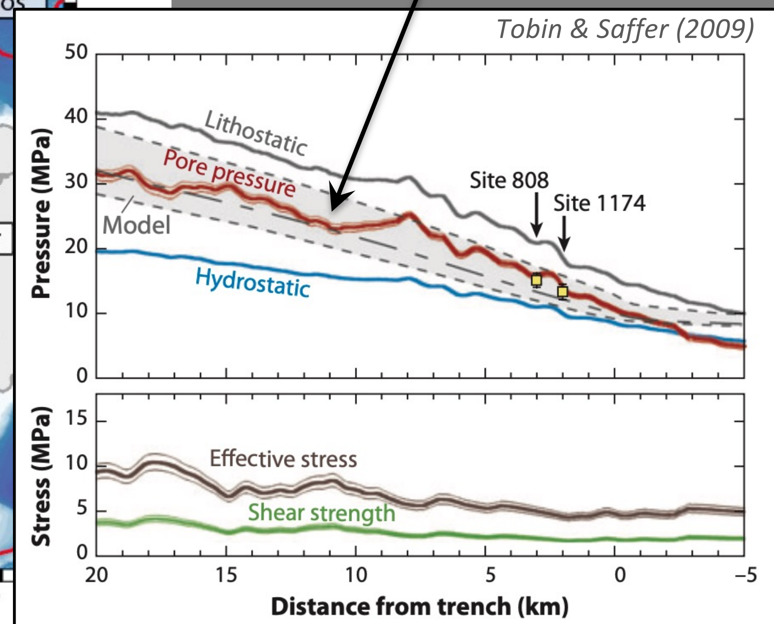
$\lambda^* = 0$ → hydrostatic

$\lambda^* = 1$ → lithostatic

High Fluid Pressure is Common

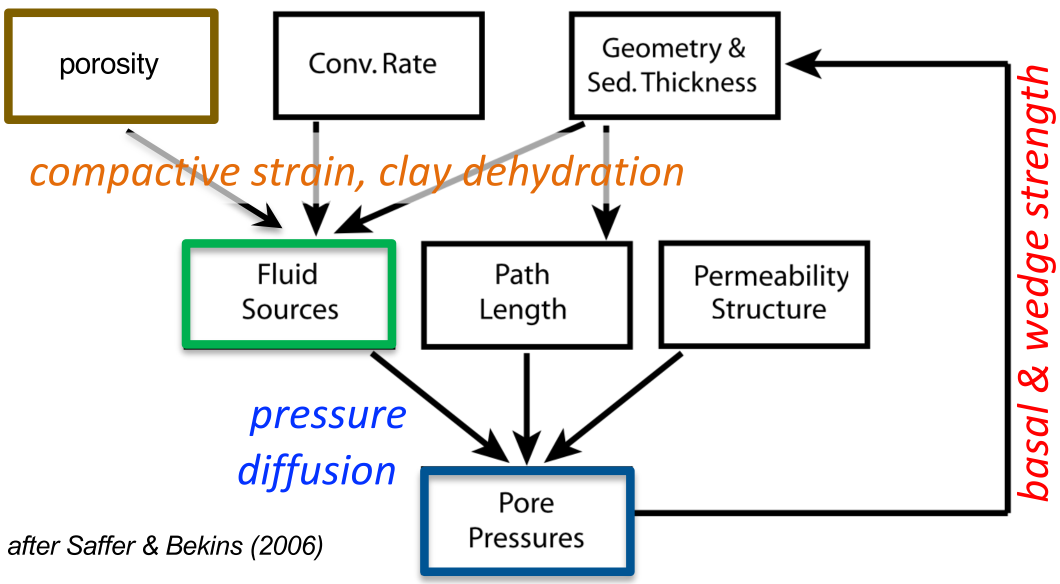
Quantitatively consistent with independent predictions from forward models.





Regional-scale sequentially coupled models of fluid flow and pressure

For more sophisticated modeling approaches: see Tian Sun's and Maria Nikolinakou's talks tomorrow

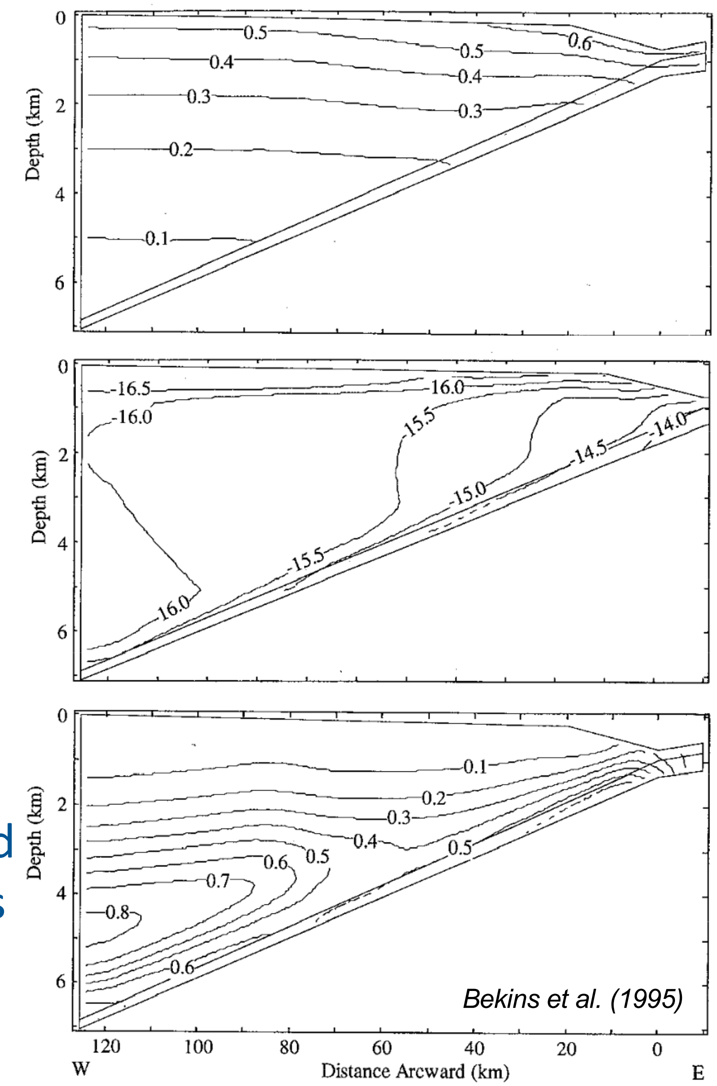


after Saffer & Bekins (2006)

porosity field

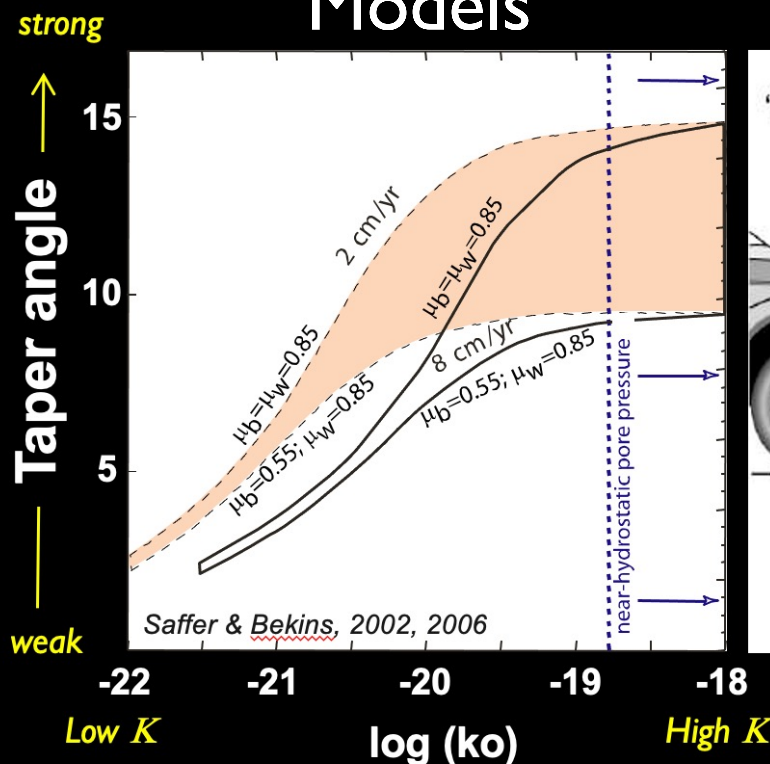
fluid sources

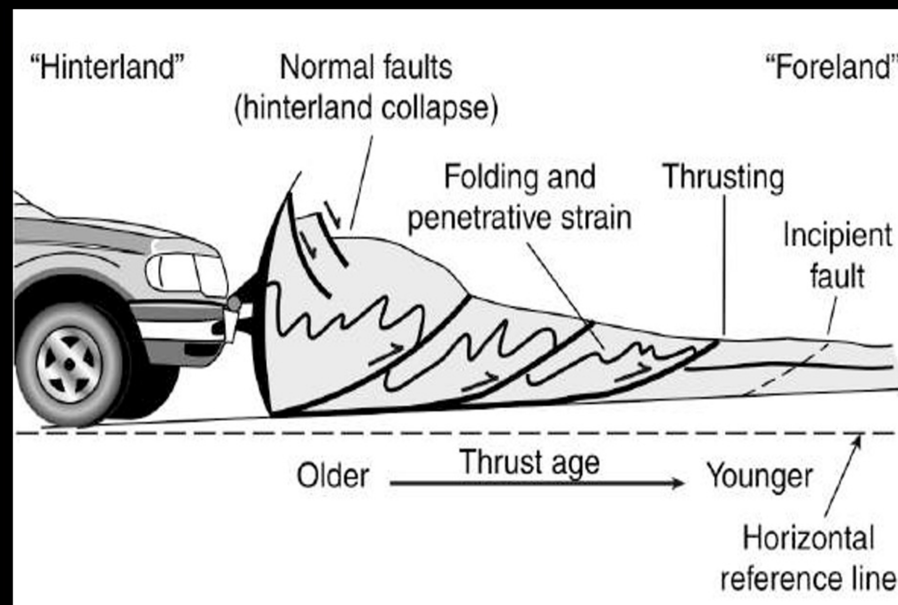
Computed pressures



Insight from 2-D models of loading & fluid flow: Feedbacks between hydrologic and mechanical processes

Models

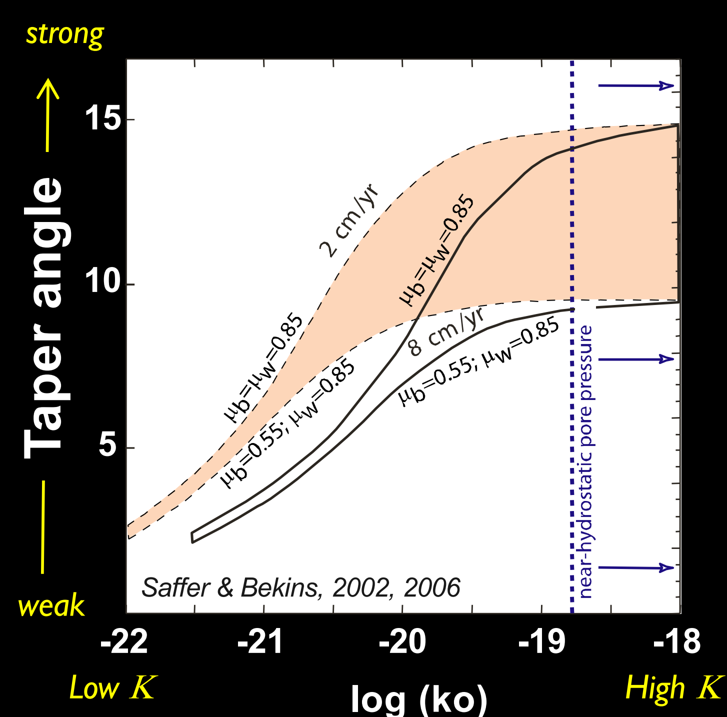




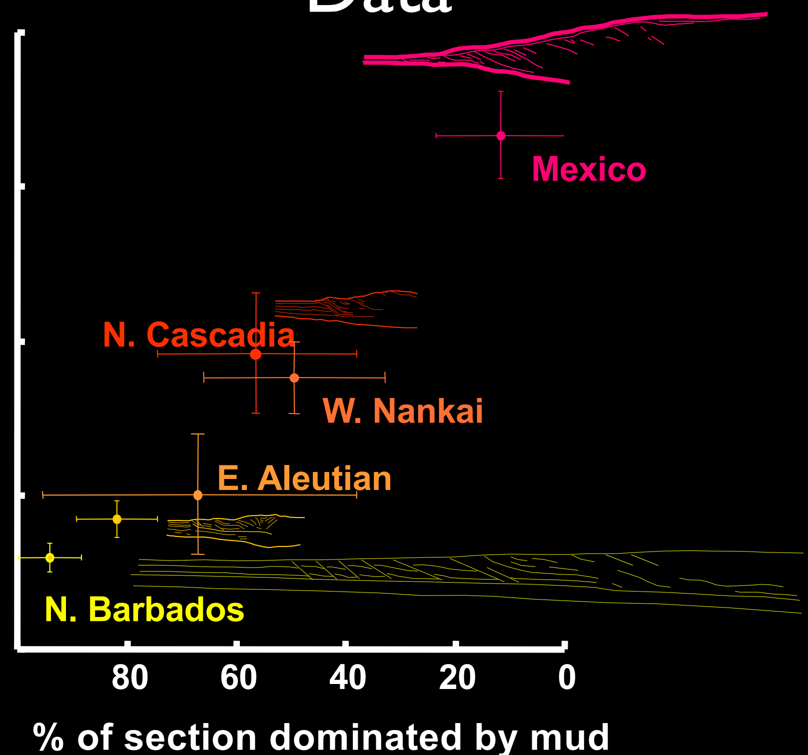
Davis et al., 1983

Permeability and the taper angle of orogenic wedges

Models

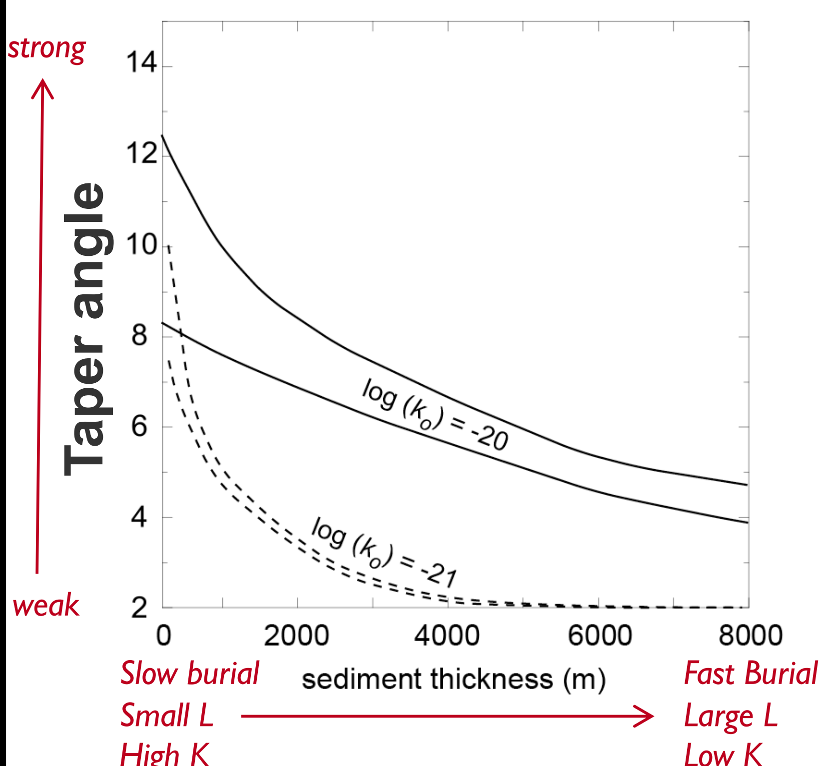


Data



Sediment Thickness and the taper of orogenic wedges

Models



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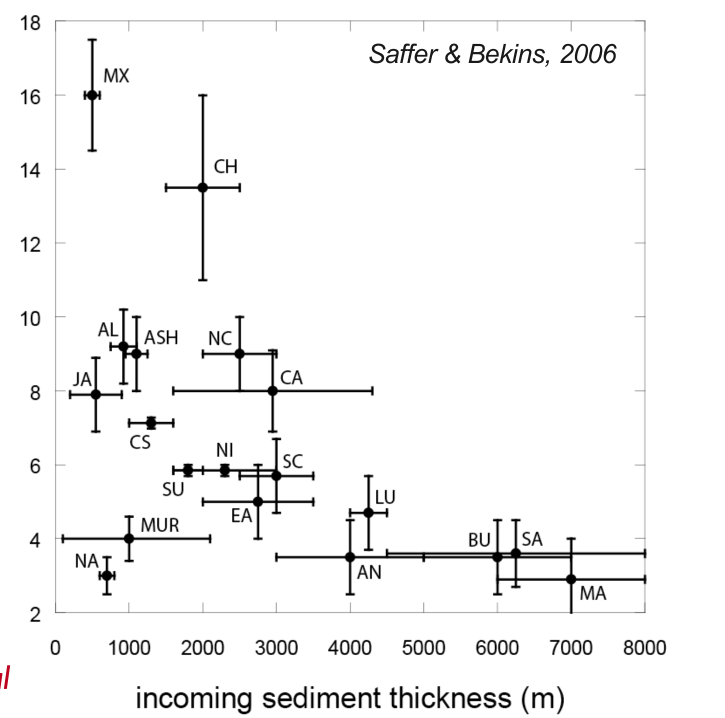
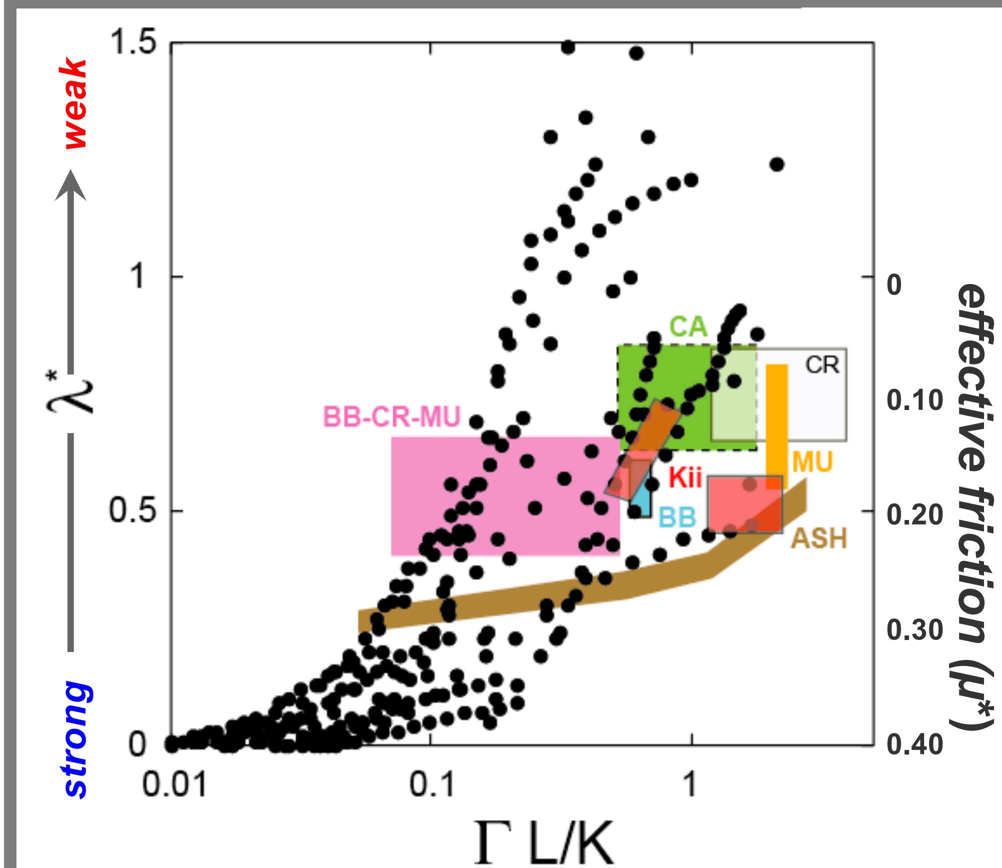


A Global View: Fundamental Factors Controlling Pore Pressure (and Crustal Strength)



Saffer & Tobin, Annual Reviews (2011)

[AMERICAN JOURNAL OF SCIENCE, VOL. 295, JUNE, 1995, P. 742–786]

ABNORMAL PRESSURES AS HYDRODYNAMIC PHENOMENA

C. E. NEUZIL

- ***Γ L/K***: dimensionless ratio of "geologic forcing" to hydraulic impedance.
- Systematic relationship to overpressure magnitude; excess pore pressure is a <u>dynamic phenomenon</u> governed by balance between competing rates.
- Ultimately mediates strength of the brittle crust in regions where hydrologic processes dominate.

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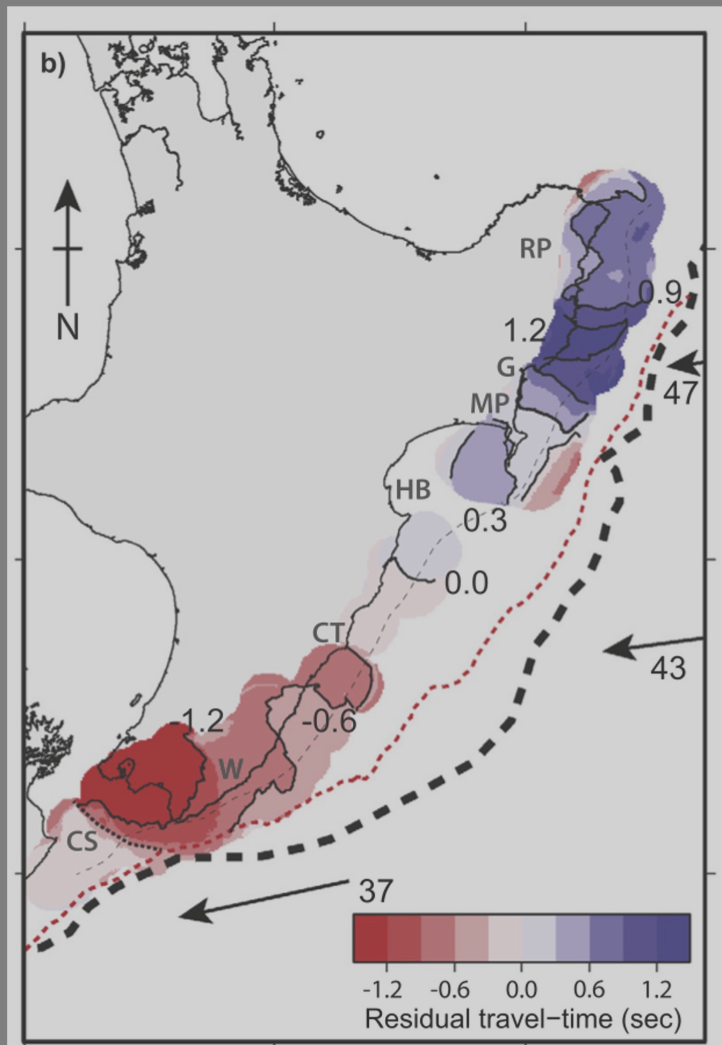
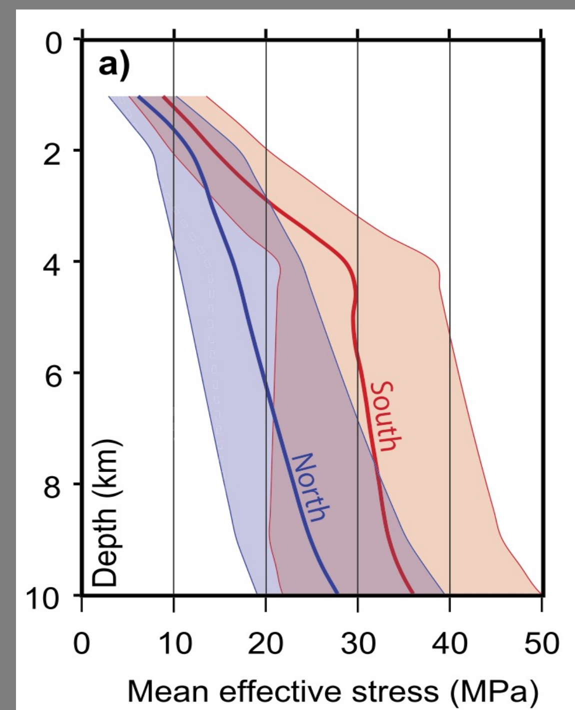
Links to Fault Slip Processes: Coupling and Slow Slip Events at the Hikurangi Margin





Bassett et al., 2014

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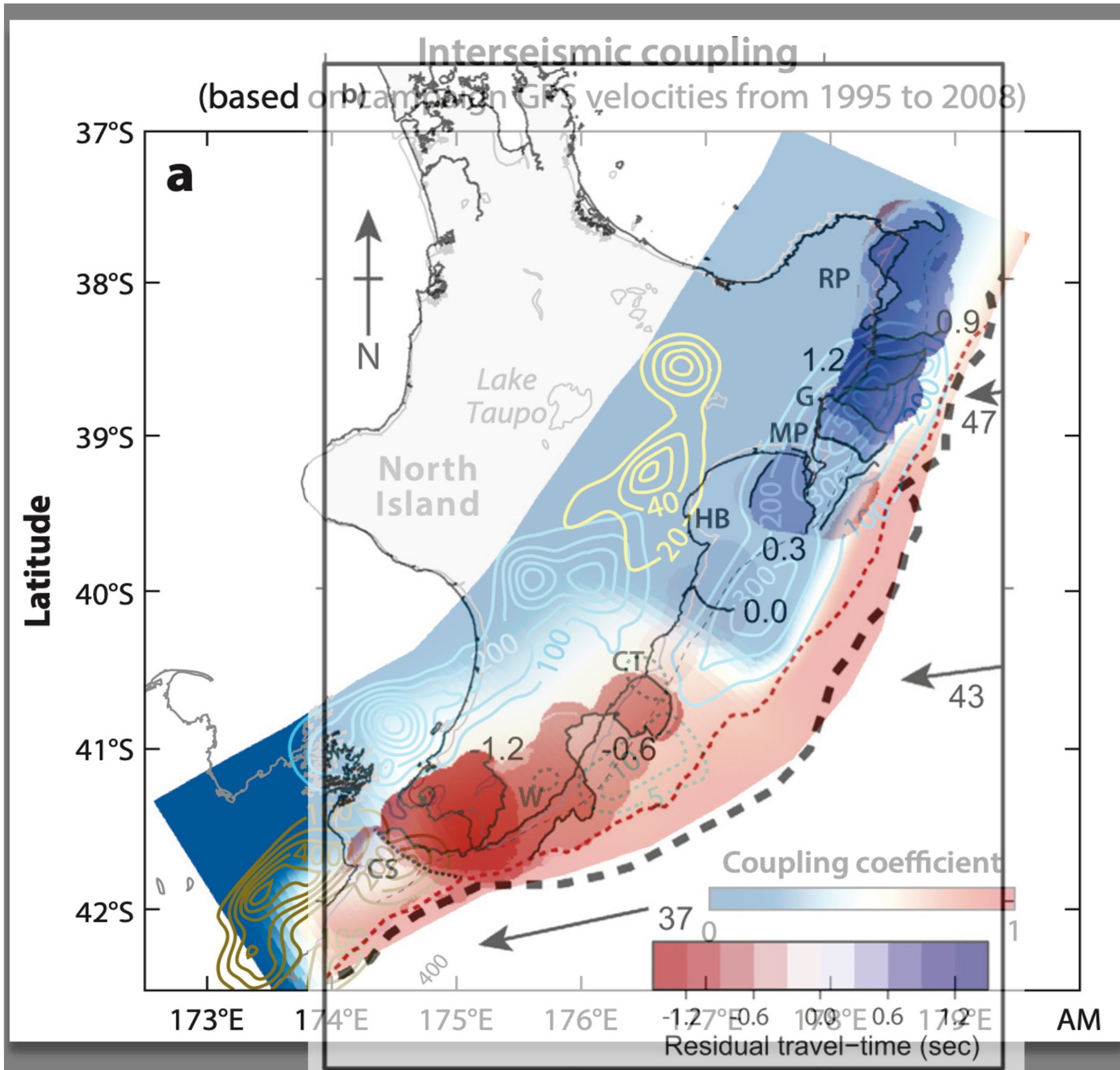
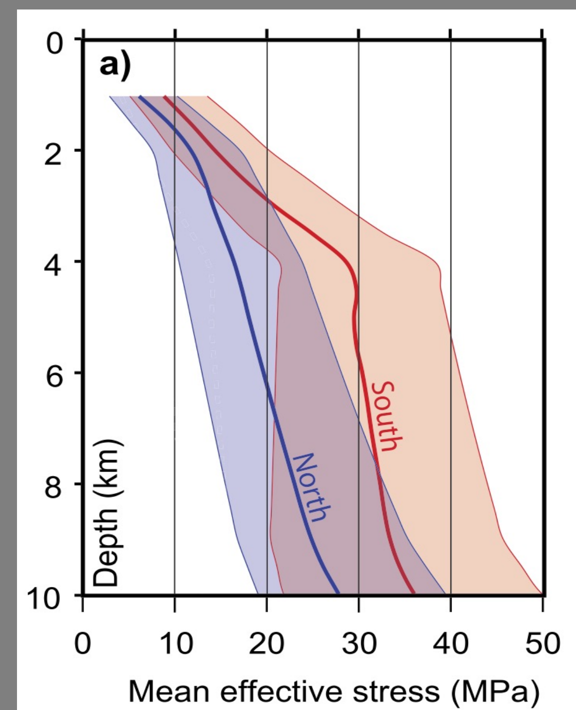
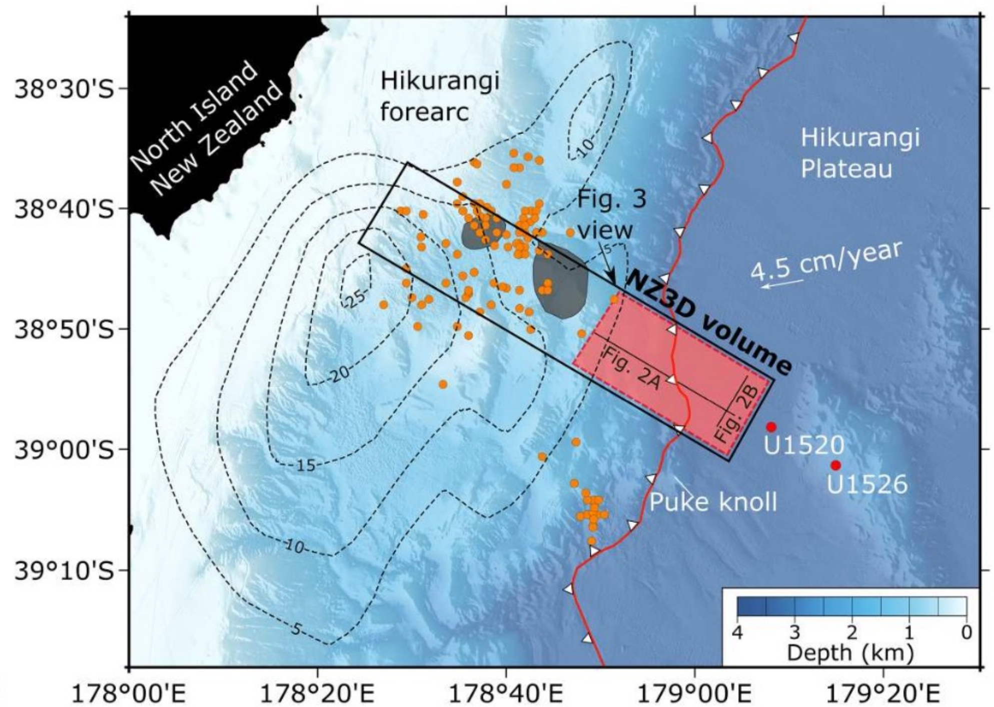




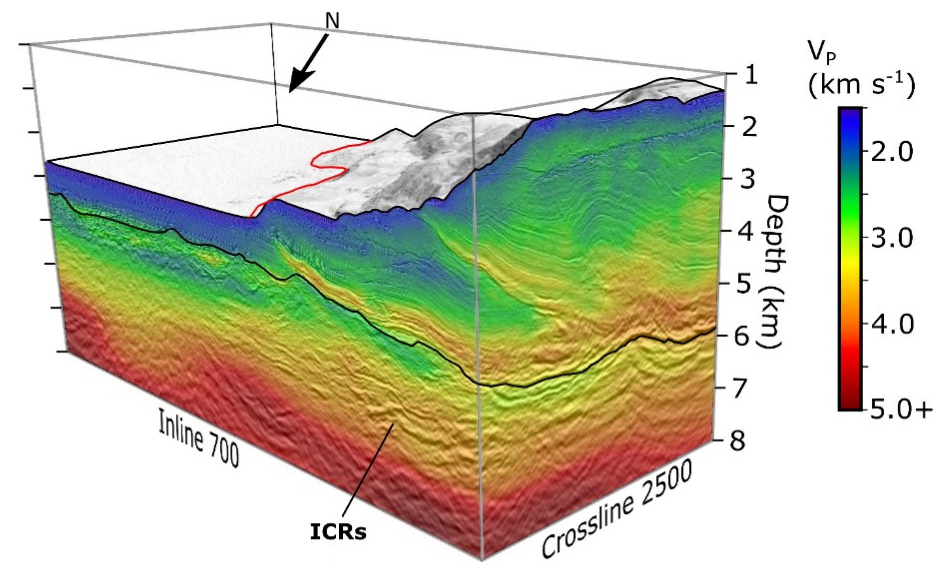
Bassett et al., 2014

Fluid influx to the shallow SSE region and megathrust

See Andrew Gase's talk tomorrow

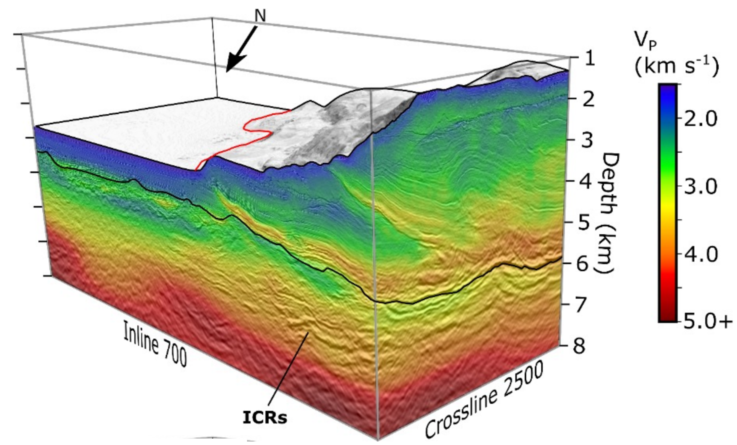


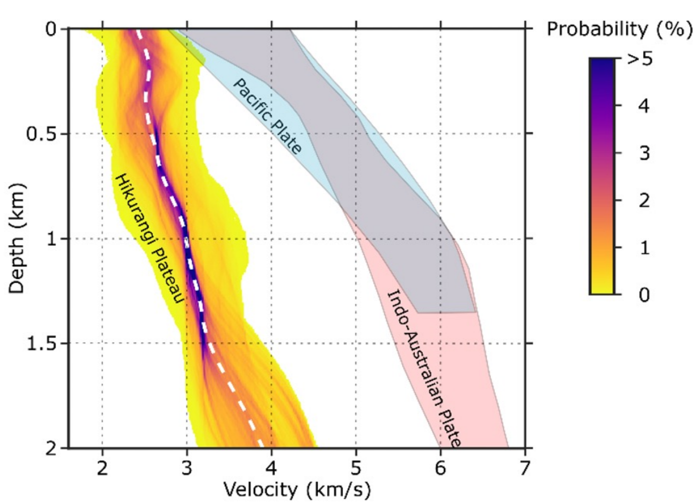
Gase et al., 2023



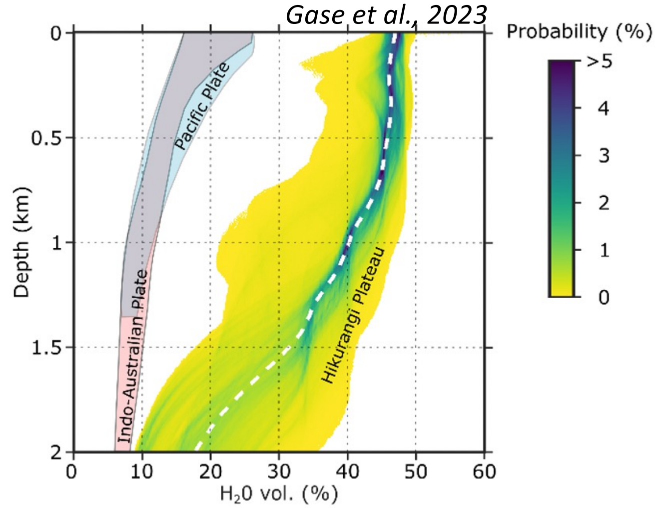
Fluid influx to the shallow SSE region and megathrust

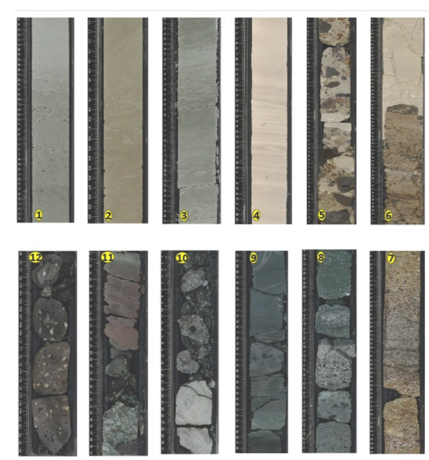
- Subduction of >2 km-thick clay-rich, heavily altered volcanic breccia/sand/mud.
- Transports large volume of water into the subduction zone and SSE source region.
- Manifests as regionally extensive low-velocity "blanket" on the Hikurangi Plateau.



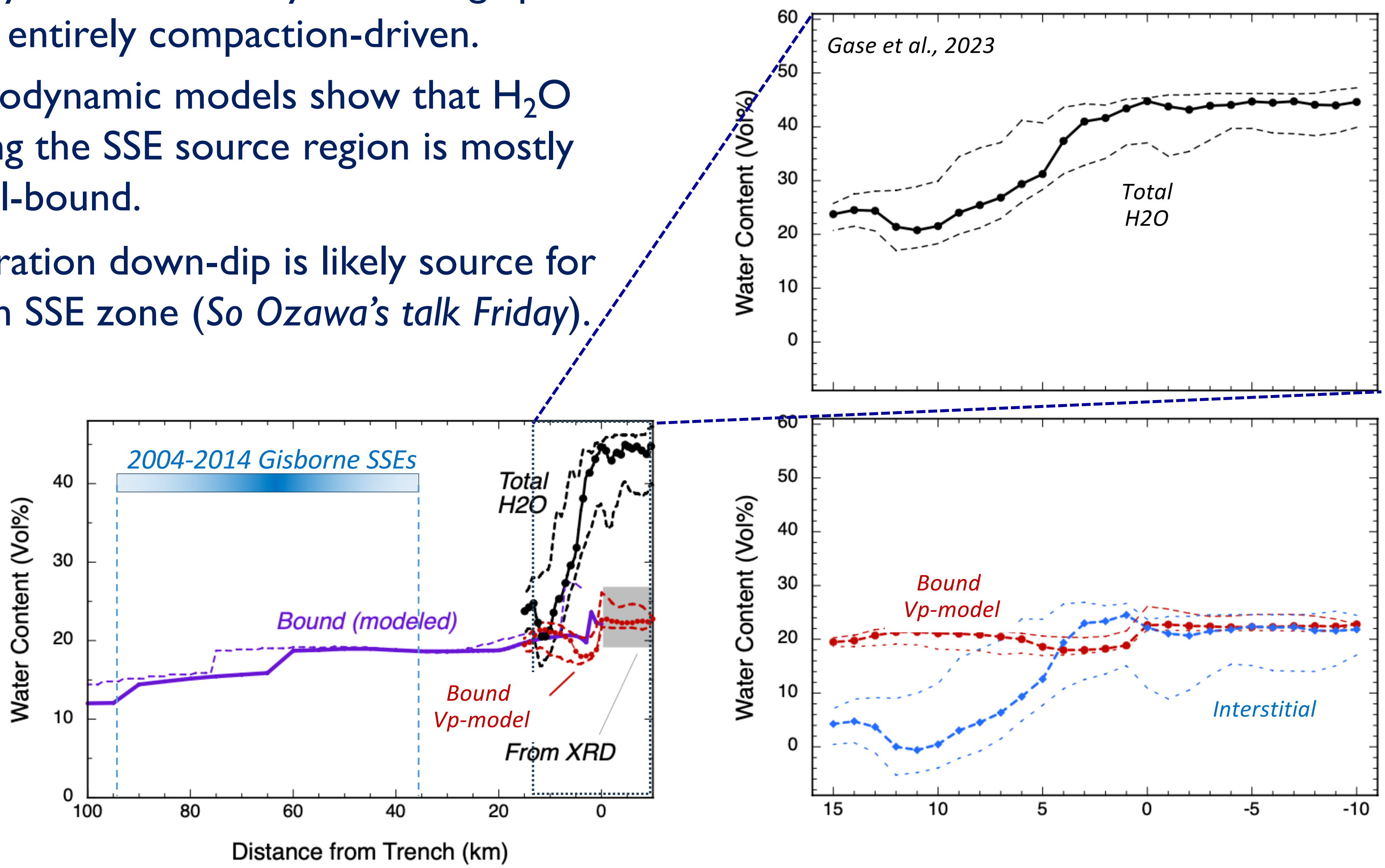


Gase et al., 2023

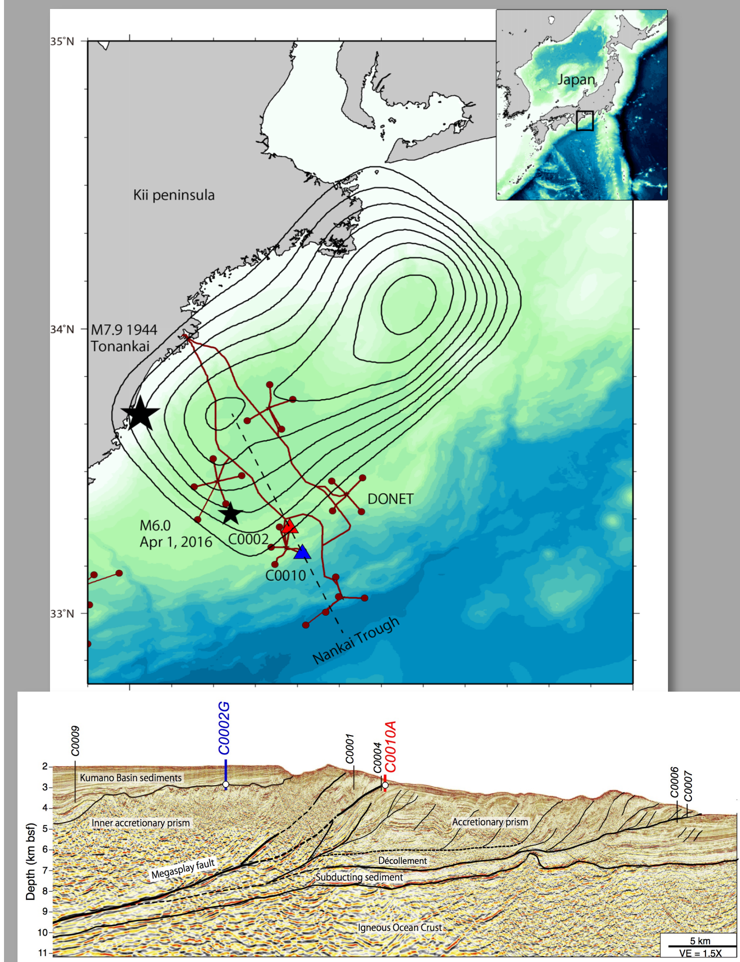


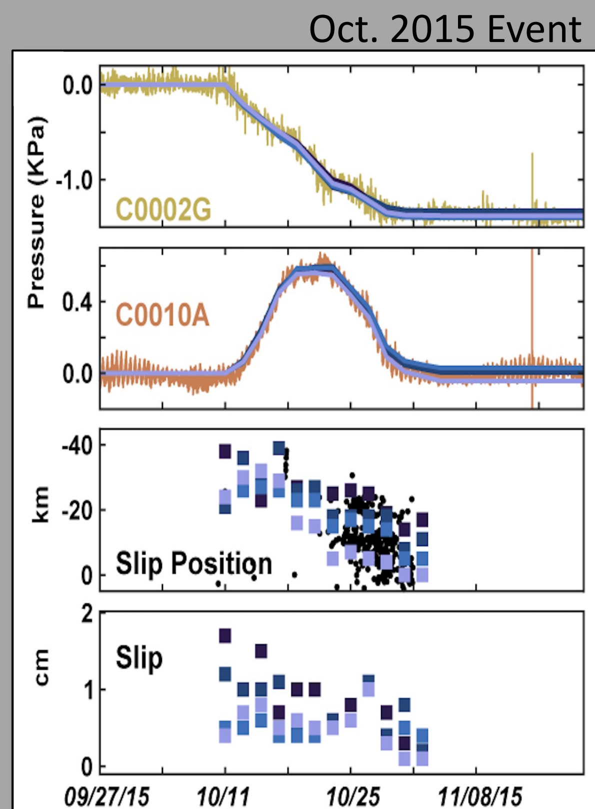


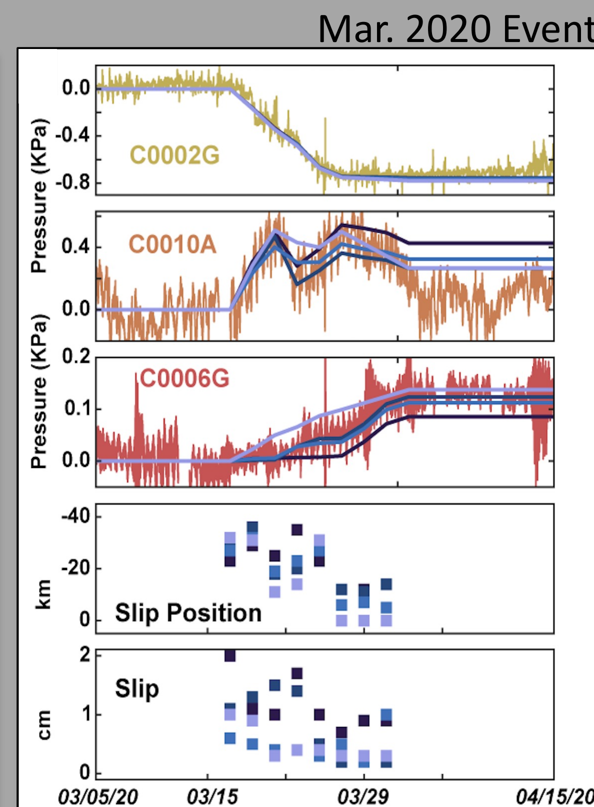
- Porosity loss revealed by increasing Vp is almost entirely compaction-driven.
- Thermodynamic models show that H_2O entering the SSE source region is mostly mineral-bound.
- Dehydration down-dip is likely source for fluids in SSE zone (*So Ozawa's talk Friday*).



Links to Shallow SSE along the Nankai Margin off Kii: Detailed constraints on slip in recurring events







Edgington, Saffer, & Williams (in press)

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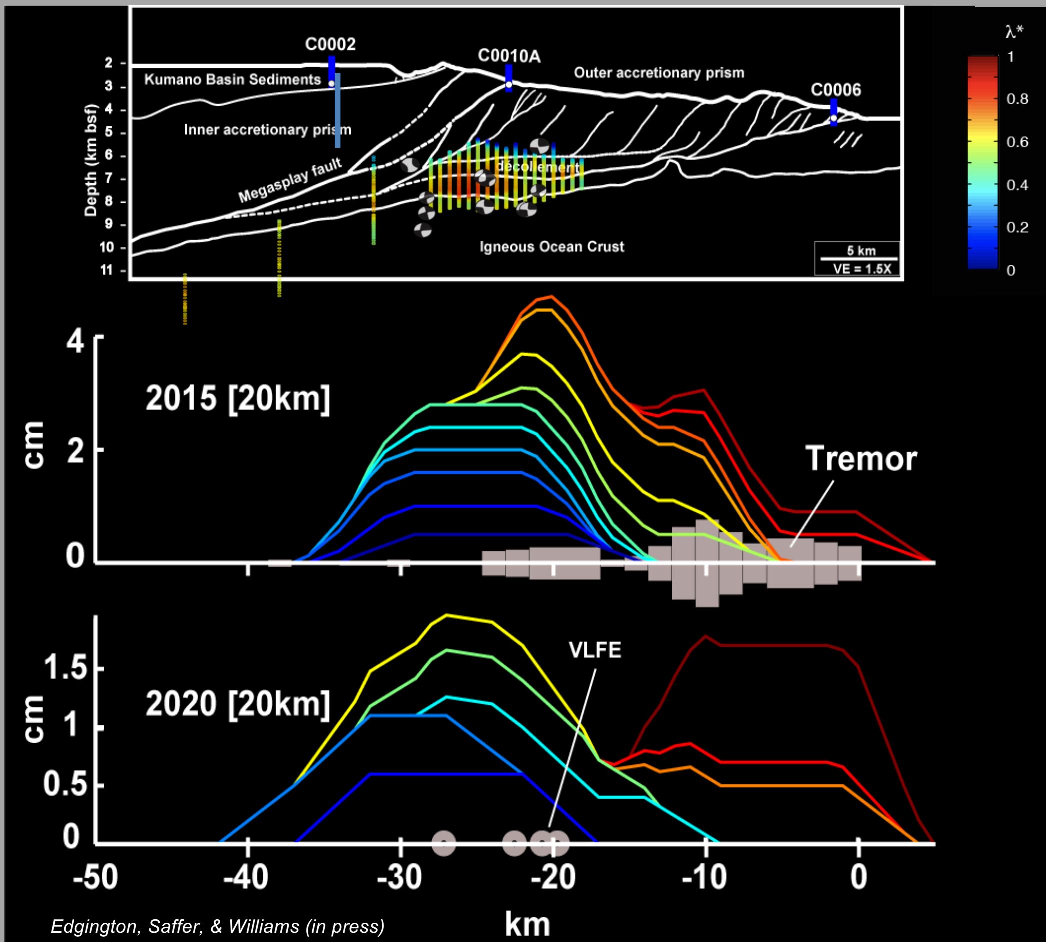

- SSE source fault and high slip zone spatially correlated with zone of low Vp and *quantified ambient high pore pressure*.
- This region is characterized by low overall stress – both surrounding the décollement near the trench and in the deep interior of the prism.

Outline

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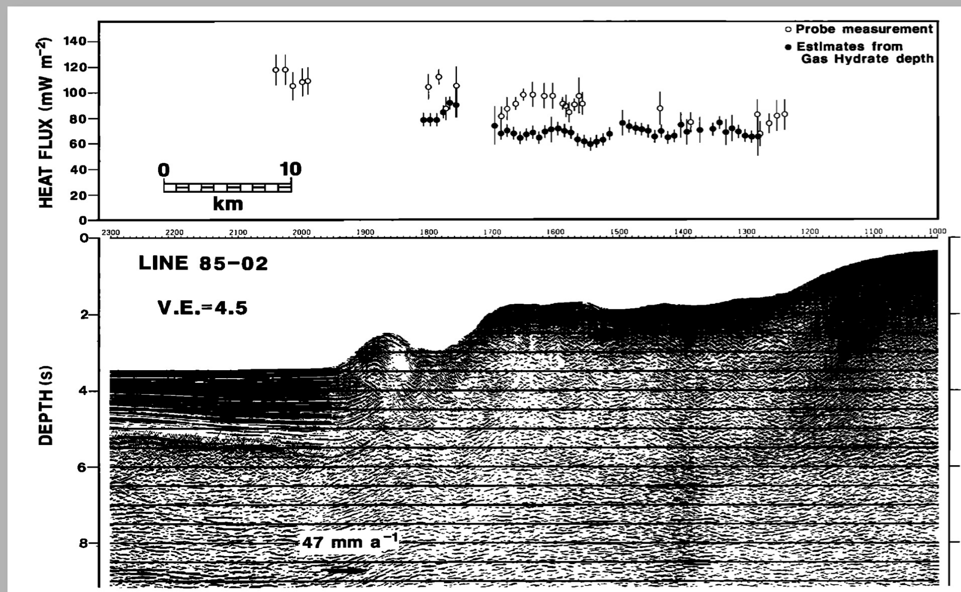
   - Insights gained from the lab and drilling
   - Mapping regional geophysical observations to stress and pressure
   - What drives pressure? - Integration of numerical models and observations
   - Links to fault slip behavior

2. Flow Pathways, Plumbing, and Localization of Flow
   - Hydraulic architecture – observations and models
   - Flow rates, tapping deep fluids & volatiles
   - Evidence and mechanisms for transient flow

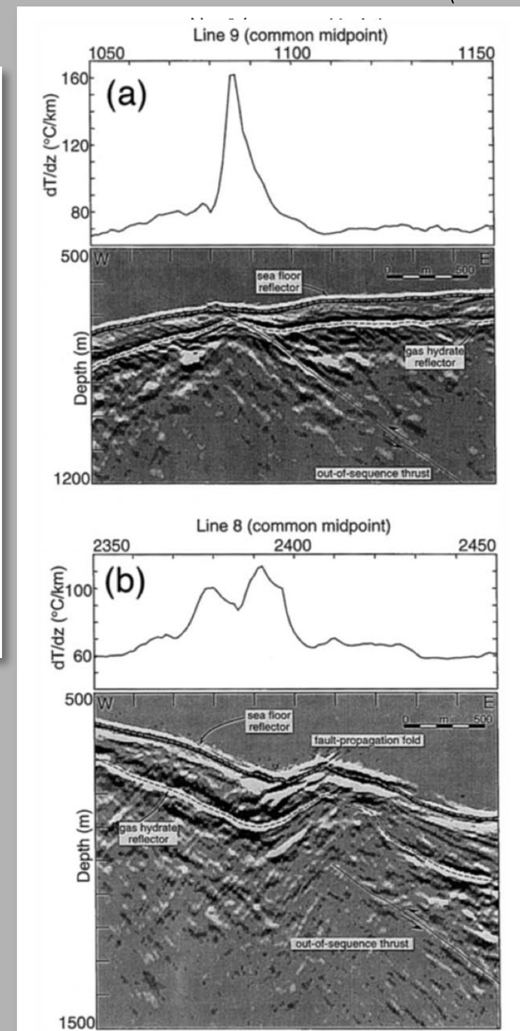
Hydraulic Architecture:

- BSR & surface heat flow as indicators of advection and flow rate.
- Document localized flow along faults and diffuse flow in matrix.

Davis et al. (1994)

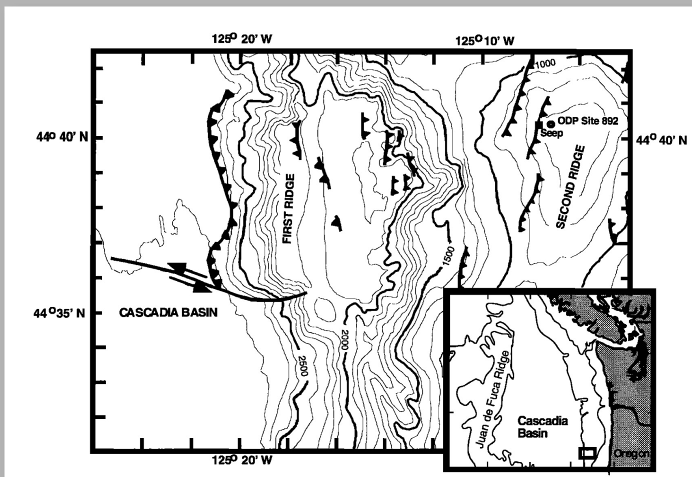


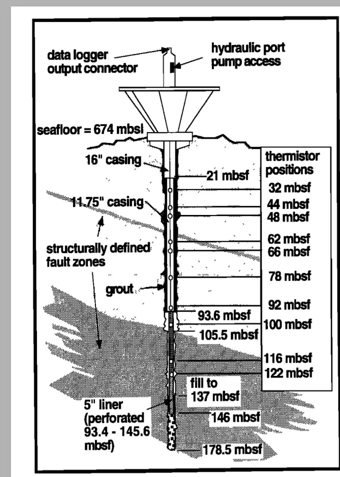
Zwart et al. (1996)



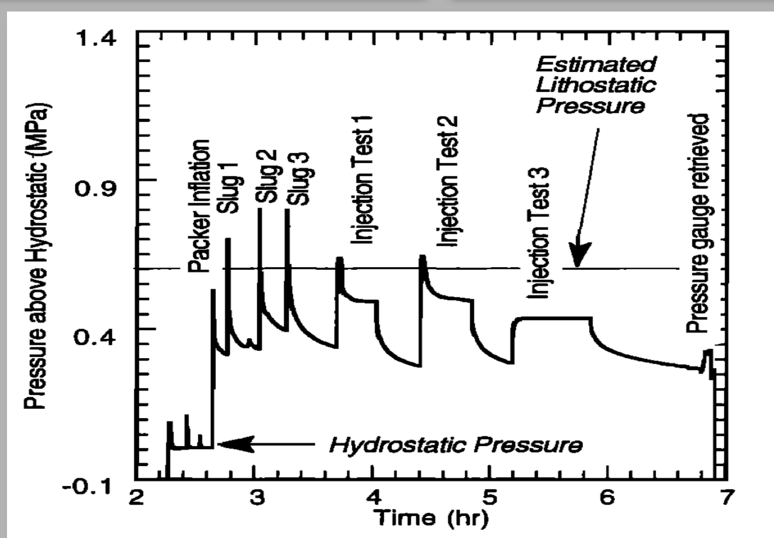
- Direct flow rate measurements and geochemical indicators of deeply-sourced fluids highlight the role of faults and permeable outcropping strata as key conduits for both transport & dewatering.
- In situ fault permeability measurements – while rare – support this model.

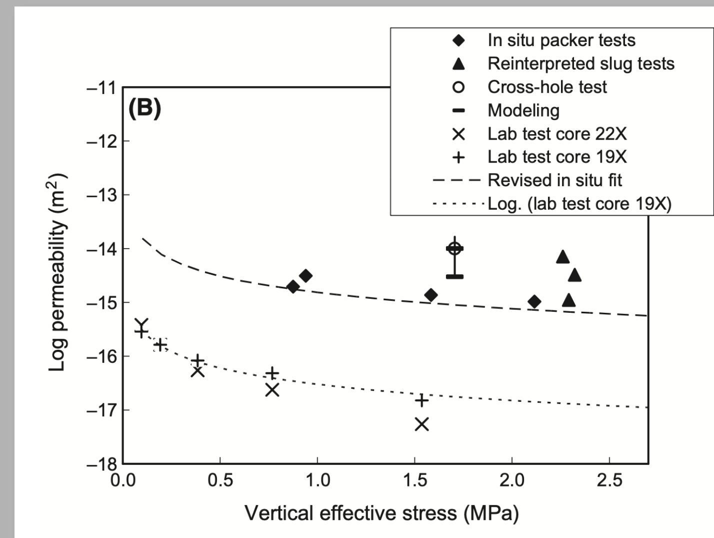
Fault conduits: direct permeability measurements





Screaton et al., 1995

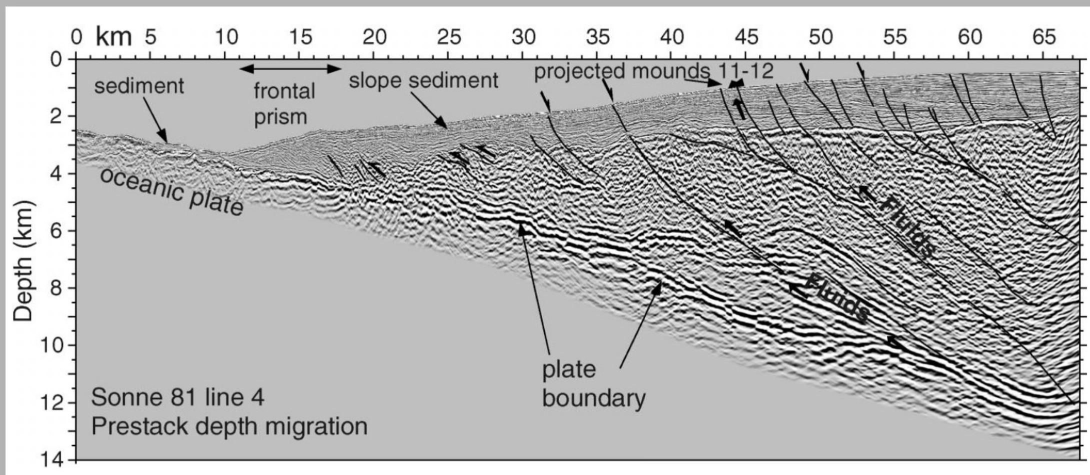




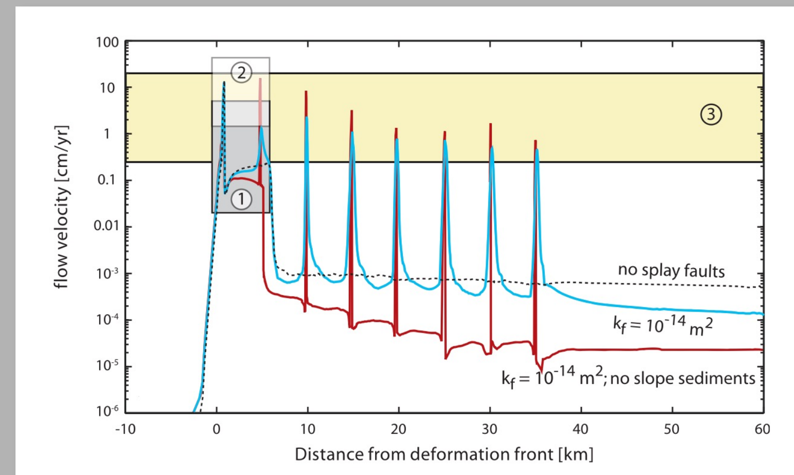
Bekins et al., 2011

- In situ borehole measurements - though few - indicate that primary faults are 2-6 orders of magnitude more permeable than matrix.
- Repeat injection tests document non-linear stress-dependence of fault zone permeability.

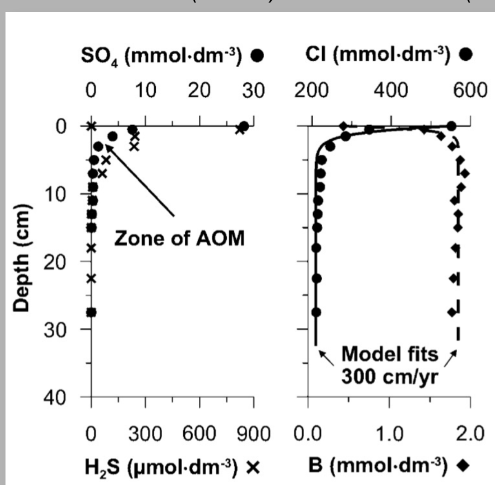
Fault conduits: Field observations and models at Costa Rica



Hensen et al. (2004); Ranero et al. (2008)



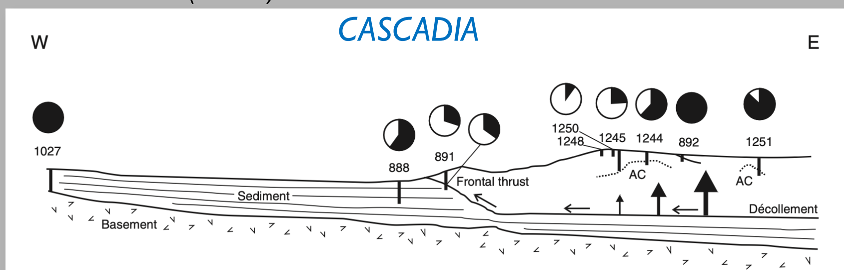
Lauer & Saffer (2012)



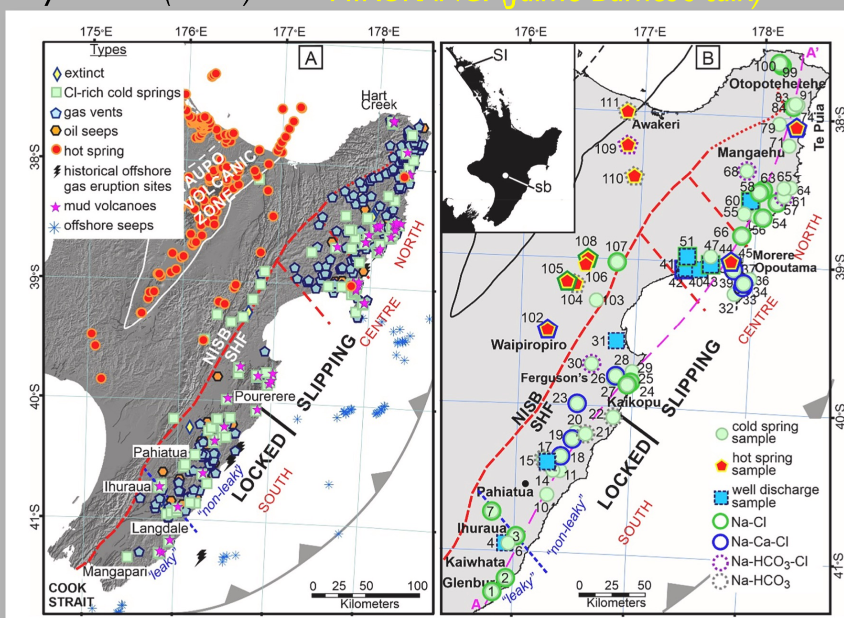
- Seep geochemistry indicates that faults tap deeply sourced (low-T metamorphic) fluids.
- Flow rates estimated from 1-D chemical profiles via simple advection-diffusion models.
- 2-D numerical models that incorporate loading and clay dehydration to generate pressure suggest fault permeabilities $>10^{-14}$ m^2 are required to deliver these fluids from depth.

Hydraulic Architecture: Tapping Deep Fluids

Teichert et al. (2006)



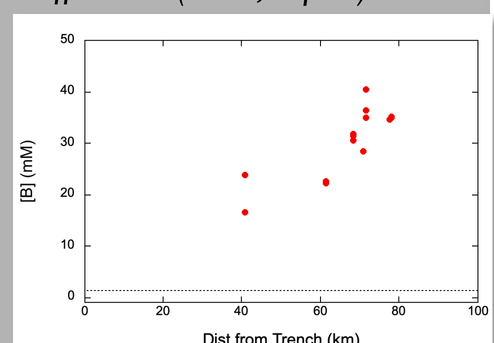
Reyes et al. (2019) *HIKURANGI (Jaime Barnes's talk)*

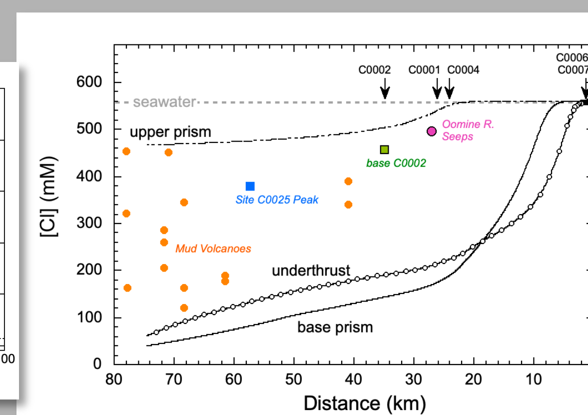


- Fluids within sediments and slab are progressively altered by diagenesis and metamorphism. [Cl] and [B] are two example tracers (also hydrocarbons, Li, etc…).
- With increasing burial, metamorphic sources become more dominant. This is consistent with hydrologic models (e.g., Lauer & Saffer, 2015).
- Focused advection along permeable pathways provides a "window" to the slab and clues about plumbing.

NANKAI

Saffer et al. (2012, unpub.)





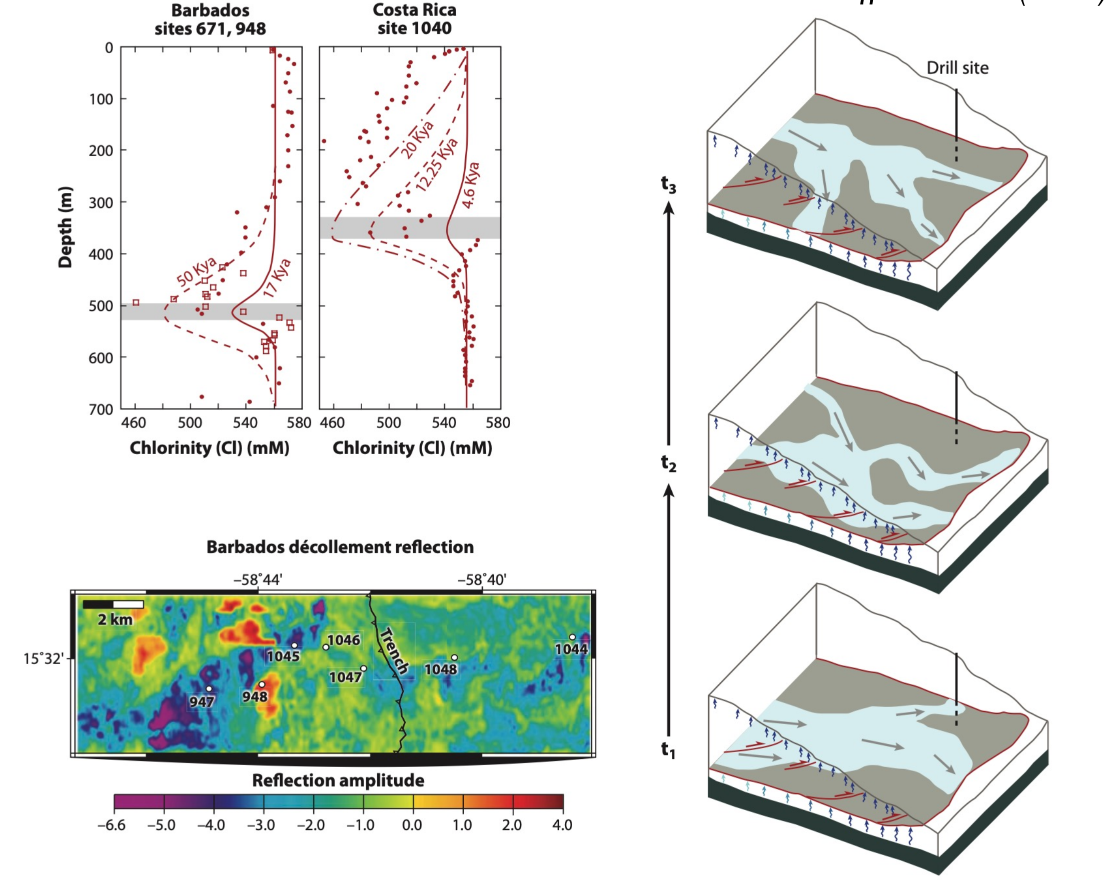
Evidence for time-varying fault permeability

- Chemical anomalies centered on fault conduits require transient flow. Simple models suggest timescales of 10's-100's kyr.

- Fluid budgets offer a second constraint. Observed flow rates at seeps require that conduits are open only a fraction of the time.

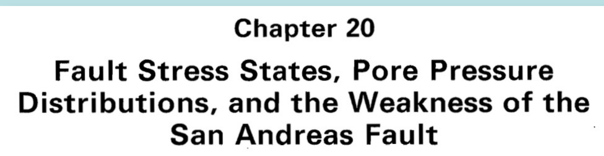
- Emerging picture is one with conduits on the fault surface that shift over time.

Saffer & Tobin (2011)



What causes transient flow? Intrinsic vs. Extrinsic mechanisms

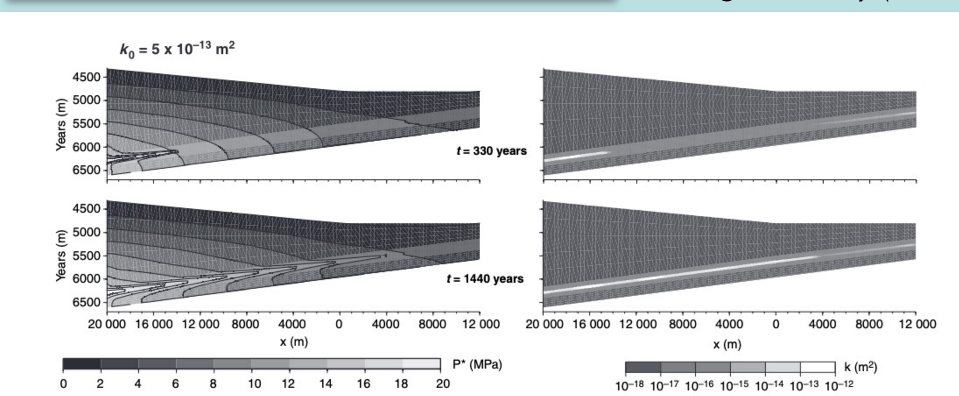
- Stress-dependent permeability can give rise to spontaneous solitary waves – increased k and flow rate *(Kidiweli et al. poster)*.
- A potential mechanism for SSE (*Ozawa & Dunham*, 2024),

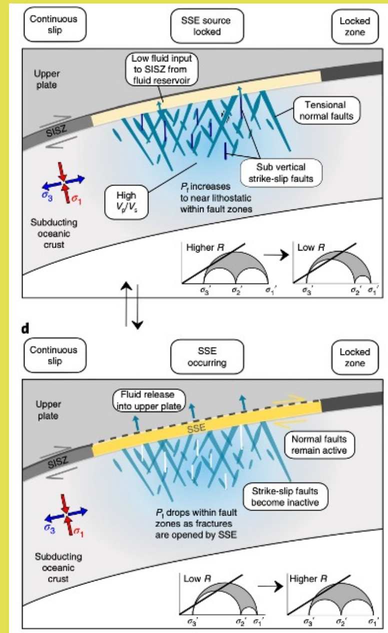

Chapter 20

Fault Stress States, Pore Pressure Distributions, and the Weakness of the San Andreas Fault

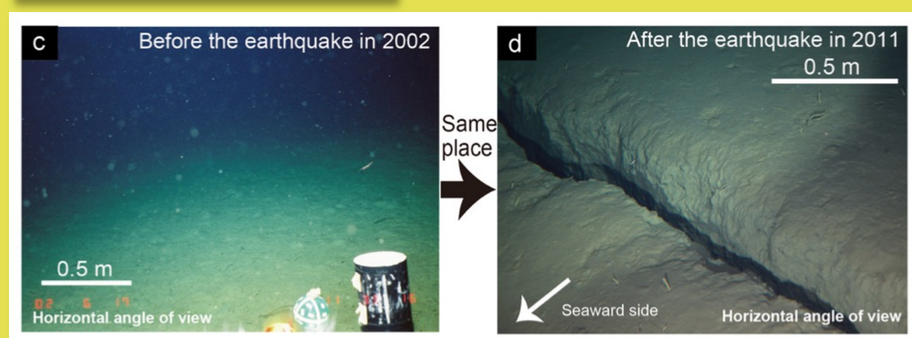
Rice (1992)

Bourlange & Henry (2007)

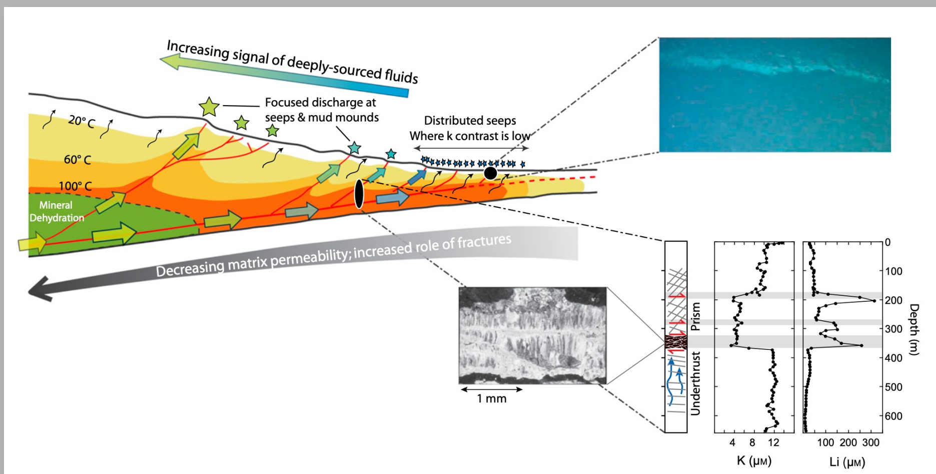


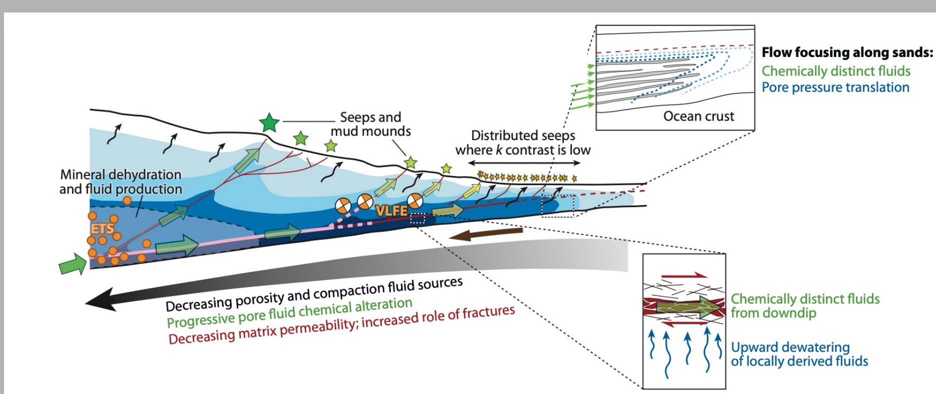


- Fault valving from slow slip events could release pressure cyclically (*Warren-Smith et al., 2019*).
- Permeability increase from damage during & after coseismic slip (e.g., *Tsuji et al.*, 2013; *see also Patrick Fulton's talk – next!*).



Key Points & Outstanding Questions





- High pore pressure is common – the result of a dynamic balance between driving mechanisms and dissipation.
- High pore pressure is linked to SSE. This is better constrained in the outer forearc than for deep SSE (*see Mann et al. poster*).
- Flow is transient and localized. Conduits are efficient *transport* pathways, but dissipate *pressure* only locally.
- Deep fluids provide a window to the slab. Better links to hydrologic models are a key next step.
- Improved quantification of stress & pressure from geophysical imaging/surveys is needed.
- Many open questions remain in the realm of fluid-chemical-geomechanical interaction.

[AMERICAN JOURNAL OF SCIENCE, VOL. 295, JUNE, 1995, P. 742–786]

ABNORMAL PRESSURES AS HYDRODYNAMIC PHENOMENA

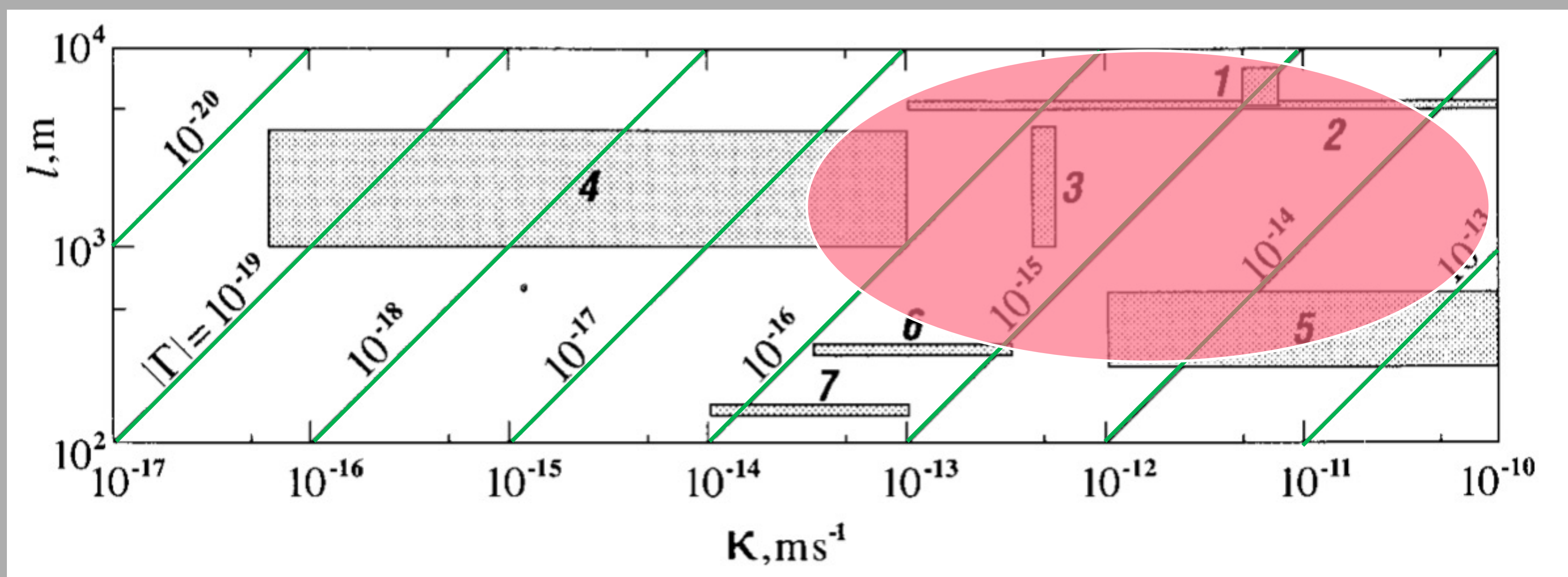
C. E. NEUZIL

Nomogram of "Geologic forcing": Fluid production or its equivalent, units of t^{-1}

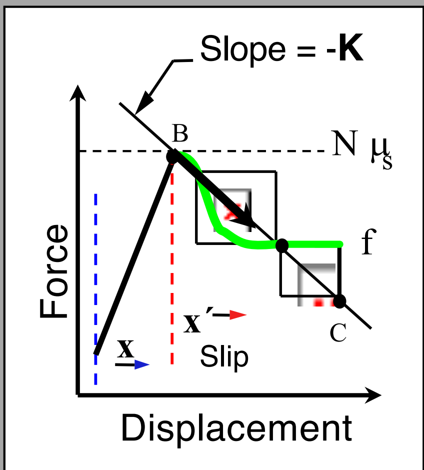
large

drainage path length

small

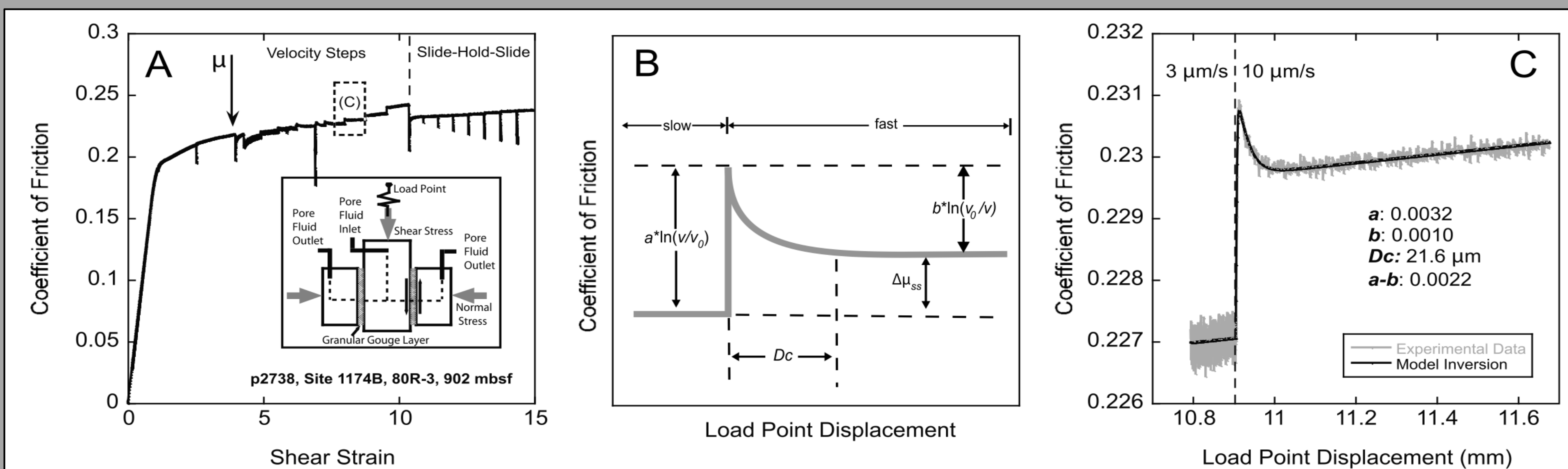


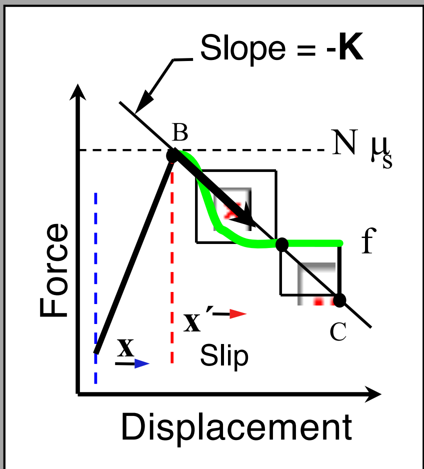
Hydraulic conductivity



The nucleation of unstable slip can be framed in terms of a balance between the (1) change in frictional resistance, and (2) rate of elastic unloading of stored stress, in response to incremental slip.

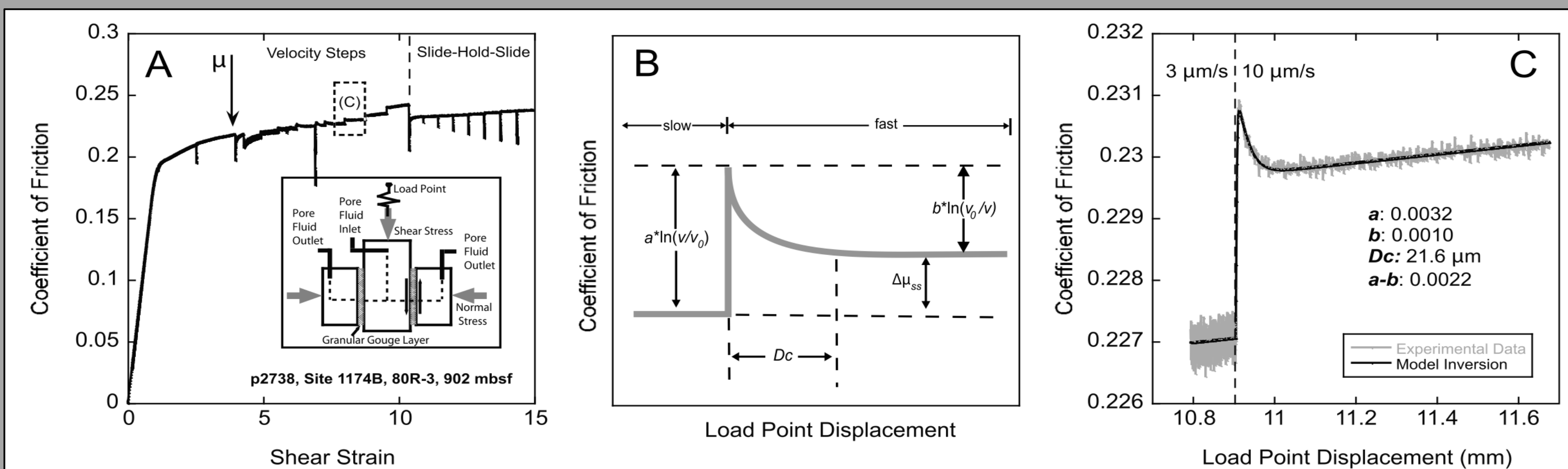
$$K < K_c = \frac{\sigma_n' (b - a)}{D_c}$$



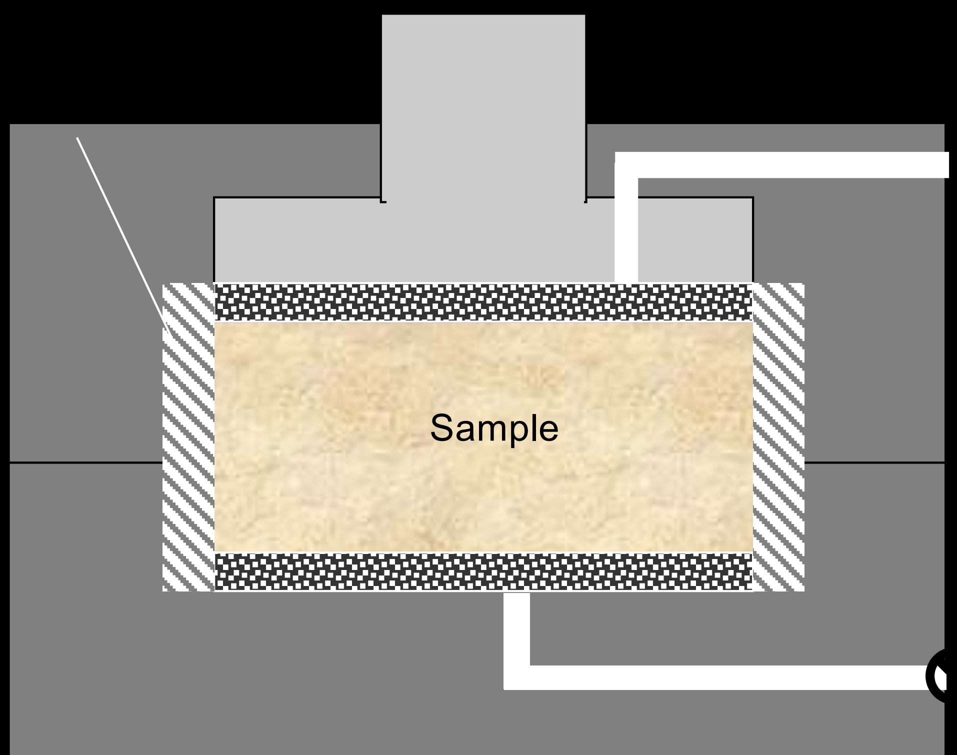


Elevated pore pressure can drive an unstable system toward slower failure modes, and ultimately promote stable sliding, via its control on effective stress.

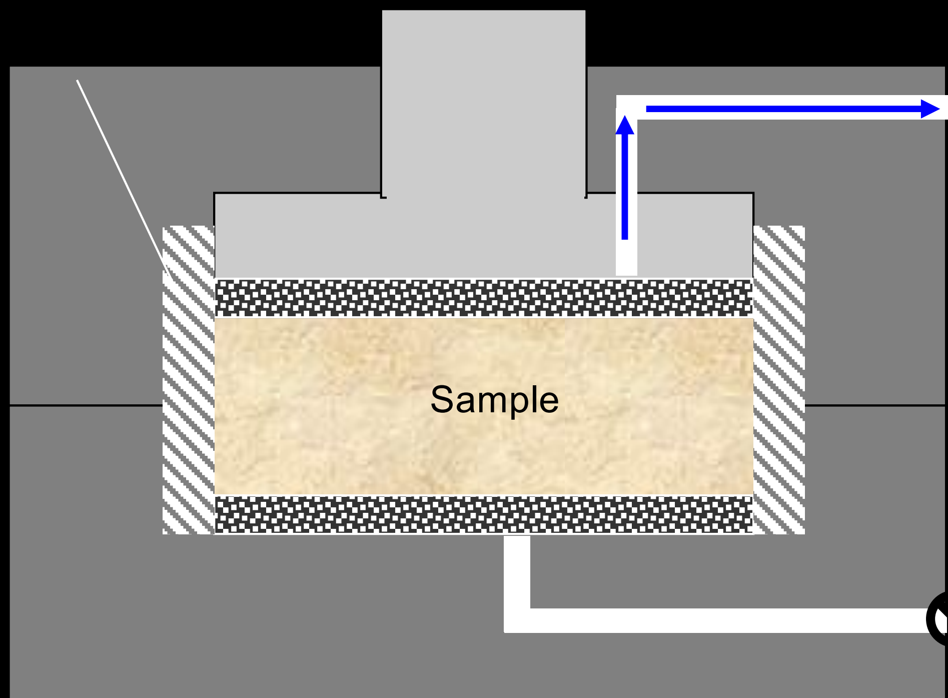
$$K < K_c = \frac{\sigma_n'(b - a)}{D_c}$$



Interrogating samples about in situ stress: Uniaxial Consolidation

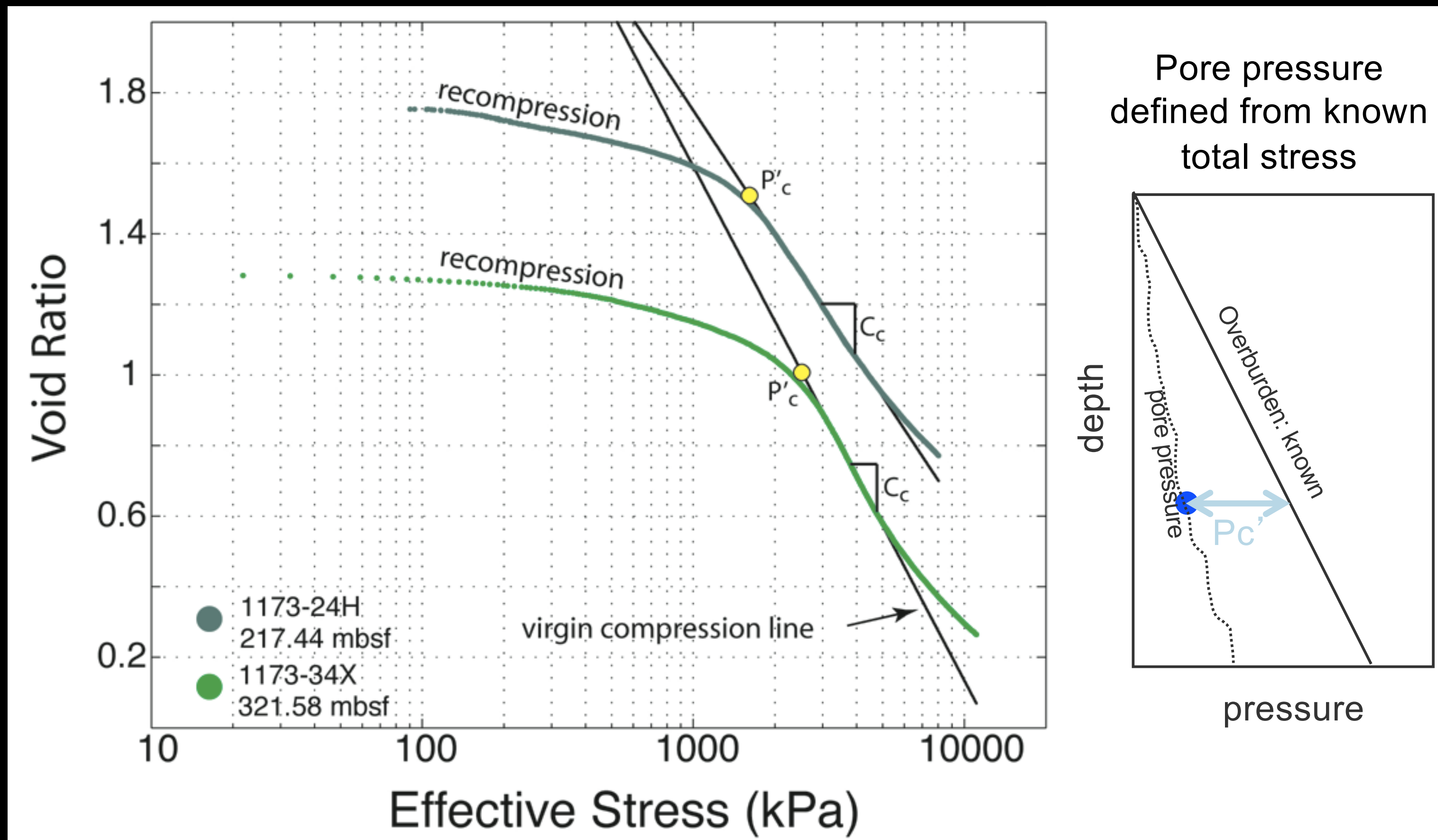


Interrogating samples about in situ stress: Uniaxial Consolidation



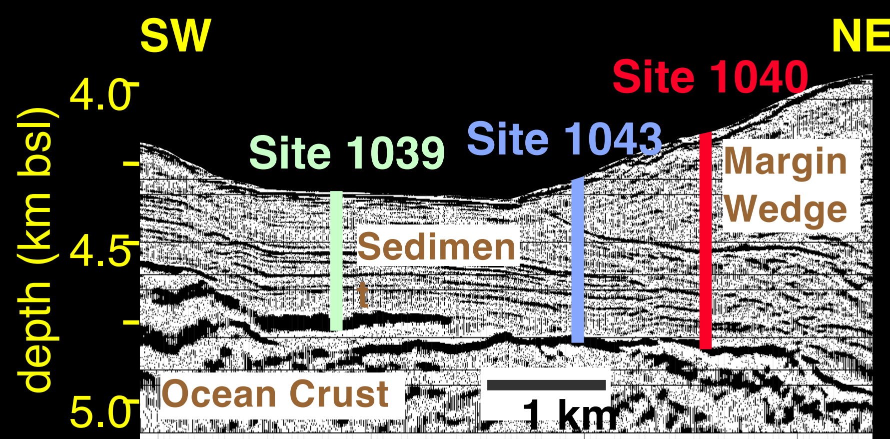
Example Consolidation Result

- Pc' encodes "memory" of in situ vertical effective stress.
- Cc (slope) defines constitutive behavior – mapping porosity to vertical effective stress.

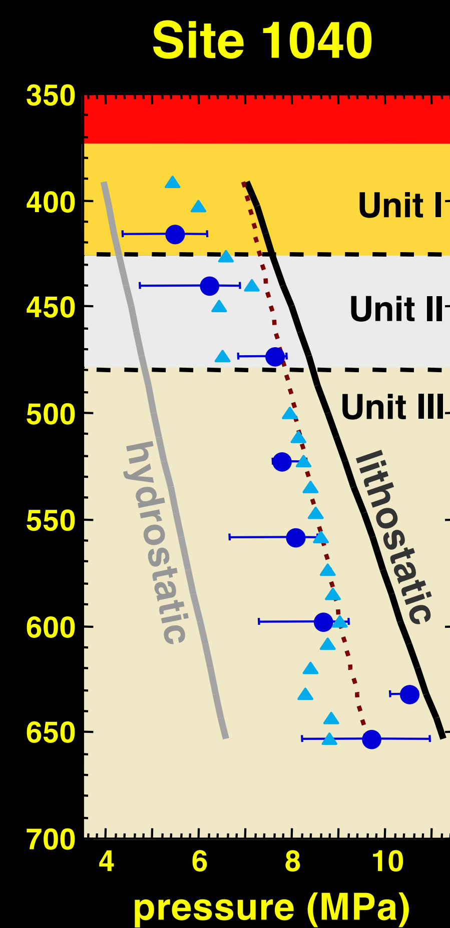


Costa Rican Margin: Multi-pronged pressure prediction

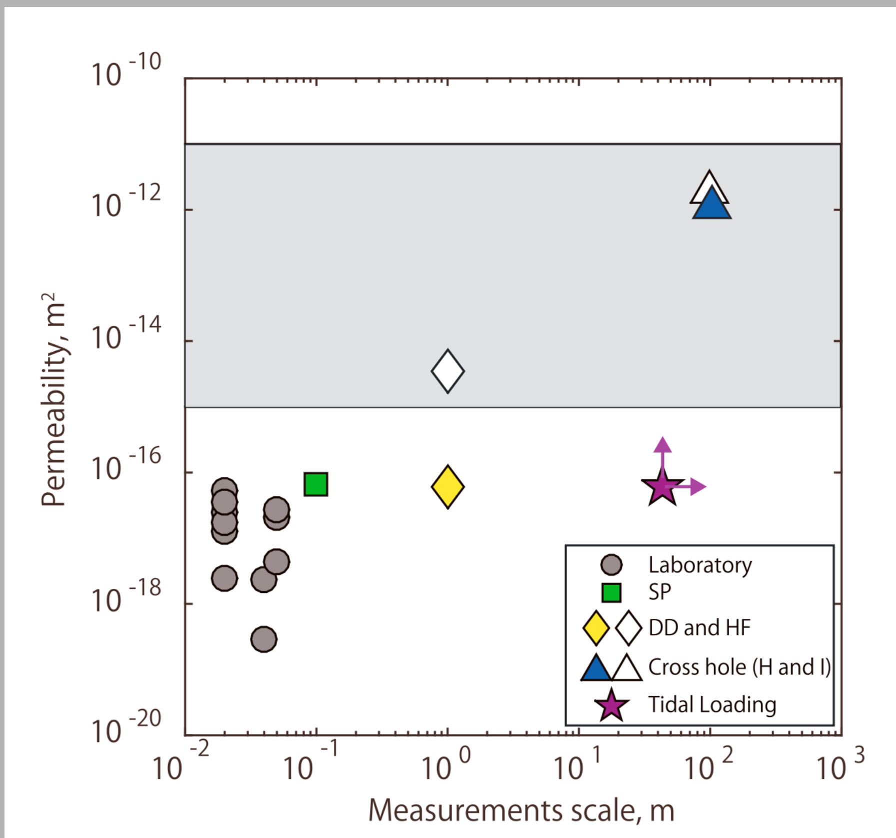
- Partly drained behavior: ~50% drained at top, undrained at base. Suggest upward drainage to permeable plate boundary fault.
- Drainage-induced downward migration of mechanically weakest horizon → *downstepping*.
- Pressures from Pc' and those from lab-derived Cc are in close agreement.



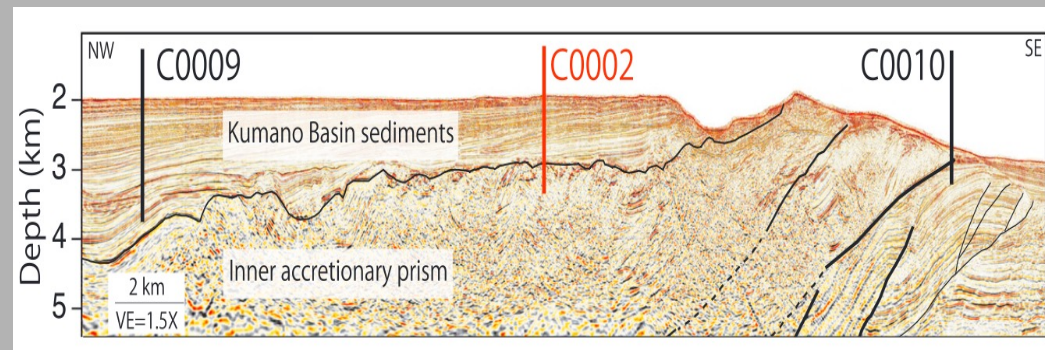
Saffer, 2003



Scale-Dependent permeability in the Nankai Accretionary Wedge

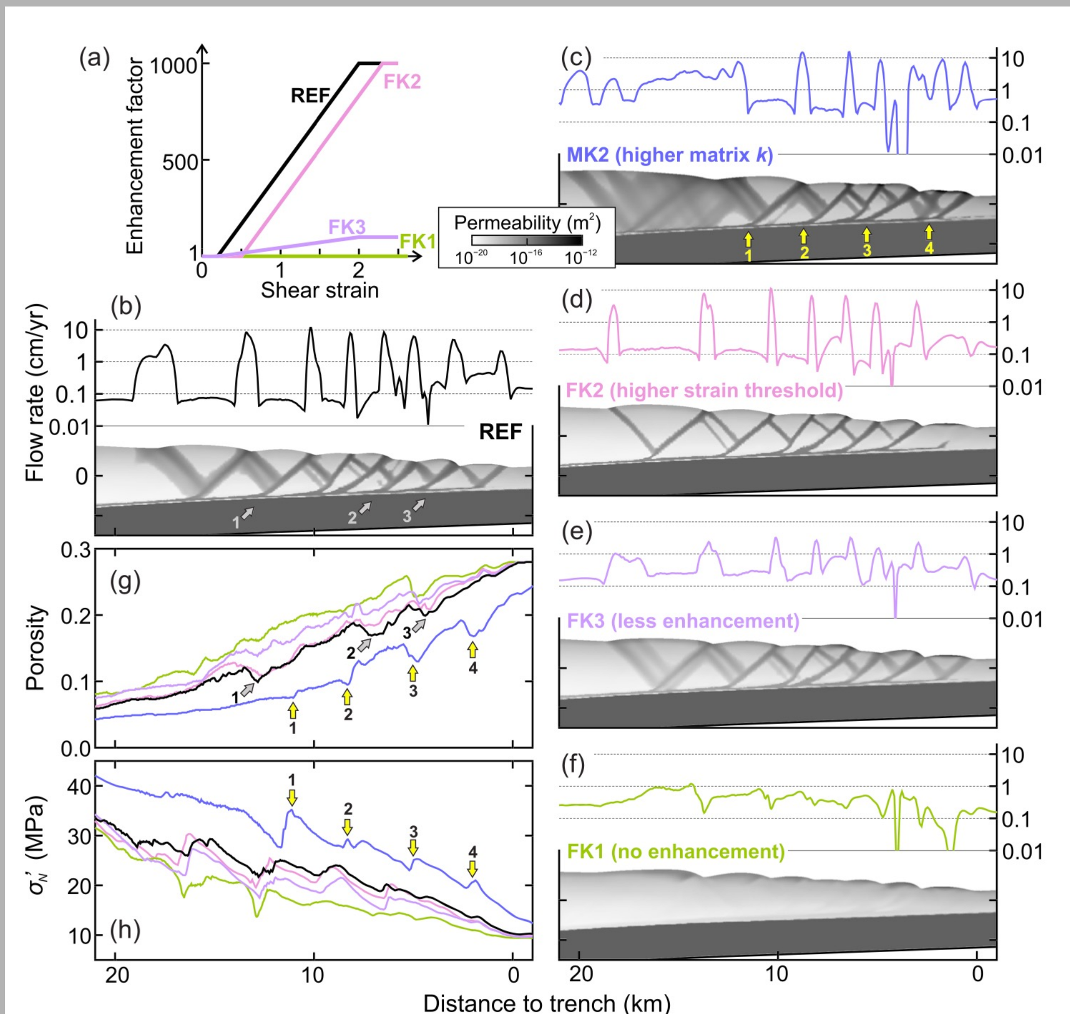


Kinoshita & Saffer (2018)



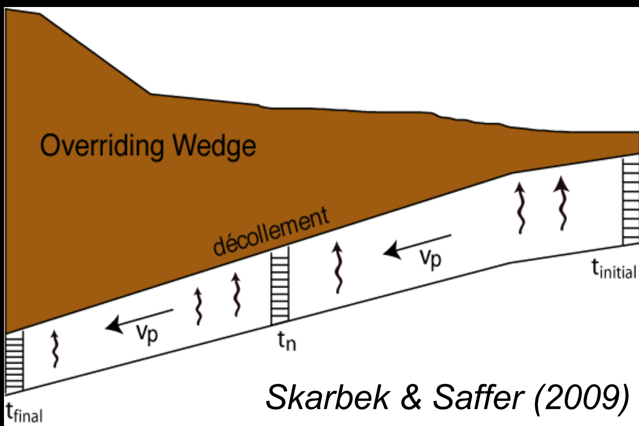
- Strong scale-dependence of permeability in the inner accretionary prism offshore Kii Peninsula – determined from inadvertent cross-hole "experiments".
- Consistent with sampling of permeable fractures and faults at scales of ~100 m.
- Values of k = ~10^{-14} – 10^{-12} m^2 are commonly reported across many studies.

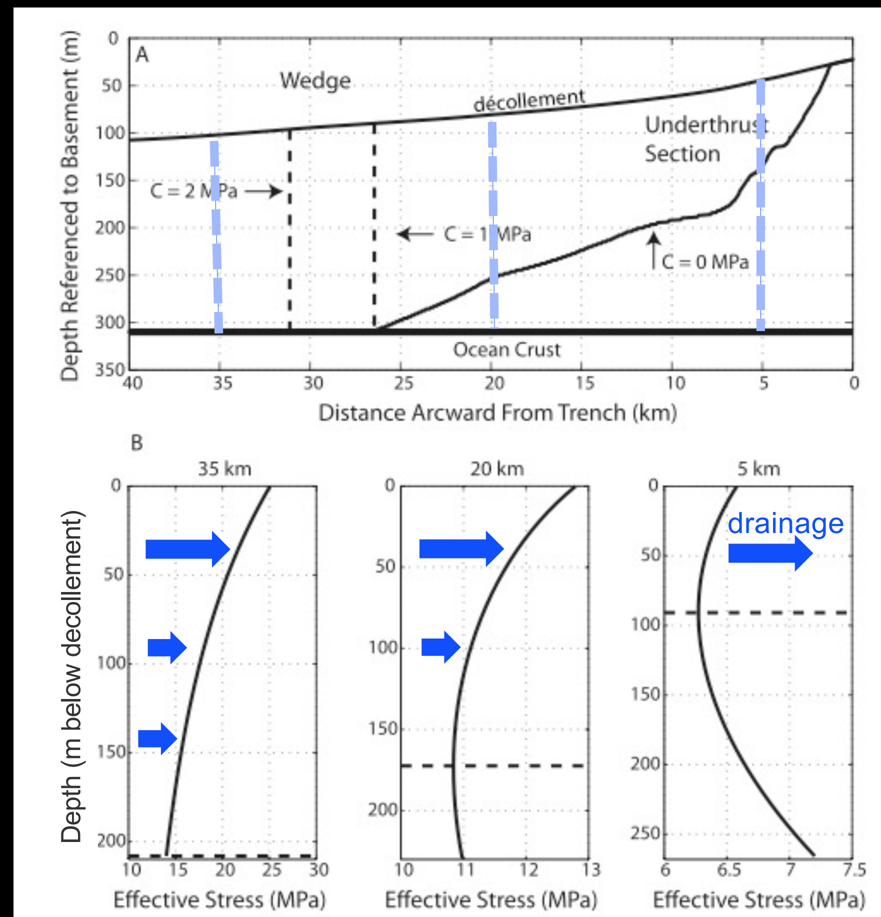
Mechanical Effects of permeable faults



- Upper plate faults likely to affect the plate interface – drainage at their roots leads to heterogeneity, increased effective stress locally, potentially onset or localization of seismicity.
- Drainage may also mediate downstepping and fault initiation in a complex feedback.

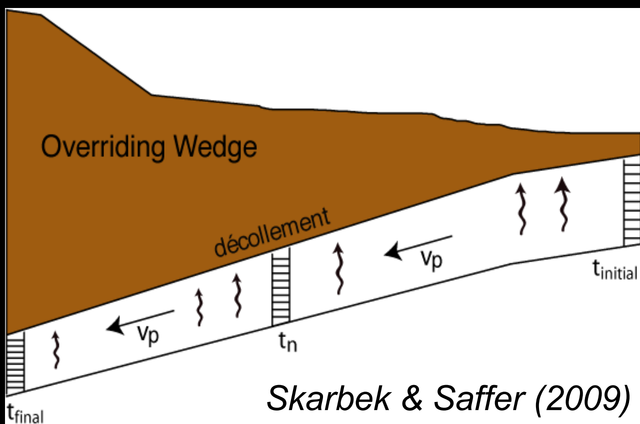
1-D coupled models of pore pressure evolution & fault downstepping: Nankai Margin

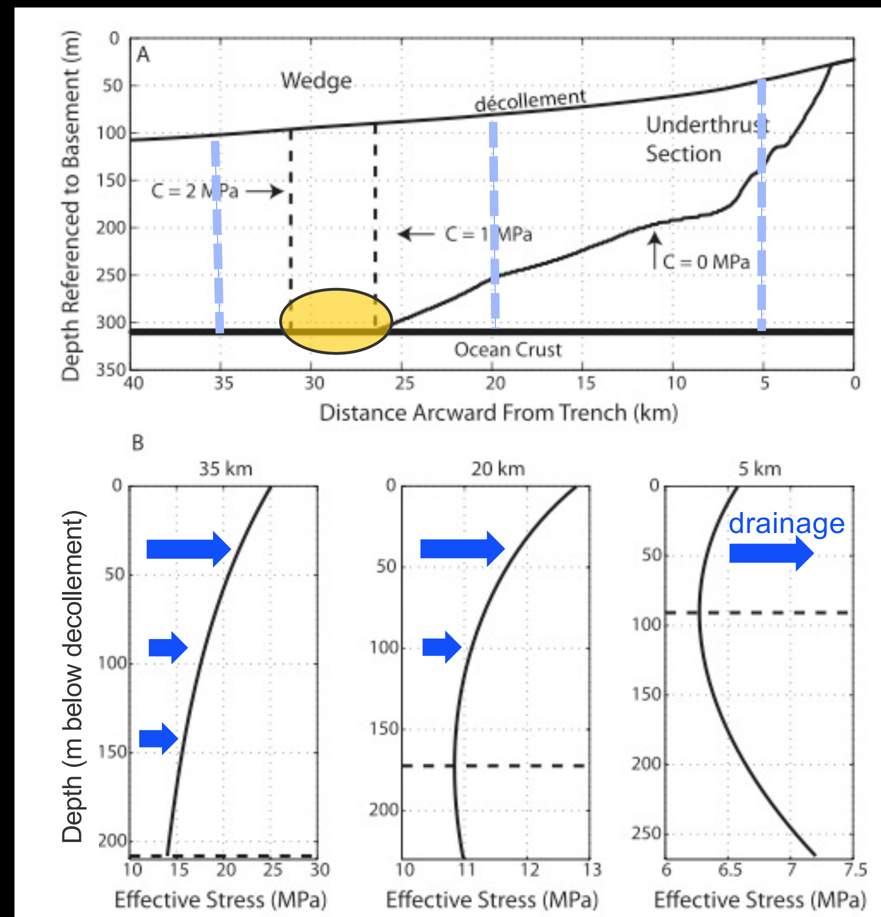




- Coupled model of loading, compaction,& flow parameterized by lab permeability and consolidation data, and constrained by depth-averaged pressure estimates.
- Predicts downward migration of weakest horizon due to drainage.

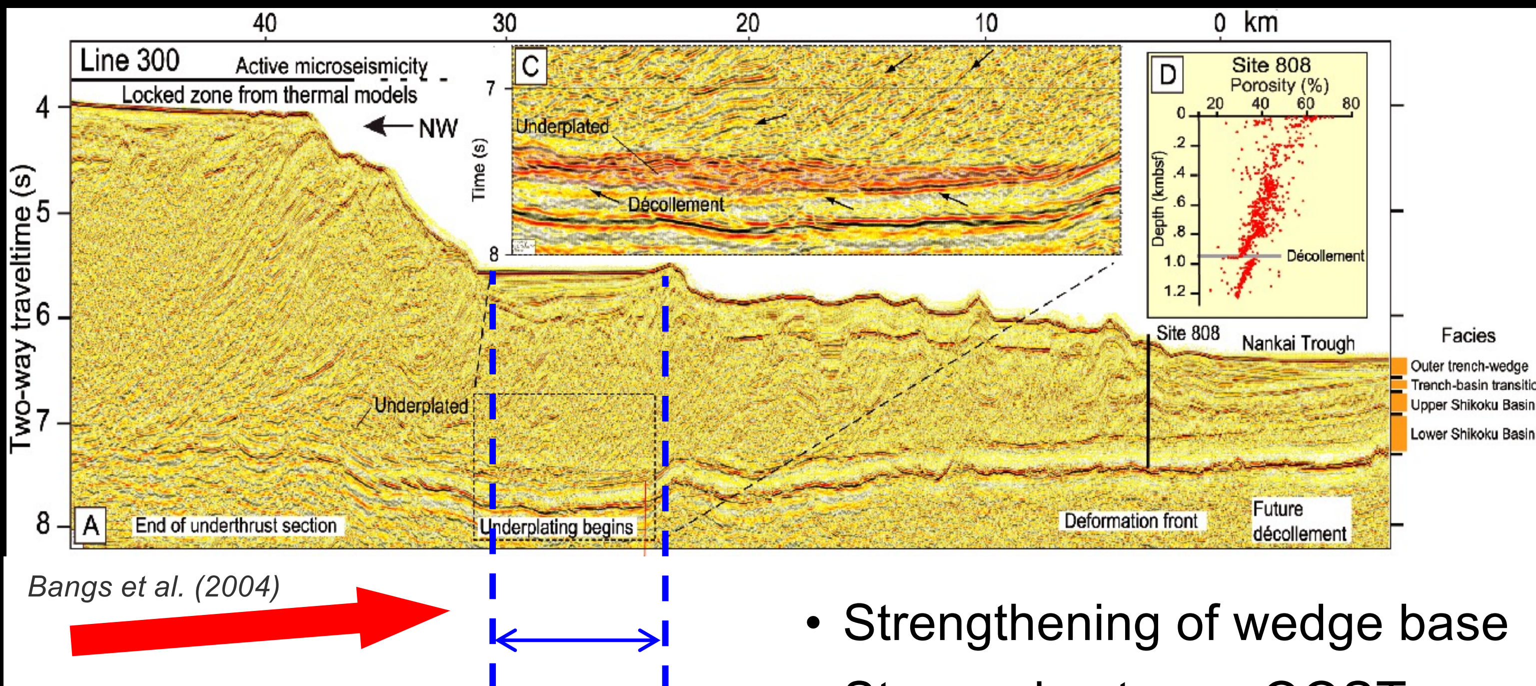
1-D coupled models of pore pressure evolution & fault downstepping: Nankai Margin





- Coupled model of loading, compaction,& flow parameterized by lab permeability and consolidation data, and constrained by depth-averaged pressure estimates.
- Predicts downward migration of weakest horizon due to drainage.

Fault behavior: Downstepping and change in reflection amplitude at ~30 km



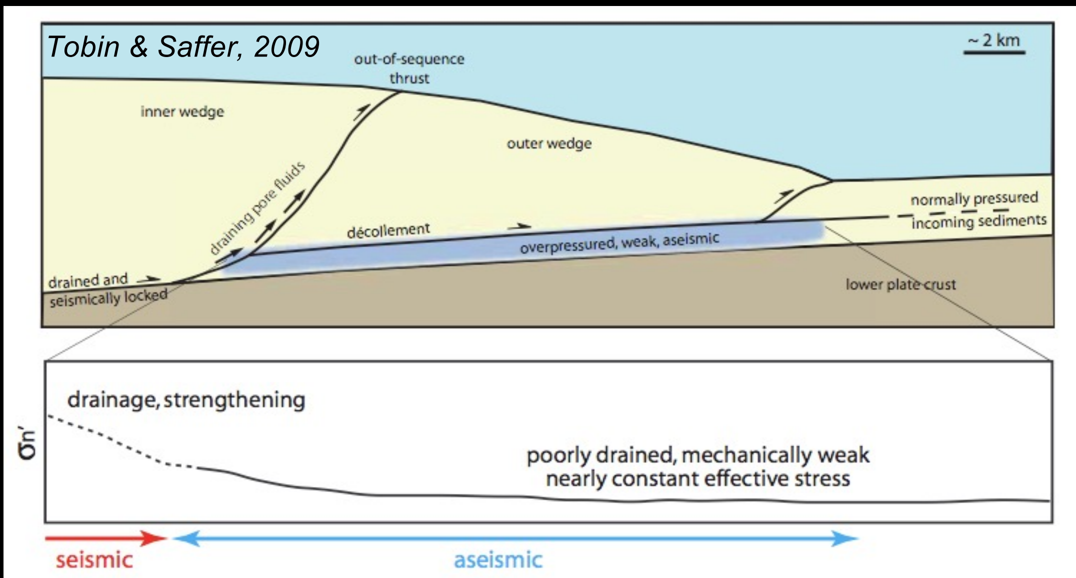
Bangs et al. (2004)

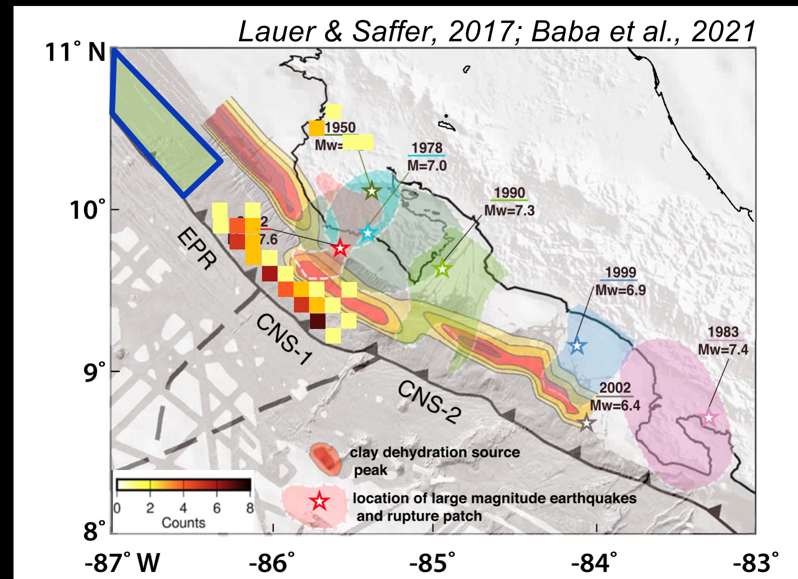
Extent of 1946 rupture

Modeled strengthening & Downstepping
[*Skarbek & Saffer, 2009*]

- Strengthening of wedge base
- Steepening taper; OOST formation landward
- Positive feedback – drainage path length

A weak and overpressured offshore megathrust





- Highly elevated pore pressure (>70% of lithostatic) & low stress are common in the outer forearc. Modulated by dynamic balance between rates of loading & diffusion.
- Poor drainage persists to 10's of km from trench - *Maria's talk tomorrow*
- Quantifiable mechanism to explain weak subduction megathrusts. Potential relationship to shallow SSE and aseismic slip; *down-dip transition to frictional instability.*
- Yet, could promote rupture propagation to the trench.