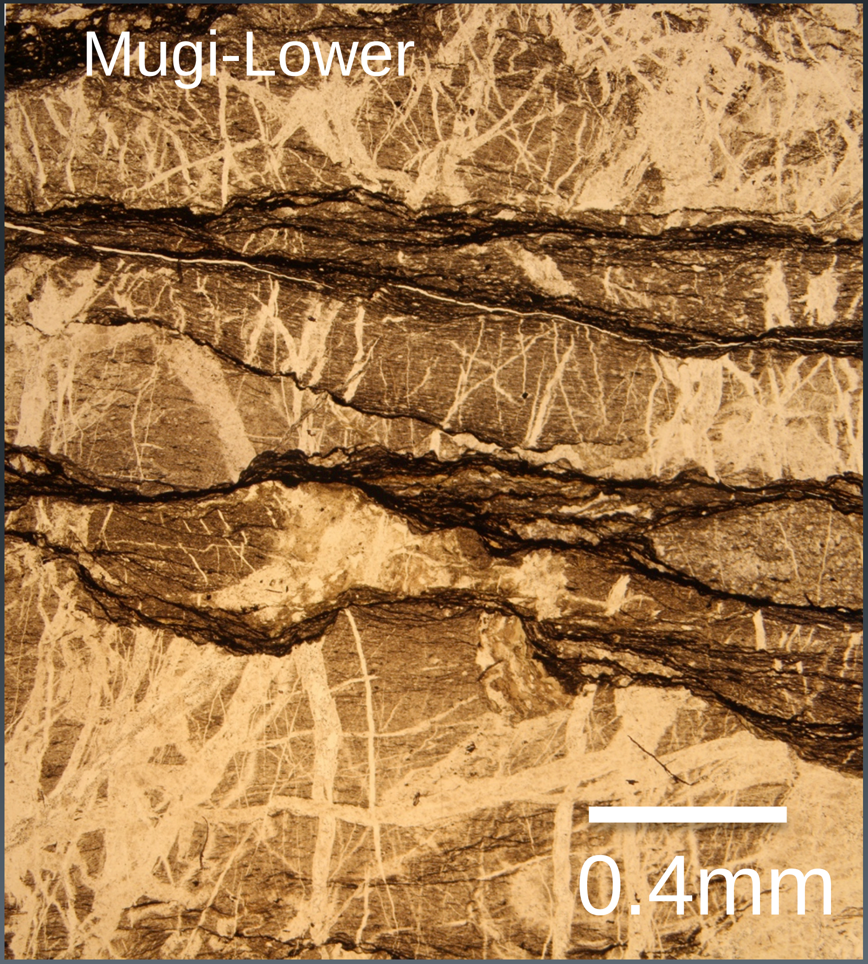
National Science Foundation
WHERE DISCOVERIES BEGIN

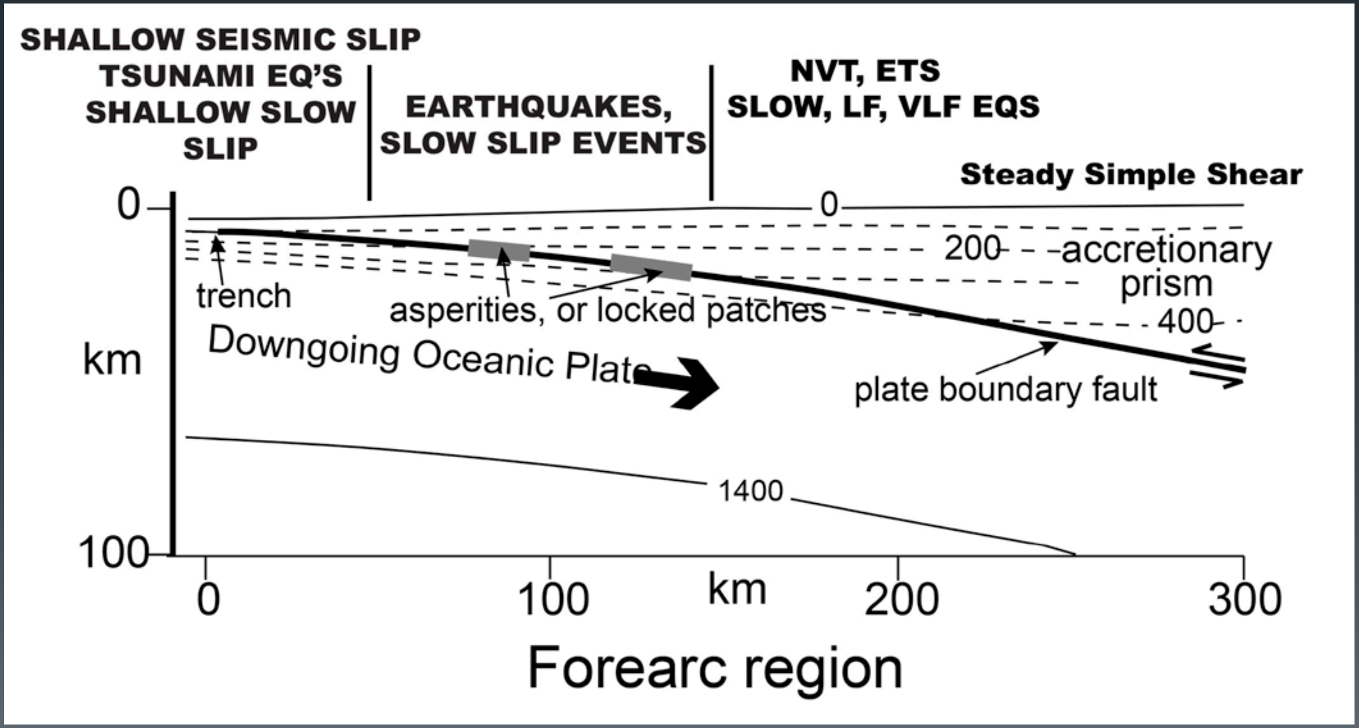
Kinetic, Mechanical, and Fluid Flow Models for the Behavior of the Subduction Interface based on Field Observations



Donald M. Fisher, Andrew Smye, John Hooker, Chris Marone
Penn State University
Asuka Yamaguchi
University of Tokyo
Peter van Keken
Carnegie

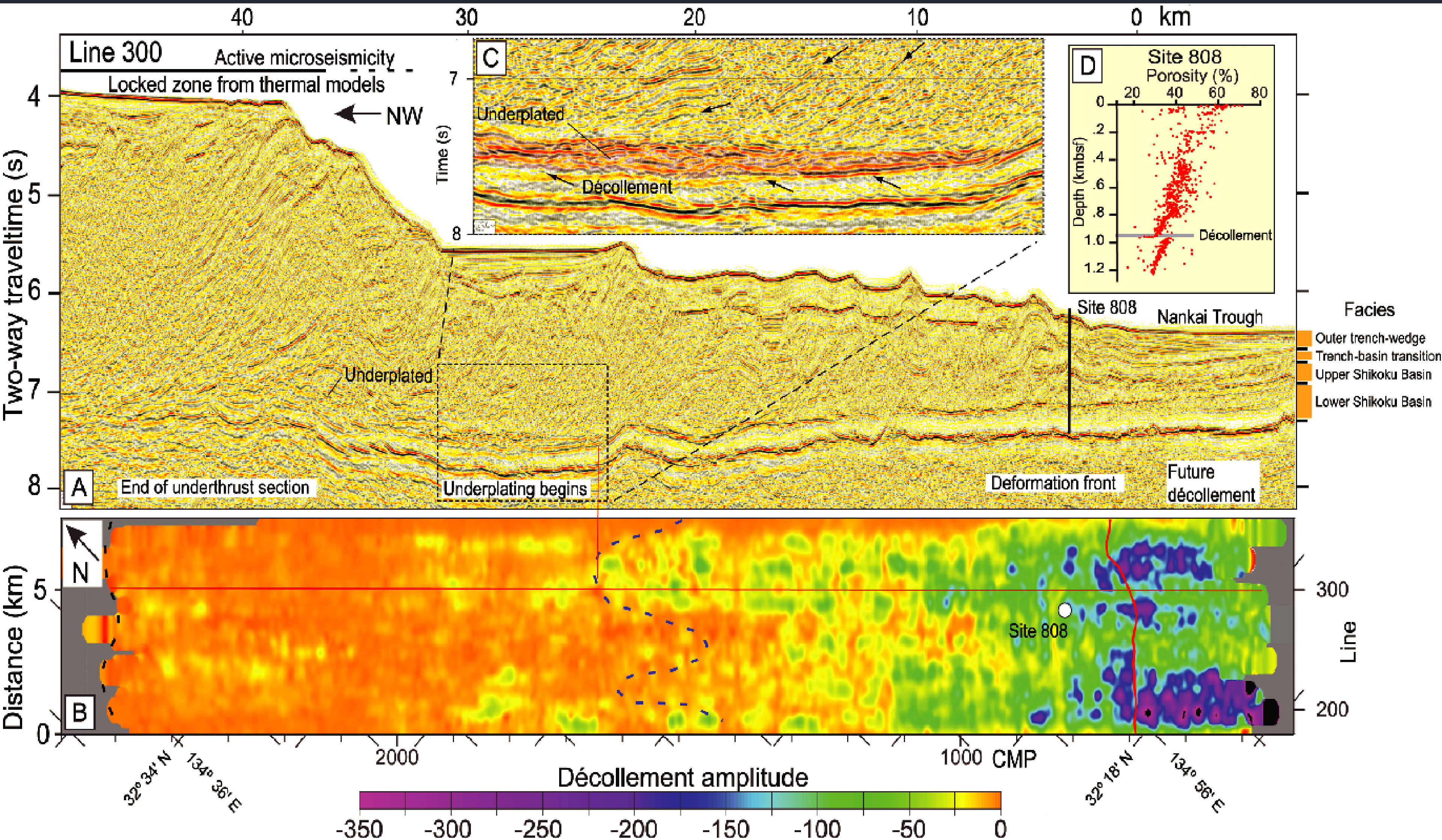
Role of Geochemistry (P-T) on slip behavior

- Subduction zones show a range of slip behavior as a function of depth and for convergent margins with different thermal structure
- In this talk, we investigate the role of geochemical processes of healing on subduction zone slip behavior (updip end of the seismogenic zone, size distributions of earthquakes)



Outline

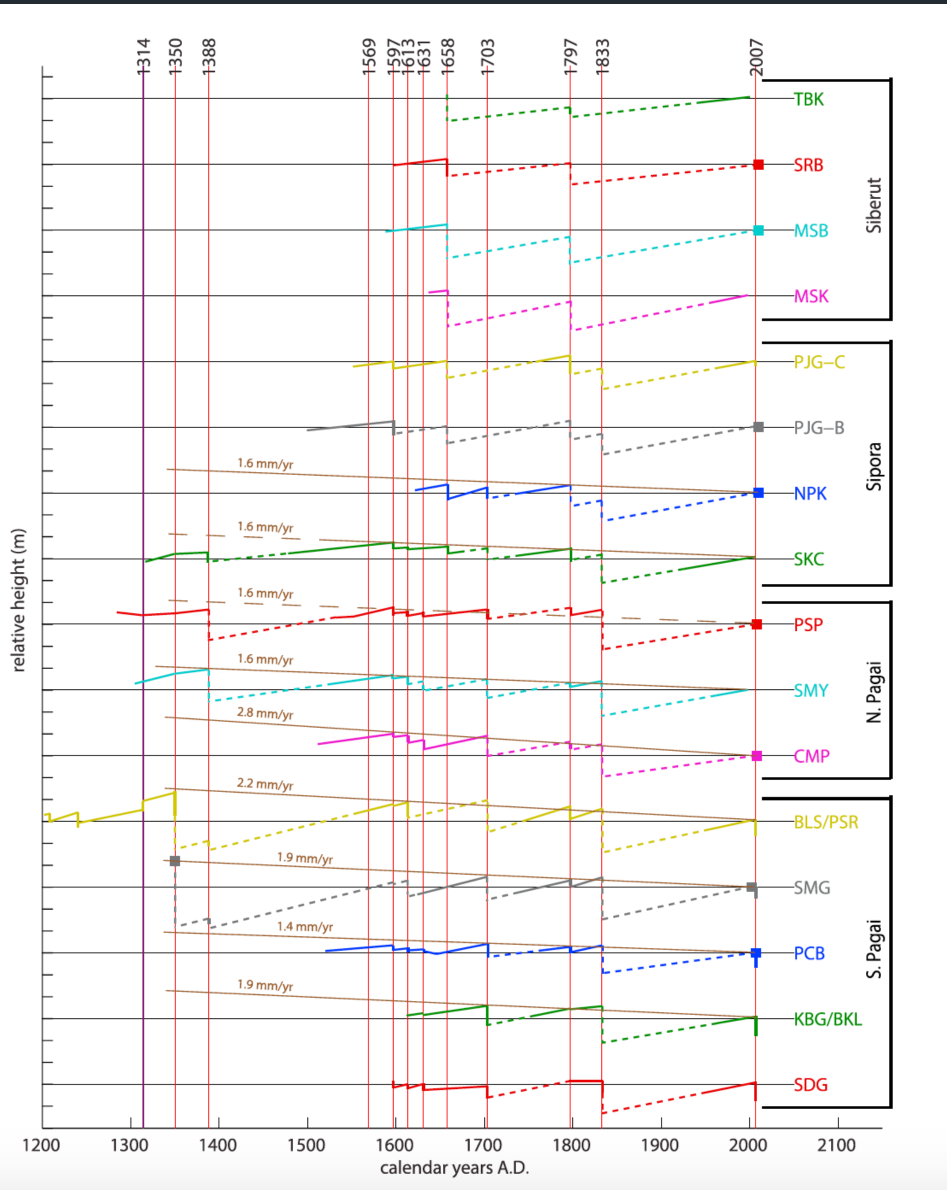
- Subduction zone dynamics and Frictional mechanics-theory and experiment
- Observations of ancient fault zones-Silica Kinetics Model
- Population balance algorithm and numerical mechanical model for interface
- Size distributions of earthquakes in natural systems
- Fluid production and fluid flow



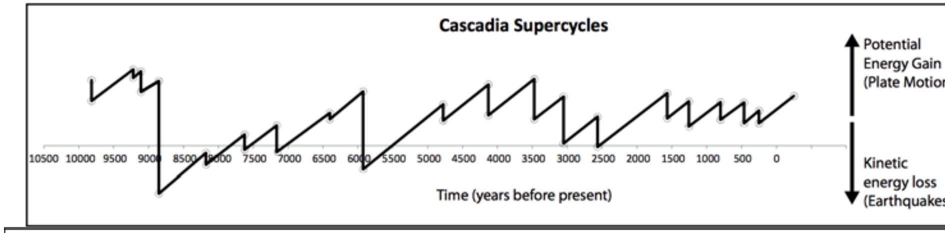
Bangs et al. (2004)

EQ clustering and Supercycles

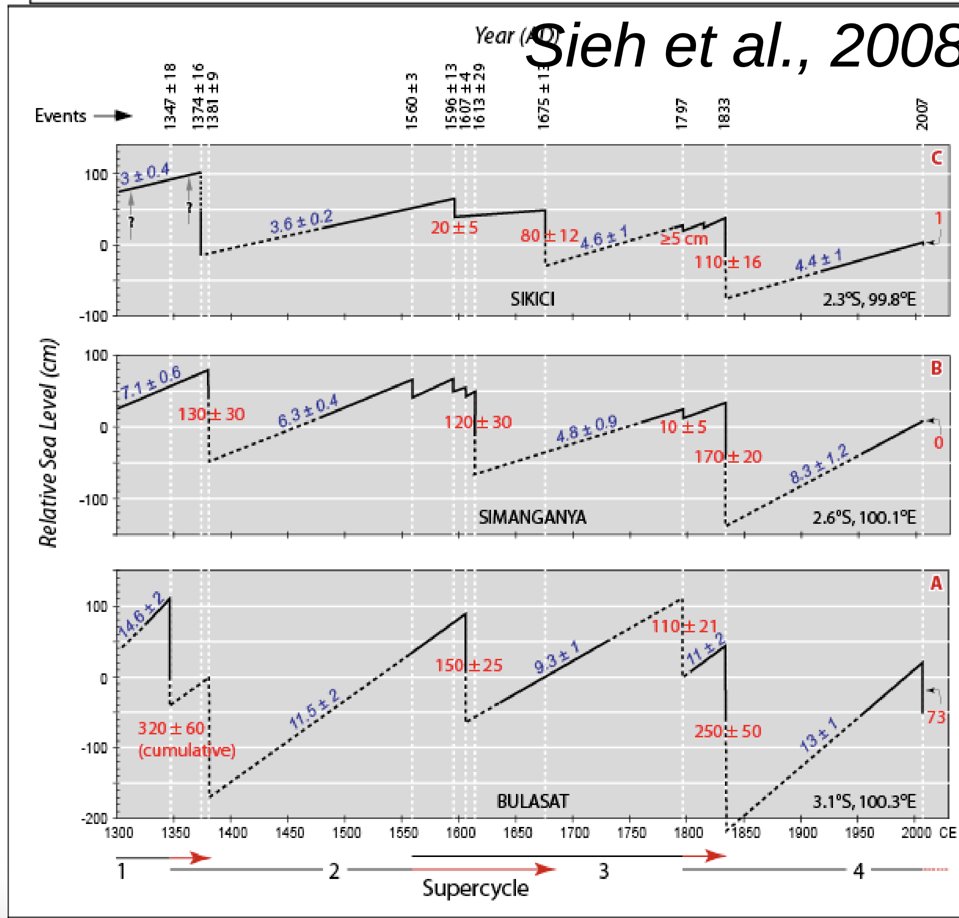
Philibosian et al., 2017

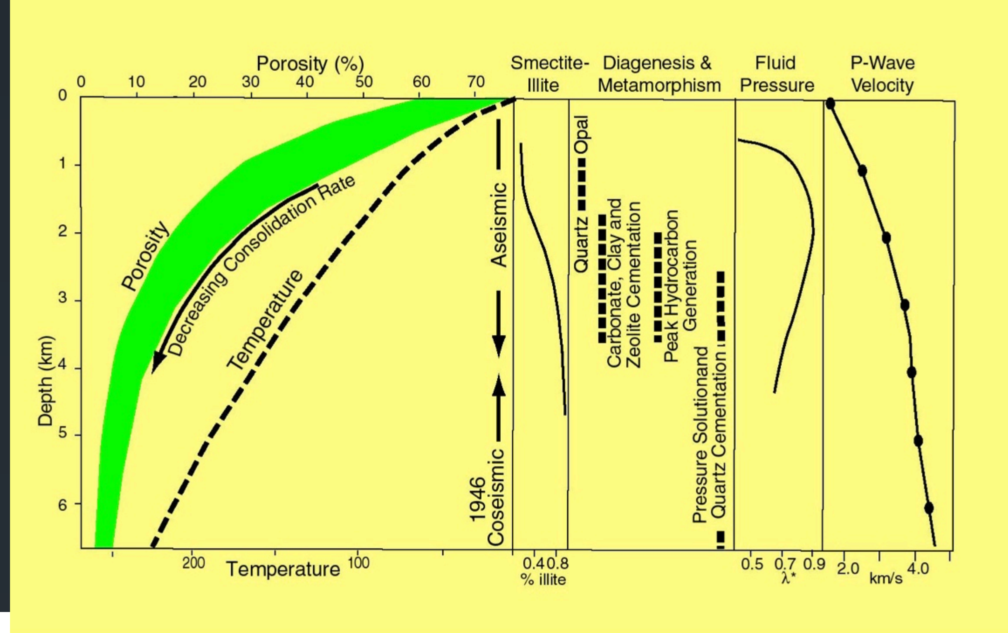


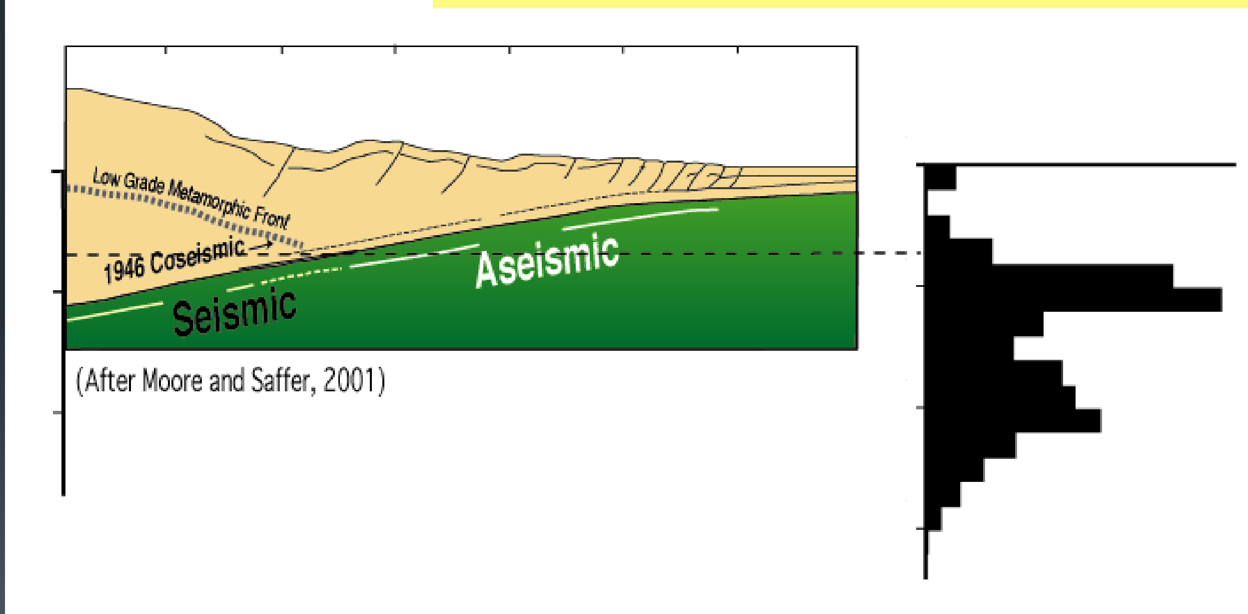
Goldfinger et al. 2013



Sieh et al., 2008







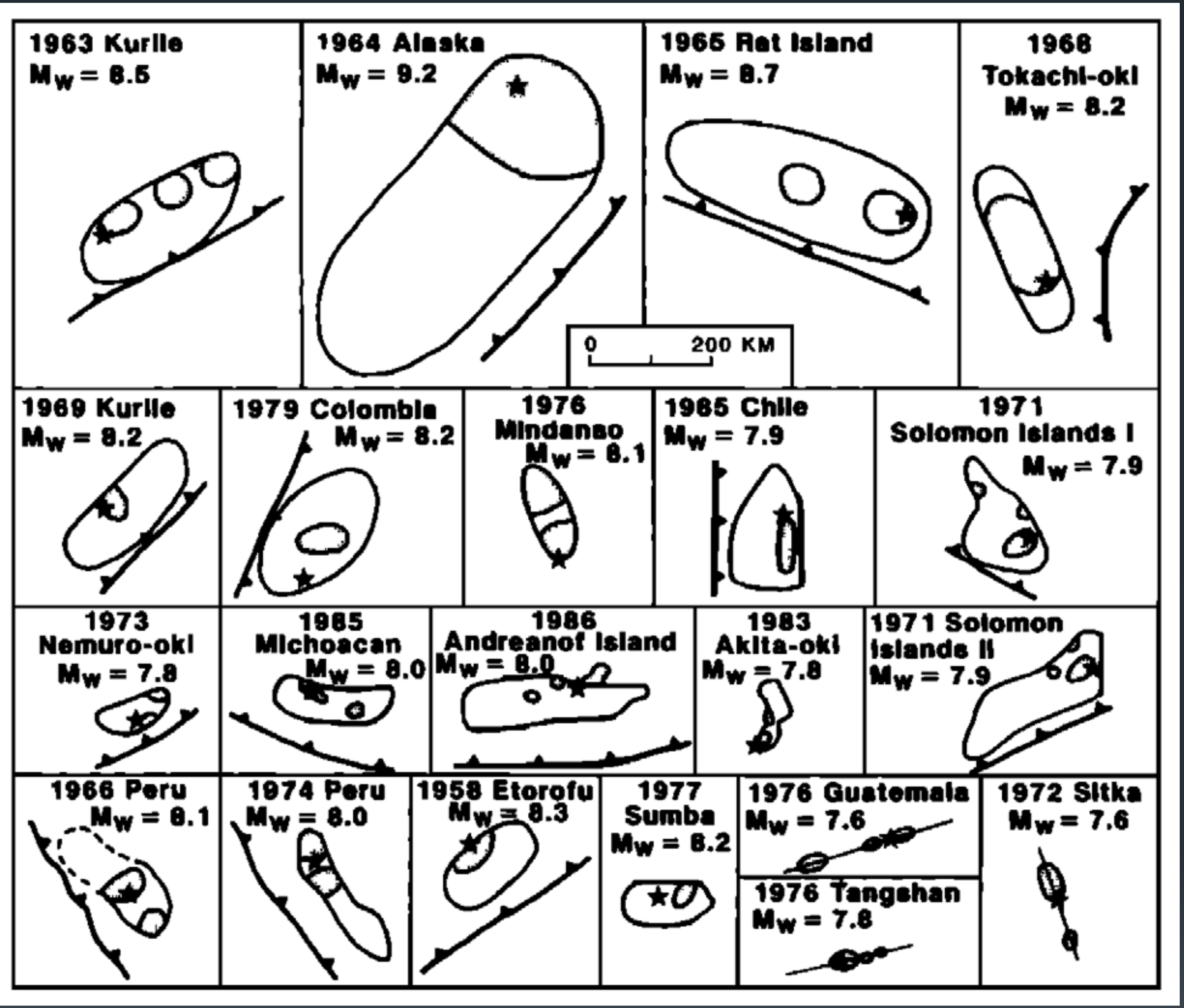
aseismic

seismogenic zone

aseismic

The Seismogenic Zone

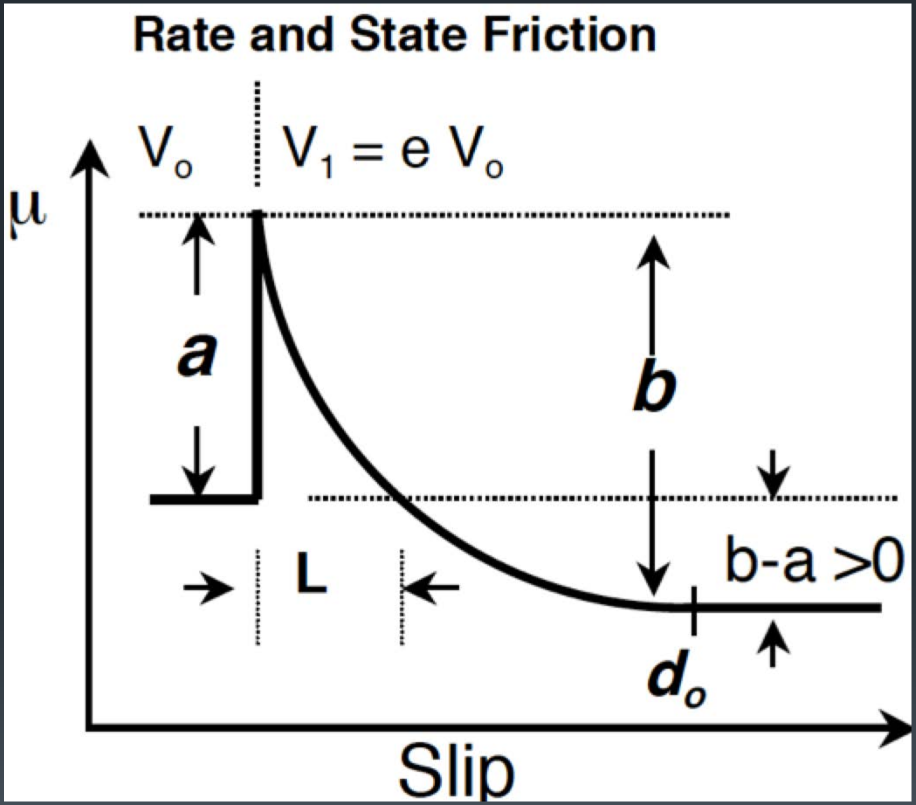
Moore and Saffer (2001)

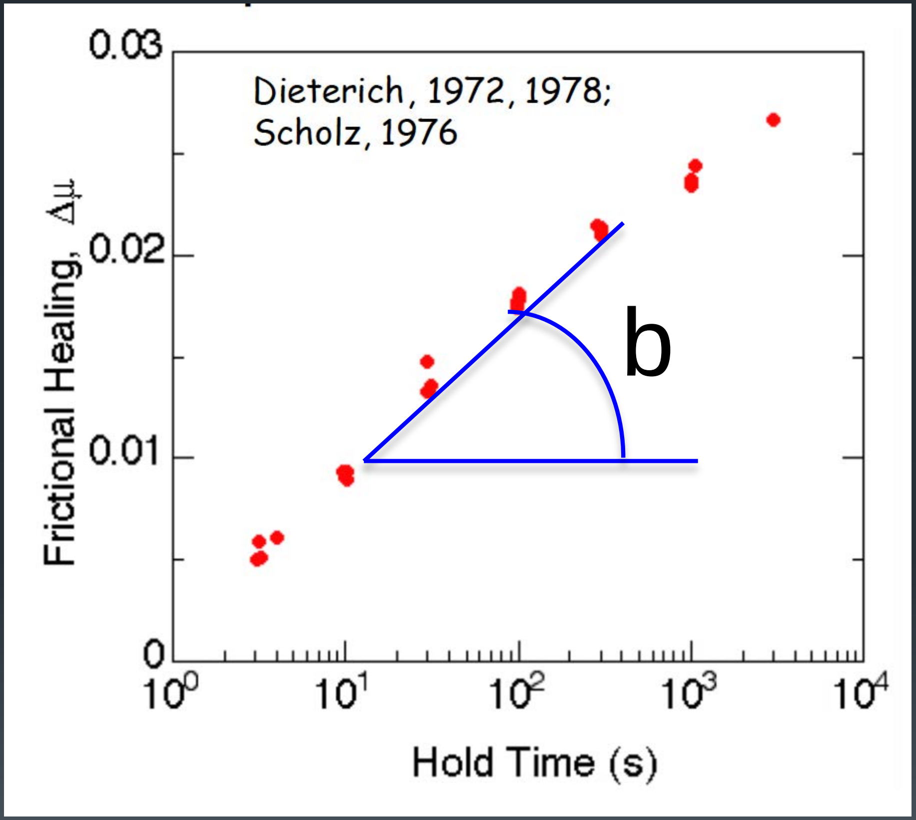


Asperity Paradigm

Thatcher, 1990

Velocity Dependence and Healing





Marone et al., 2006

Rate state friction mechanics:

$$K_c = \frac{\overline{\sigma}_n * (b - a)}{L}$$

Rice and Ruina., 1983

- Stable Slip- $K > K_c$ Creep
- Unstable Slip- $K < K_c$ EQ's
- Slow EQs-Instabilities that stabilize

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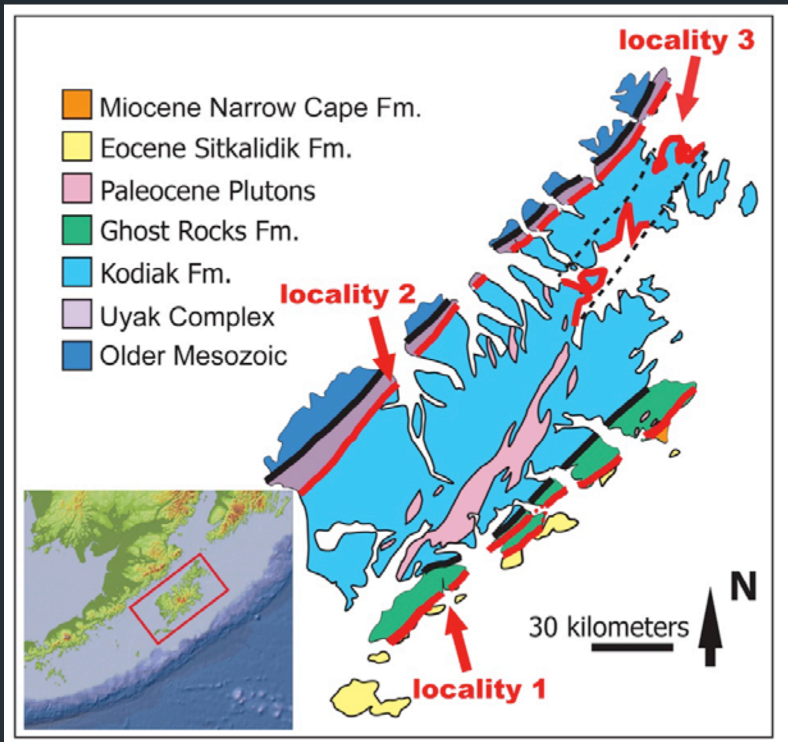
A different view of “asperities”

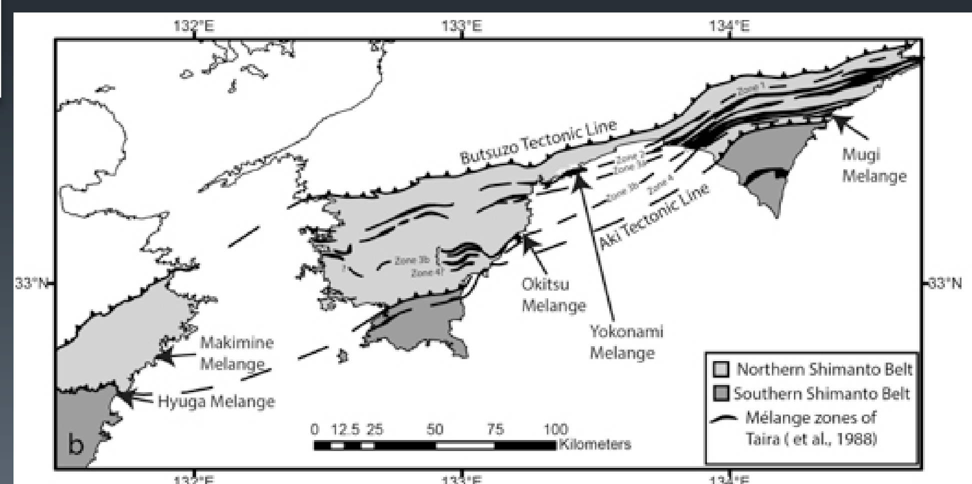
- Patches of the interface heal in response to mineral redistribution as a stochastic process that reflects roughness in the composition of underthrusting materials.
- Healing during the interseismic period occurs at rates determined by mineral kinetics.
- Hotter margins are greater coupled than cold margins
- “Asperity” formation is fundamentally a geochemical process.

Kodiak Accretionary Complex



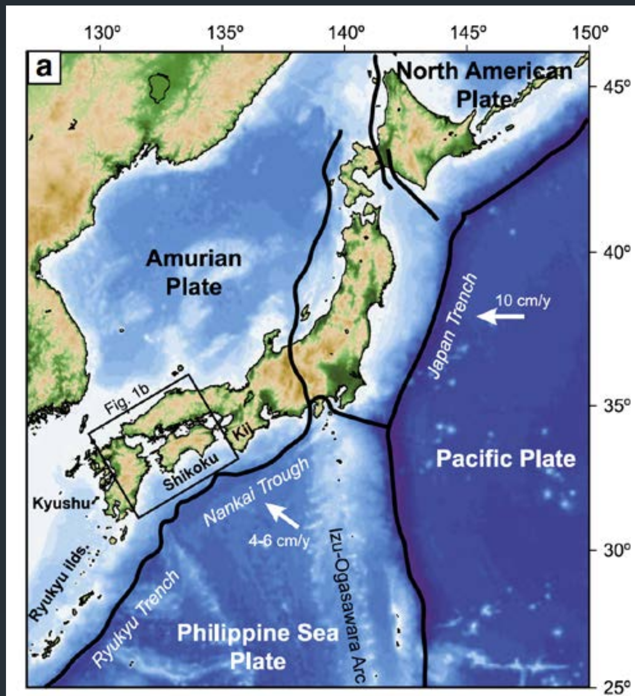
- Subduction since the Jurassic
- One ridge-trench encounter
- Accreted oceanic lithologies
- Northwest to southeast, oldest to youngest
- Boundaries are northwest dipping thrusts

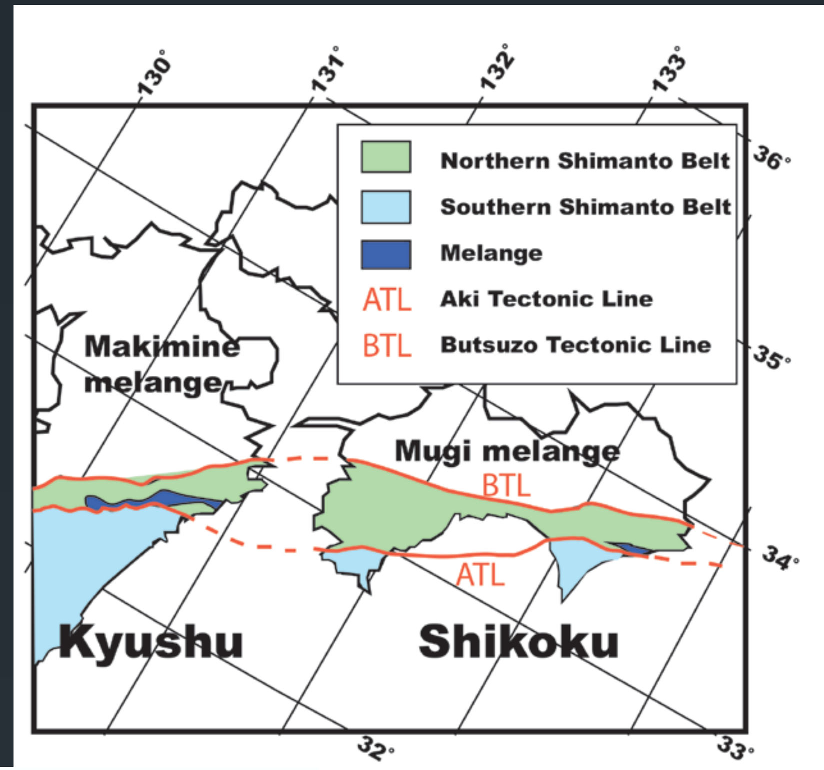
Lower Shimanto Belt



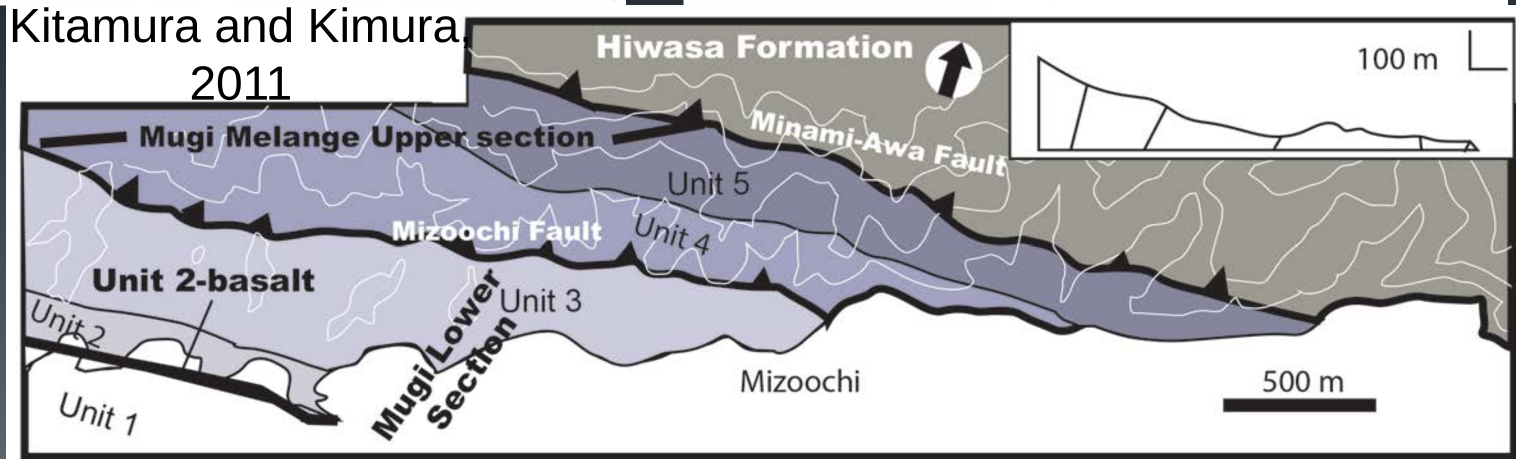
- Accreted oceanic lithologies
- Northwest to southeast, oldest to youngest
- Conditions of faulting span the T's of the seismogenic zone

Melanges of the Northern Shimanto Belt





Kitamura and Kimura, 2011



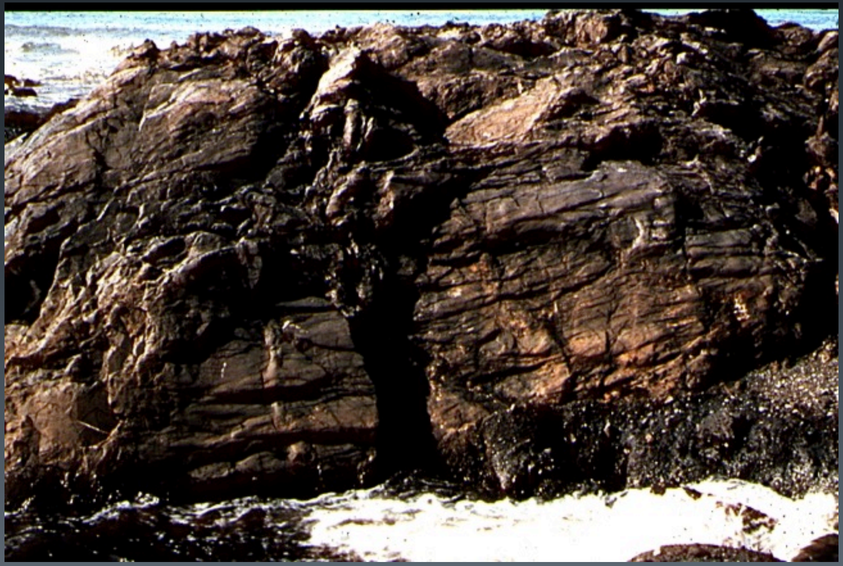
Mugi lower section

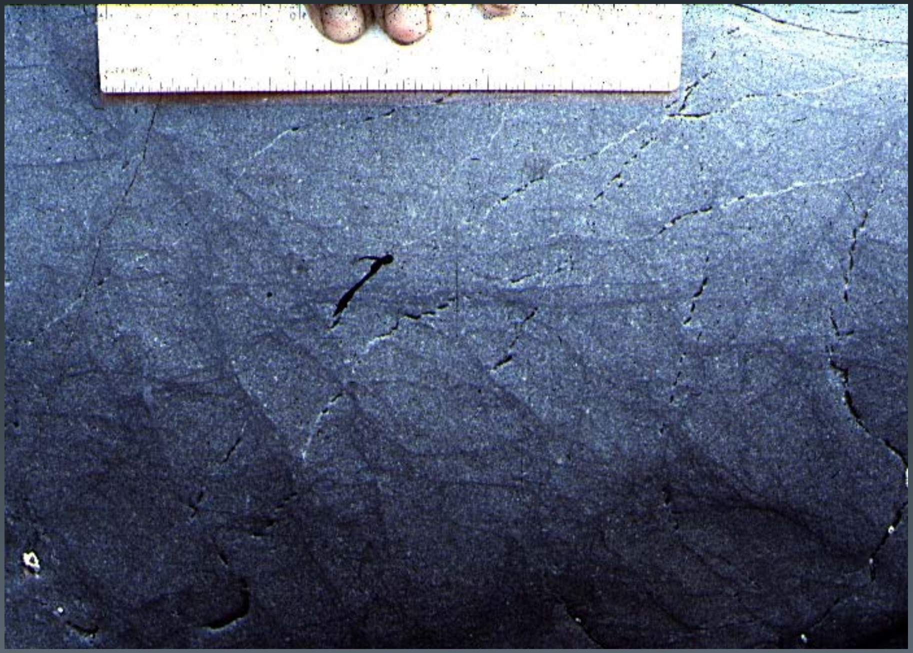
Mugi Upper Section

Makimine melange

Ghost Rocks Melange

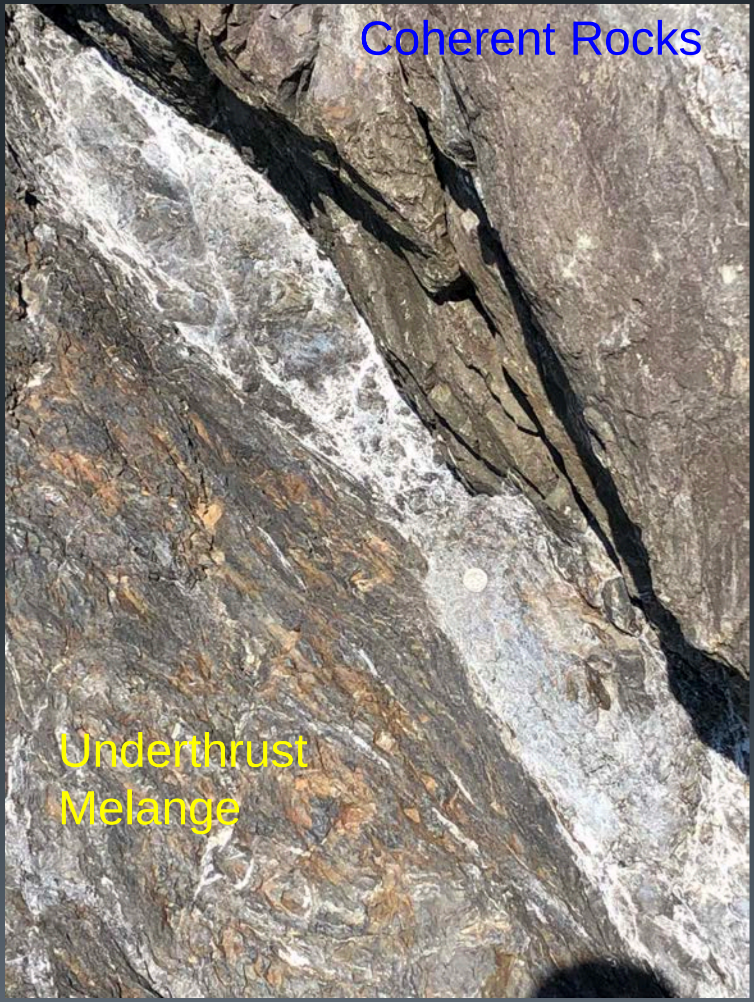
Fisher and Byrne, 1987





Rowe et al. 2011

Variable behavior along the subduction interface



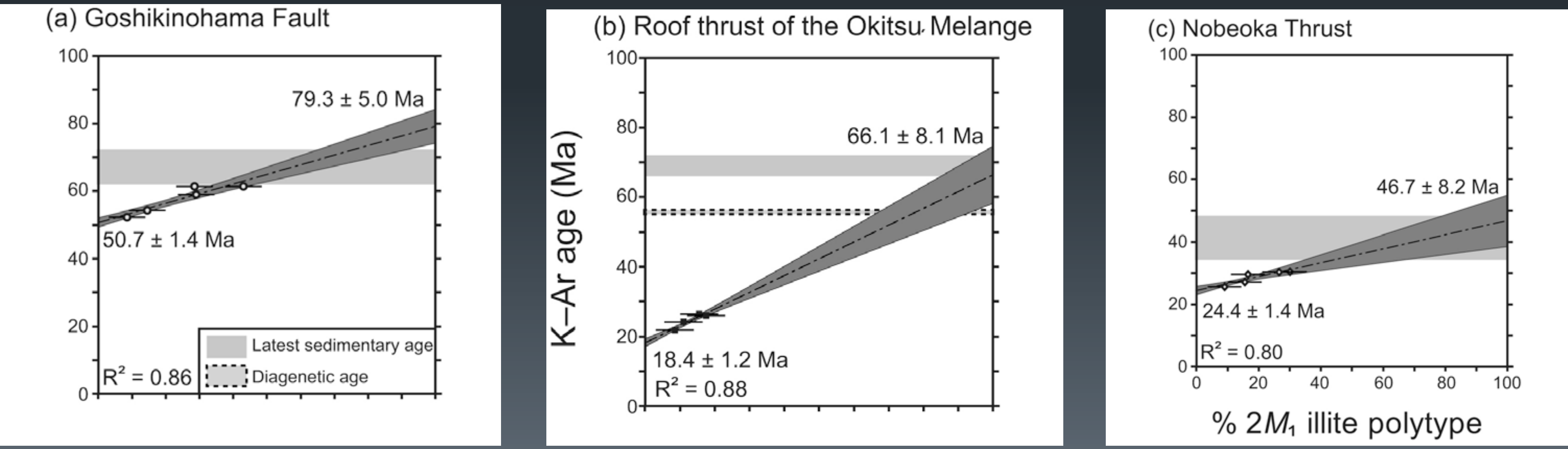
Pseudotachylite

Ikesawa et al., 2003
Rowe et al., 2005
Ujiie et al., 2007

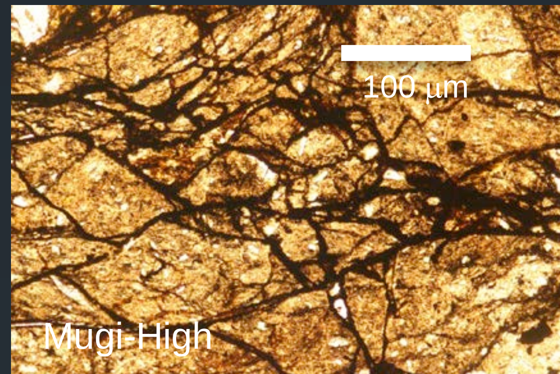
- Slow strain rates- Wide fault zone (10's-100s of m) of melange dominated by cracking, distributed simple shear on scaly slip surfaces, mineral redistribution. Linear Viscous Flow-Low effective stress
- Fast strain rates-Narrow (1-15 m) of ultracataclasite along sharp faults, typically at the top of the melange zone. Pseudotachylite.

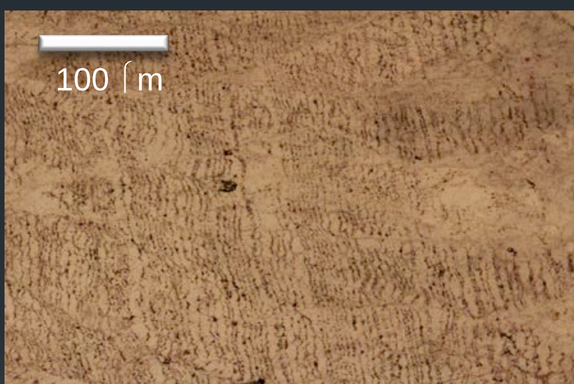
Fisher et al., in review

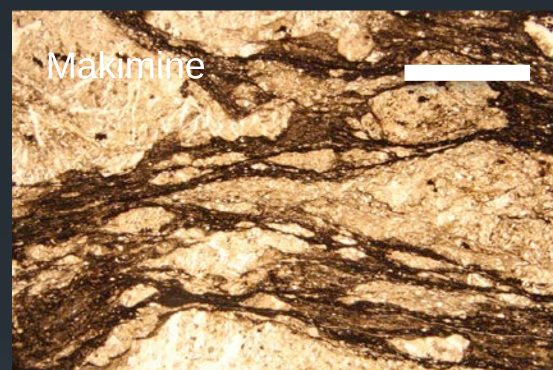
An aside: Are the narrow cataclastic fault zones with pseudotachylite related to reactivation in the prism, or to slip on the plate interface

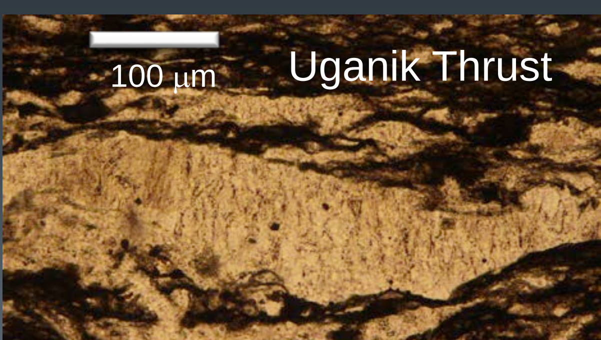


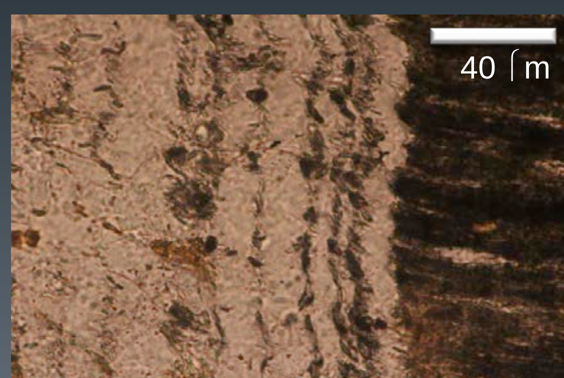
Veins and Scaly fabrics





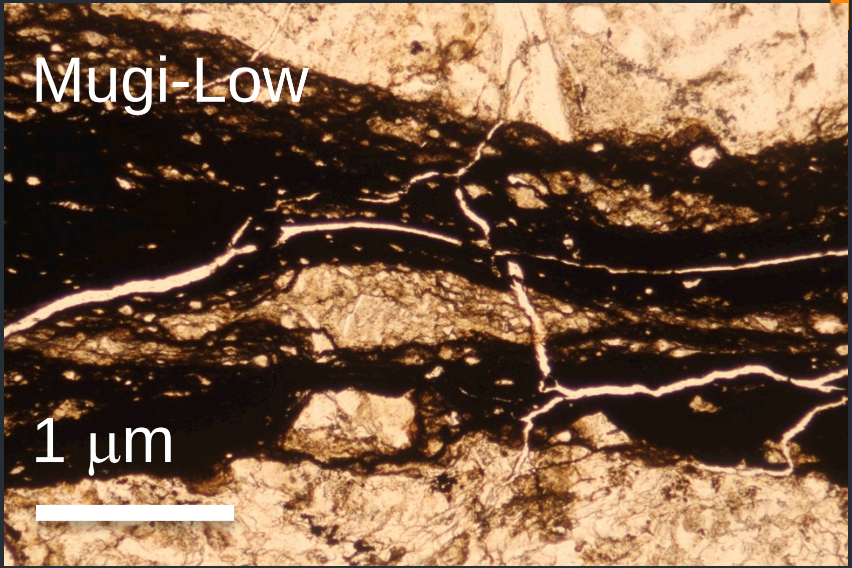


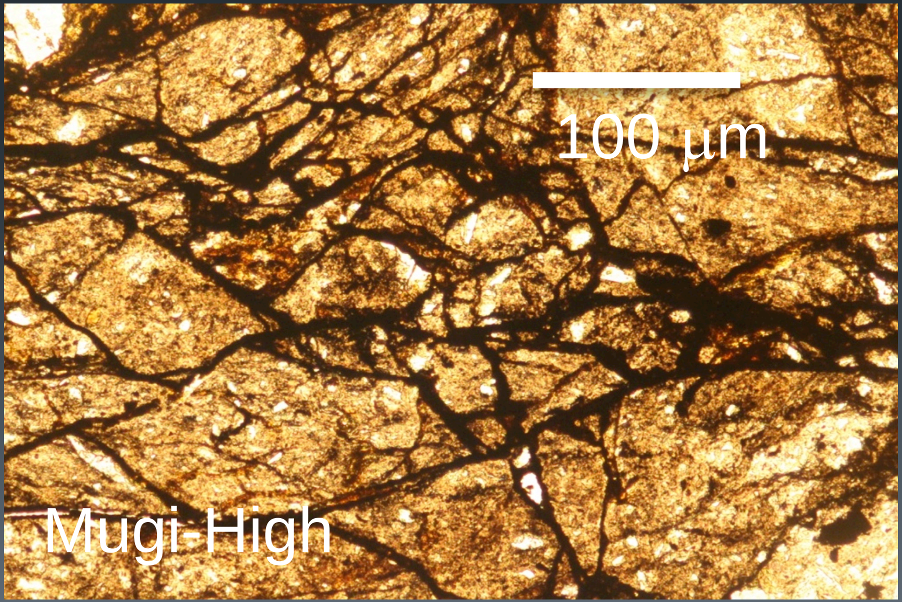


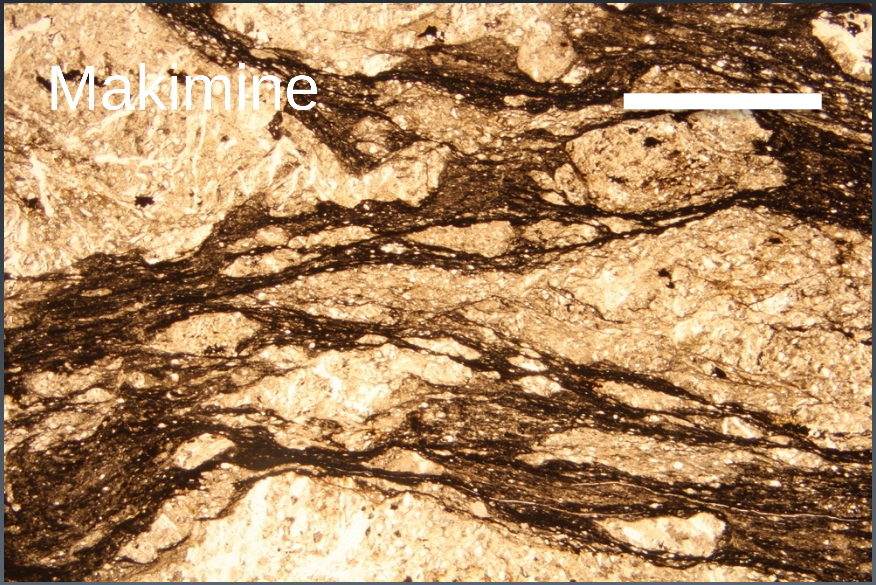


Byrne, 1984
Moore and Byrne, 1987
Fisher and Byrne, 1987
Vrolijk et al., 1988
Meneghini and Moore, 2007
Vannucchi et al., 2010
Kitamura and Kimura, 2011
Fagereng et al., 2011
Kimura et al., 2012
Yamaguchi et al., 2012
Hashimoto et al., 2012
Fisher and Brantley, 2014
Raimbourg et al., 2015
Vannucchi, 2018

Slip surfaces-Scaly Fabric

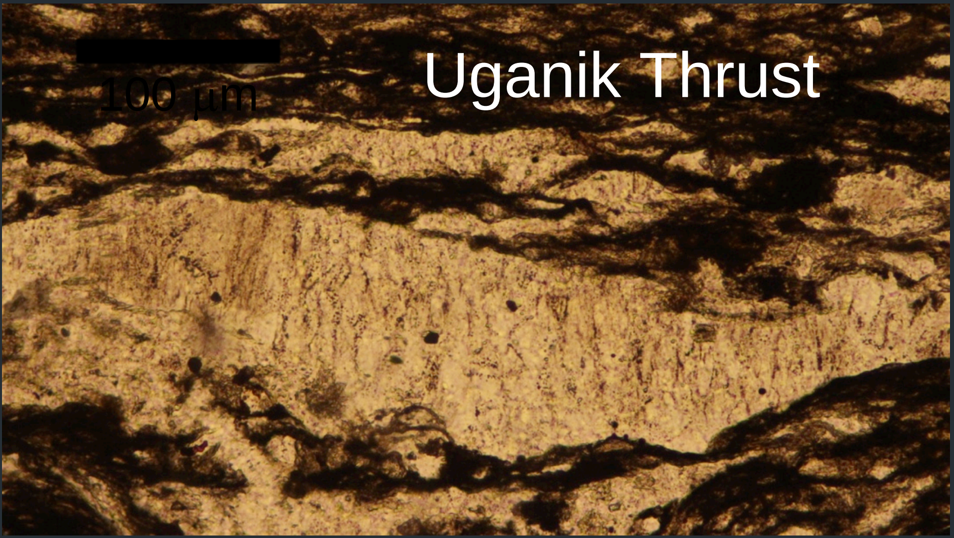


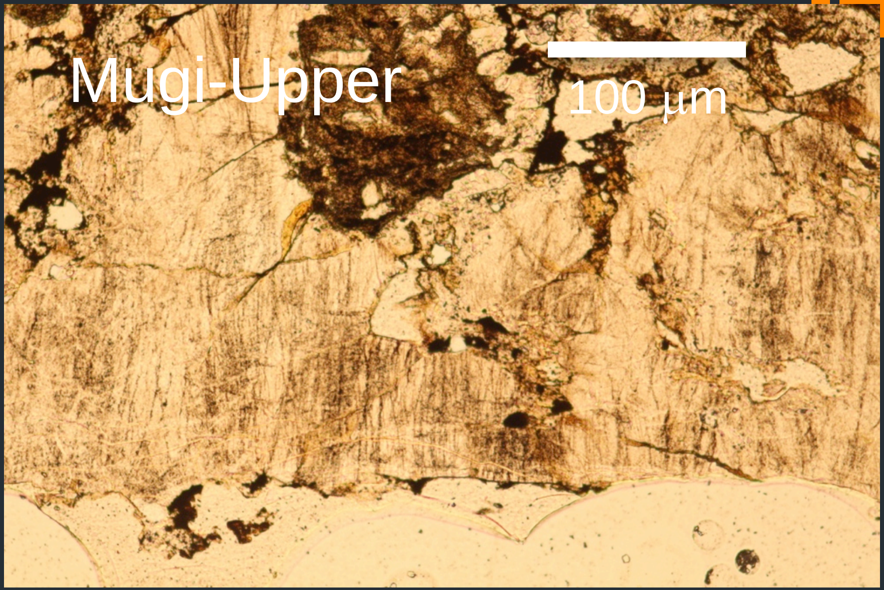


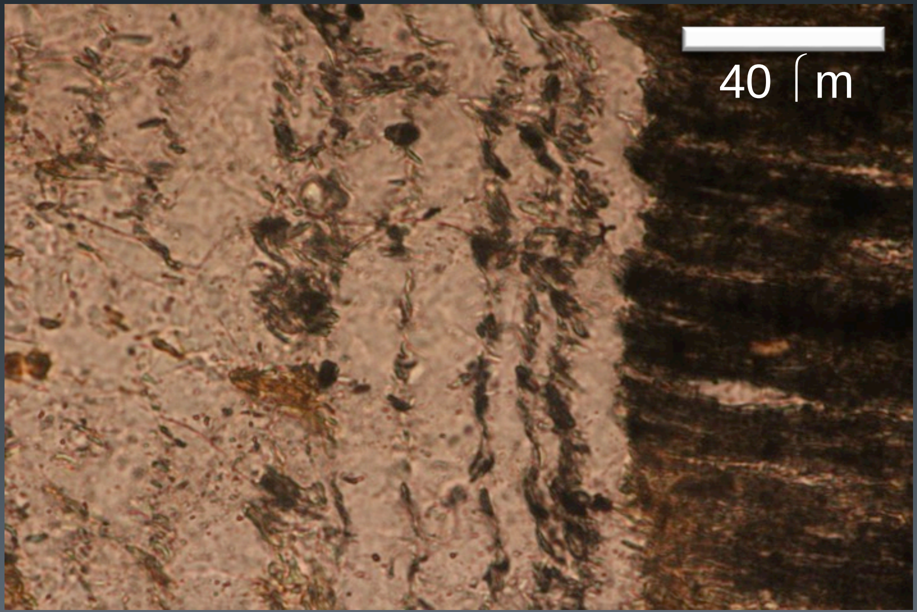


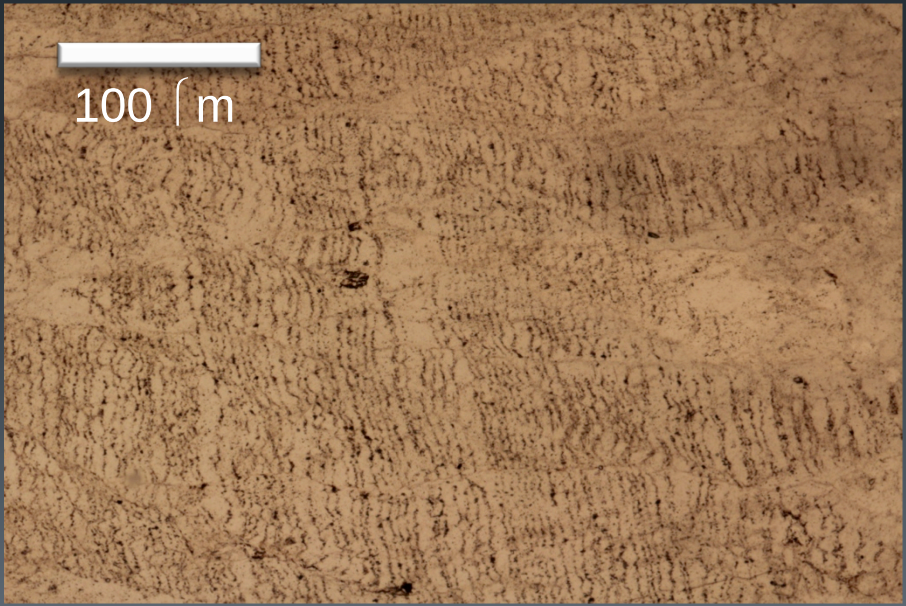
Fisher et al., in review[a]

Crack Seal Microstructures

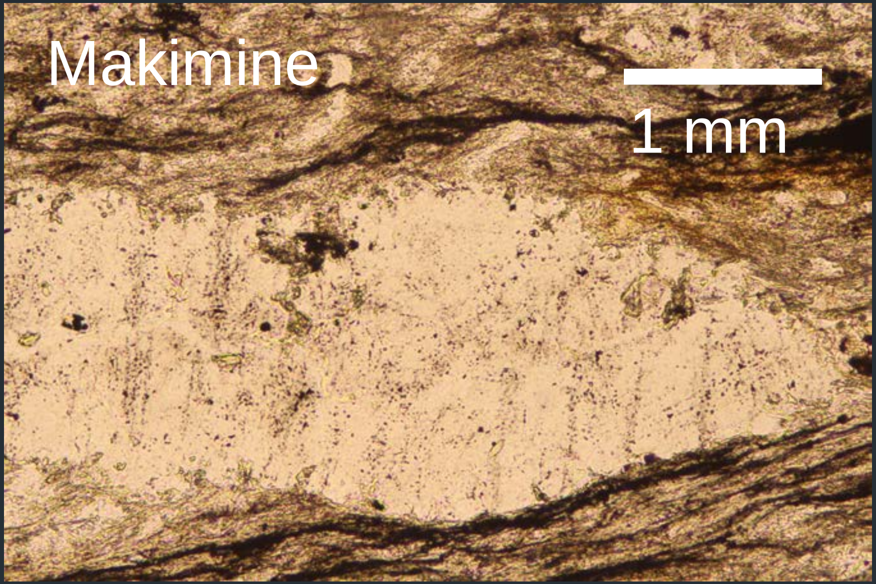


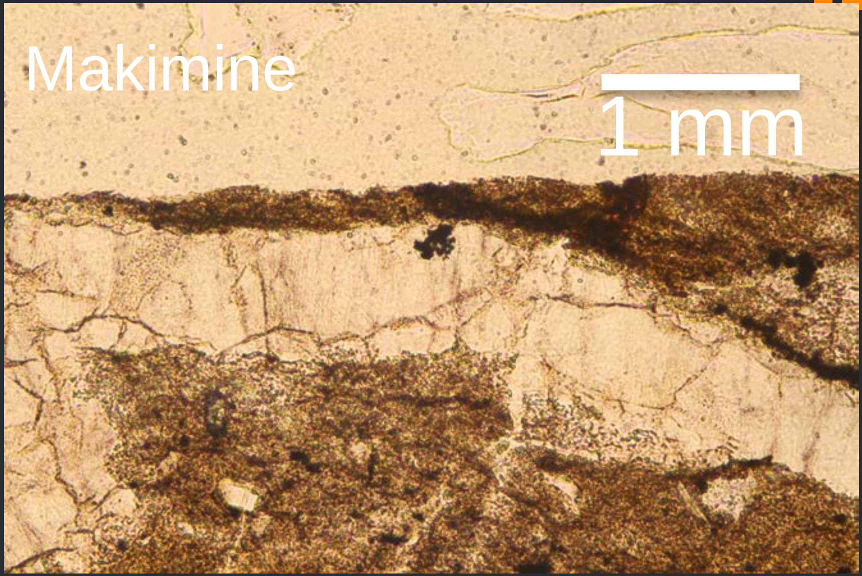


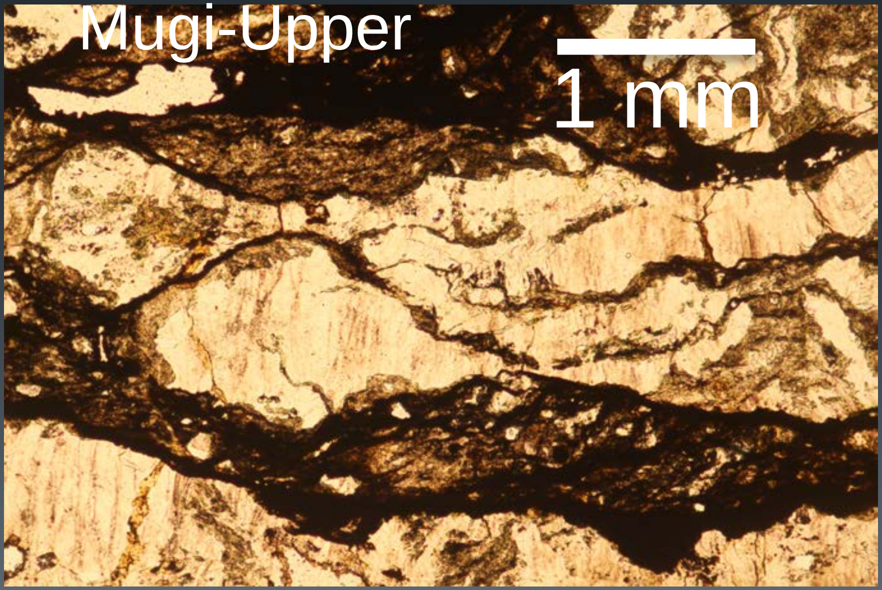


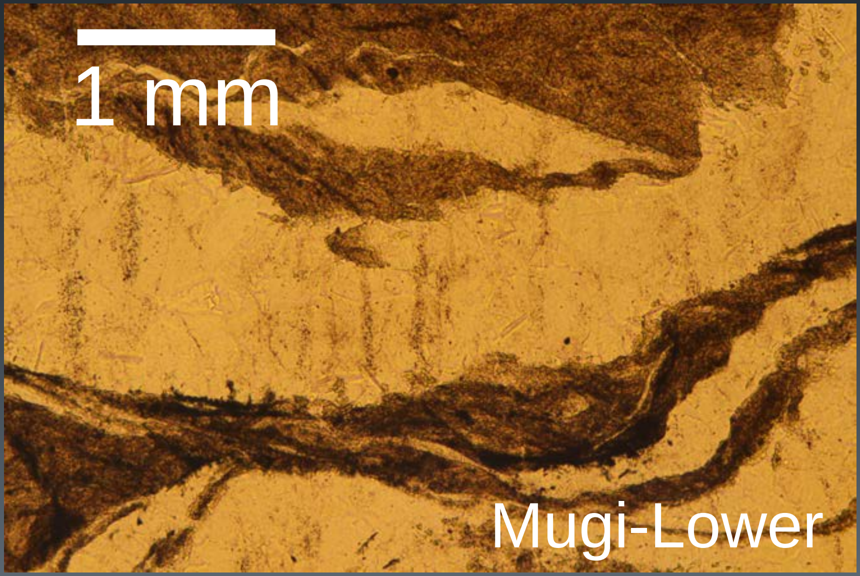


Crack Seal Microstructures-syntaxial

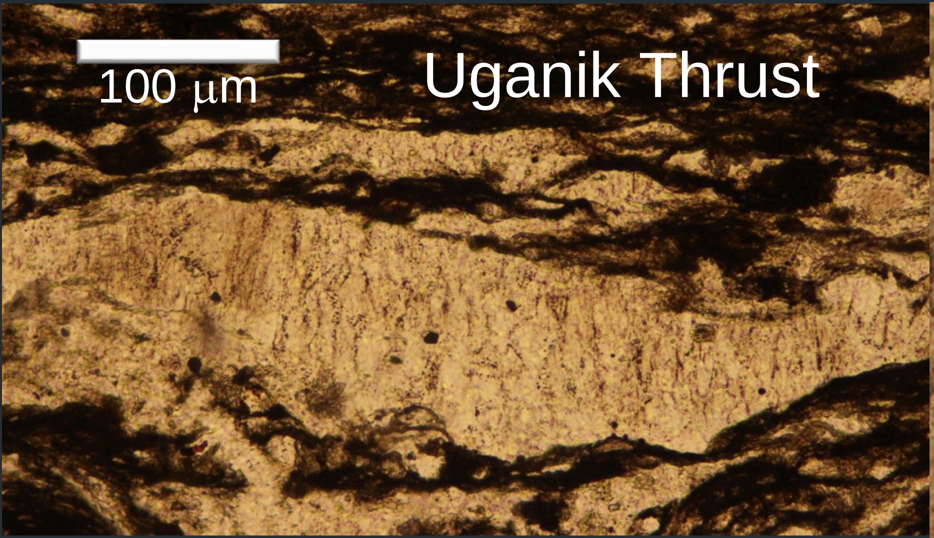


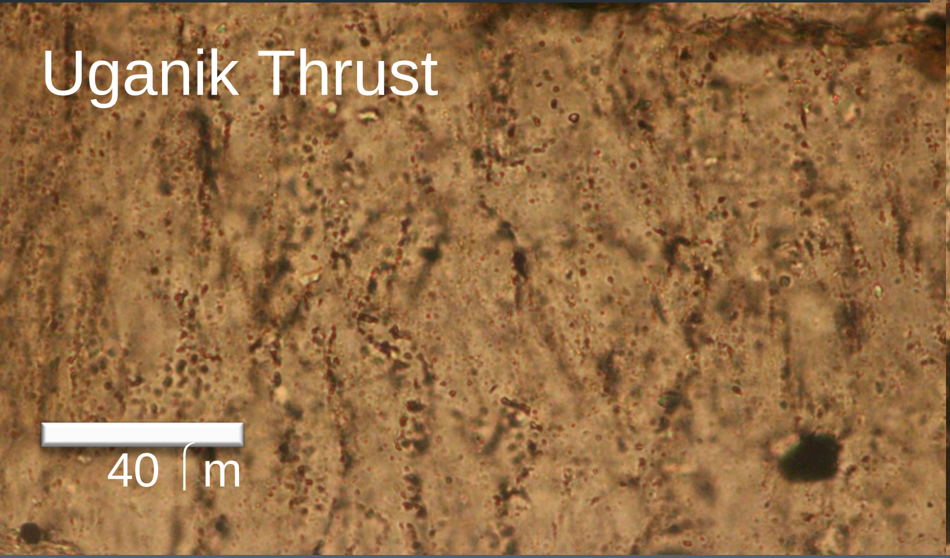




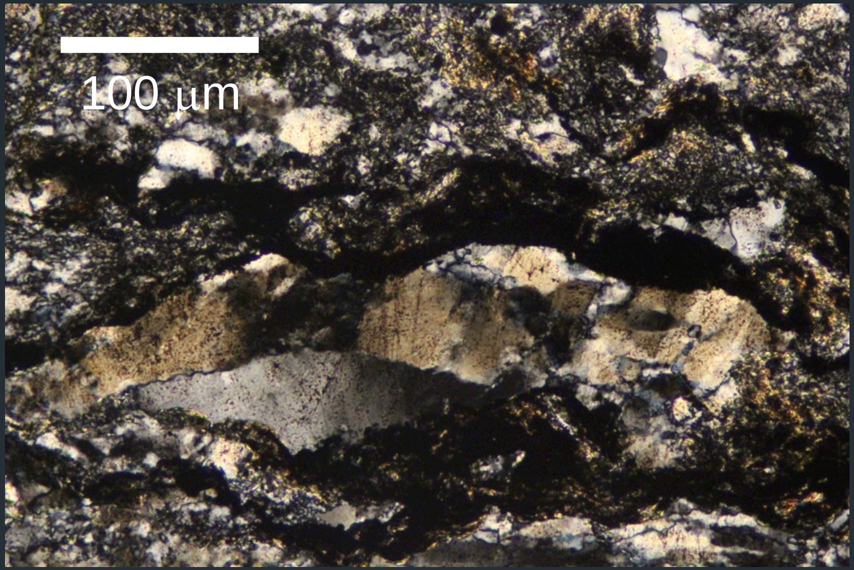


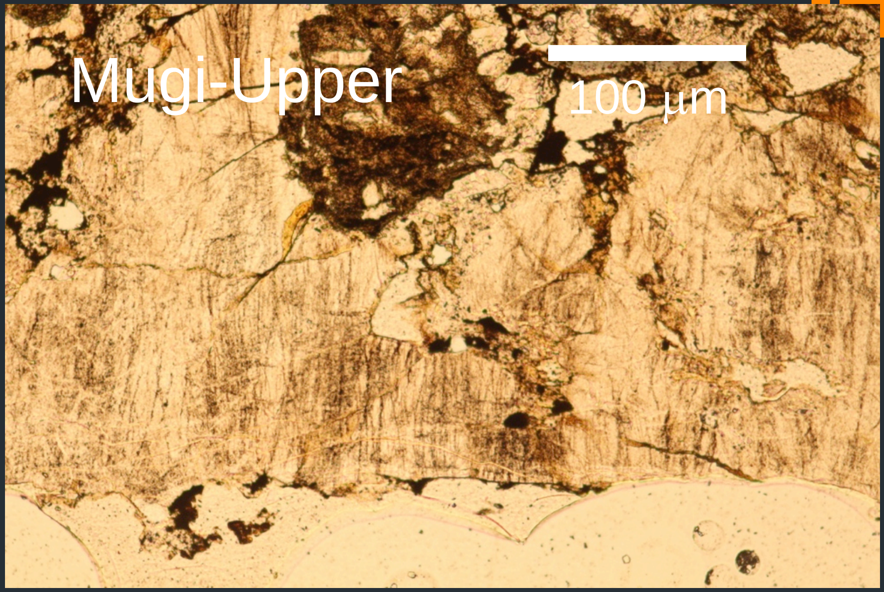
Crack Seal Microstructures-syntaxial

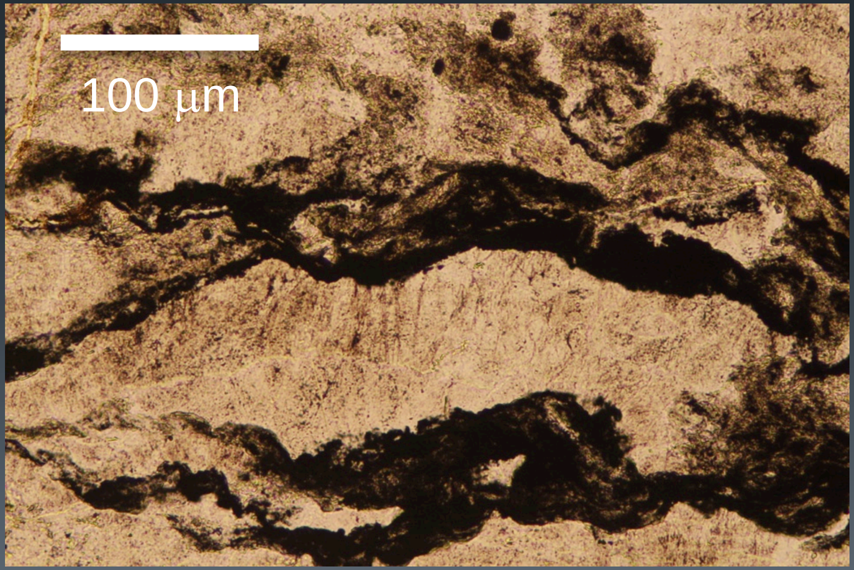


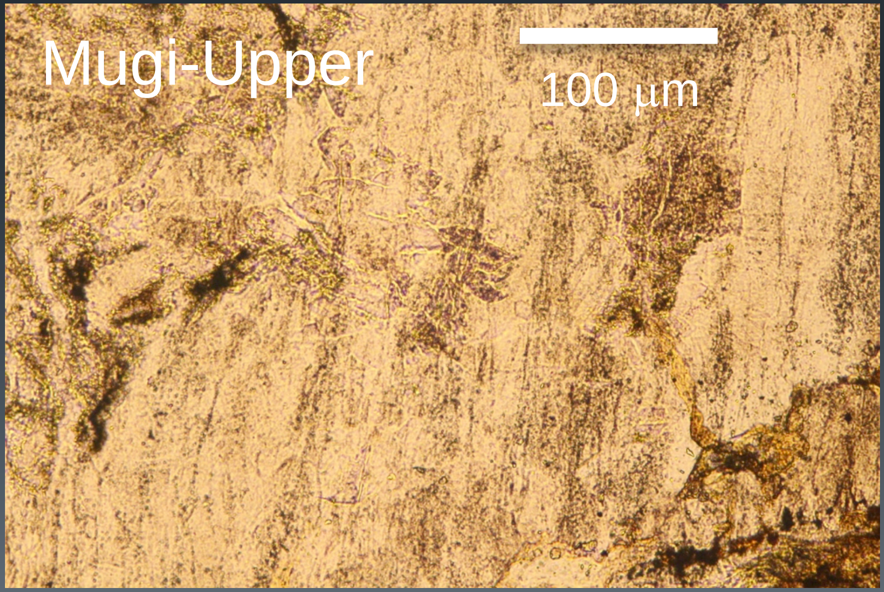


Crack Seal Microstructures-syntaxial

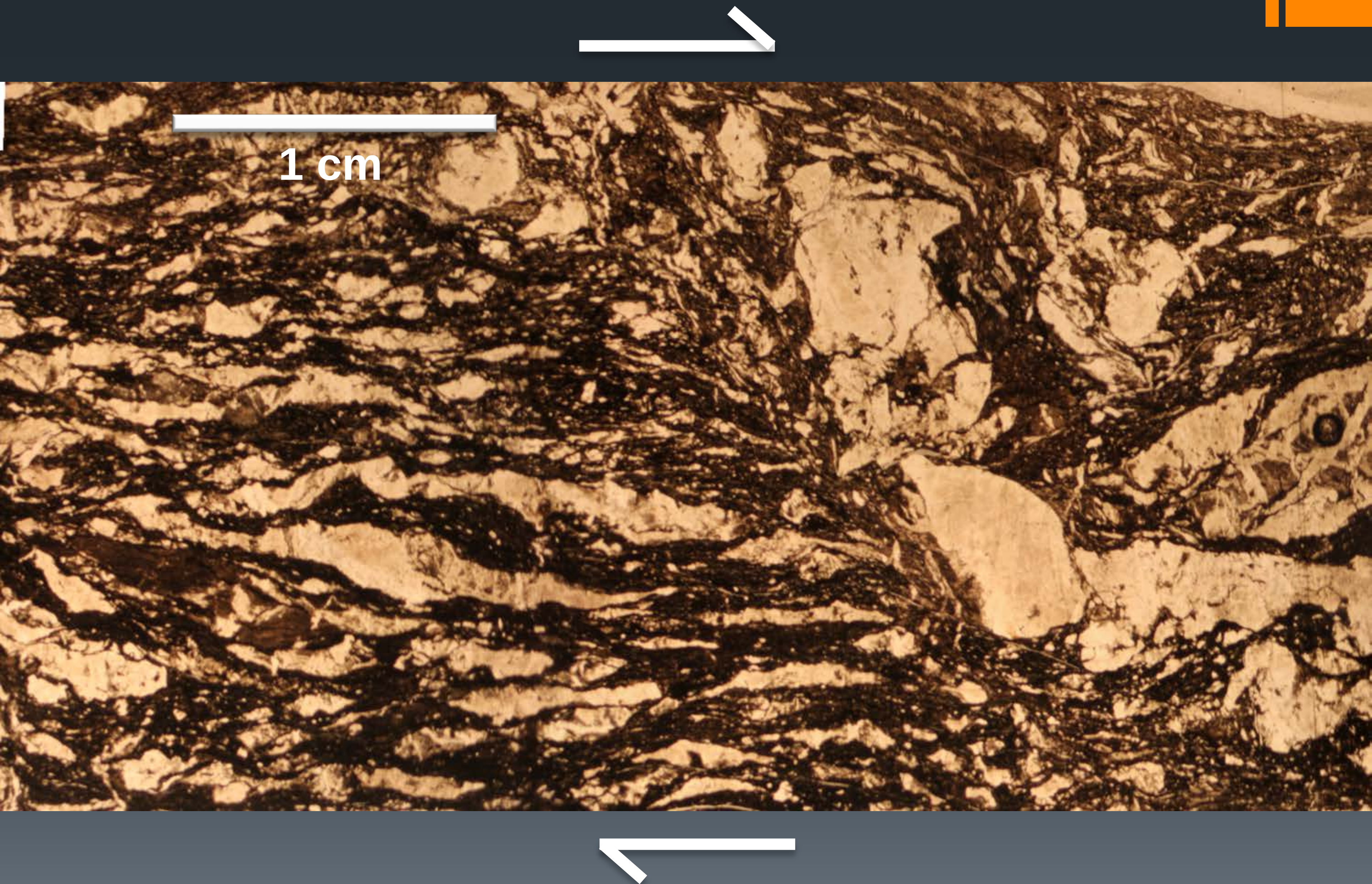






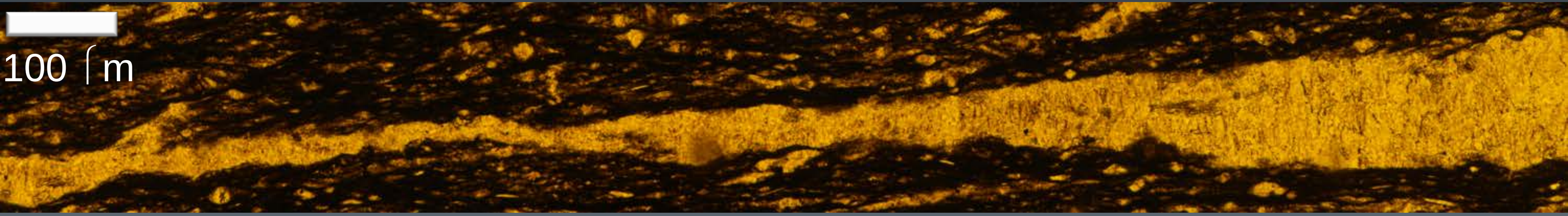


Uganik Thrust Fault Zone

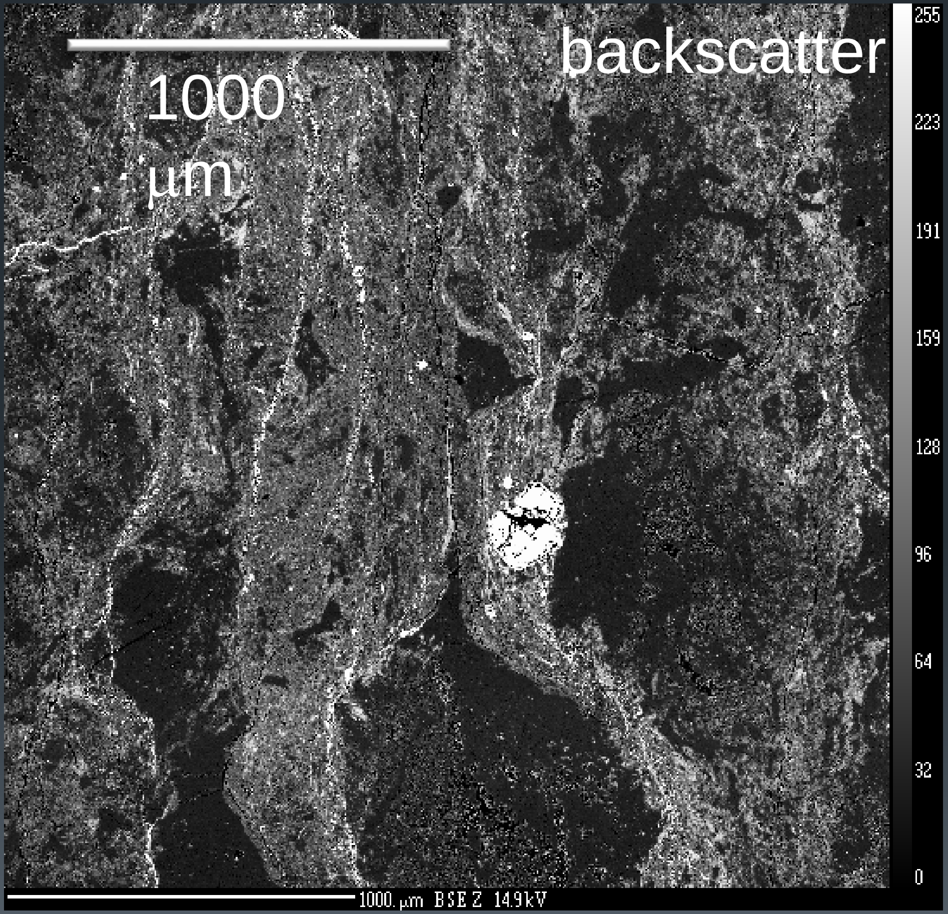


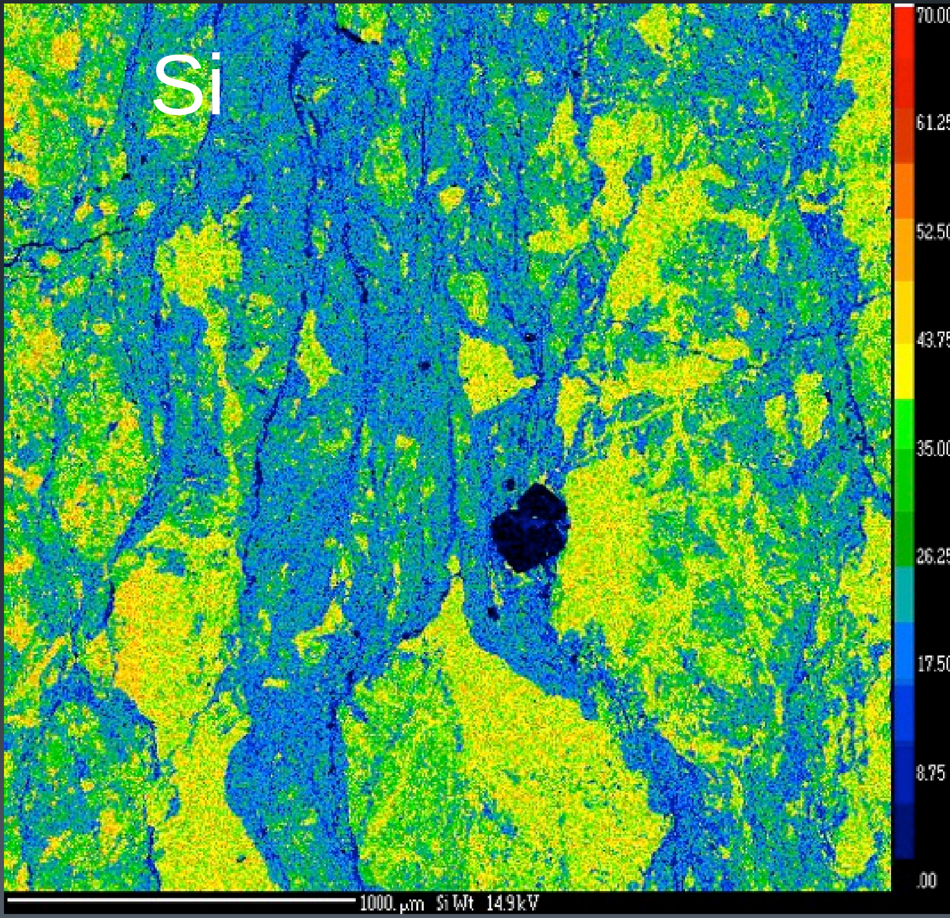
σ_1 orientations-Pervasive high P_f

Uganik Thrust

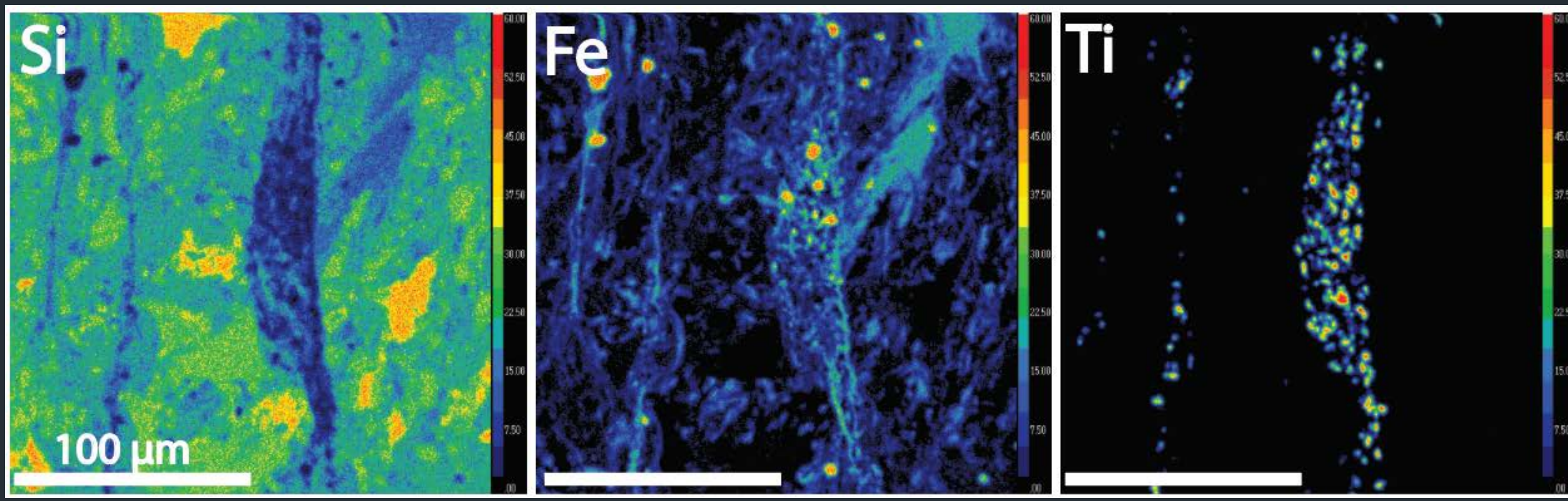


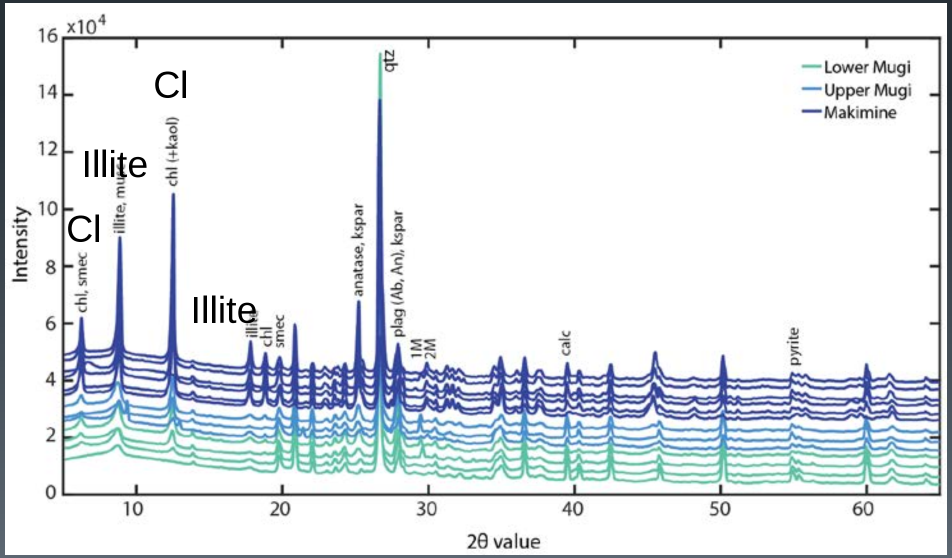
Scaly fabrics are Si depletion zones

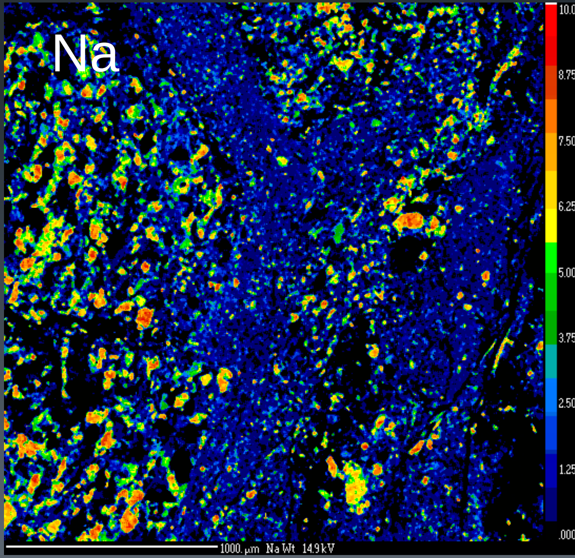




Geochemical reactions

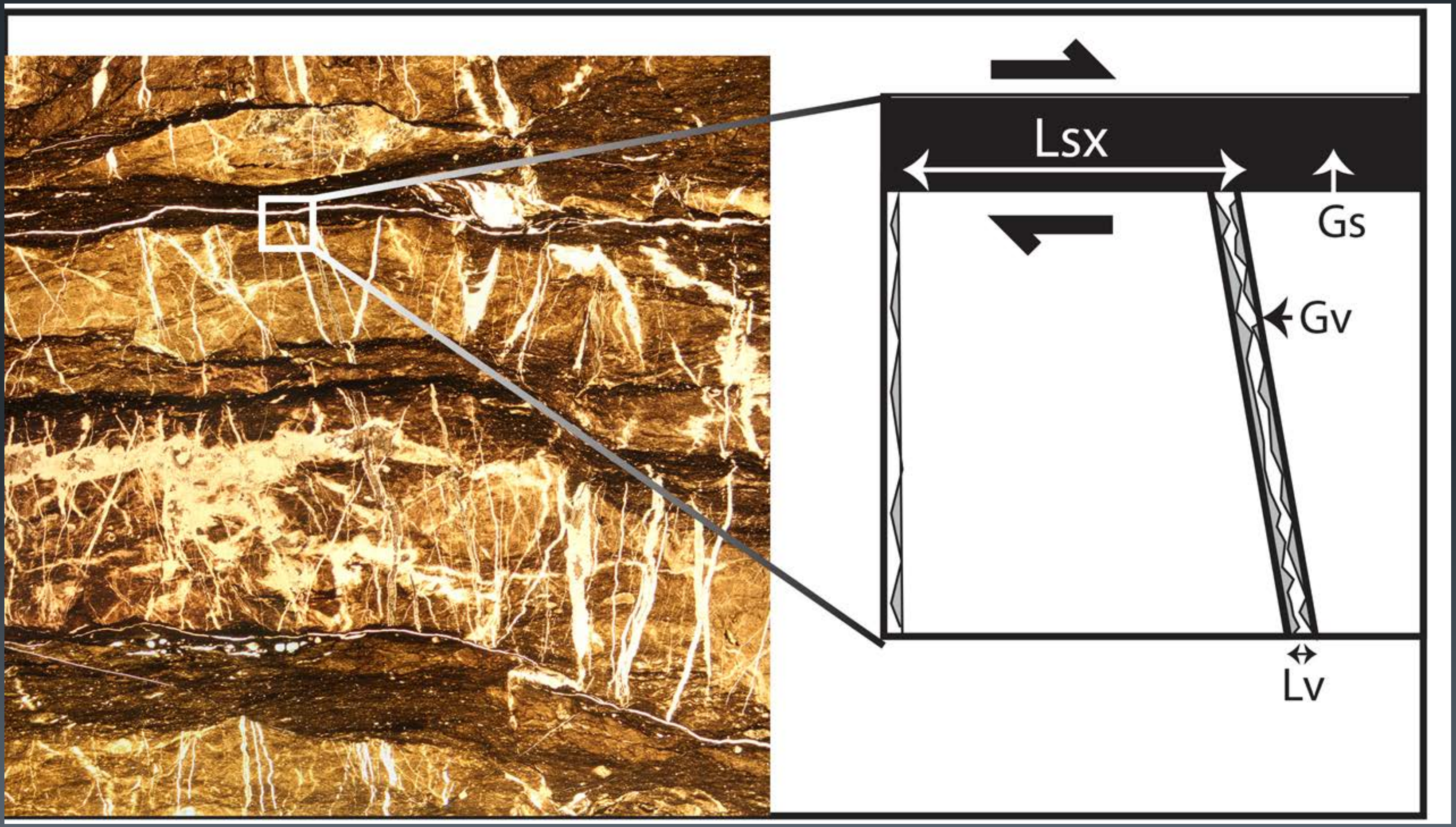






Fisher et al., 2019b

Model Geometry

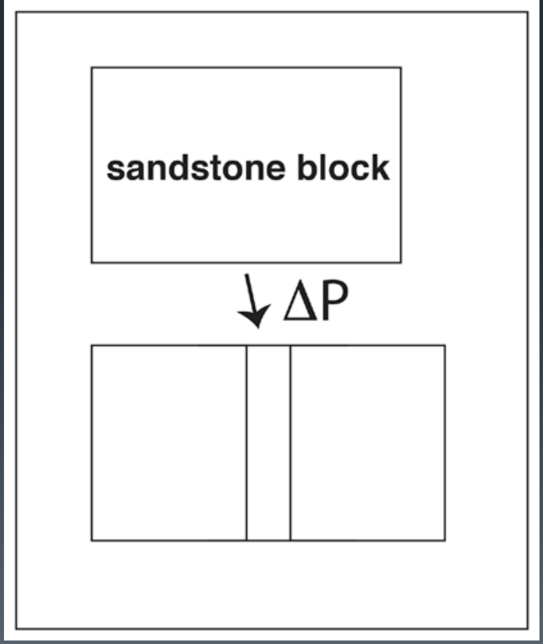


Driving force for Silica Redistribution

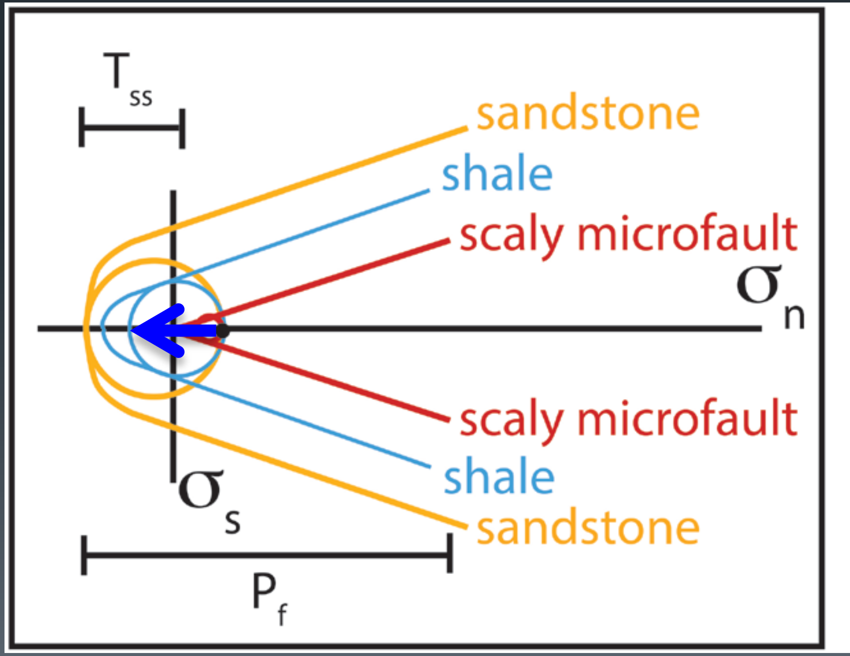
Fisher et al., 2019b

Fisher and Brantley, 1992
Fisher and Brantley, 2014
Ujiie et al., 2018
Renard et al., 2001

Fluid Pressure Drop

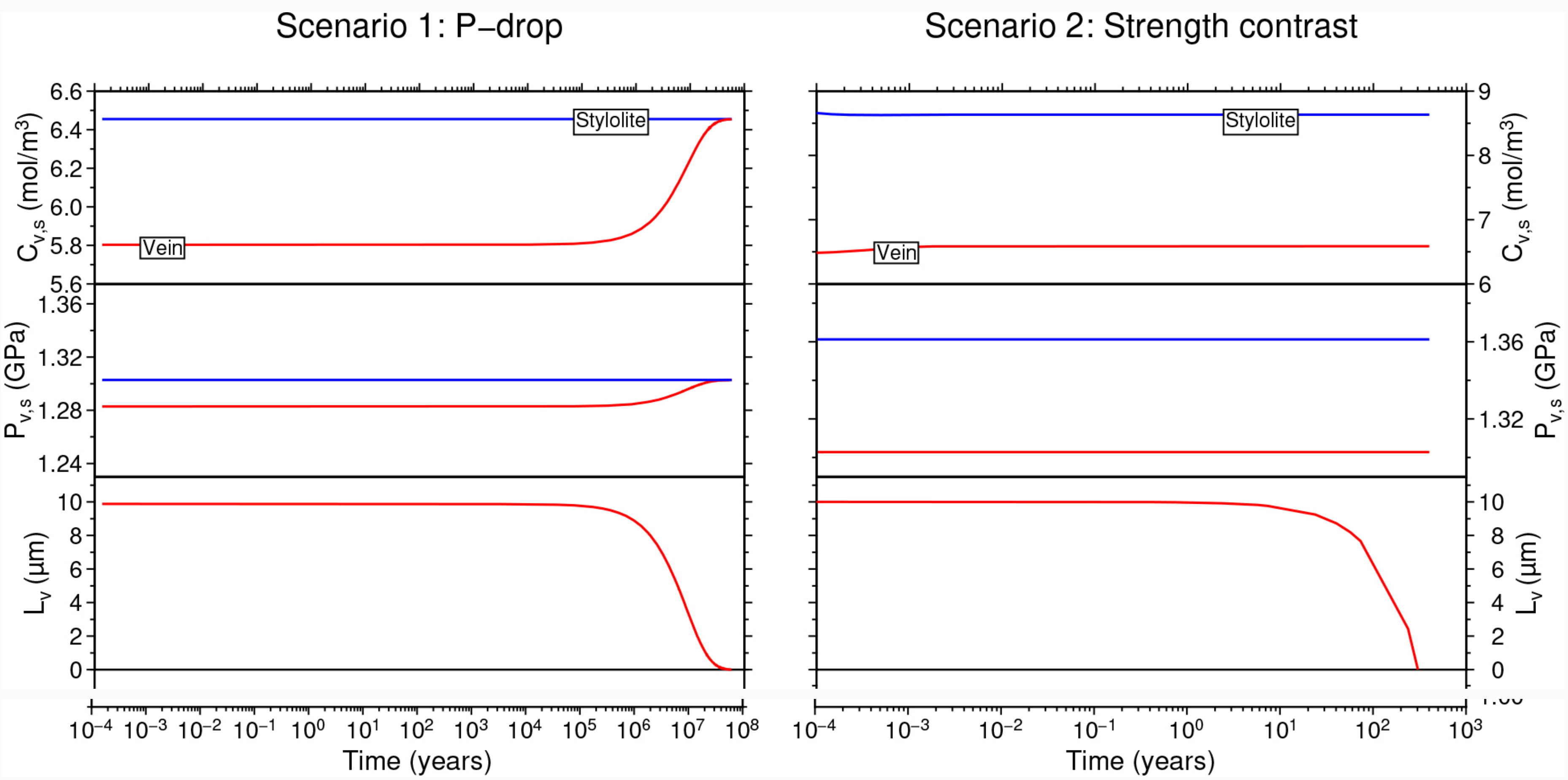


Differences in Mean stress related to Strength Contrast

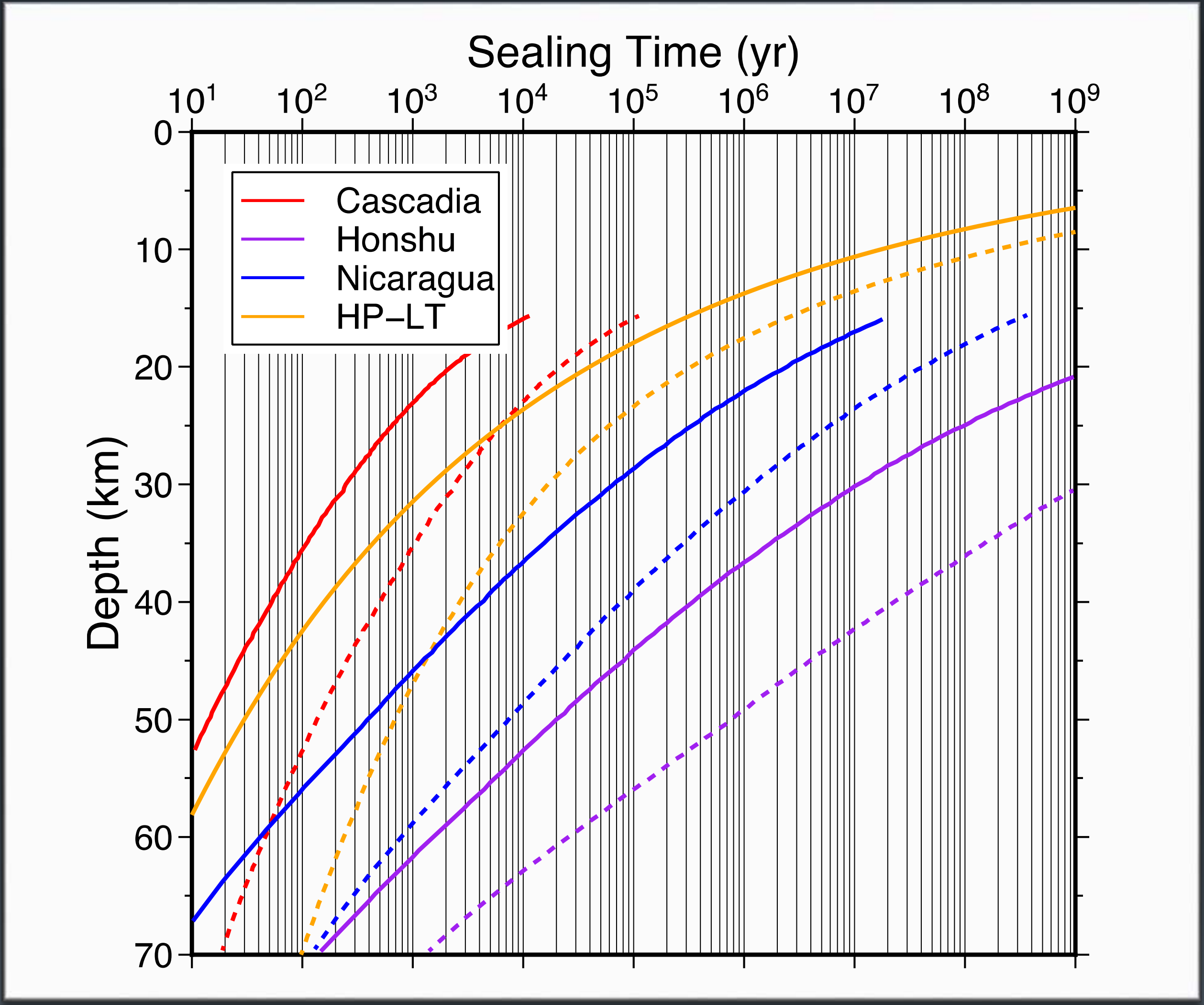


Fisher et al., 2019b

Crack Sealing Times



Downdip and Global variability



Fisher et al., 2019b

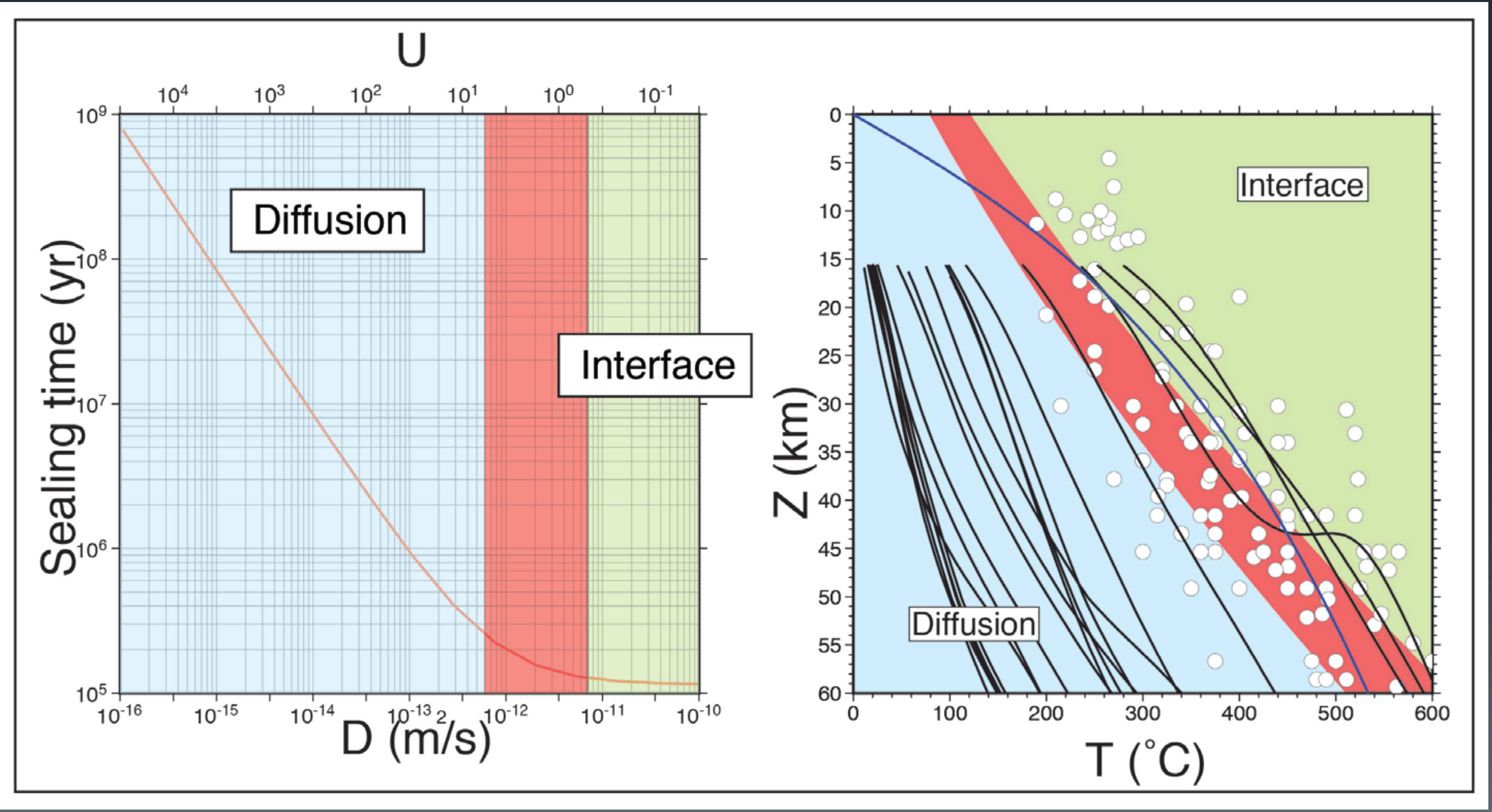
Diffusion vs. Interface control

Fisher et al., 2019b

Penniston-Dorland et al., 2015

Syracuse et al., 2010

Gunderson et al., 2002



Take home from the kinetics model

- Si redistribution due to chemical potential gradients driven by local σ_n differences can seal cracks at rates relevant to plate boundary healing during the seismic cycle (<10^3 years)
- Natural rates are likely to be much faster (quartz-phyllosilicate mixtures, low-T reactions)
- Rates are likely to vary between convergent margins with different thermal structures

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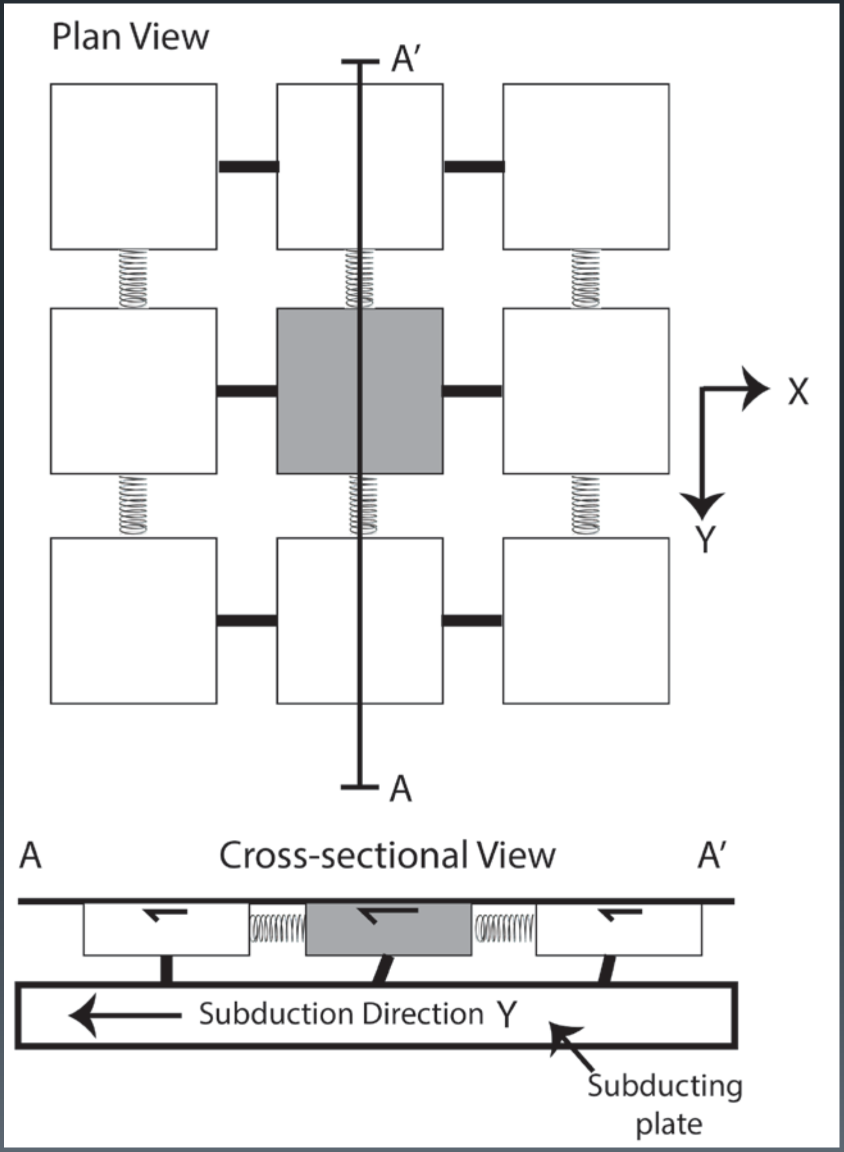
Cellular Block-Slider Model

Fisher et al., 2019a

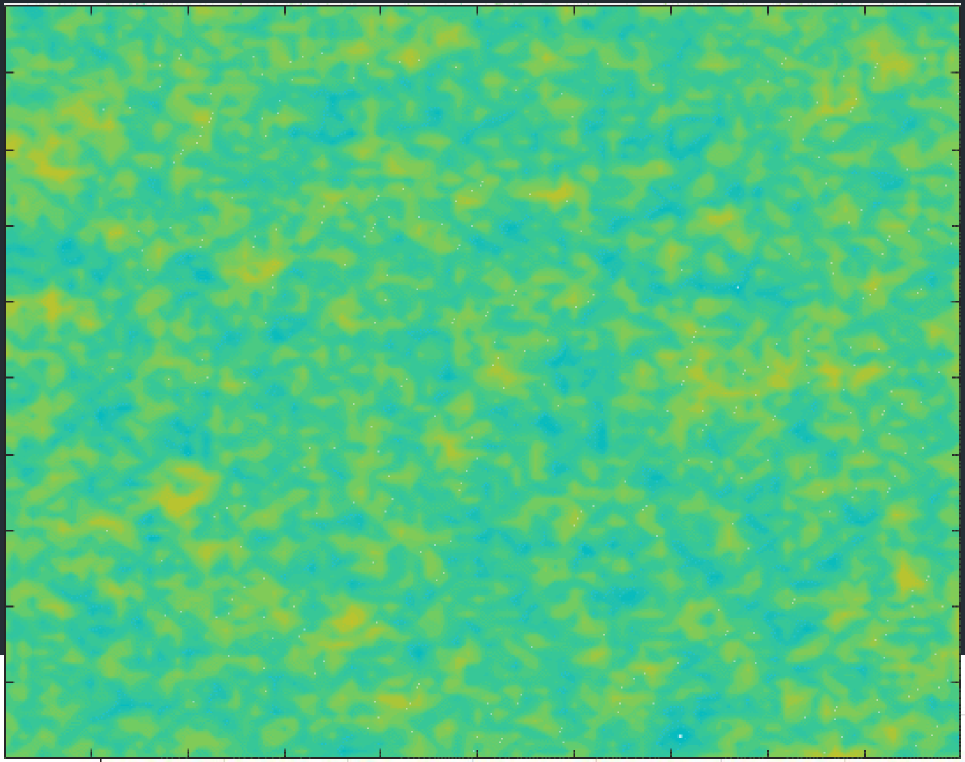


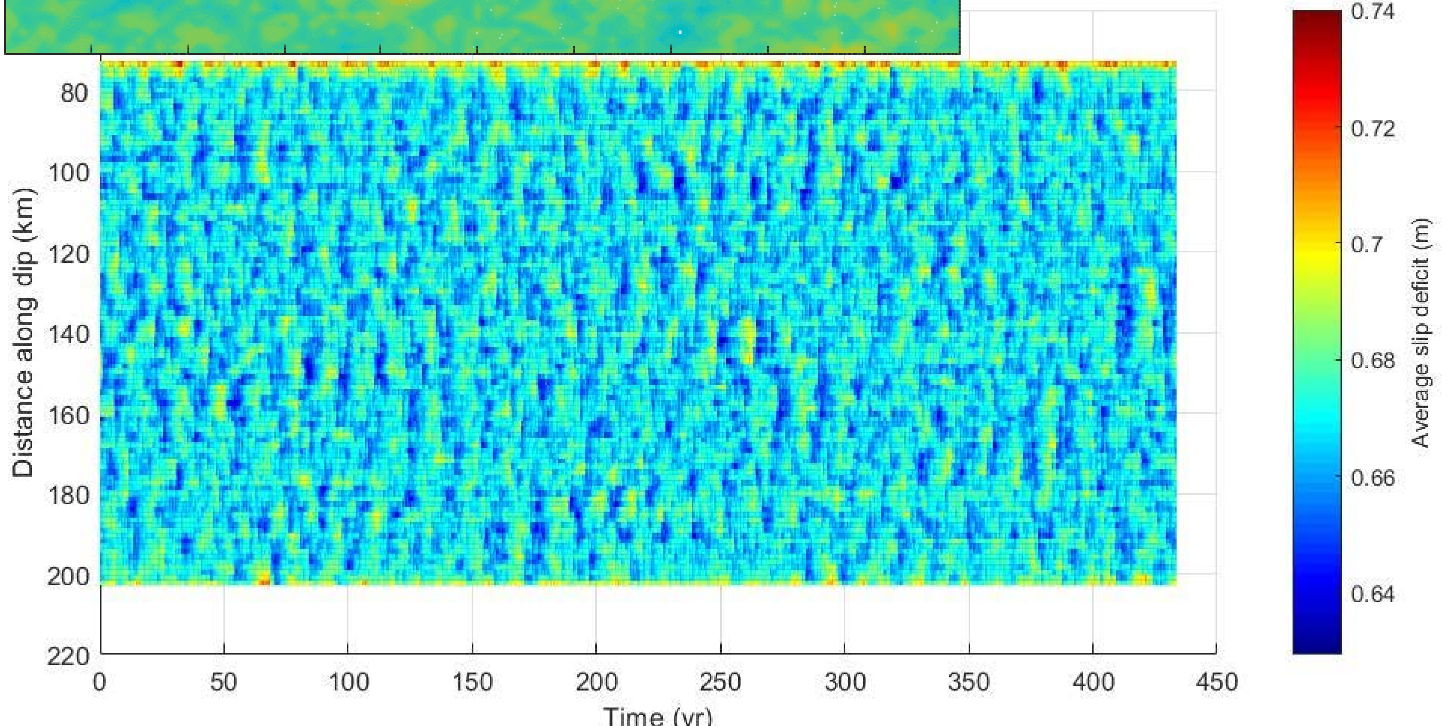
A population balance algorithm for asperities

Birth (nucleation)
Growth
Death (failure)

Fisher et al., 2019a

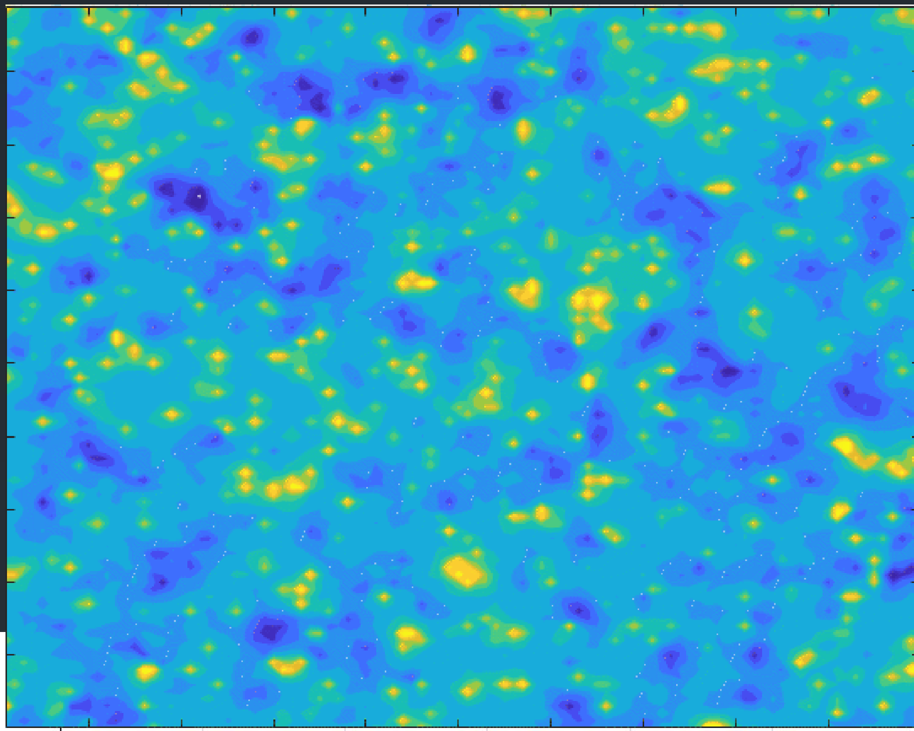
No Asperities

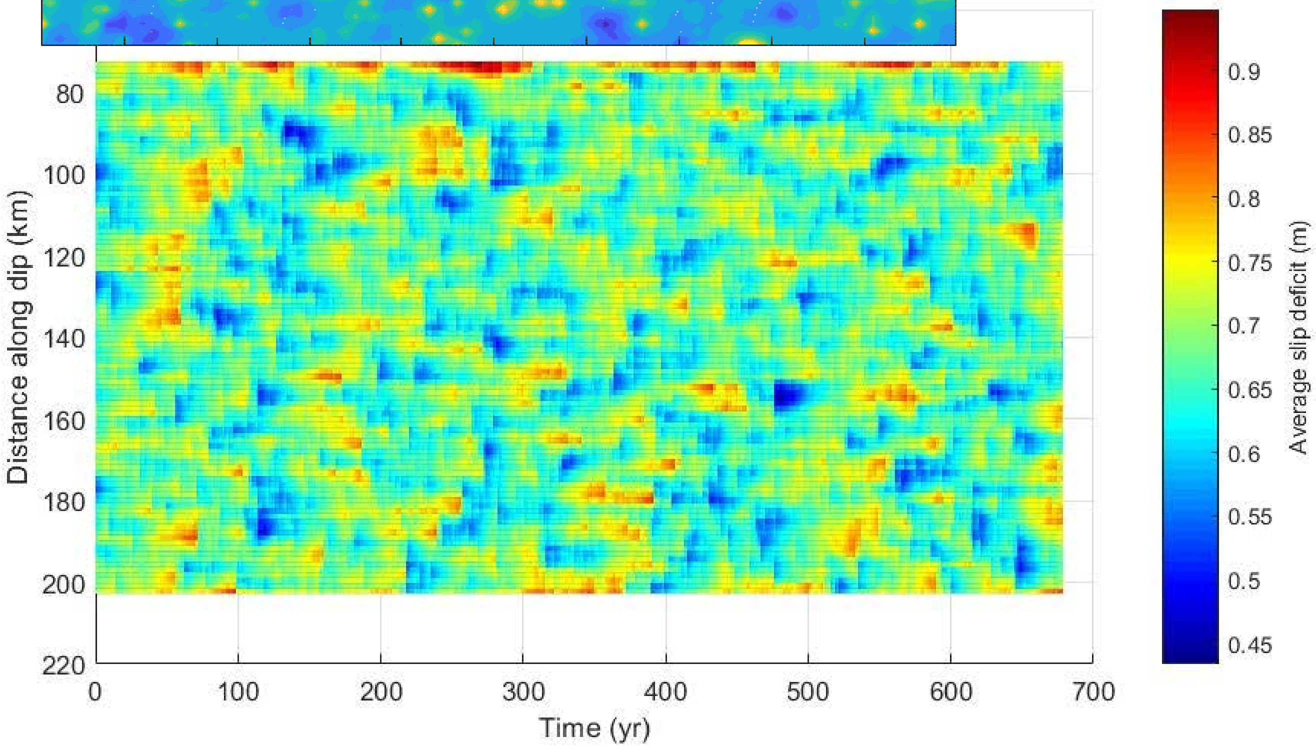


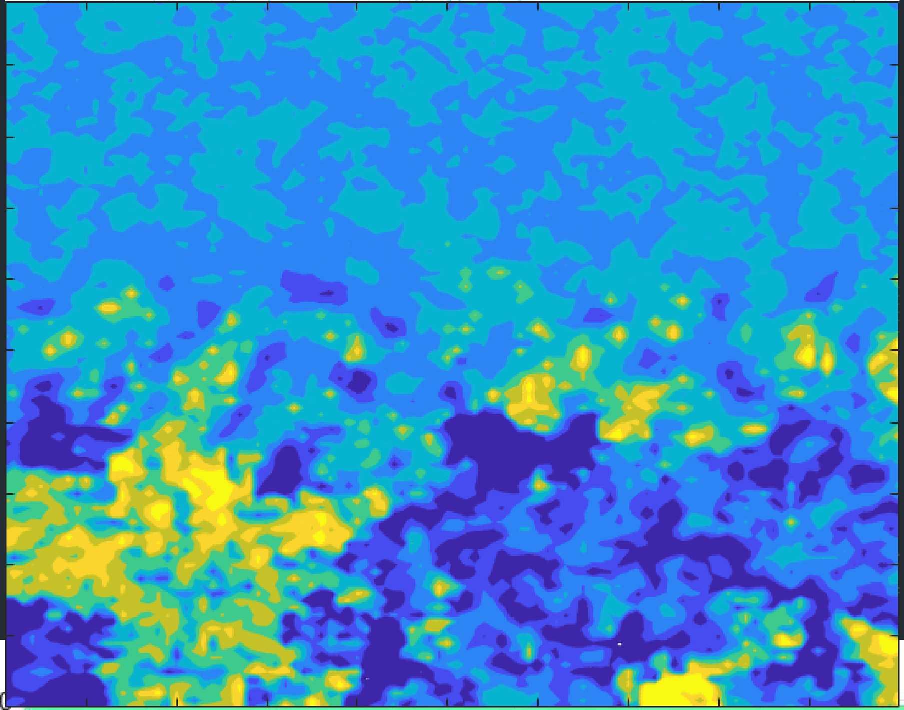


Fisher et al., 2019a

Asperity nucleation independent of T

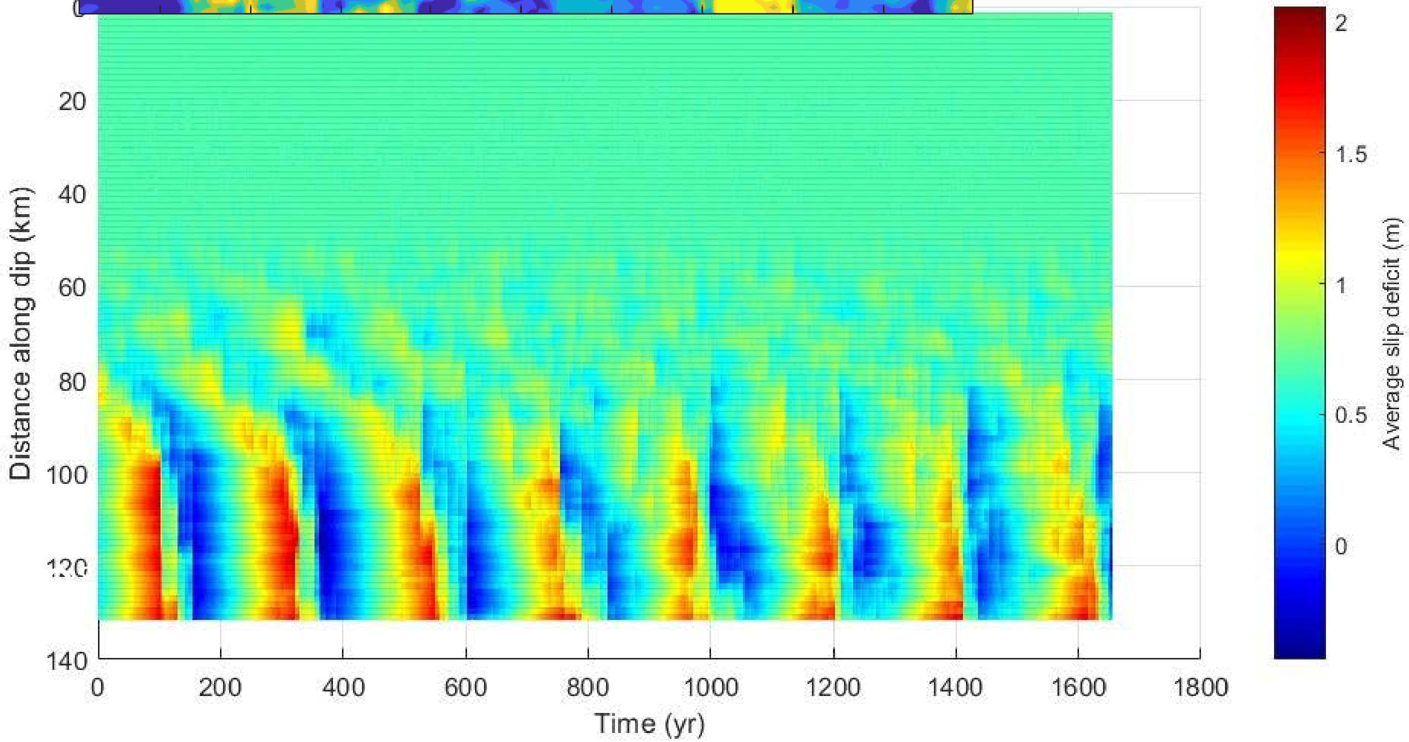






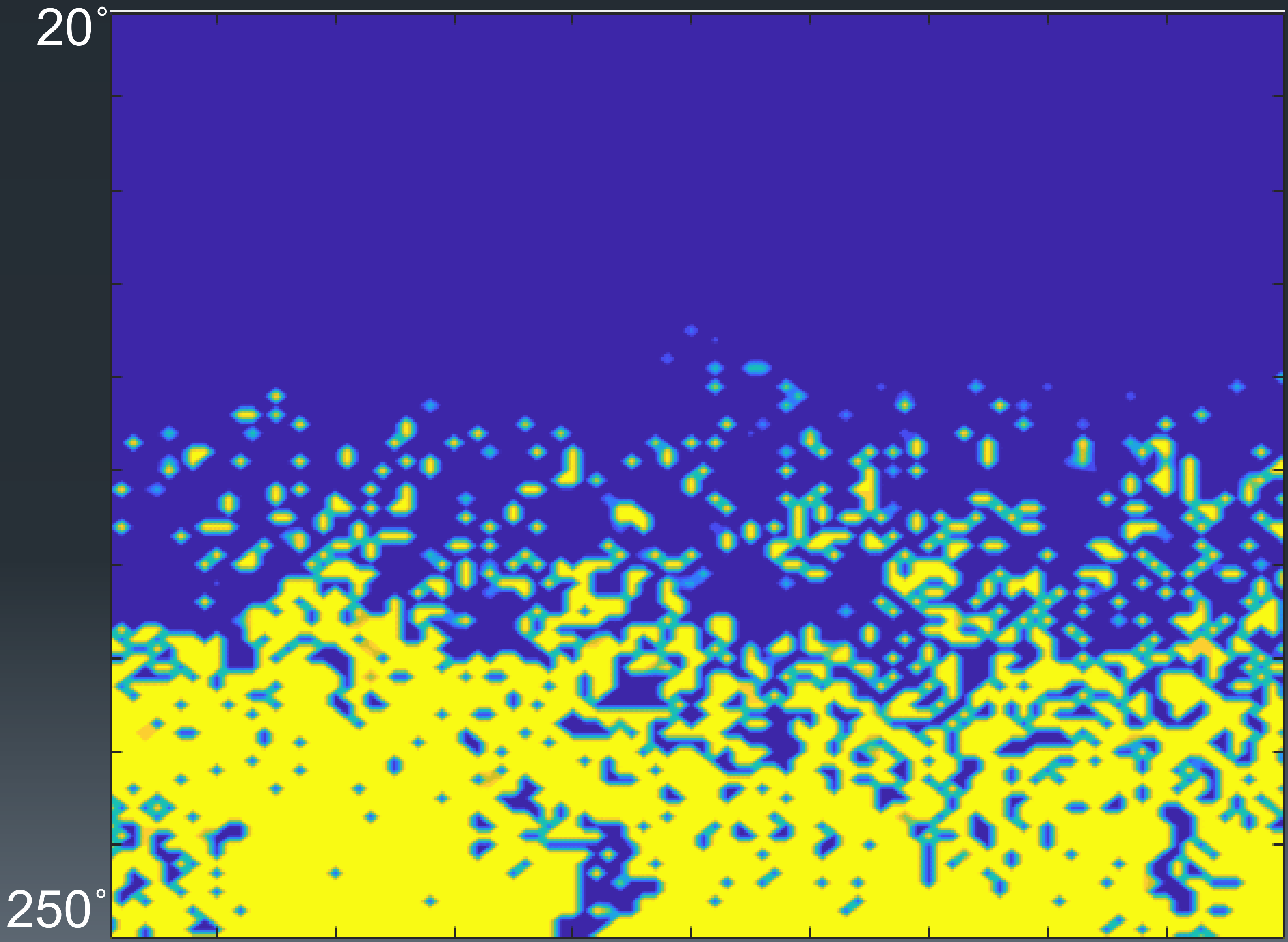
Fisher et al., 2019a

Thermally activated asperity nucleation



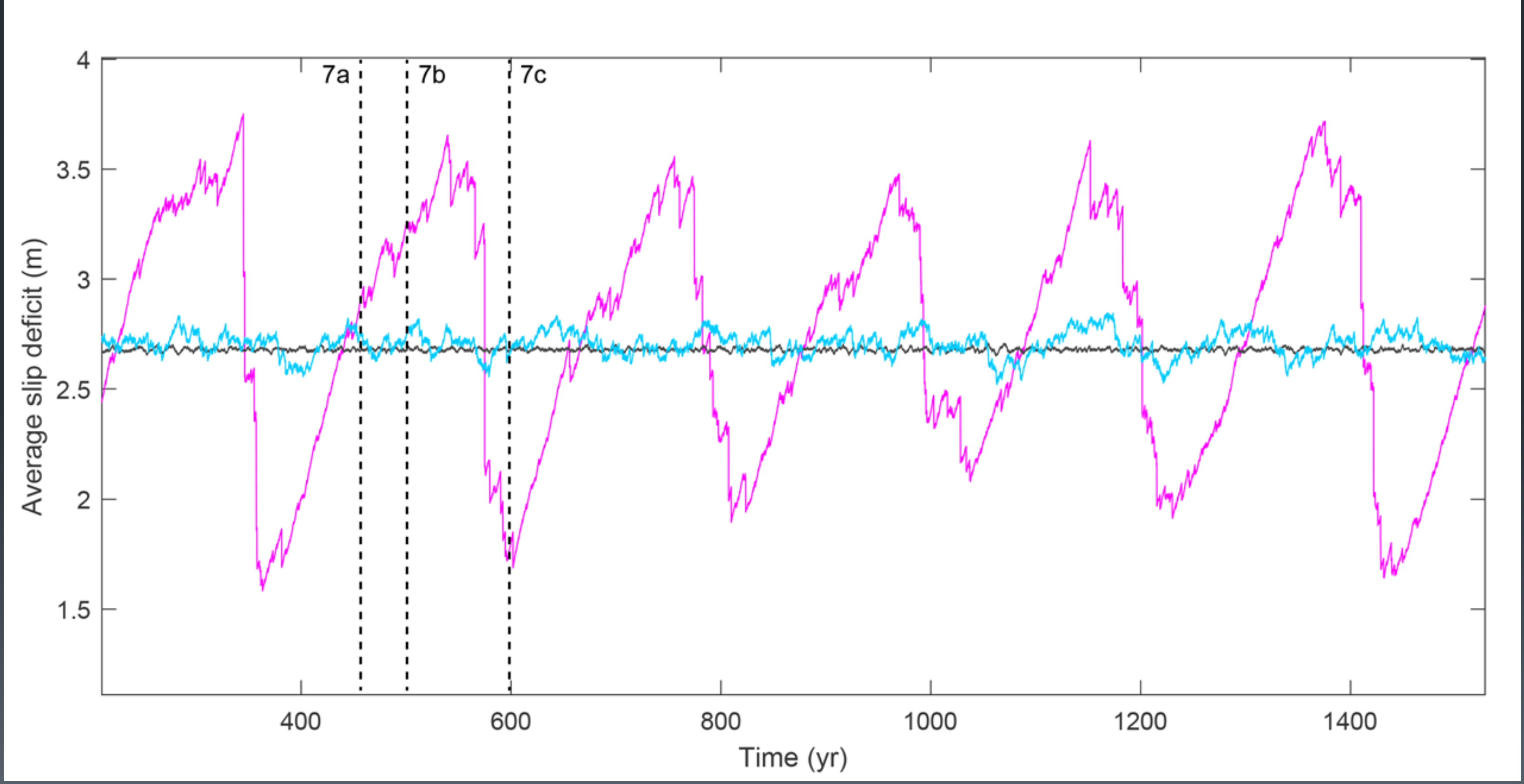
Asperity Maps

Fisher et al., 2019a



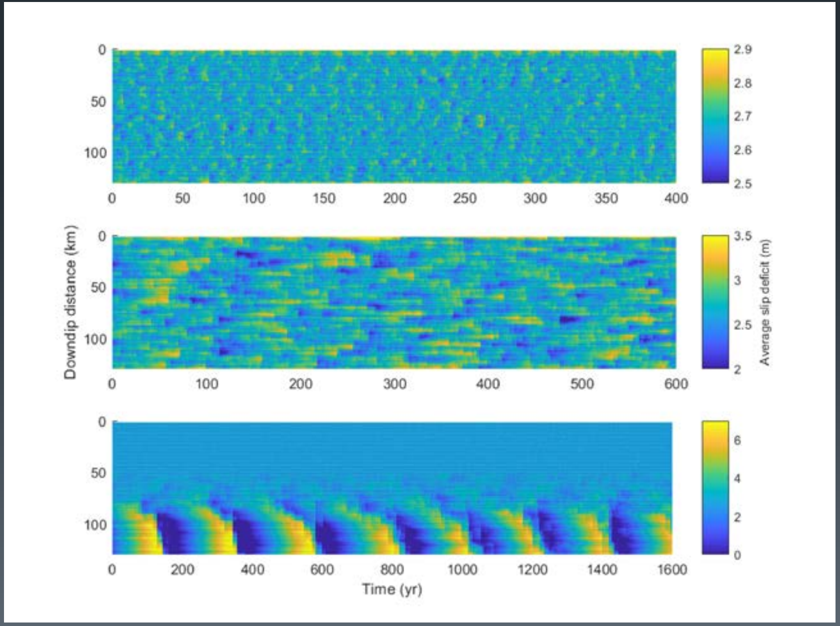
Time Series of Slip Deficit

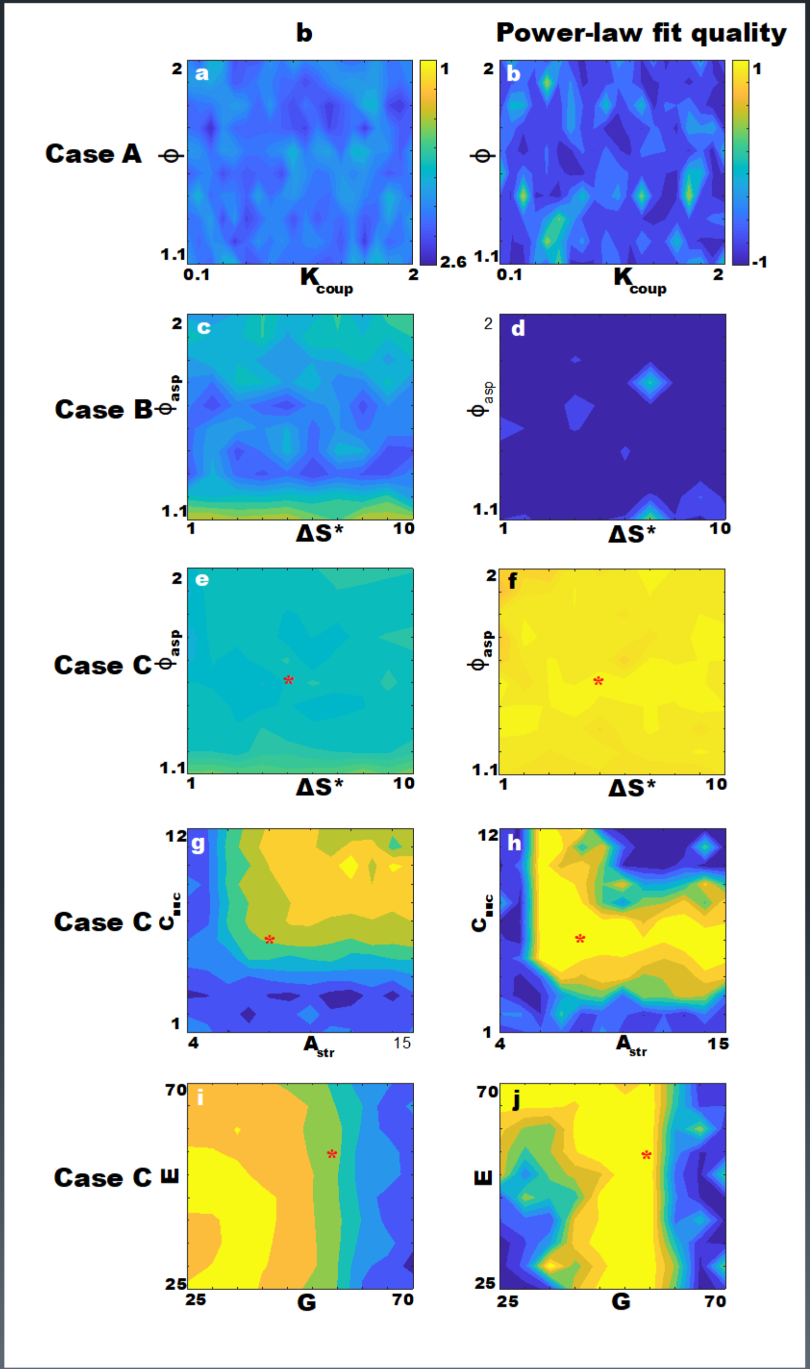
Fisher et al., 2019a



Sensitivity Analyses

Fisher et al., 2019a

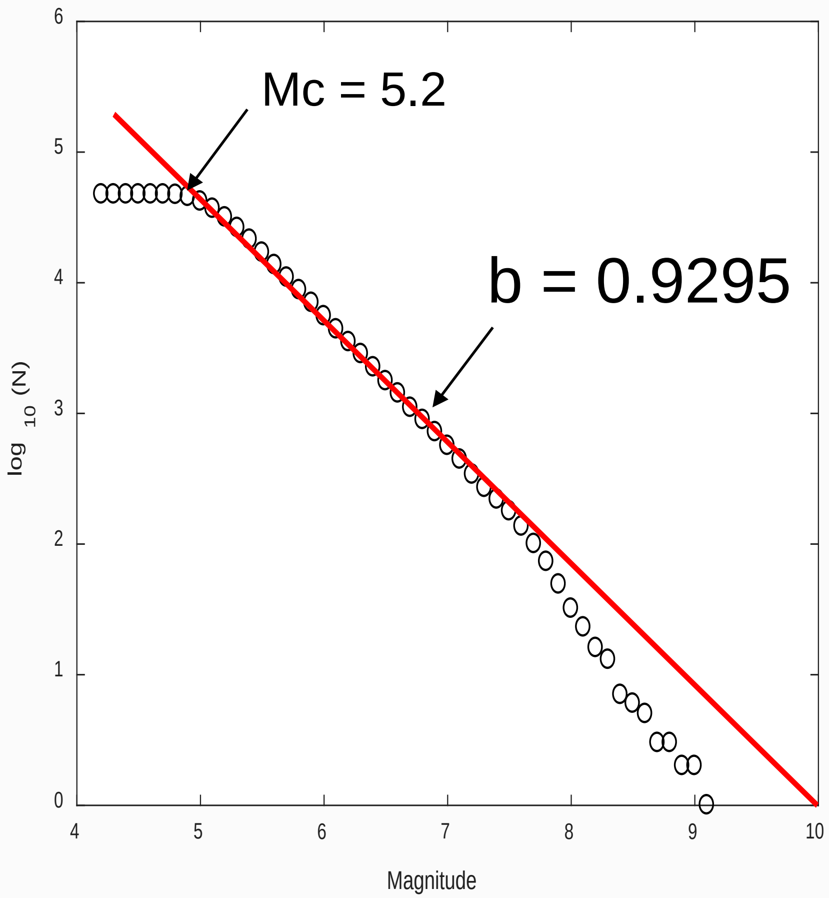




Outline

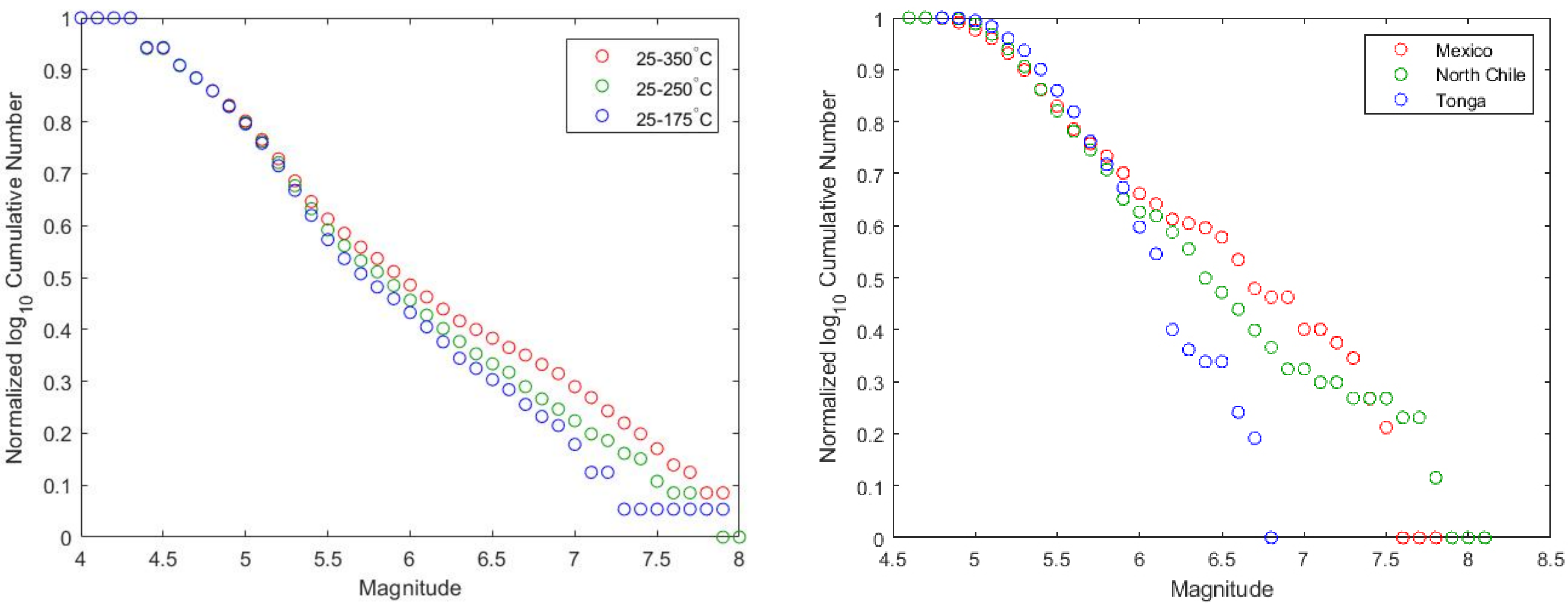
- Subduction zone dynamics and Frictional mechanics-theory and experiment
- Observations of ancient fault zones-Silica Kinetics Model
- Population balance algorithm and numerical mechanical model for interface
- Size distributions of earthquakes in natural systems
- Fluid production and fluid flow

Gutenberg-Richter



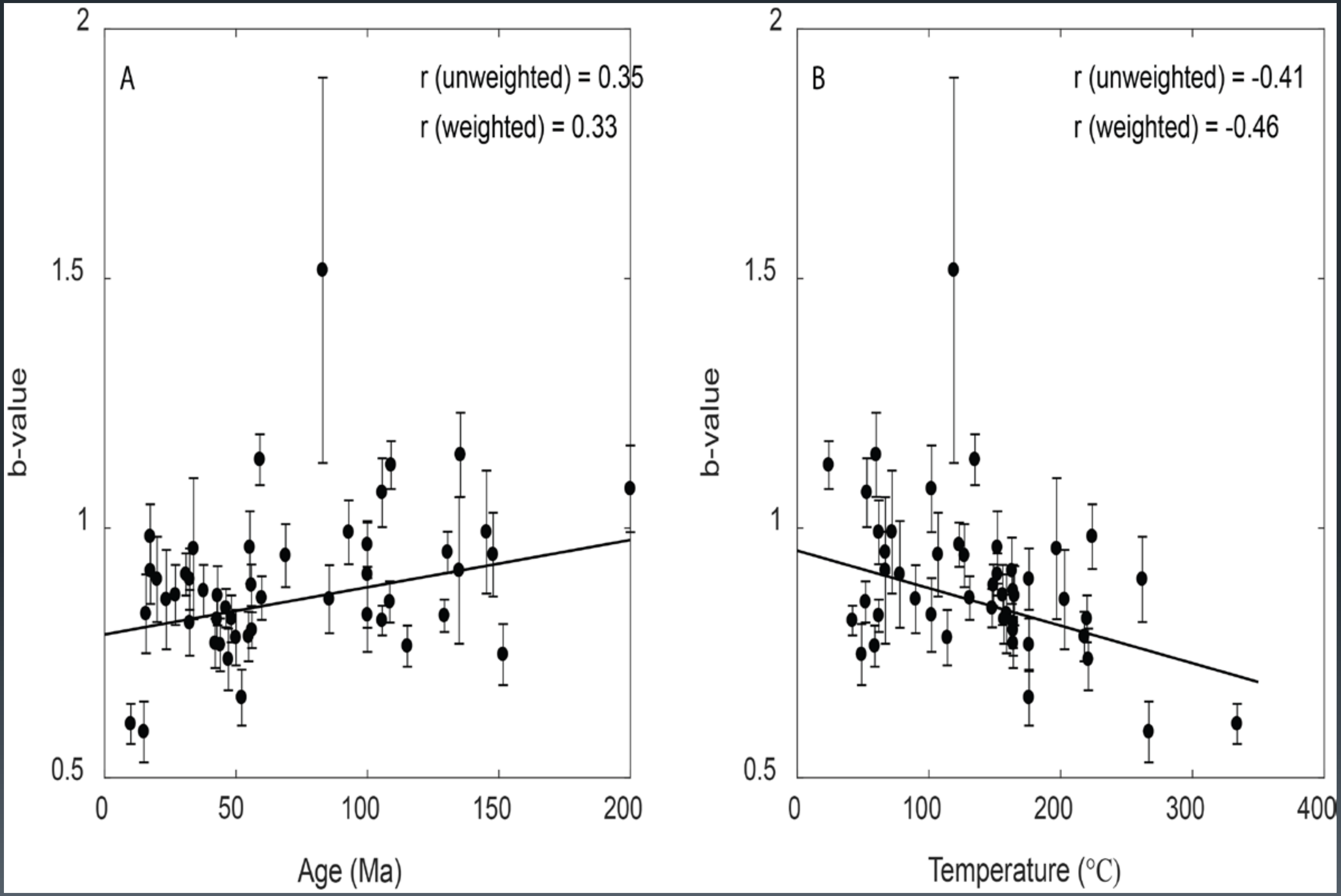
Model versus Natural Earthquake Size Distributions

Fisher et al., 2019a



Oakley et al., in prep.

b-value vs. temperature



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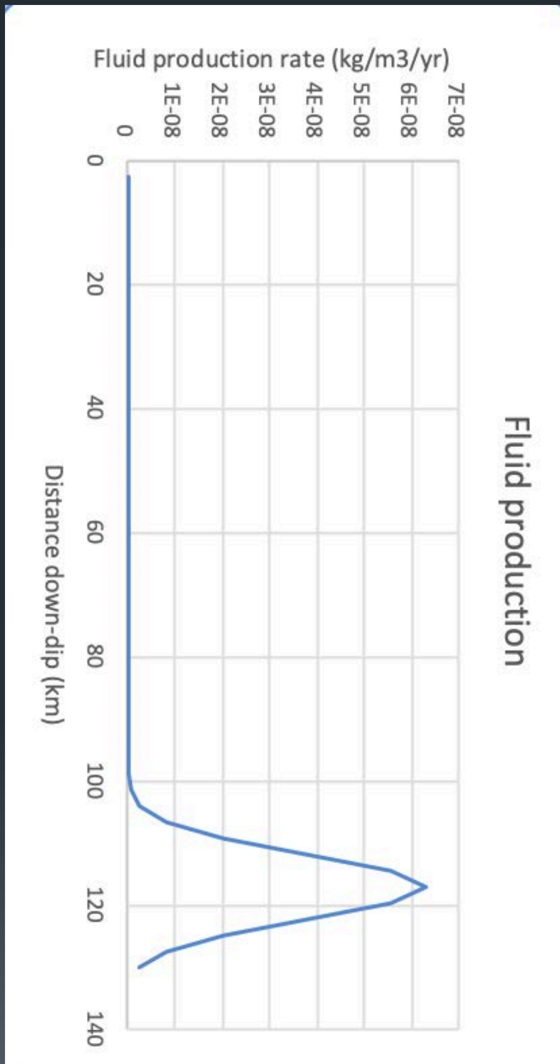
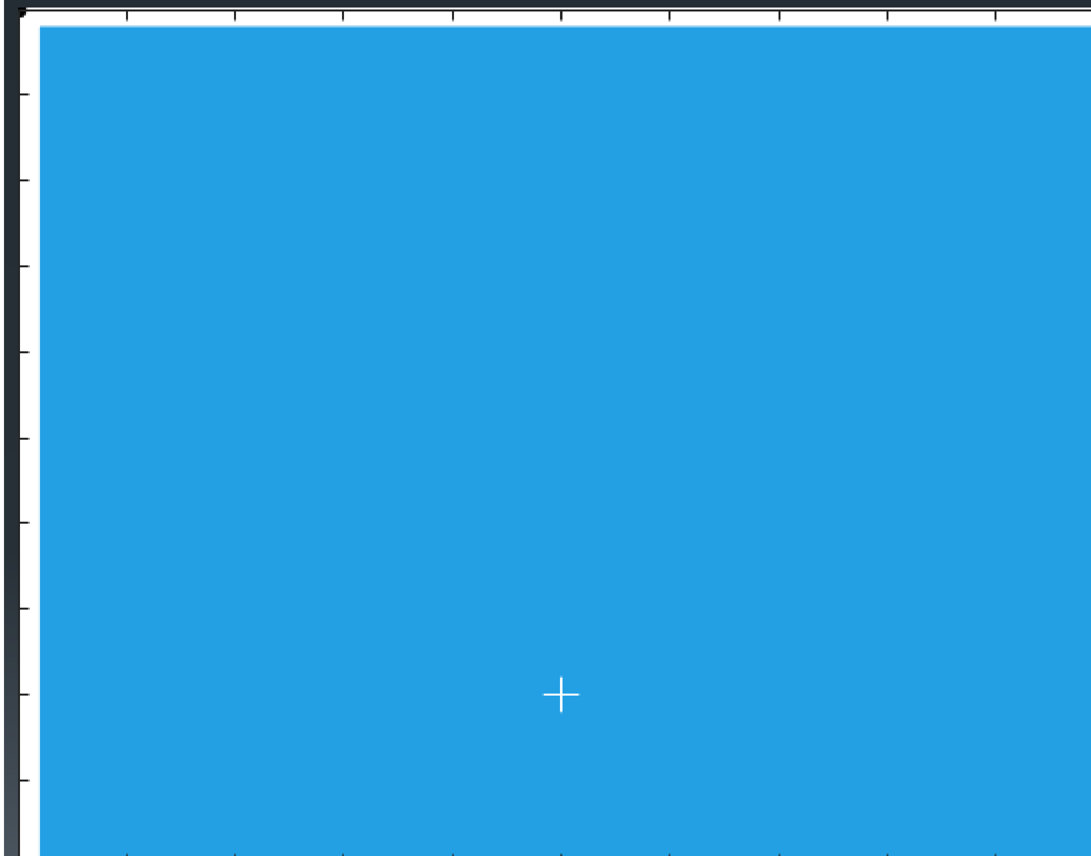
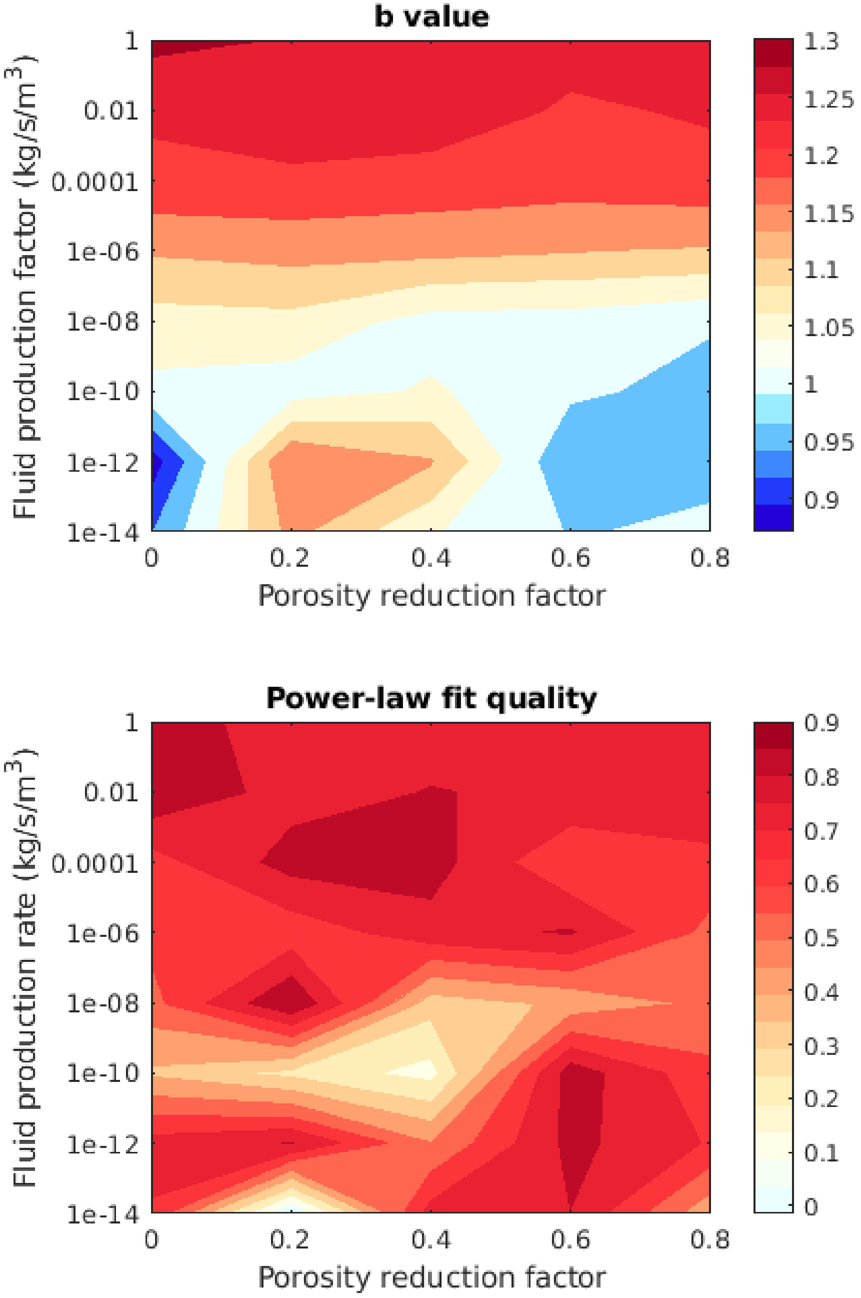
Fluid Flow Cellular Automaton



Hooker and Fisher, in prep.





Hooker and Fisher, in prep.

Effect of fluid system on earthquake size distributions

Conclusions

- The subduction interface shows evidence for variable slip behavior-important involvement of mineral redistribution.
- Silica kinetics modeling suggest healing at rates that can impact slip on the interface.
- A numerical block-slider model for the interface evaluates a population balance equation for asperity formation based on stochastic healing by silica redistribution.
- An exponential temperature-dependent rate law for nucleation and strengthening, based on Arrhenius-equation silica kinetics, leads to: 1) supercycles of buildup and release of elastic strain, 2) a temperature-based up-dip limit to genesis of large earthquakes, and 3) a power law size distribution of earthquakes that varies as a function of temperature.
- Slip behavior on the Subduction interface is modulated by feedbacks between geochemical processes and the fluid flow system