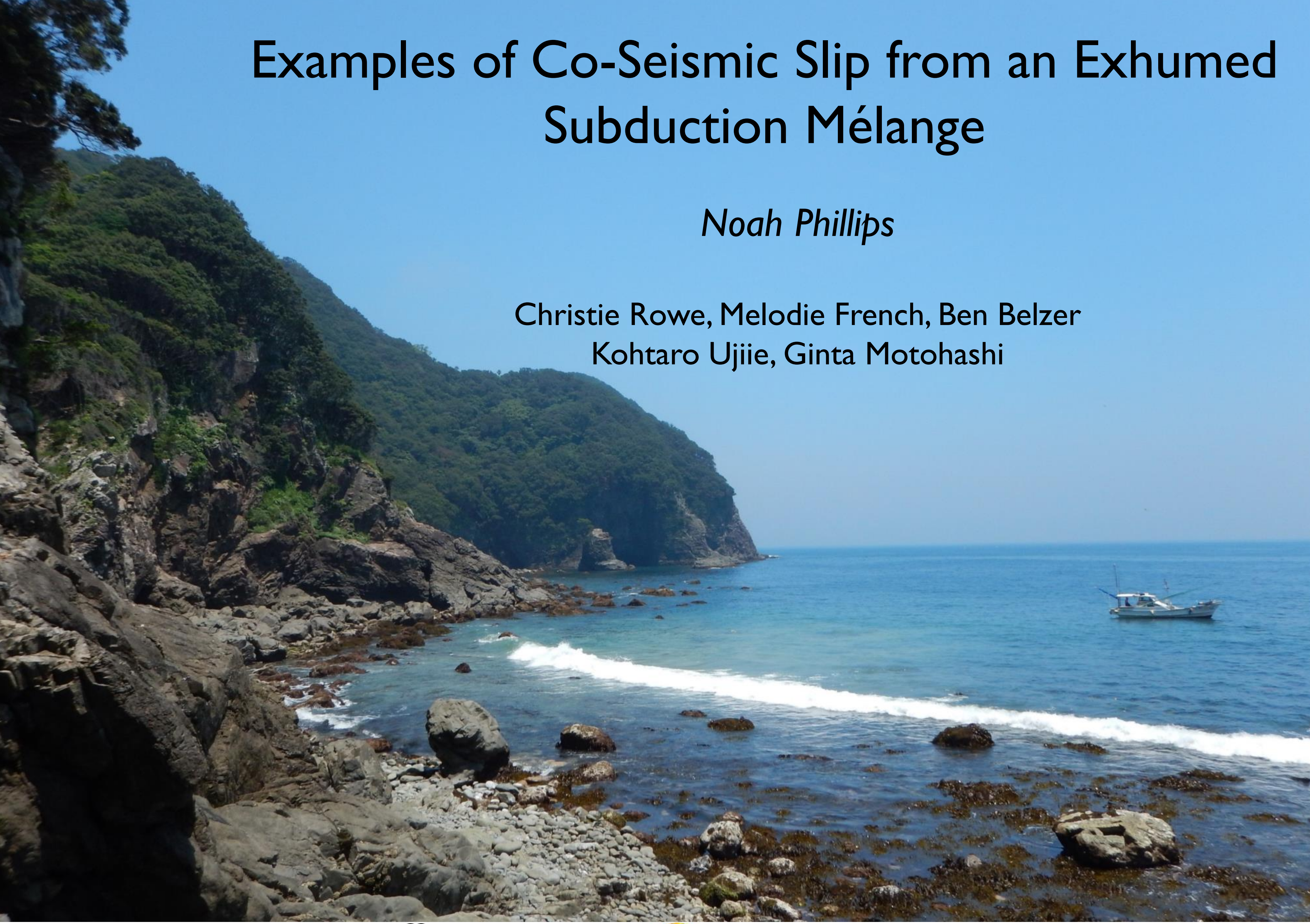
Examples of Co-Seismic Slip from an Exhumed Subduction Mélange

Noah Phillips

Christie Rowe, Melodie French, Ben Belzer
Kohtaro Ujiie, Ginta Motohashi



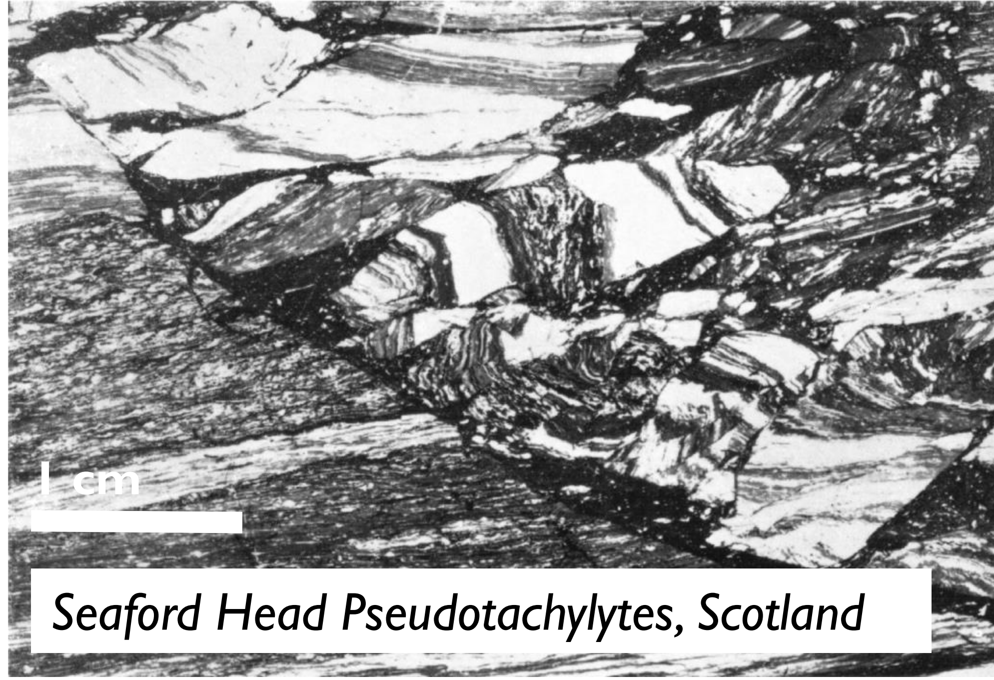
McGill 筑波大学 University of Tsukuba EEPS NSERC CRSNG THE GEOLOGICAL SOCIETY OF AMERICA® Science of Slow Earthquakes

Talk Outline

1) The Case of Frictional Melts:
   -Pseudotachylyte strength during and post formation

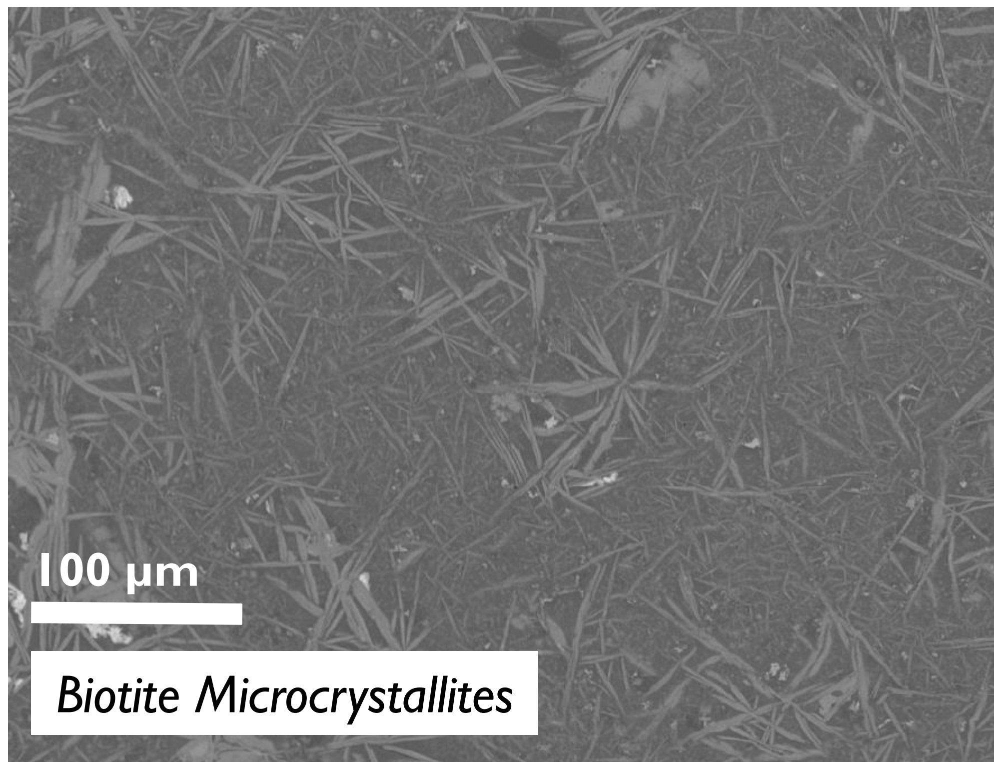
2) The Frictional Properties of an Exhumed Subduction Mélange
   -Which lithologies control the "seismogenic zone"?

Fort Foster Pseudotachylytes, USA



Seaford Head Pseudotachylytes, Scotland

Lower Crustal Pseudotachylyte, Namibia



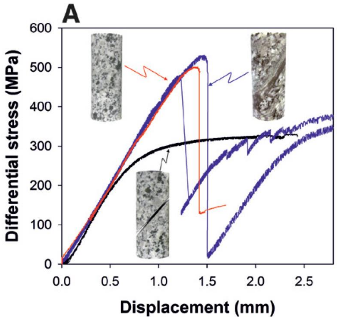
Biotite Microcrystallites

What is the Strength of Pseudotachylyte in Different Stages of the Earthquake Cycle?

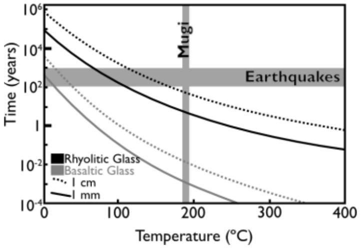
1) During Seismic Slip

(e) $\tau = 2.27$ MPa

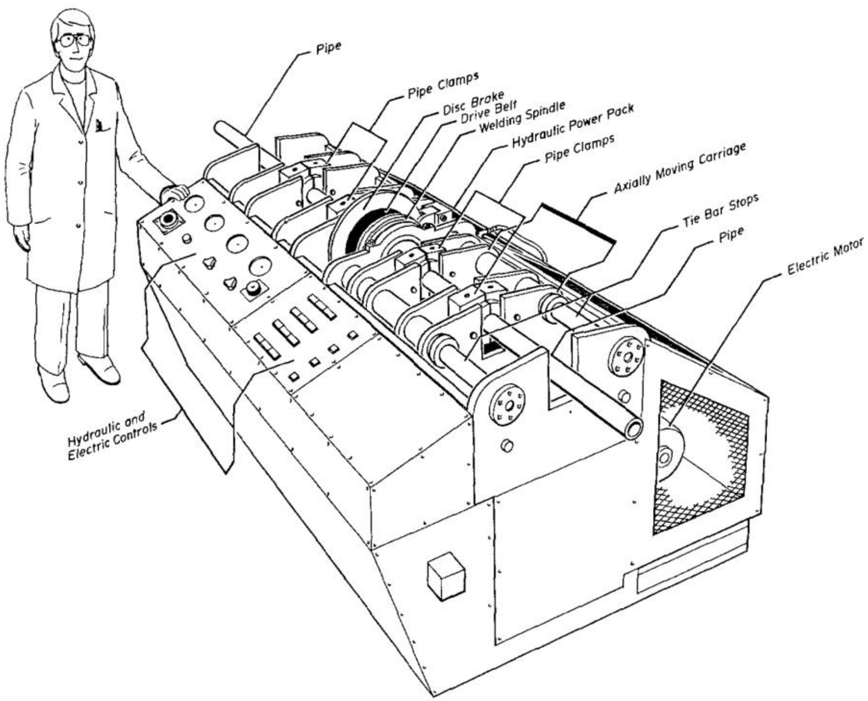
2) Immediately Following Slip



3) Years Following Slip



During Seismic Slip

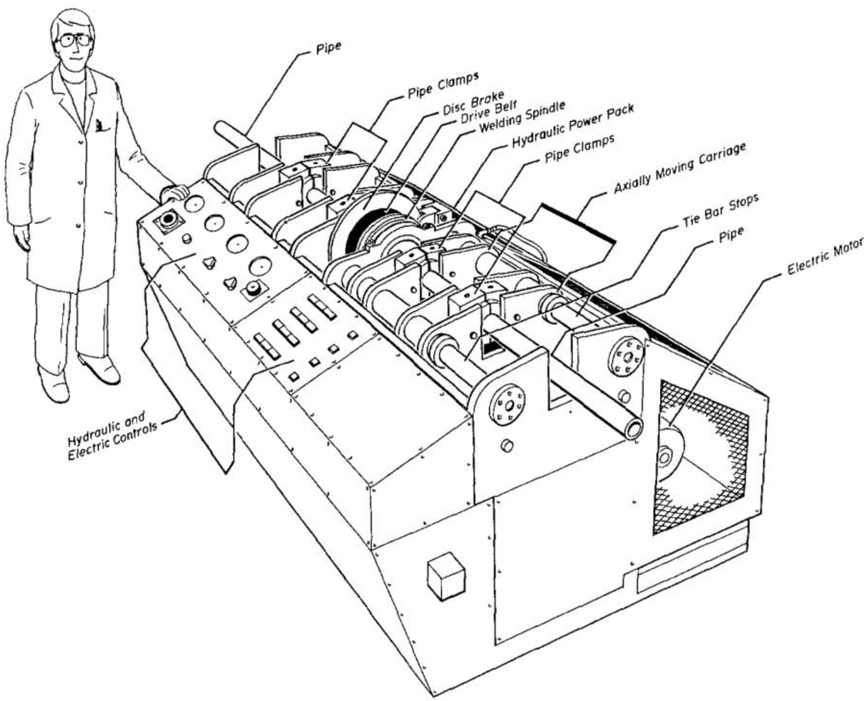


Spray 1987 , 1988

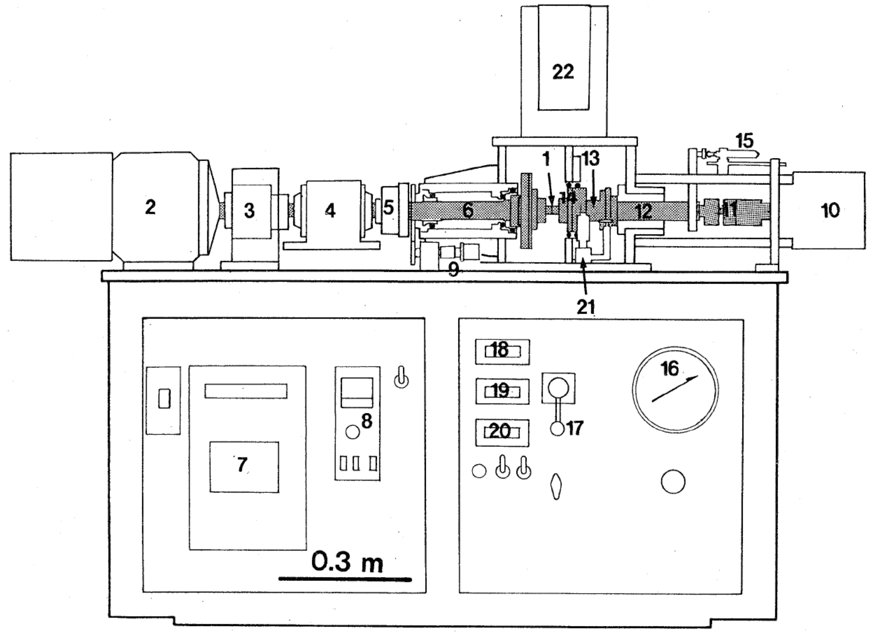
First High-Velocity Rotary Shear Apparatus used on Rocks

- A "Friction Welder": Machine used to weld metal pipes together
- Modified the apparatus for rocks
- Limitations: Could not accurately measure the torque or shear stress required to melt the rocks

During Seismic Slip



Spray 1987 , 1988

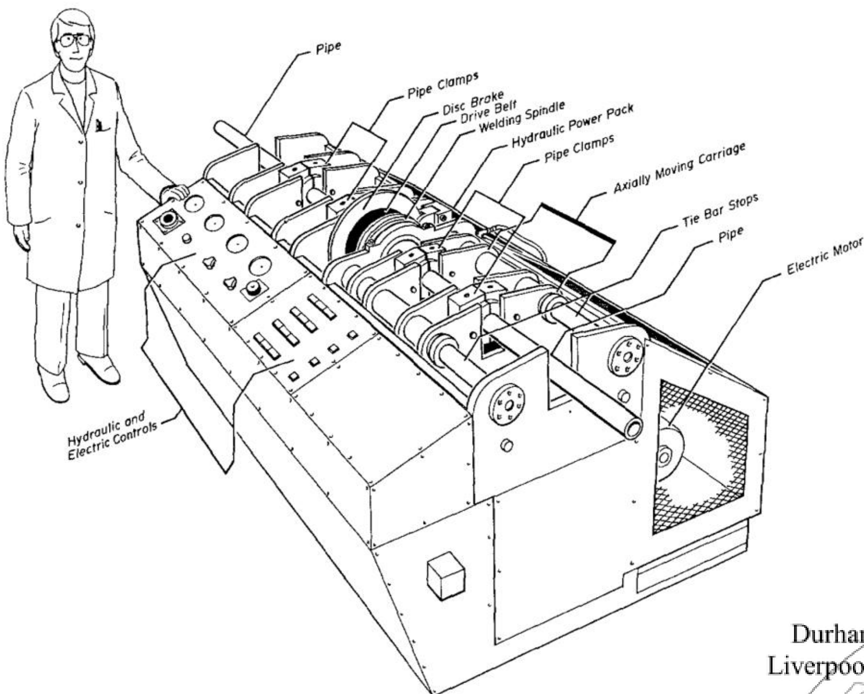


Shimamoto & Tsutsumi 1994
Tsutsumi & Shimamoto 1996

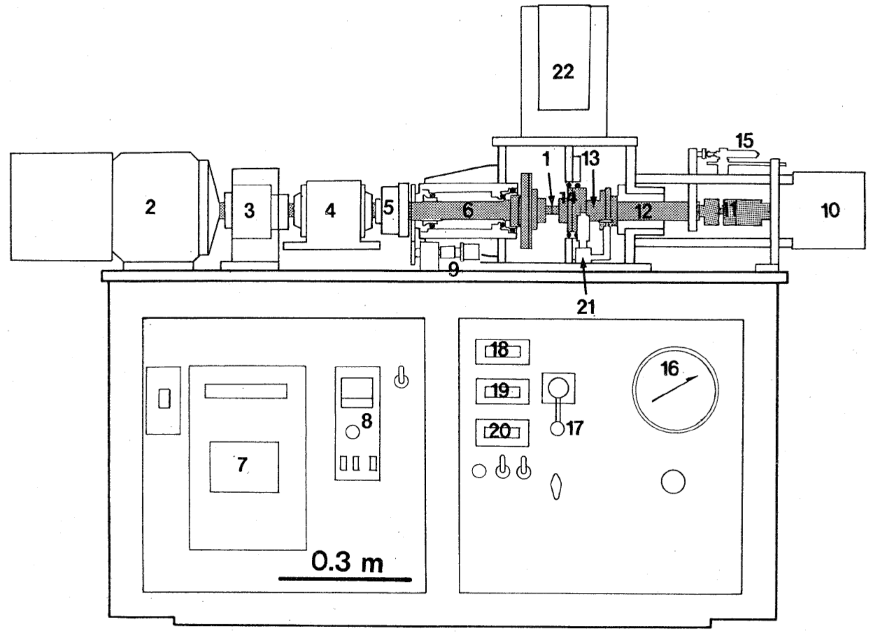
First High-Velocity Rotary Shear Apparatus that could Measured Shear Stress

- Designed by Shimamoto-san and Tsutsumi-san (Kyoto University)
- First Experiments that Demonstrated Dramatic Weakening During Earthquake Slip Rates

During Seismic Slip

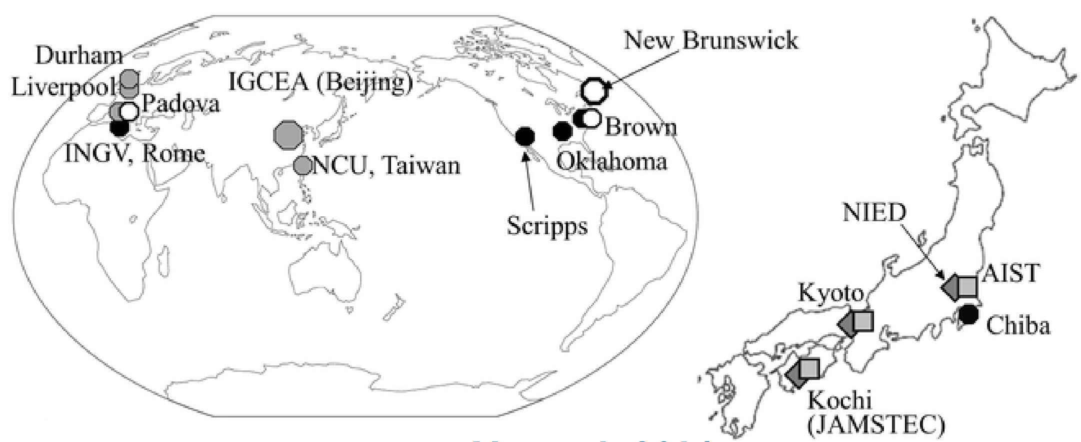


Spray 1987 , 1988



Shimamoto & Tsutsumi 1994
Tsutsumi & Shimamoto 1996

High-Velocity Frictional Testing Apparatuses

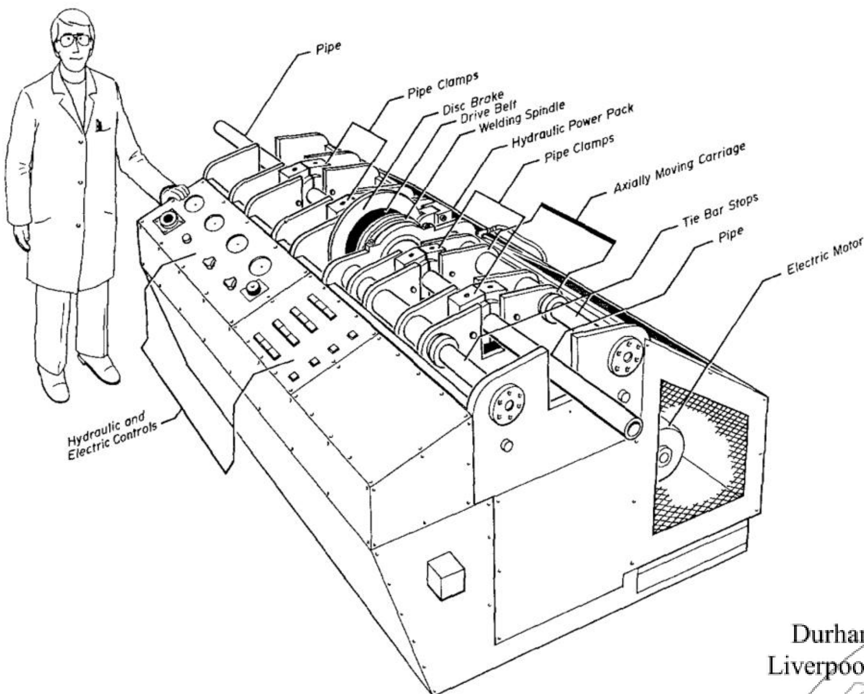


Ma et al. 2014

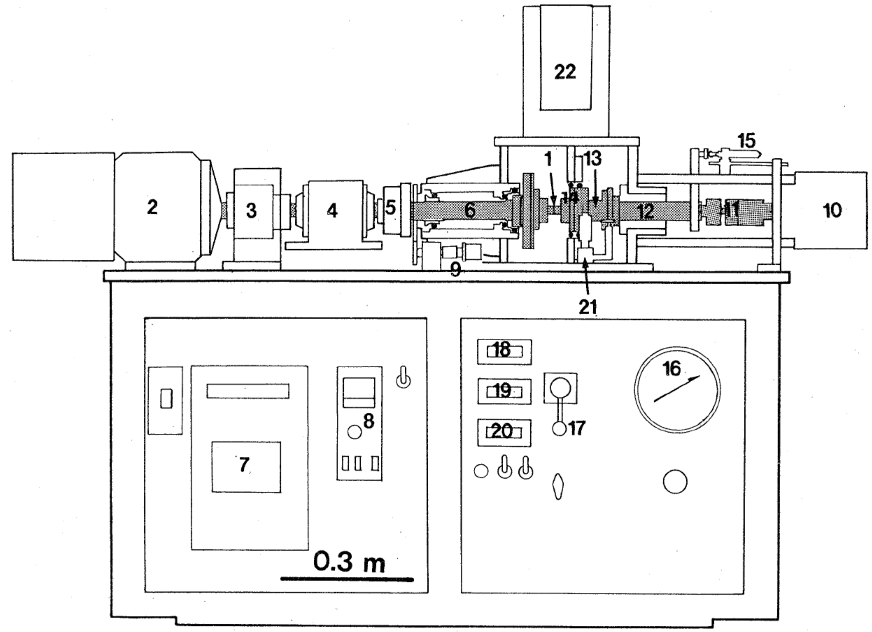
During Seismic Slip

Limitations: - Normal Stress < ~25MPa

- Measuring conditions <1 km depth



Spray 1987 , 1988



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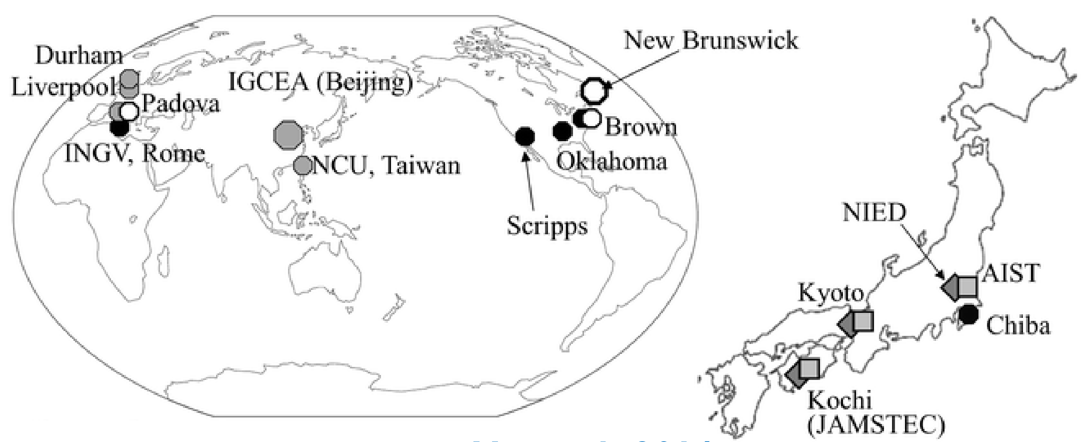
High-Velocity Frictional Testing Apparatuses

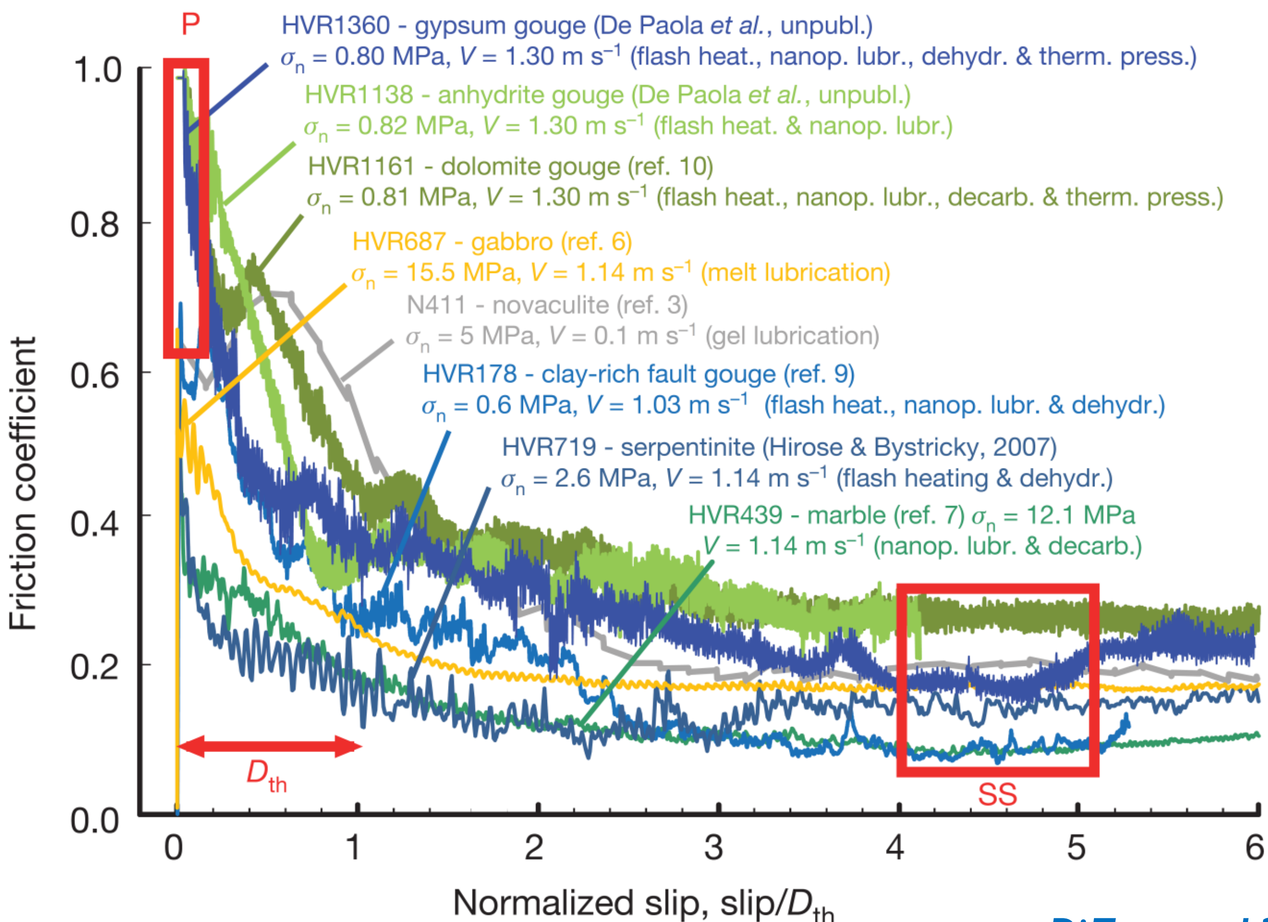


Ma et al. 2014

During Seismic Slip

University of Liverpool , Andesite

During Seismic Slip



Di Toro et al 2011

Key Points

- All materials become weak during seismic slip

During Seismic Slip

Ujiie et al 2007b

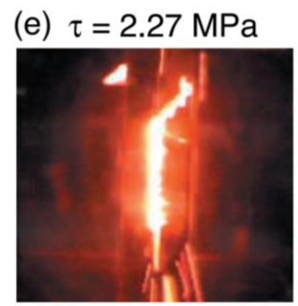
Microstructural observations of natural pseudotachylyte confirm very low shear stresses

Calculate viscosity from composition and melting temperature

Flow stress ~0.1 MPa

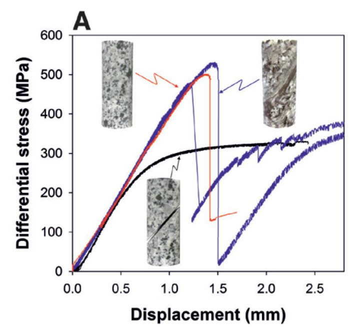
What is the Strength of Pseudotachylyte in Different Stages of the Earthquake Cycle?

1) During Seismic Slip

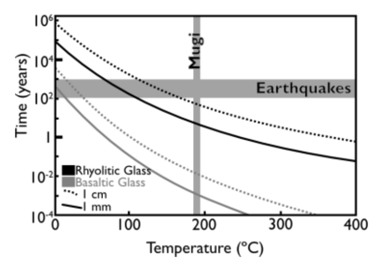


WEAK

2) Immediately Following Slip



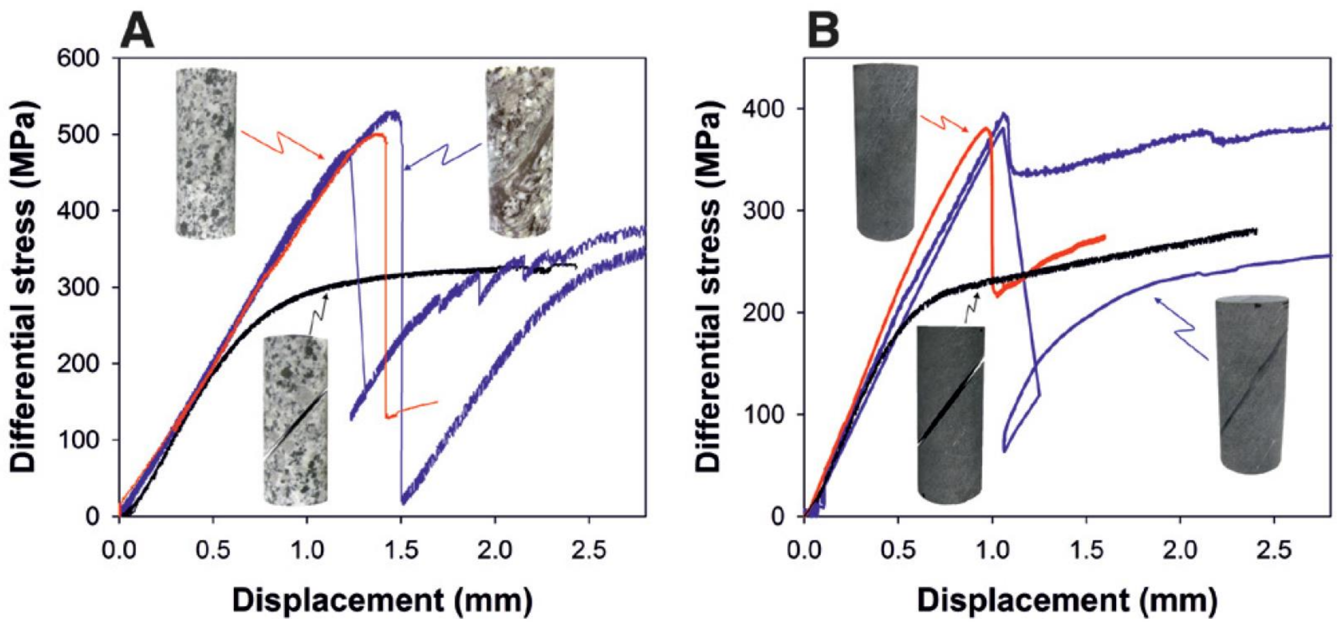
3) Years Following Slip



Immediately Following Slip

Three recent sets of experiments have examined the strength of pseudotachylyte.

Mitchell et al 2016 examined the strength of pseudotachylytes hosted in tonalities and felsic mylonites. They found that the strength of the pseudotachylyte was as high as intact host rock.



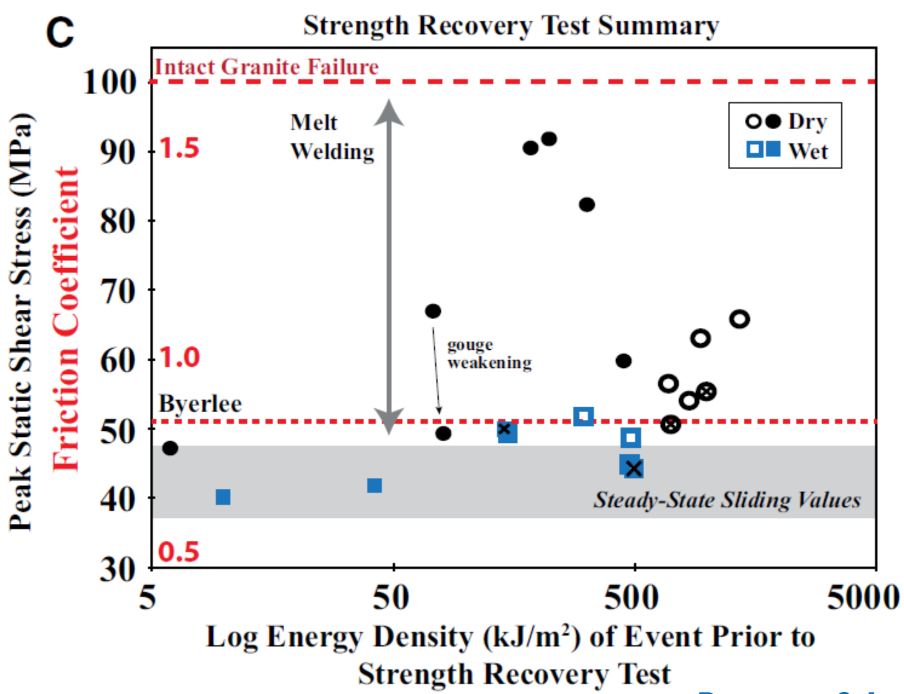
Mitchell et al 2016

BLUE – Intact Host Rock , **RED** – Host with Pseudotachylyte , **BLACK** – Sawcut

Immediately Following Slip

Three recent sets of experiments have examined the strength of pseudotachylyte.

Proctor & Lockner 2016 produced pseudotachylyte in granite during stick-slip triaxial experiments. They found that when pseudotachylyte formed that the fault was stronger than the sliding strength (Byerlee friction).

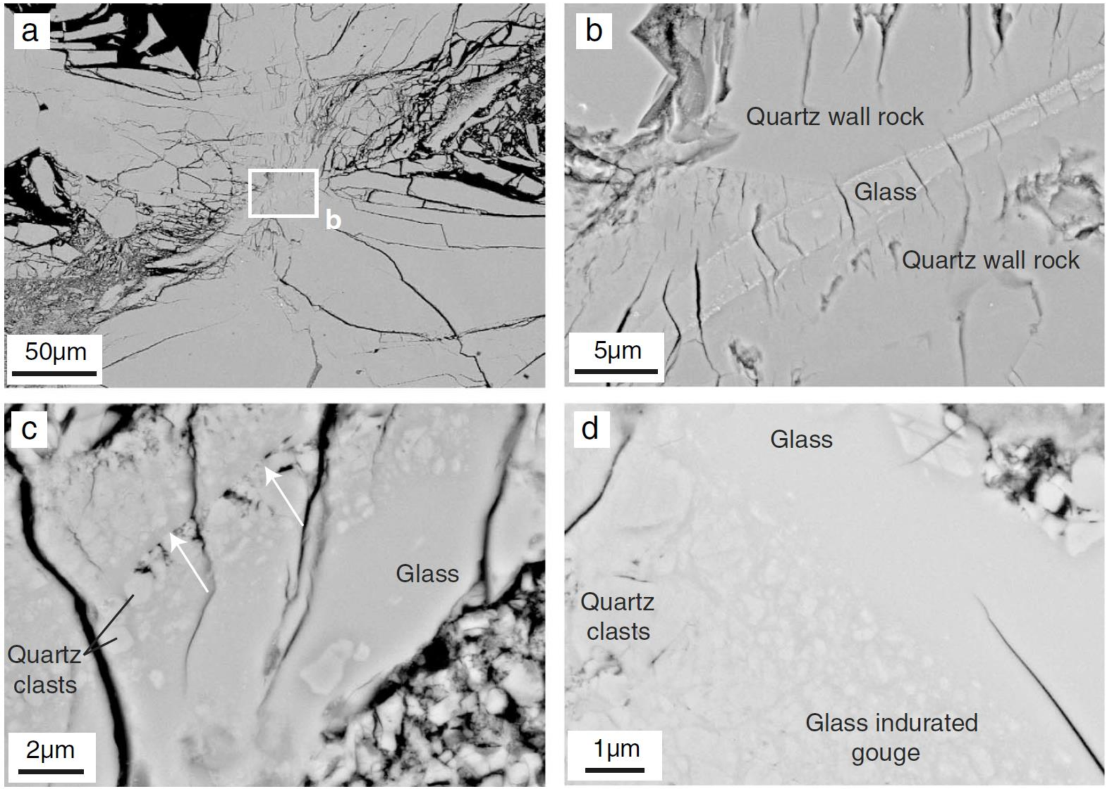


Proctor & Lockner 2016

Immediately Following Slip

Three recent sets of experiments have examined the strength of pseudotachylyte.

Hayward & Cox 2017 produced pseudotachylyte in sandstone then reoriented the sample and conducted another experiment. They found that where pseudotachylyte was present that a new fault would form on a new surface.



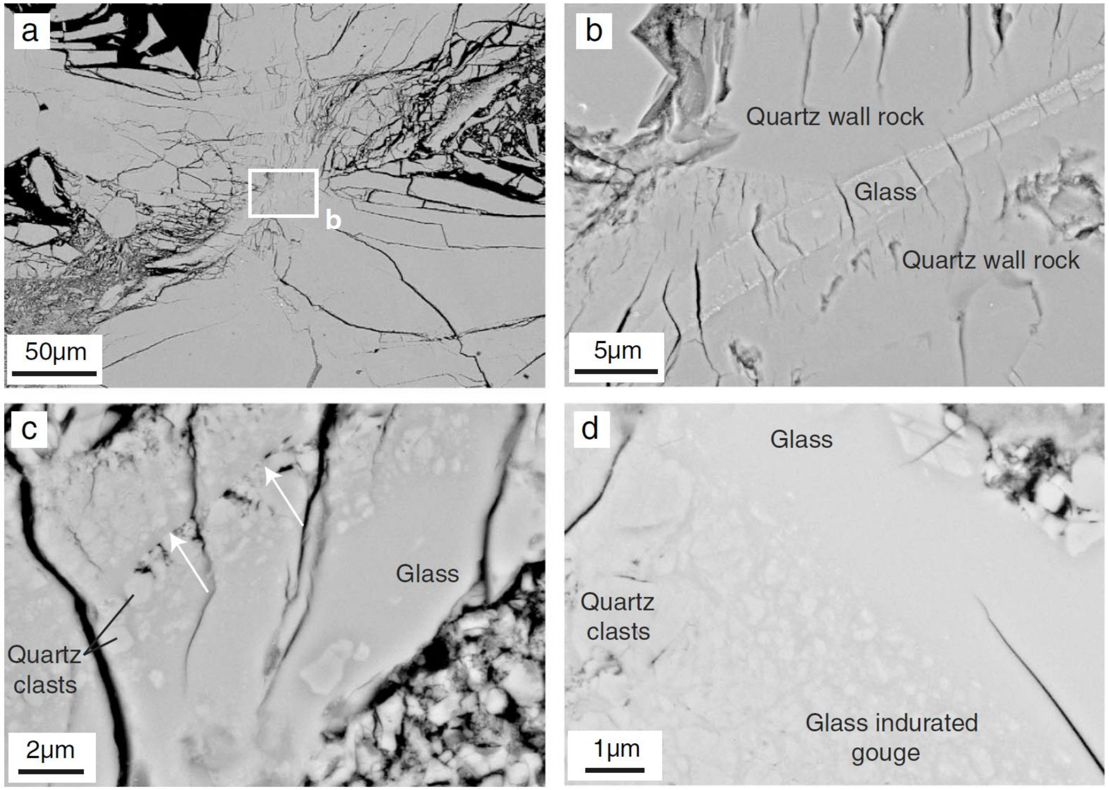
Hayward & Cox 2017

Immediately Following Slip

Three recent sets of experiments have examined the strength of pseudotachylyte.

ALL EXPERIMENTS SHOW THAT PSEUDOTACHYLYTES ARE STRONG!!!

Imply that pseudotachylytes should be easily preserved in rock record.



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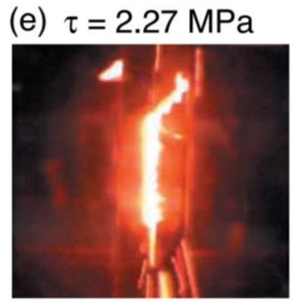

WEAK

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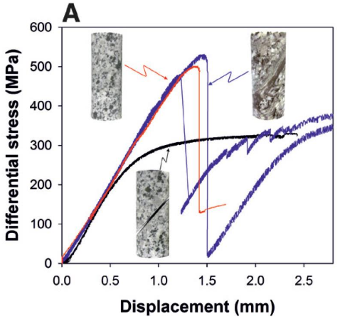
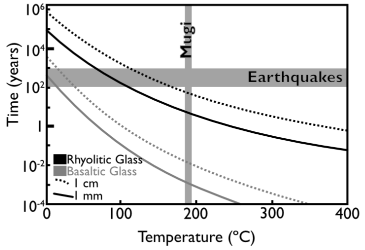
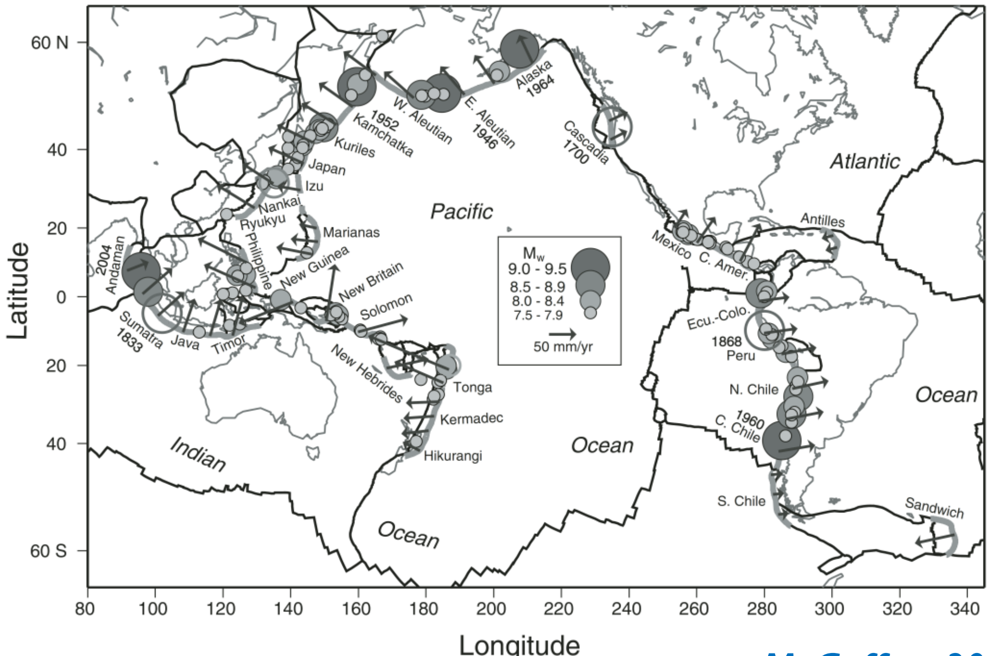


STRONG

3) Years Following Slip



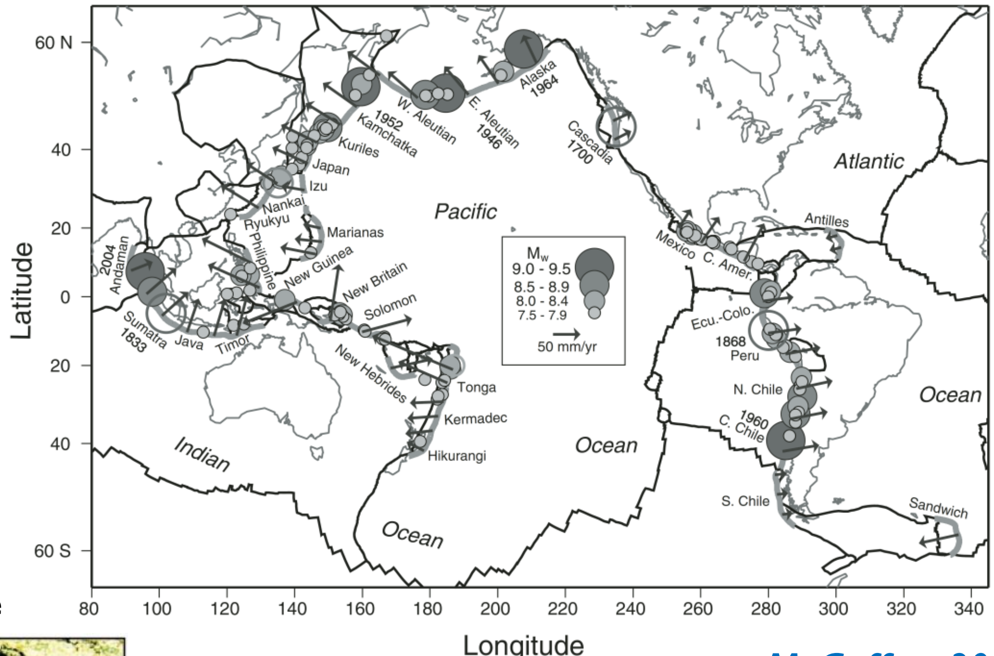
Years Following Slip



McCaffrey 2008

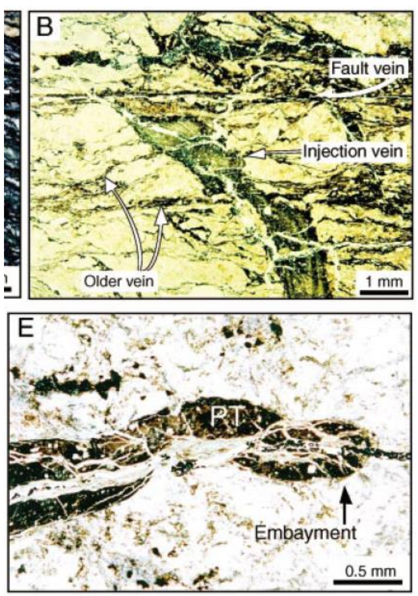
If pseudotachylytes are strong, and large magnitude earthquakes are ubiquitous in subduction zones, then we should find pseudotachylyte all the time.

Years Following Slip



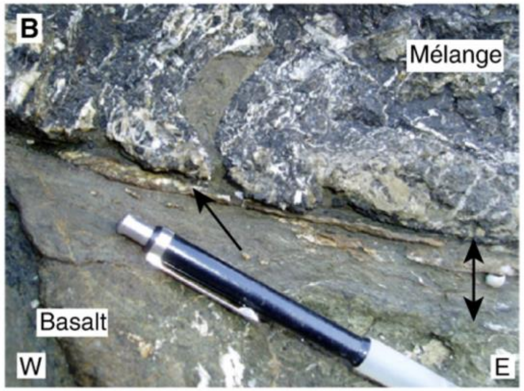
McCaffrey 2008

Pseudotachylyte



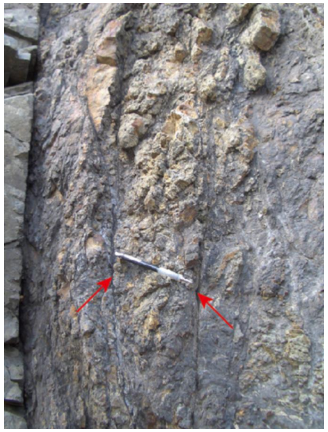
Ikesawa et al 2003

Fluidized Ultracataclasite



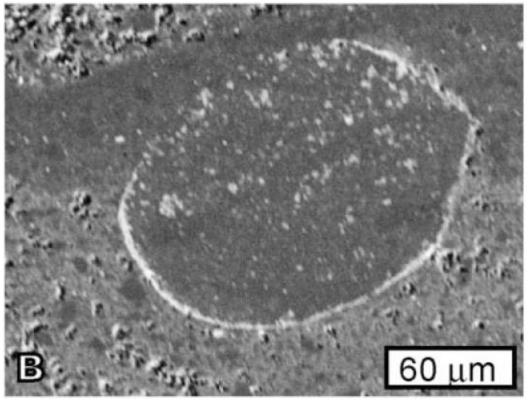
Ujiie et al 2007a

Pseudotachylyte



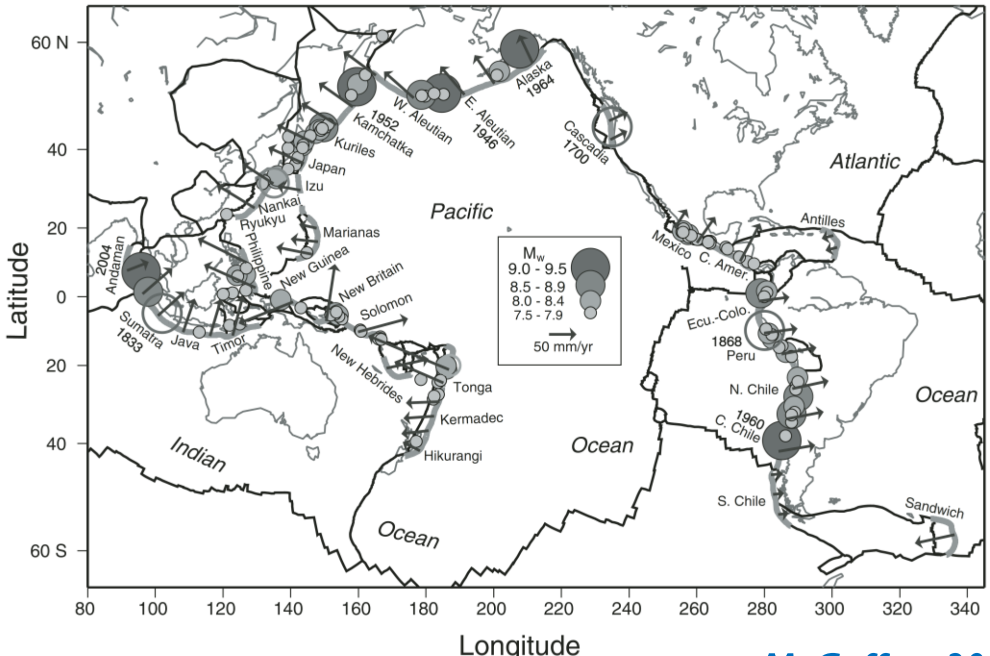
Ujiie et al 2007b

Pseudotachylyte



Rowe et al 2005

Years Following Slip



McCaffrey 2008

Why are there so few pseudotachylytes in exhumed subduction zones?

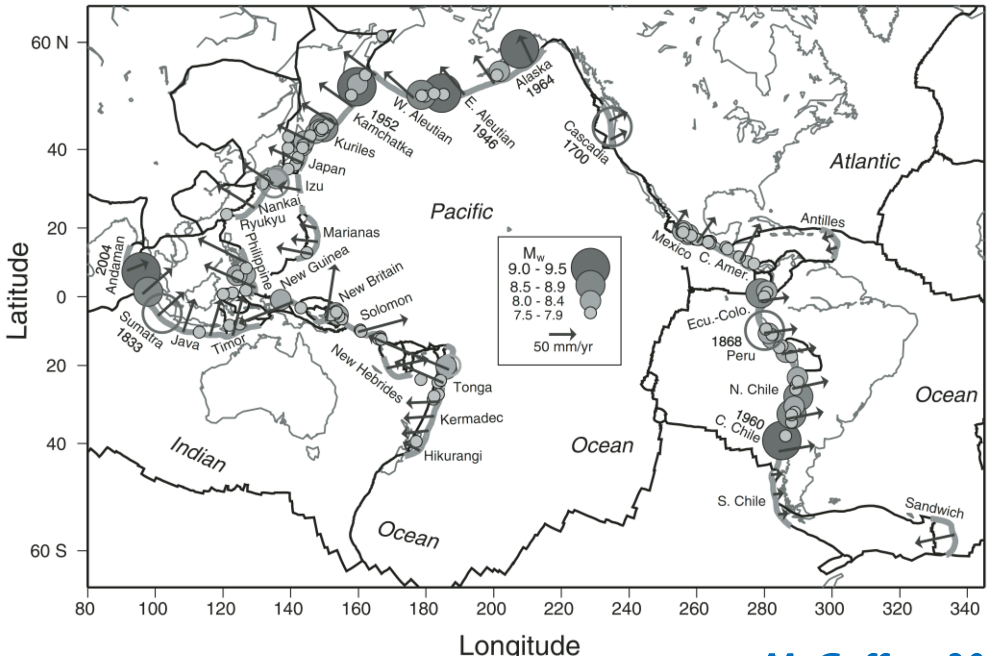
POSSIBILITIES

1) They are hard to find *Kirkpatrick et al 2009*

2) They don't form (other mechanisms occur during seismic slip) *Sibson & Toy 2006*

3) They are replaced by other minerals *Kirkpatrick & Rowe 2013*
This Study

Years Following Slip



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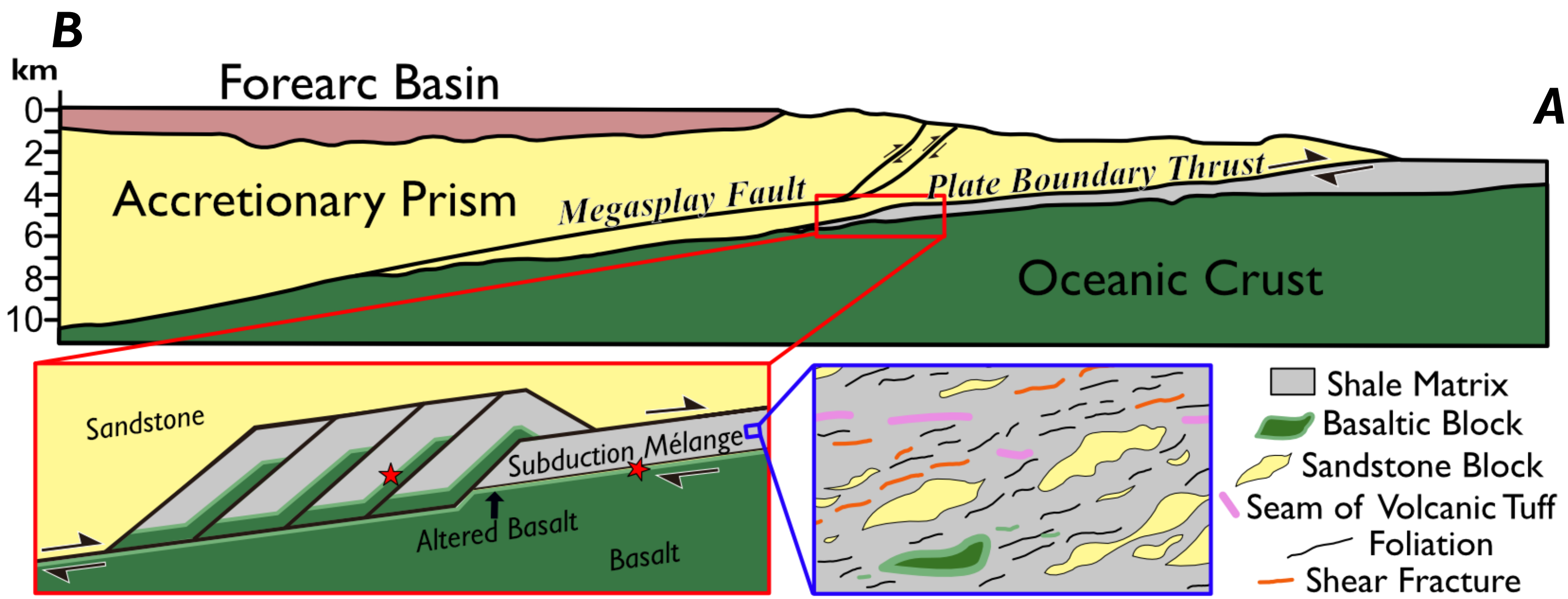


Paleo-setting of Mugi Mélange

Phillips et al 2019

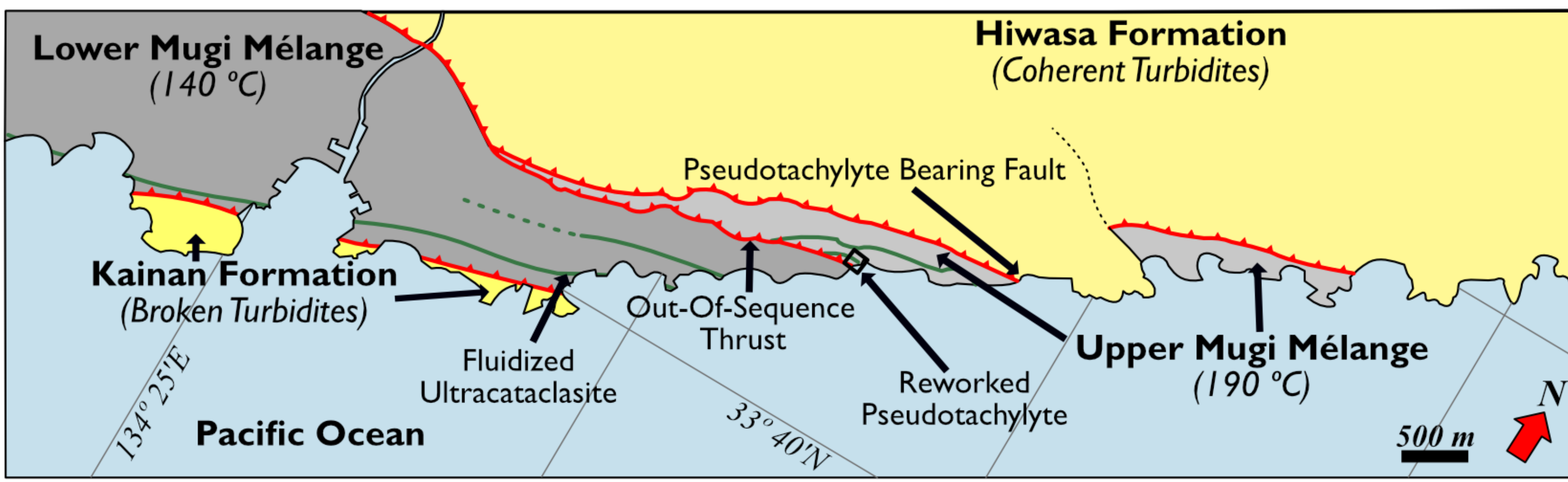
The Mugi Mélange is an exhumed analogue of present day subduction at Nankai.

Subducting sediment forms a zone of distributed shear between the downgoing plate and the overriding accretionary prism. This zone of distributed shear is the host for megathrust earthquakes and shallow tremor

Years Following Slip

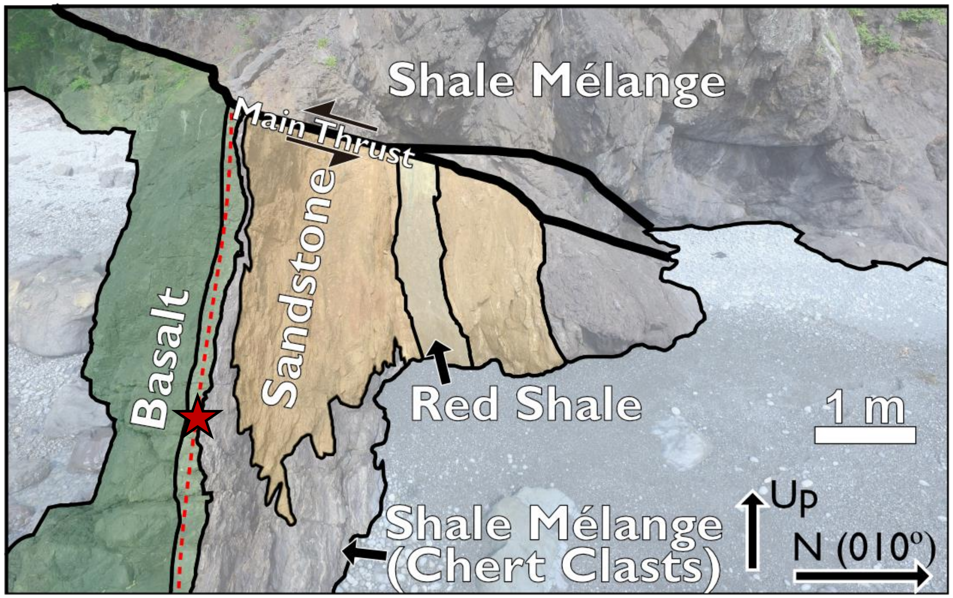
Seismic features are located at three sites in the Mugi Mélange:

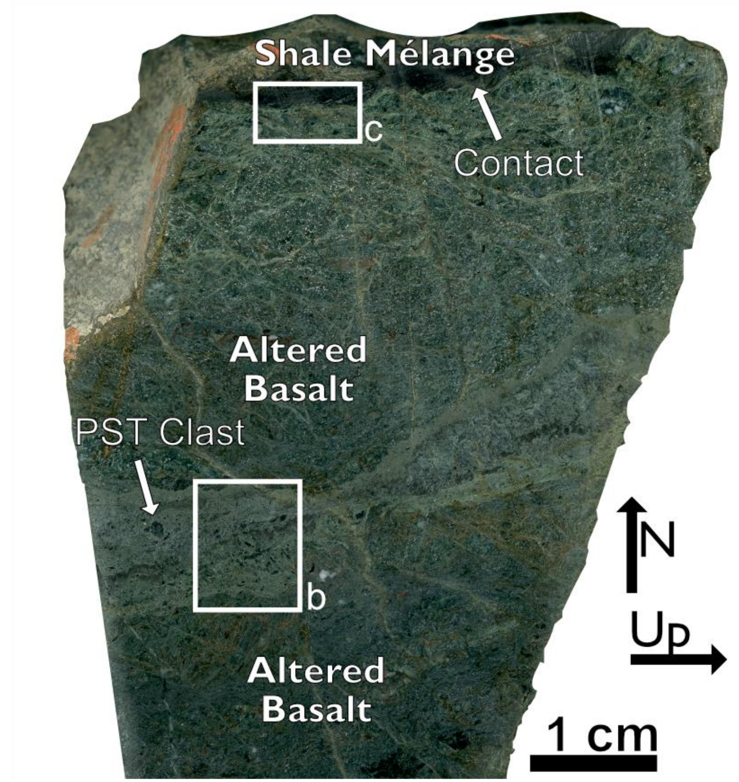
1) *Pseudotachylyte exists at the interface between the accretionary prism and the mélange*
2) *A fluidized ultracataclasite exists along the upper contact of a basaltic slab*
3) *Reworked pseudotachylyte exists along the upper contact of a basaltic slab*



Phillips et al 2019 ; Adapted from Shibata et al 2008

Years Following Slip



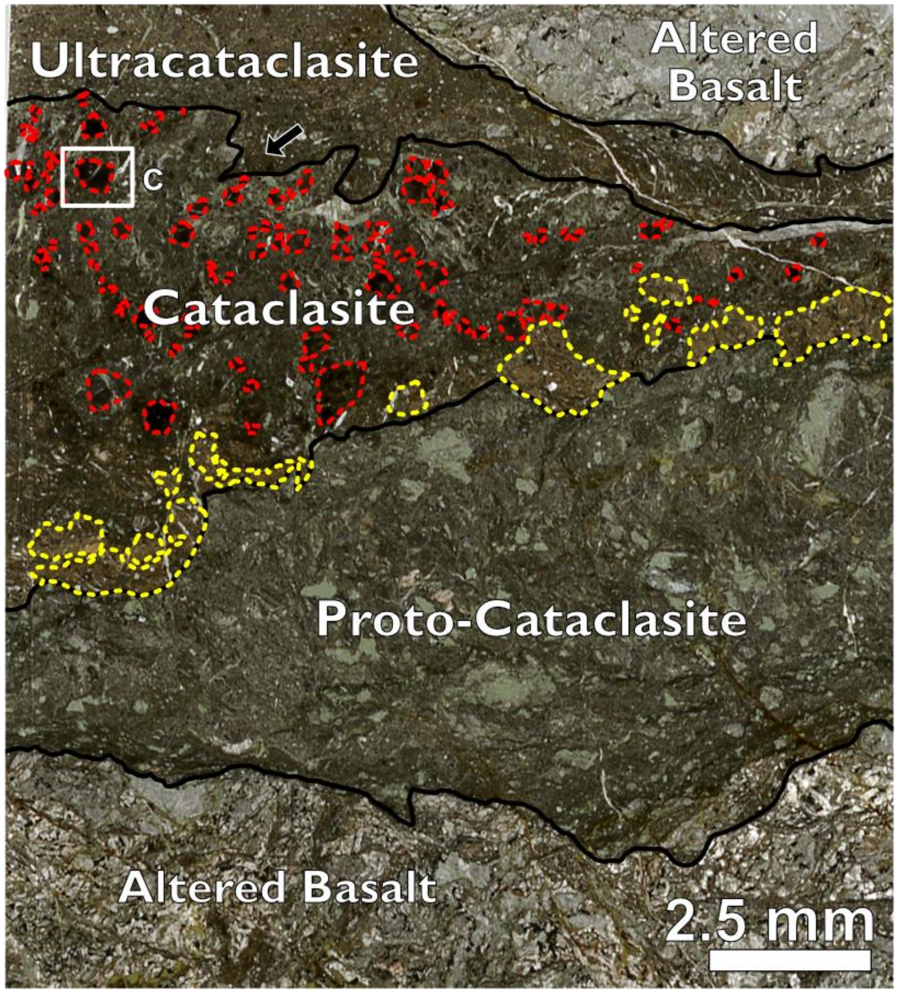


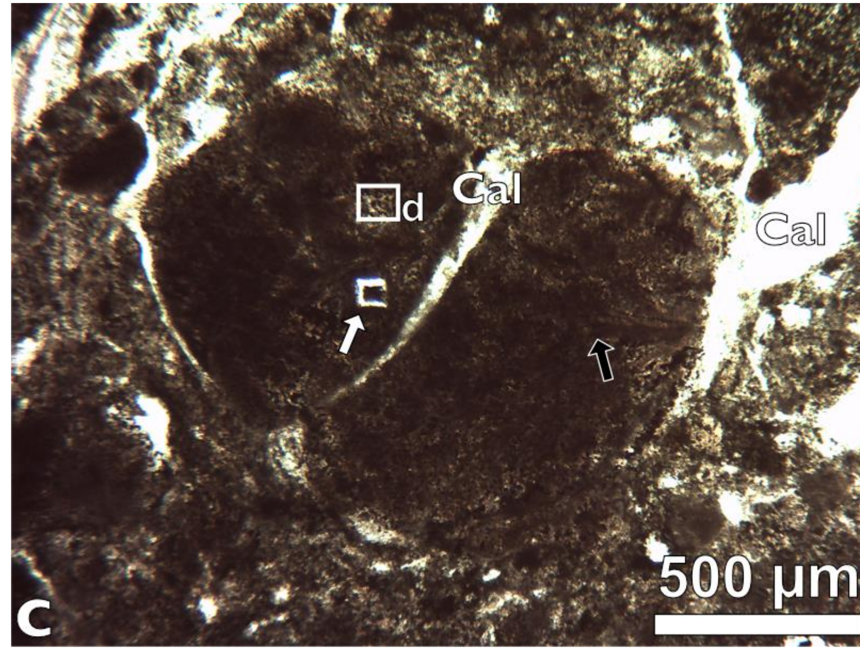
Phillips et al 2019

Altered basalt has well developed faults with widths ranging from 100's of μm to mm.

Composed of plagioclase, chlorite, and Ti-oxides.
Deformation features are localized.

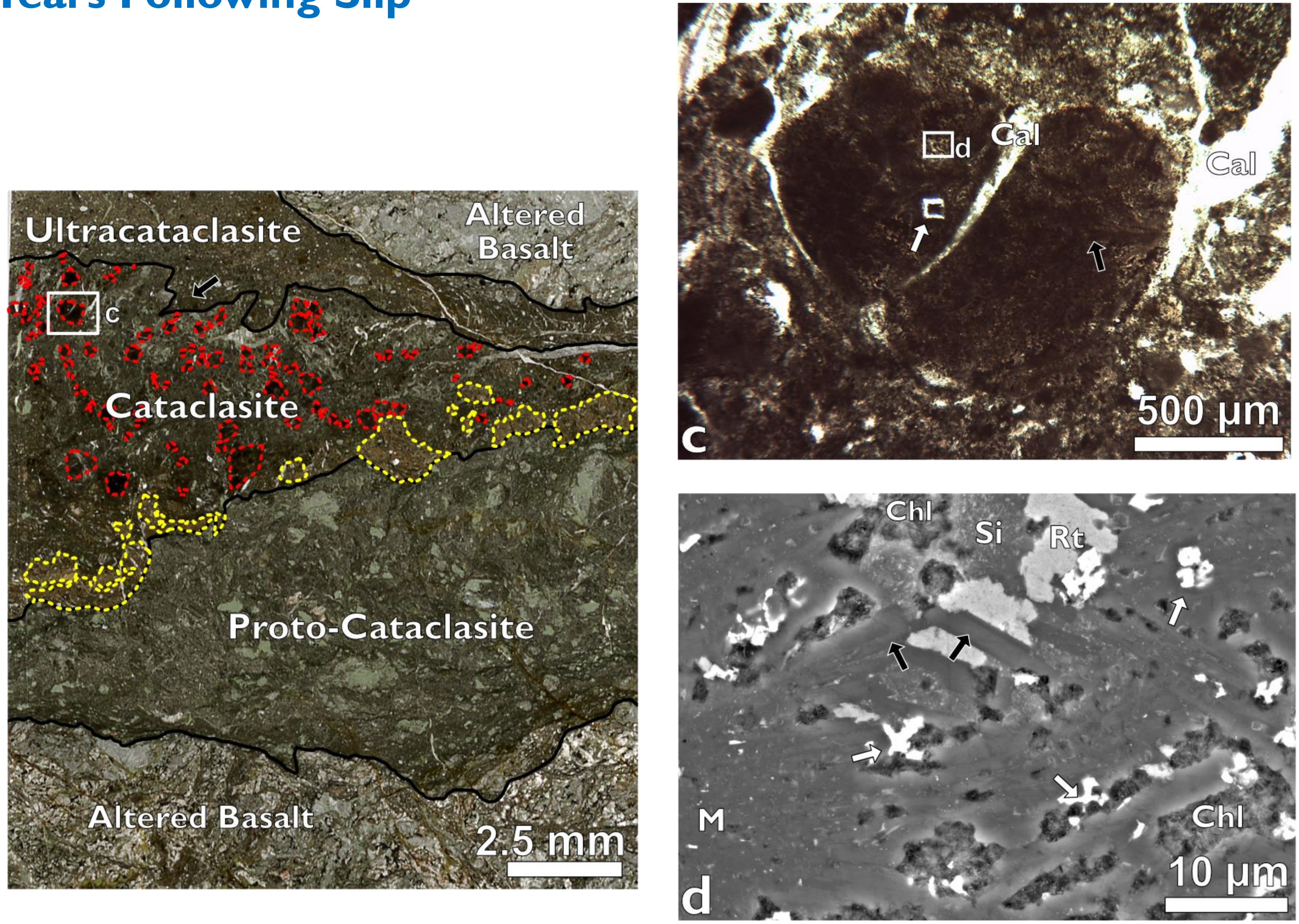
Years Following Slip

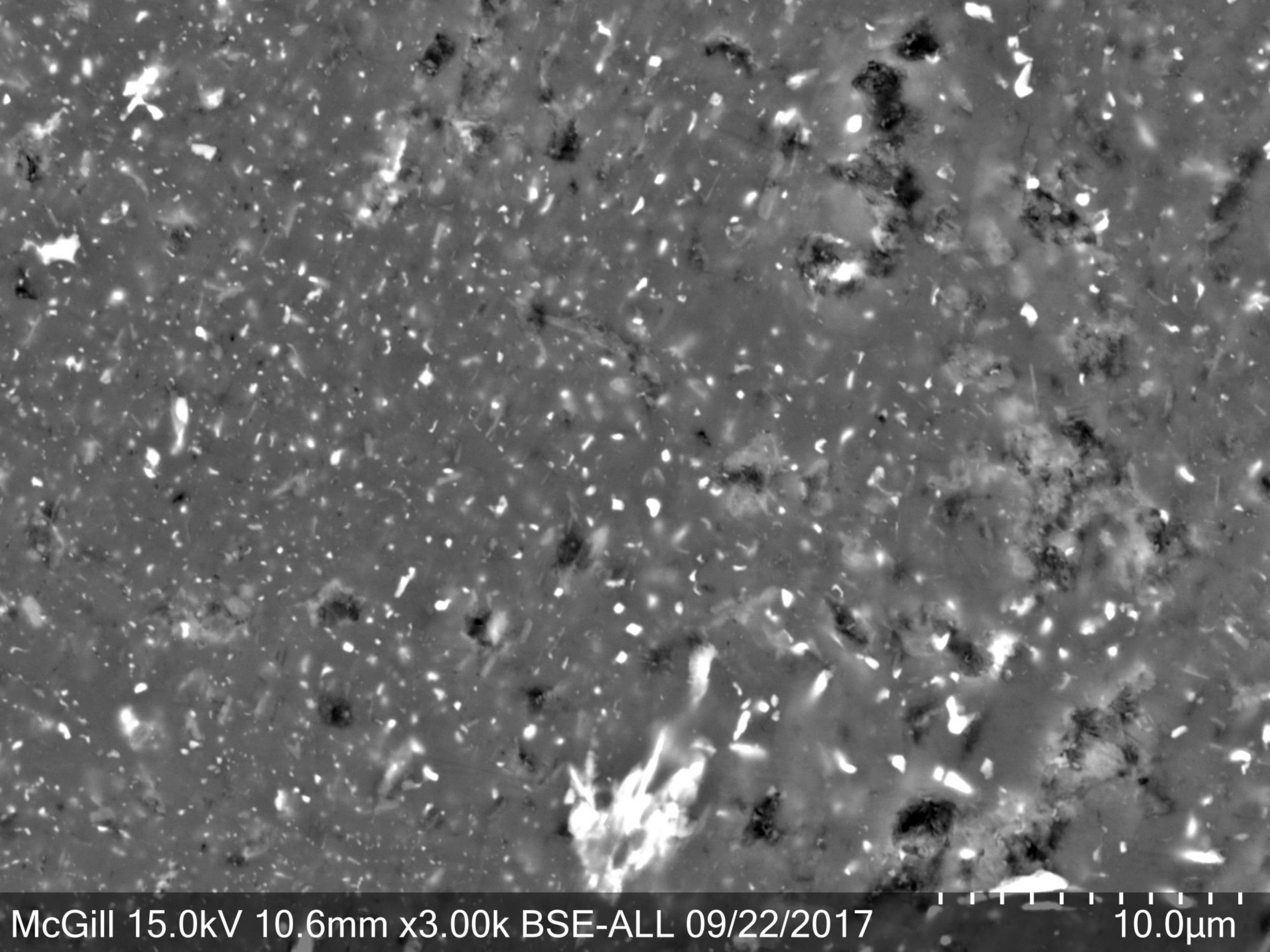




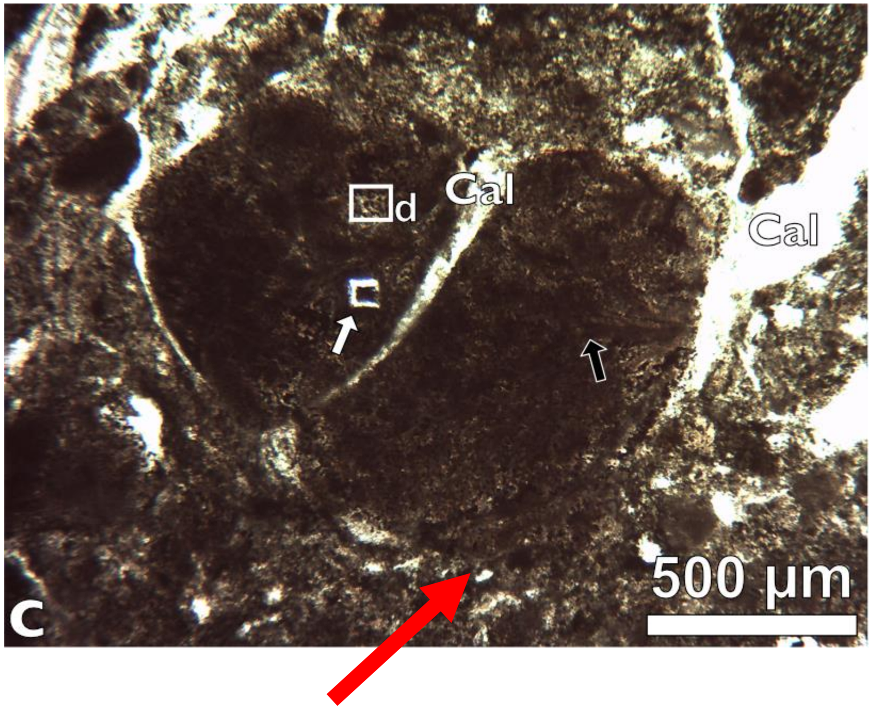
Reworked pseudotachylyte exists within the altered faults and is evidence for seismic events.

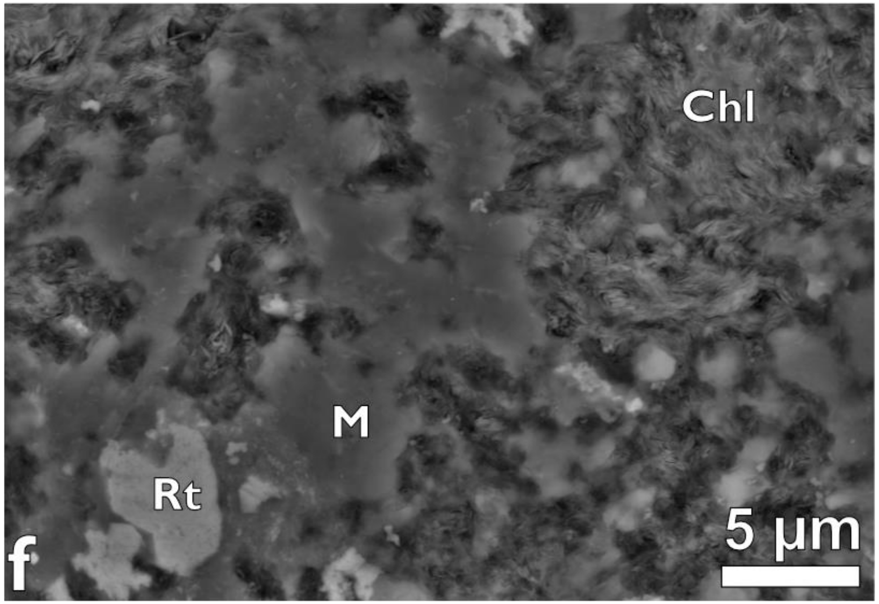
Years Following Slip




McGill 15.0kV 10.6mm x3.00k BSE-ALL 09/22/2017
10.0μm

Years Following Slip





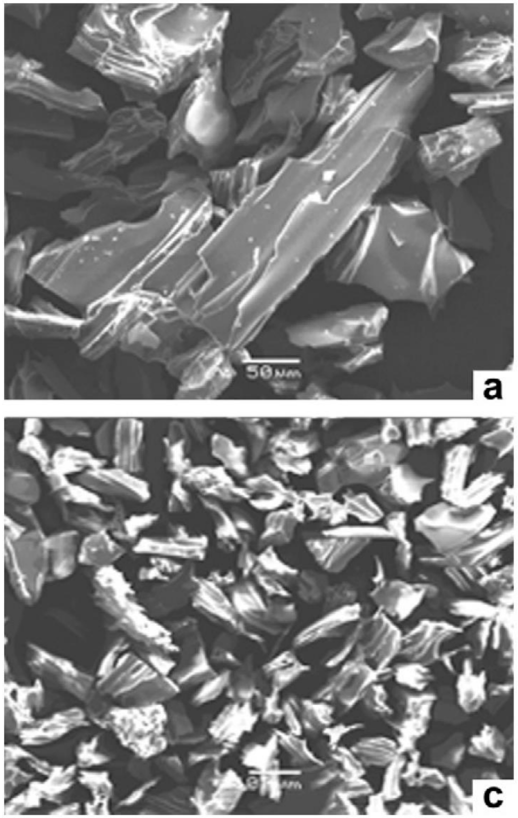
Phillips et al 2019

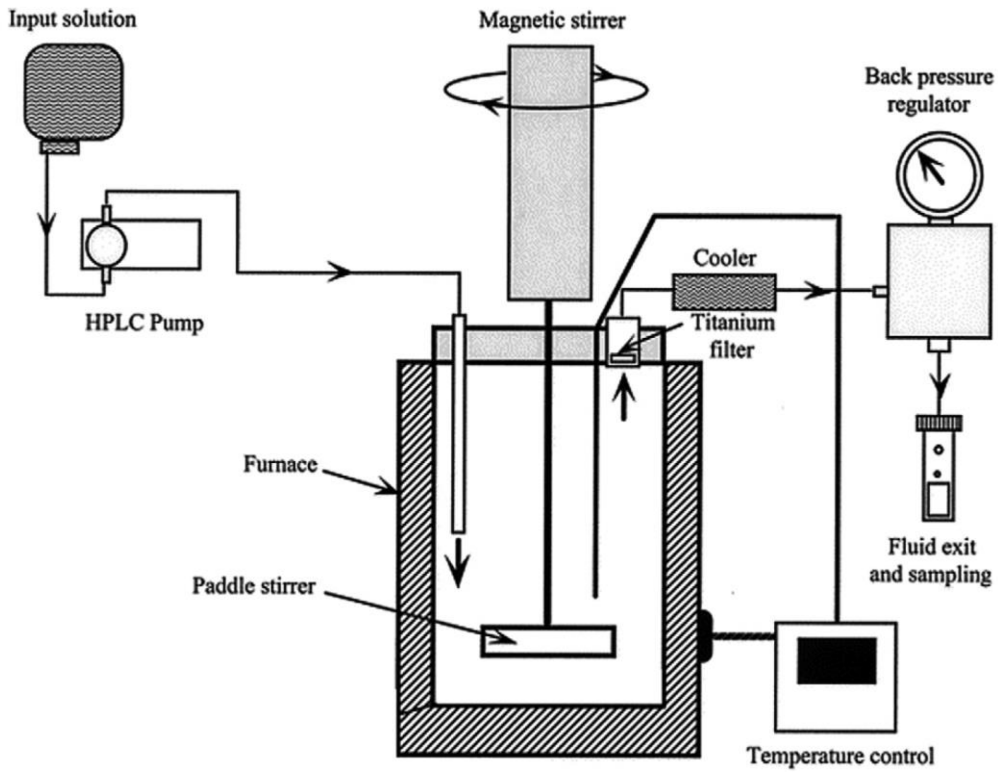
Along the margins of the pseudotachylyte clasts alteration to chlorite occurs

Chlorite is weak compared with most rocks and minerals ($\mu = 0.3$)

e.g. Behnsen & Faulkner, 2012

Years Following Slip



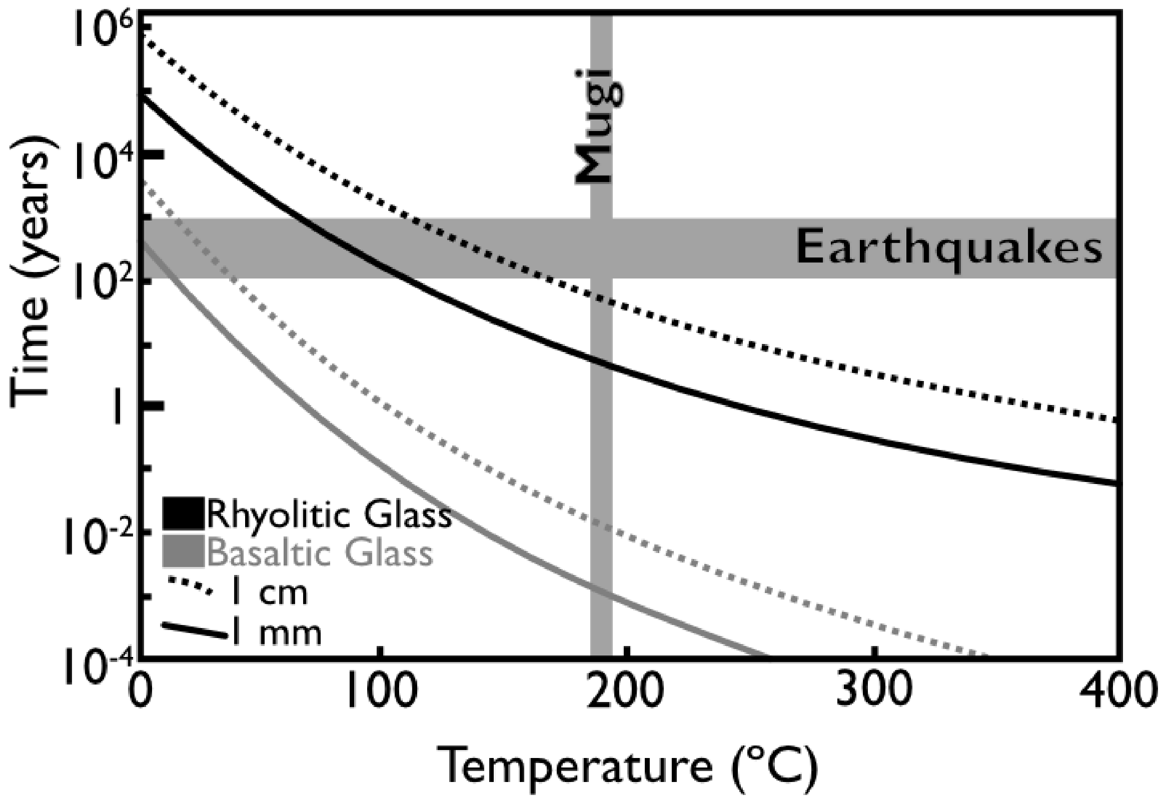


Declerq et al 2013

We calculate the rate of alteration of pseudotachylyte based on dissolution experiments on basaltic and rhyolitic glasses in seawater

Originally used to calculate how quickly basaltic glasses at the surface dissolve and enter the ocean (for Si, Fe, and Mg budgets)

Years Following Slip

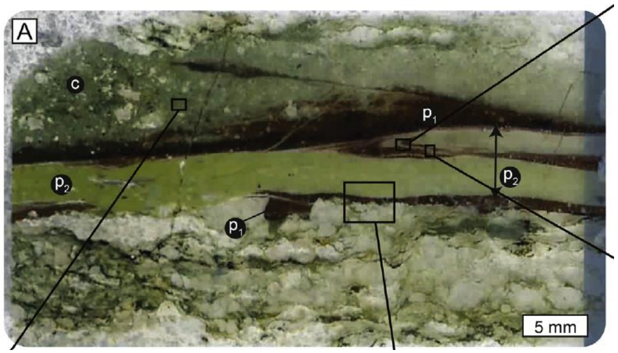


Phillips et al 2019

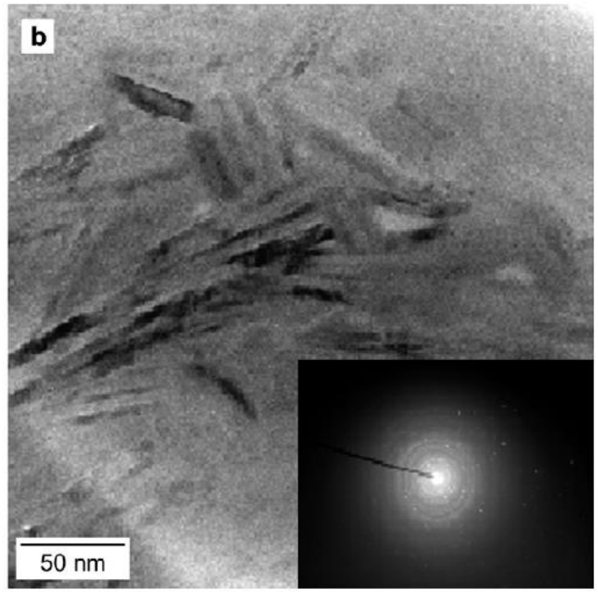
Hydration Rates:

- Pseudotachylytes are replaced by clay minerals faster than megathrust earthquake cycle
- Permanently weakens fault allowing for reactivation and removal from rock record

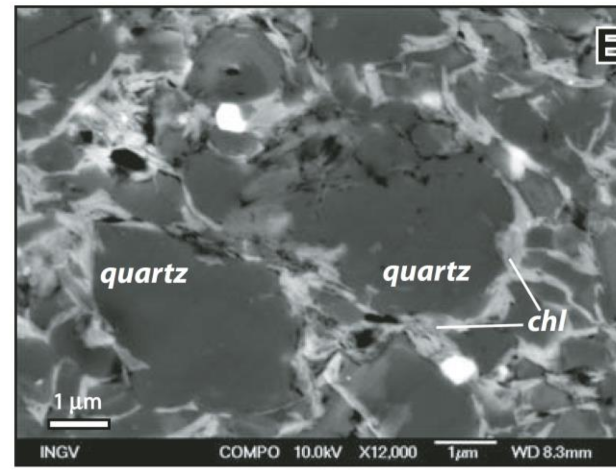
Years Following Slip



Kirkpatrick and Rowe 2013



Ujiie et al 2007



Meneghini et al 2010

<u>Is this a Common Process?</u>

YES! Most pseudotachylytes found today are not fresh and have been replaced by some form of phyllosilicate phase

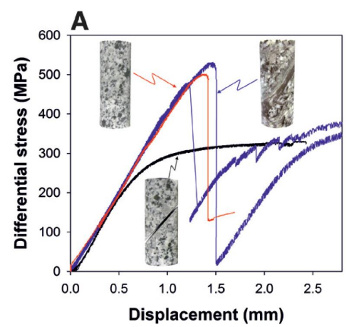
What is the Strength of Pseudotachylyte in Different Stages of the Earthquake Cycle?

1) During Seismic Slip

(e) $\tau = 2.27$ MPa

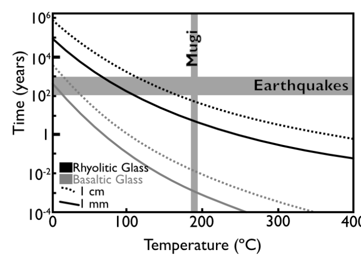
WEAK

2) Immediately Following Slip



STRONG

3) Years Following Slip



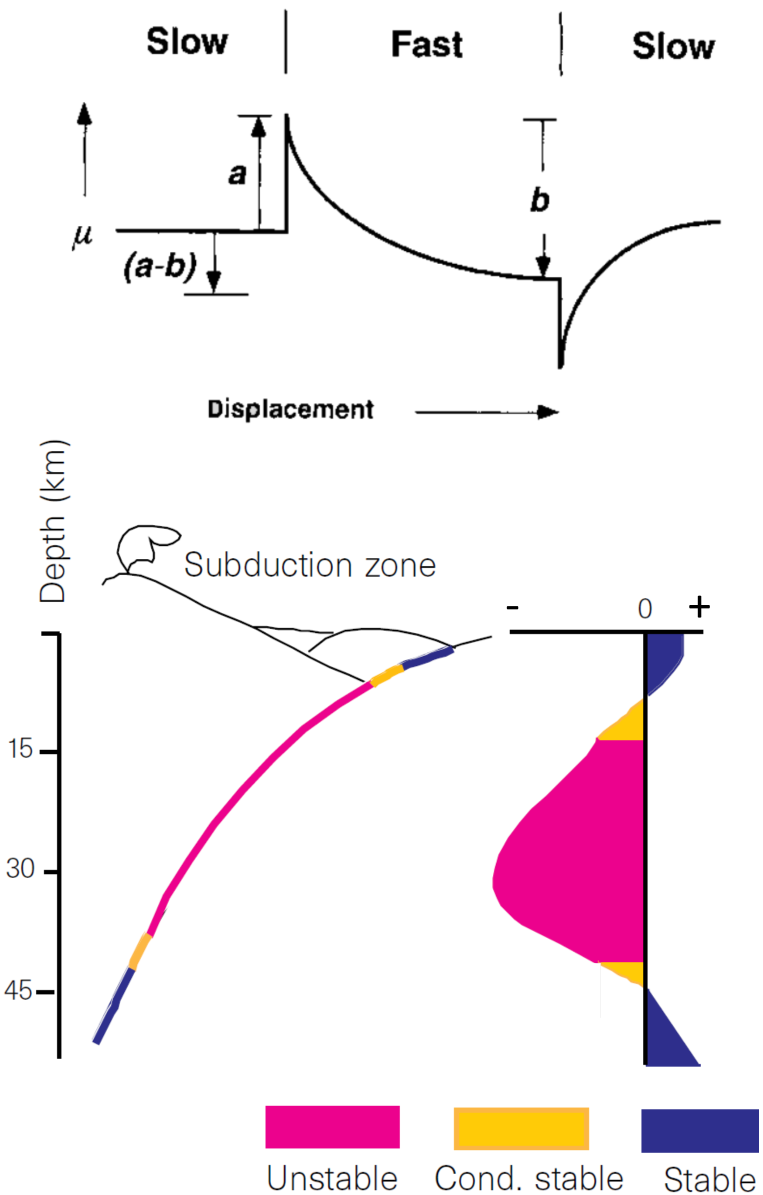
WEAK

Talk Outline

1) The Case of Frictional Melts:
   -Pseudotachylyte strength during and post formation

2) The Frictional Properties of an Exhumed Subduction Mélange
   -Which lithologies control the "seismogenic zone"?

The Seismogenic Zone



Scholz, 1998

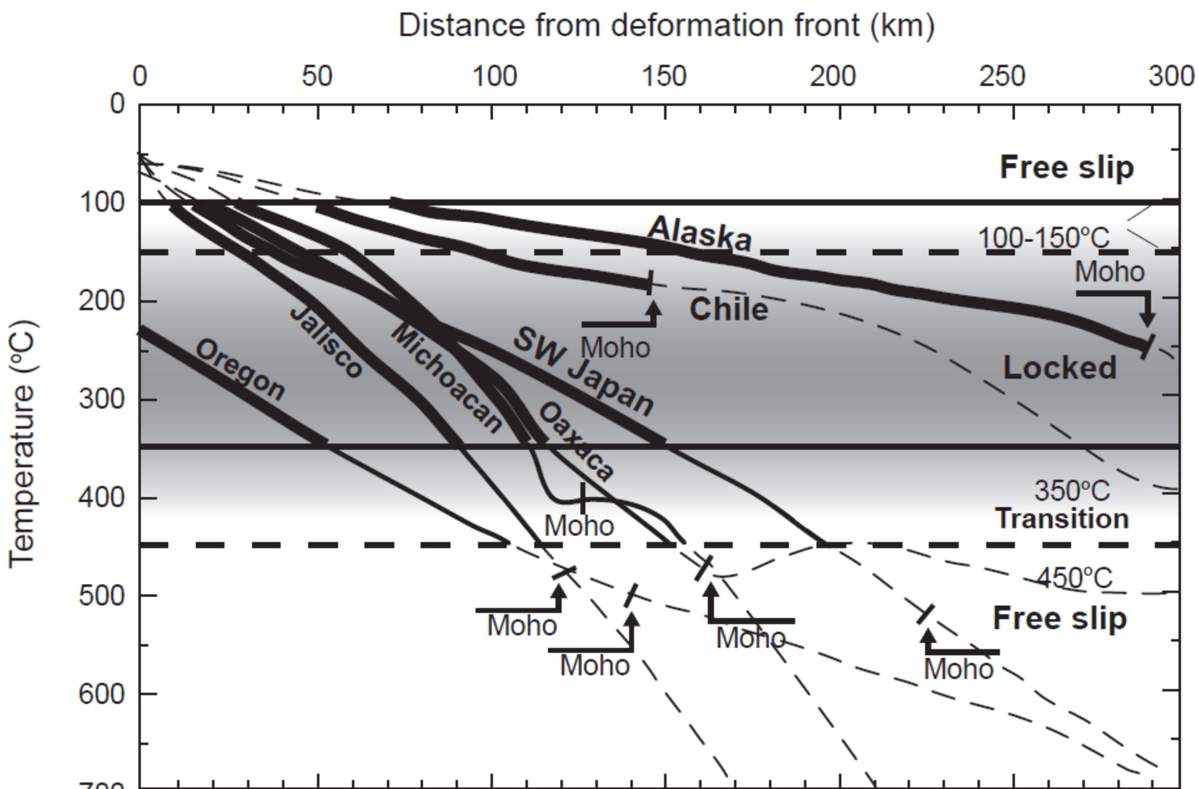
What Controls the Locked Zone?

Rate-and-State Friction

<u>Velocity weakening</u>: Slides at lower shear stress with increasing velocity: *Unstable Slip (Earthquake)*

<u>Velocity strengthening</u>: Slides at higher shear stress with increasing velocity: *Stable Slip (Creep)*

The Seismogenic Zone



Moore et al 2007
After Hyndman et al 1997

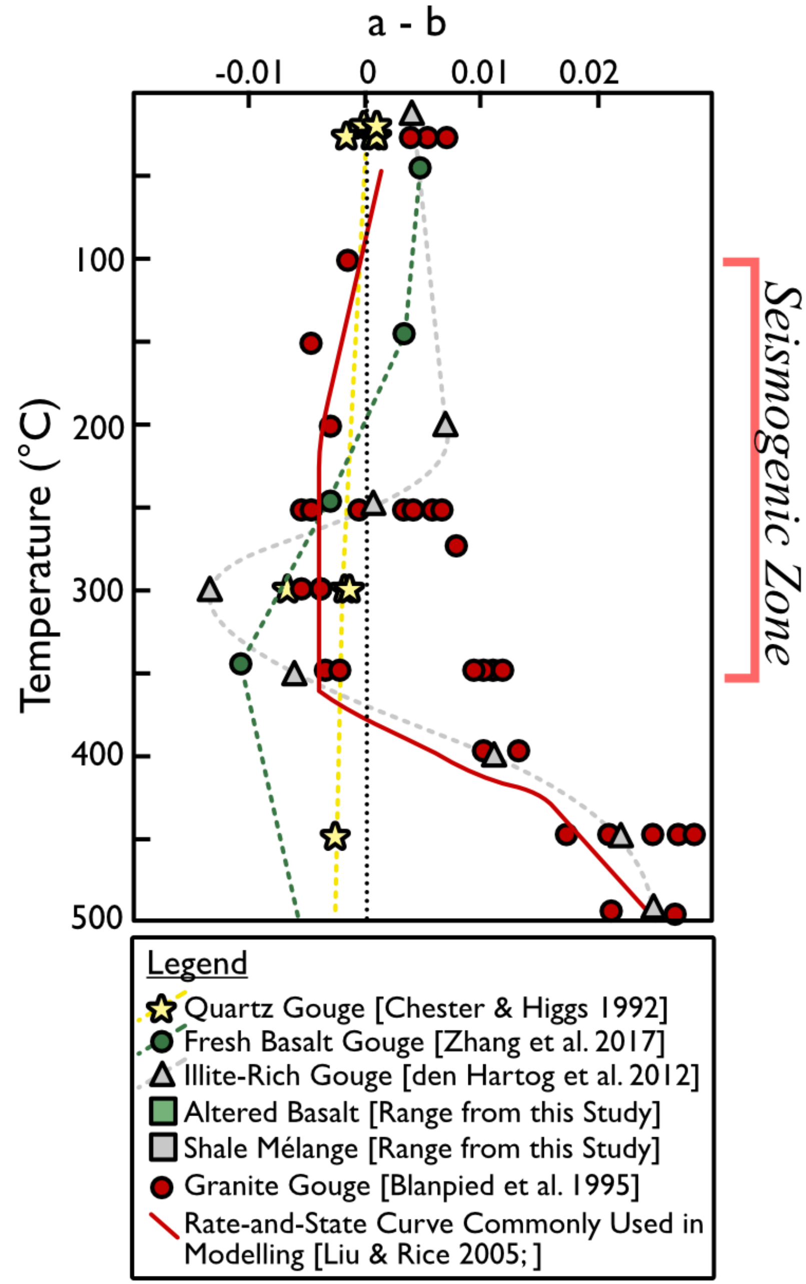
Subduction Seismogenic Zone:

- Thermally controlled locked zone between ~100 and 350 °C

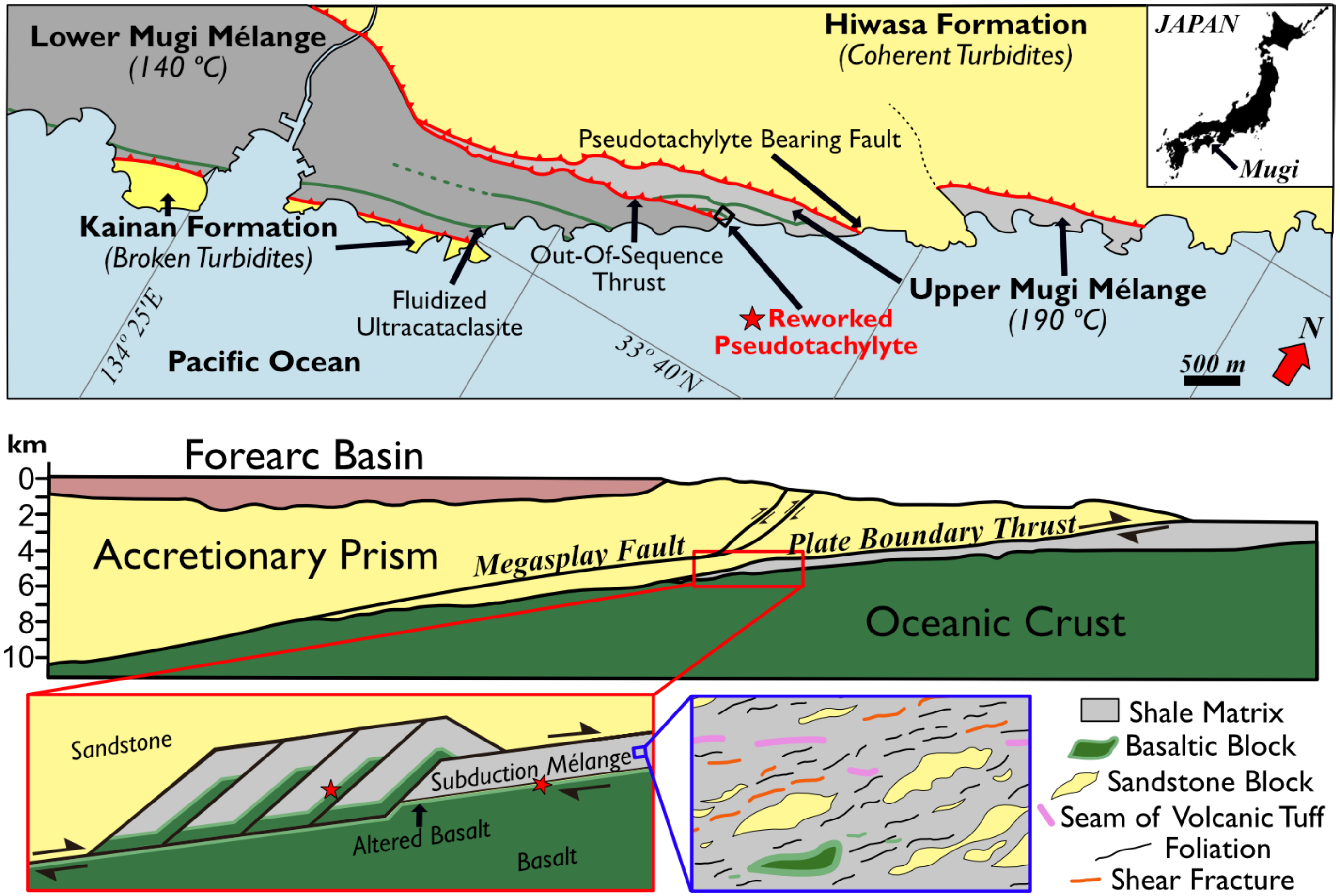
The Seismogenic Zone

Subduction Seismogenic Zone:

- Disconnect between measured rate-and-state frictional properties for common subduction zone materials and observed seismogenic zone



Ancient Earthquakes

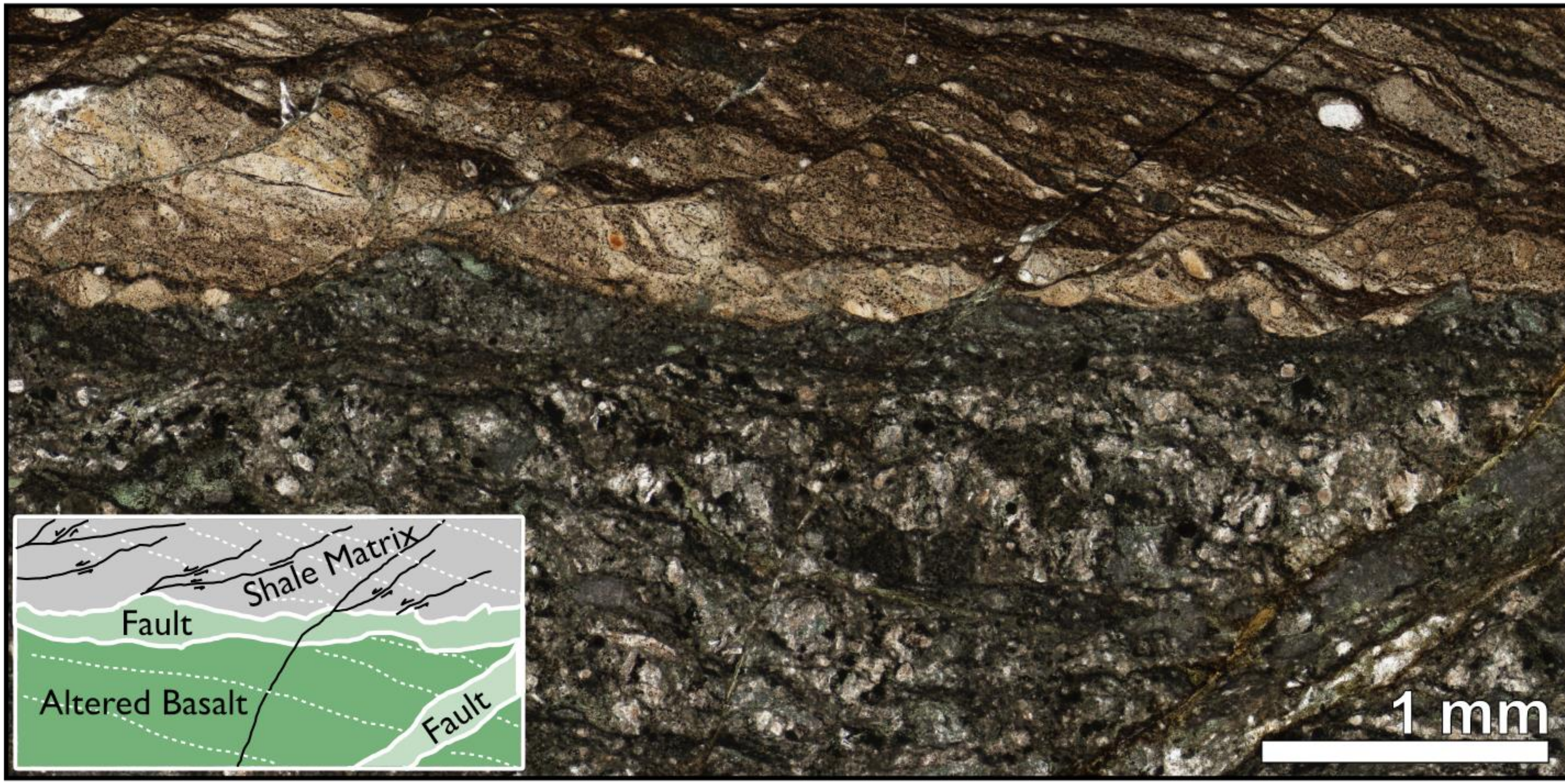


Phillips et al 2019

The Mugi Mélange:

- 2 preserved ancient earthquakes hosted in altered basalt
- Evidence of distributed deformation in the shale

Frictional Properties



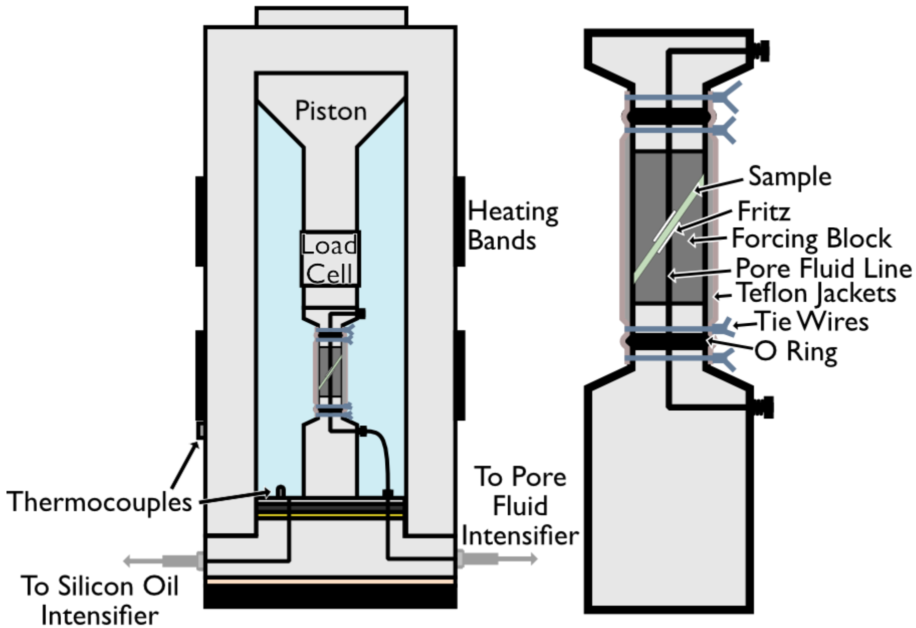
Phillips et al in review

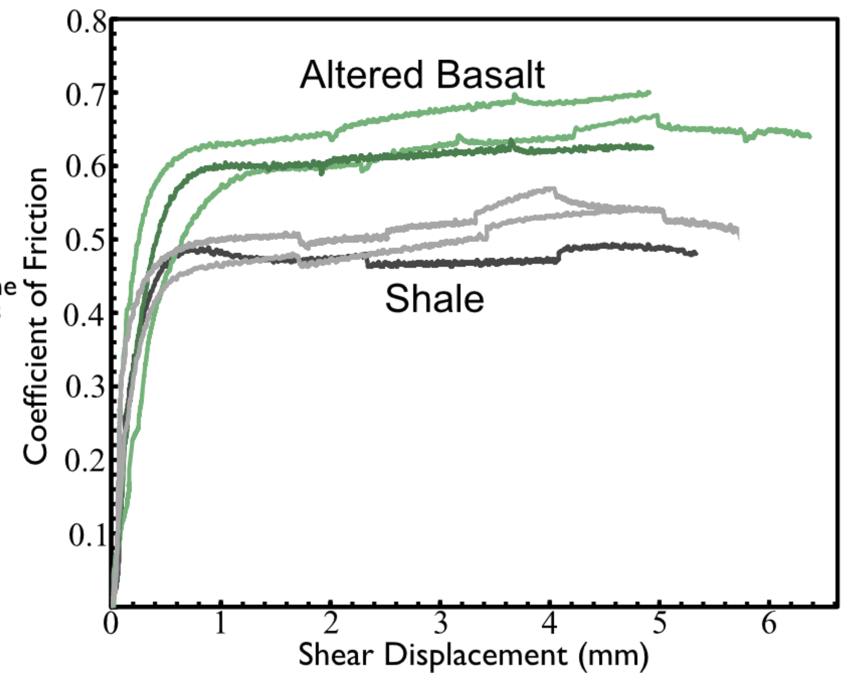
Simplified Microstructures:

- Altered basalt has localized faults: hosted earthquakes
- Shale has distributed deformation: evidence for fault creep

Hypothesis: Altered basalt is velocity weakening and shale is velocity strengthening

Frictional Properties





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Triaxial Friction Experiments:

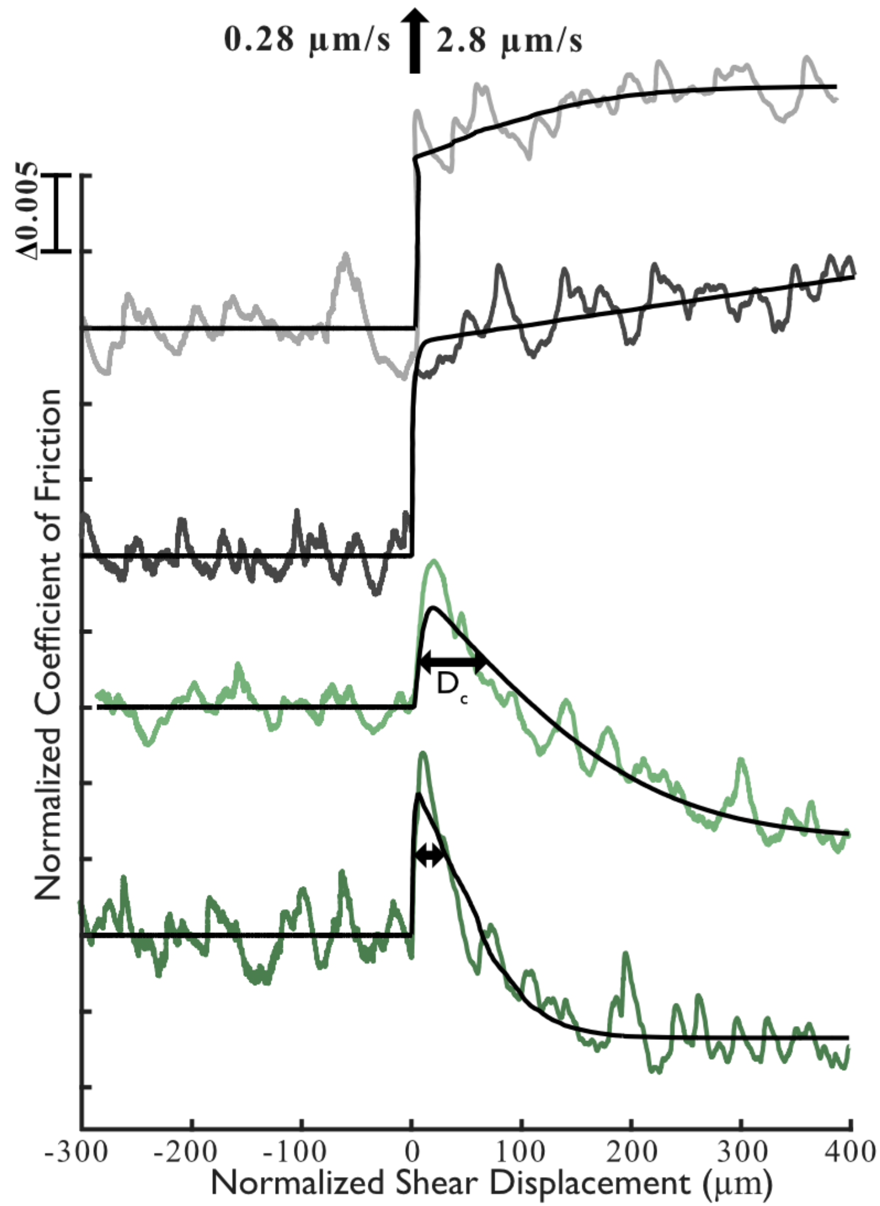
- Tested frictional properties of altered basalt and shale at *in situ* conditions (T = 150°C , P = 120 MPa, λ = 0.36 or 0.7)
- Shale is weaker than altered basalt

Frictional Properties

Rate-and-State Properties:

- Altered basalt exhibits velocity-weakening behavior

- Shale exhibits velocity-strengthening behavior



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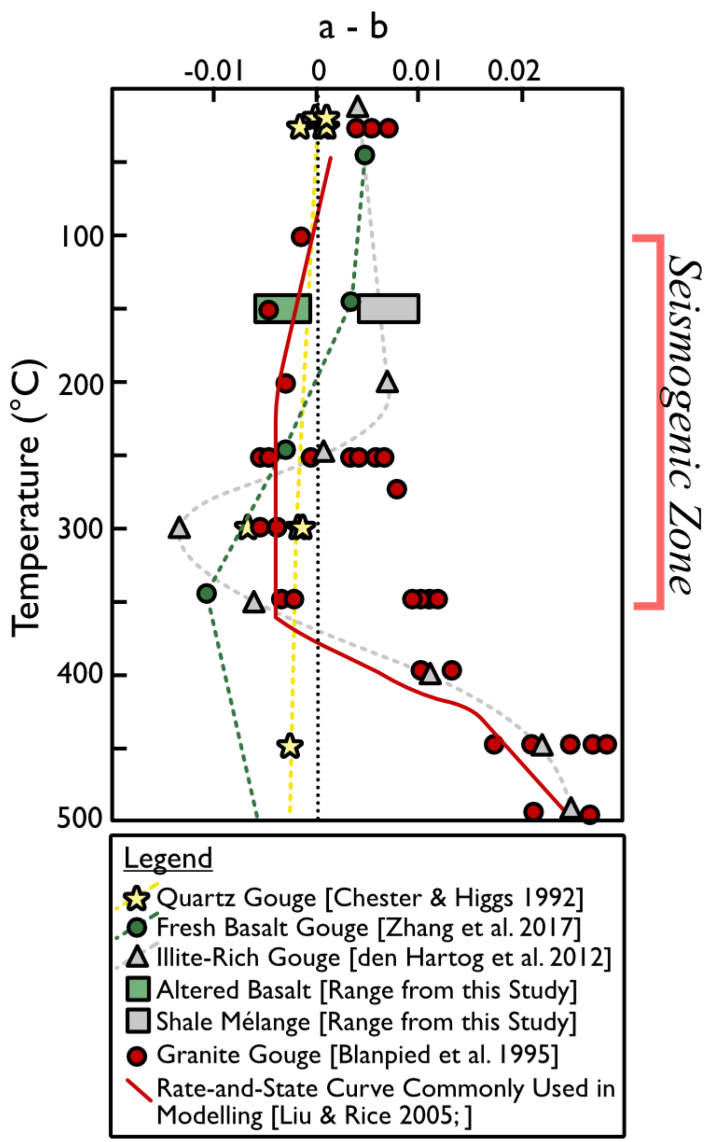
Frictional Properties



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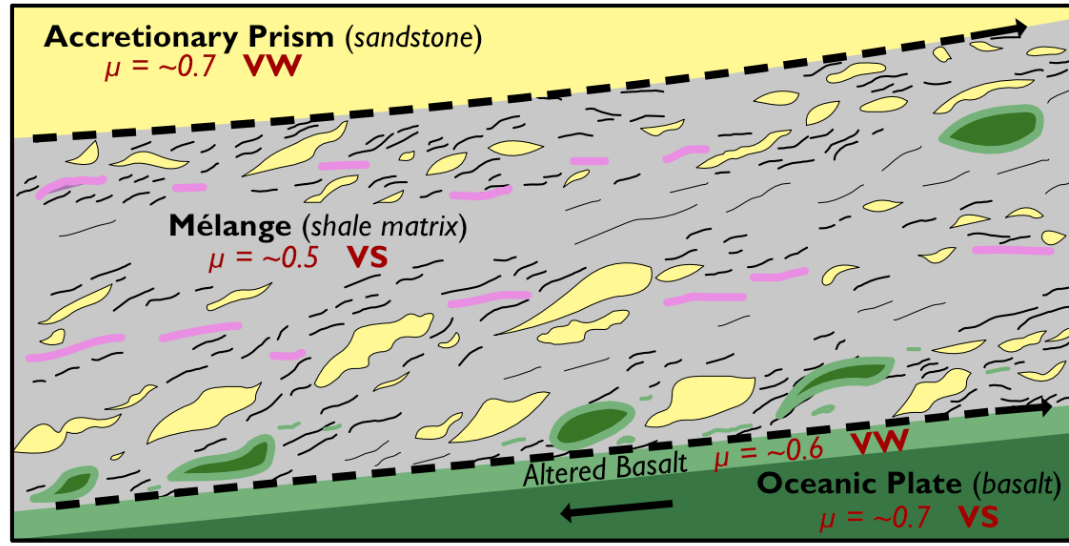

***Phillips et al* in review**

Implications of Frictional Properties:

- Altered basalt exhibits velocity weakening behaviour at updip limit of seismogenic zone
- Most other common subduction zone lithologies (shale, calcite, fresh basalt, fresh gabbro) exhibit velocity strengthening behavior
- Altered basalt may preferentially nucleate earthquakes at updip limit

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