Fault strength, reaction softening and the slip behaviour of fluid pressurized experimental faults

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&
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erc

2007-2013 SEVENTH FRAMEWORK PROGRAMME

Fault strength

- Intro
- Examples of weak faults in different tectonic environments
- Reaction softening
- Frictional properties
- Implications for seismic & aseismic slip

Slip behaviour of fluid pressurized experimental faults

1905

What is the state of stress on crustal faults?

XLII. *The Dynamics of Faulting.* By ERNEST M. ANDERSON, M.A., B.Sc., H.M. Geological Survey.

(Read 15th March 1905.)

The object of the present paper is to show a little more clearly the connection between any system of faults and the system of forces which gave rise to it.

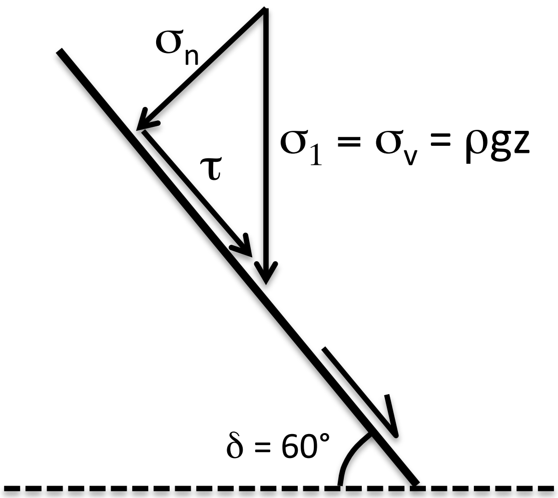
Anderson, E.M., 1951, The dynamics of faulting (2nd edition): Edinburgh, Oliver and Boyd, 206 p.

1951

On the assumption that:

- Earth's surface is a principal plane of stress ($\tau = 0$) and
- faults result from brittle fracture following the Mohr-Coulomb criterion, $\tau = C + \mu \cdot \sigma_n$

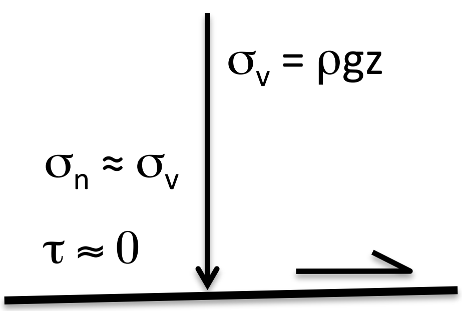
Anderson defined three classes of faulting and their geometries, i.e. fault orientation within the stress field.........



$$\tau = C + \mu \cdot \sigma_n$$

.......providing the base for the first fault strength evaluation.

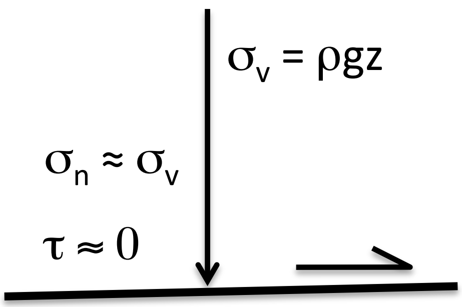
1959



How can thrust faulting be active for hundreds of kilometres along sub-horizontal faults?

$$\tau = C + \mu \cdot \sigma_n$$

1959



How can thrust faulting be active for hundreds of kilometres along sub-horizontal faults?

$$\tau = C + \mu \cdot (\sigma_n - P_f)$$

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA

VOL. 70, PP. 115-166, 32 FIGS. FEBRUARY 1959

ROLE OF FLUID PRESSURE IN MECHANICS OF OVERTHRUST FAULTING

I. MECHANICS OF FLUID-FILLED POROUS SOLIDS AND ITS APPLICATION TO OVERTHRUST FAULTING

BY M. KING HUBBERT AND WILLIAM W. RUBEY

What about friction?

$$\tau = C + \mu \cdot (\sigma_n - P_f)$$

Pageoph, Vol. 116 (1978), Birkhauser Verlag,

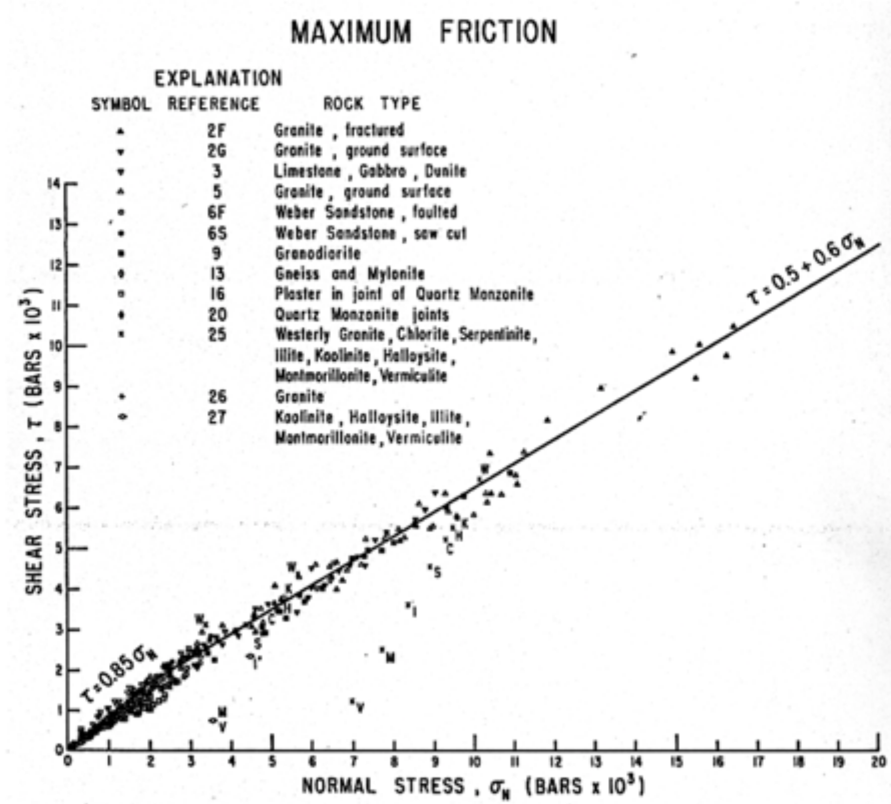
Friction of Rocks

By J. BYERLEE

Abstract - Experimental results in the published literature show that at low normal stress the shear stress required to slide one rock over another varies widely between experiments. This is because at low stress rock friction is strongly dependent on surface roughness. At high normal stress that effect is diminished and the friction is nearly independent of rock type. If the sliding surfaces are separated by gouge composed of montmorillonite or vermiculite the friction can be very low.

Byerlee's rule

$0.6 < \mu < 0.85$



1) Frictional fault reactivation as a test for Byerlee's friction

$$\tau = \mu \cdot (\sigma_n - P_f)$$

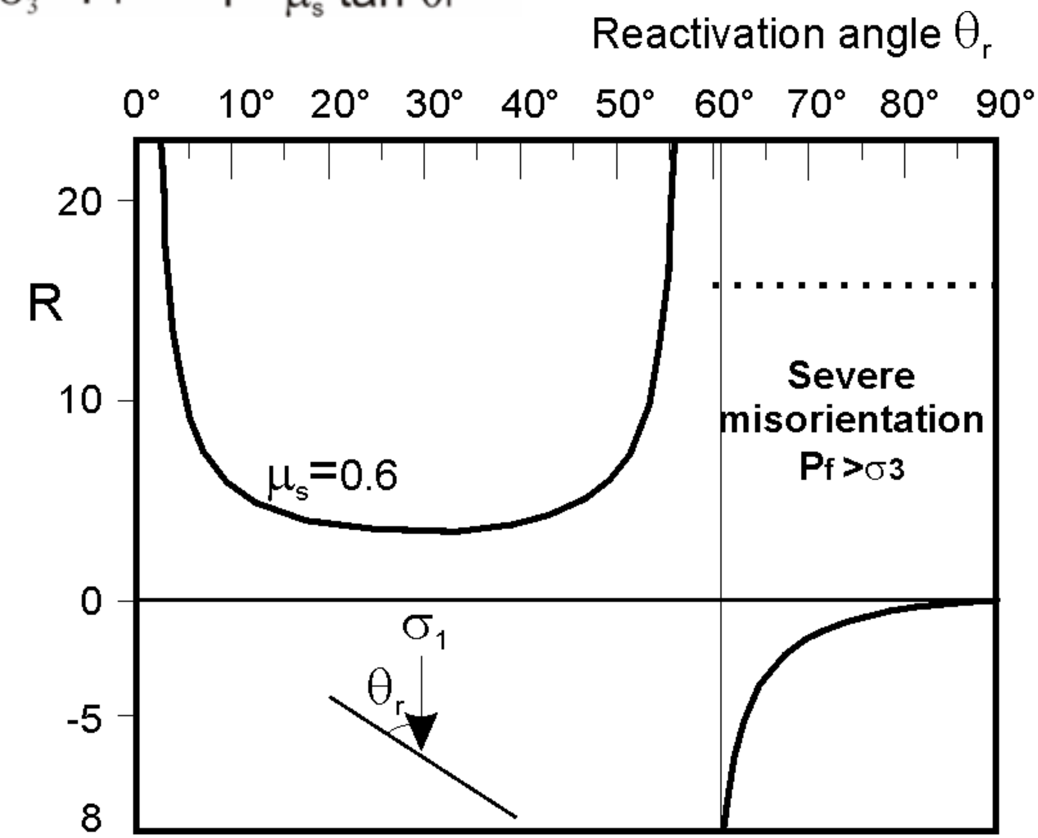
SHORT NOTES

A note on fault reactivation

RICHARD H. SIBSON

Journal of Structural Geology, Vol. 7, No. 6, pp. 751 to 754, 1985
Printed in Great Britain

$$R = \frac{\sigma_1 - P_f}{\sigma_3 - P_f} = \frac{1 + \mu_s \cot \theta_r}{1 - \mu_s \tan \theta_r}$$

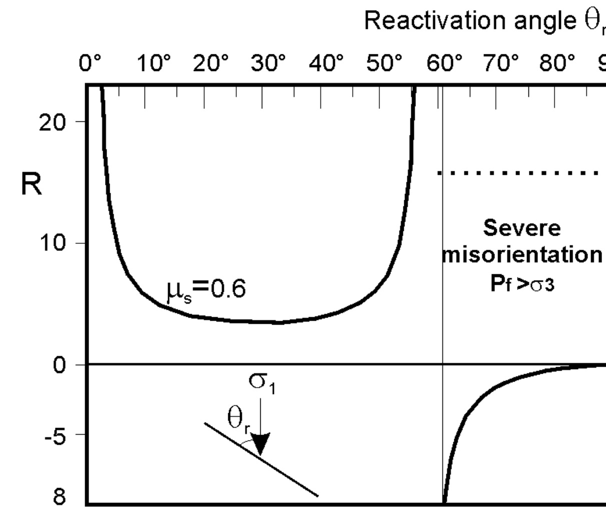


For Byerlee's friction $\mu = 0.6$, frictional lock-up is expected for $\theta_r = 60°$

2001

1) Frictional fault reactivation as a test for Byerlee's friction

Histogram of active fault dips

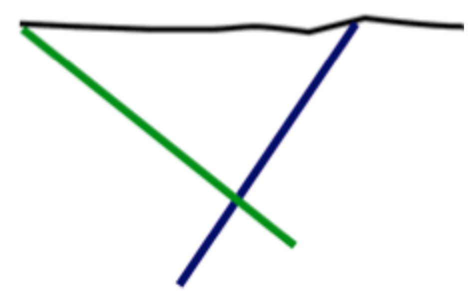


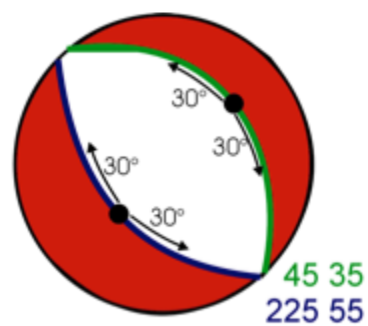
METHOD

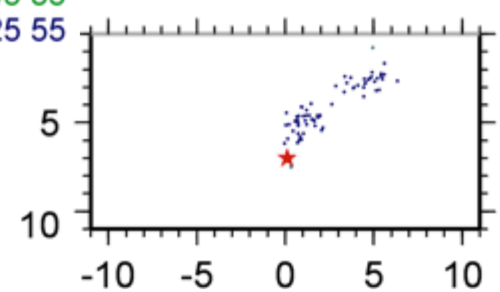
- EQs selection: intracontinental, dip-slip earthquakes (slip vector raking 90° ±30°), M>5.5

- Dip from focal mechanism

- The ambiguity of the rupture plane in the focal mechanism has been resolved by auxiliary techniques such as: correlation with surface breaks, aftershocks distribution..



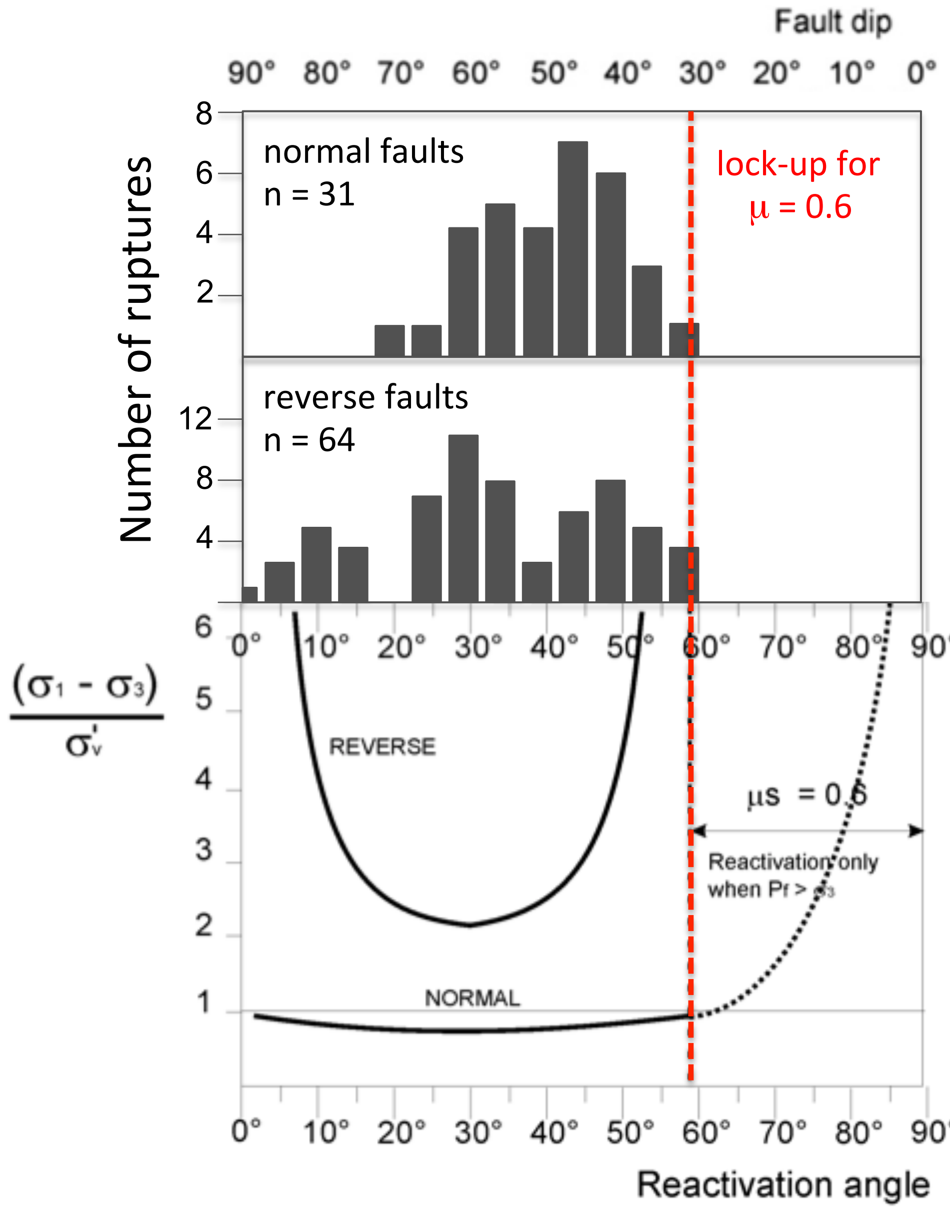




Collettini and Sibson, Geology, 2001

1) First test for Byerlee's friction

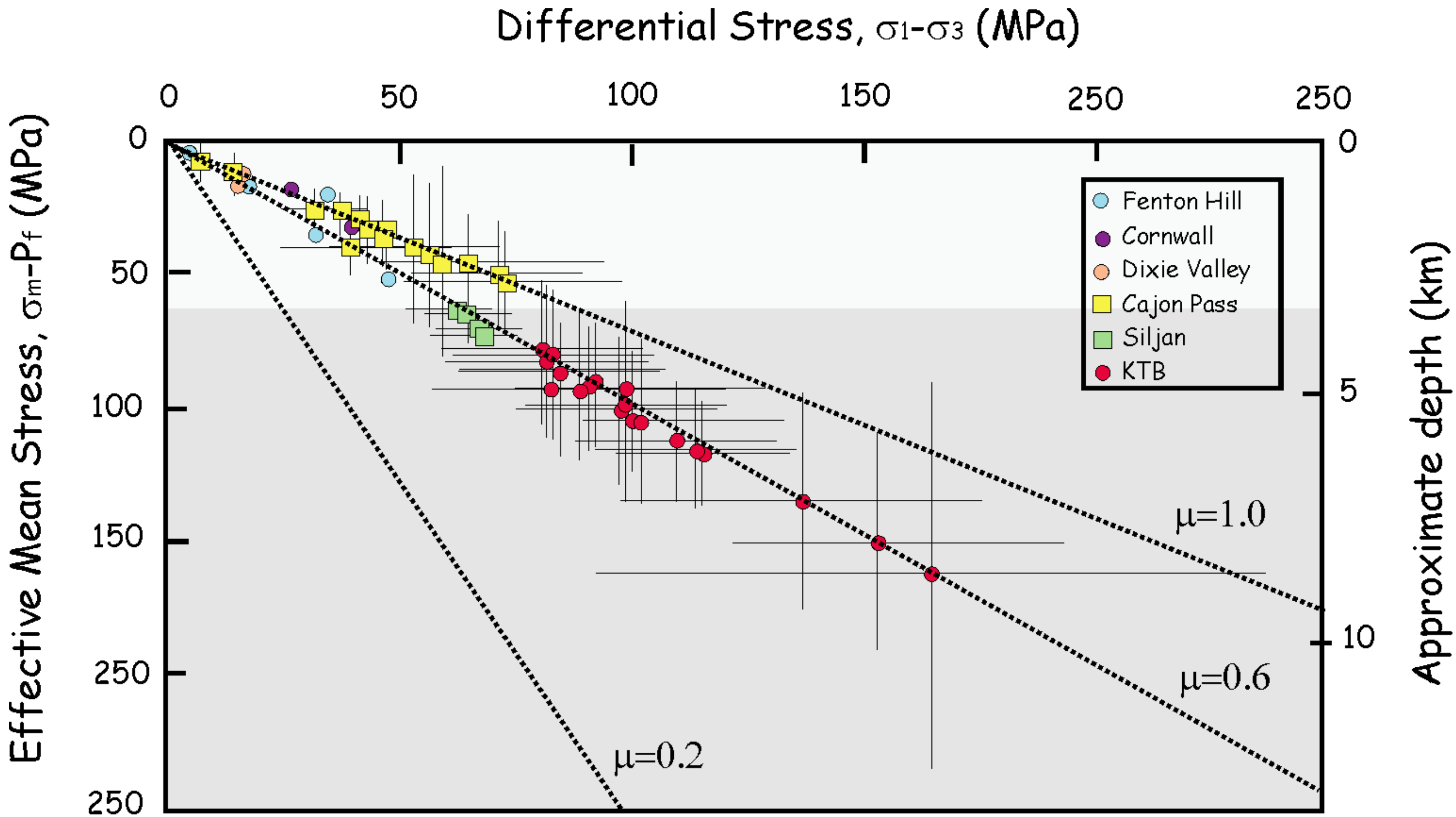
The dip of moderate and large main shock fault-ruptures, in extensional and compressional environments, are consistent with Anderson-Byerlee frictional fault mechanics.



Up-dated from Collettini and Sibson, Geology, 2001

2) Second test for Byerlee's friction

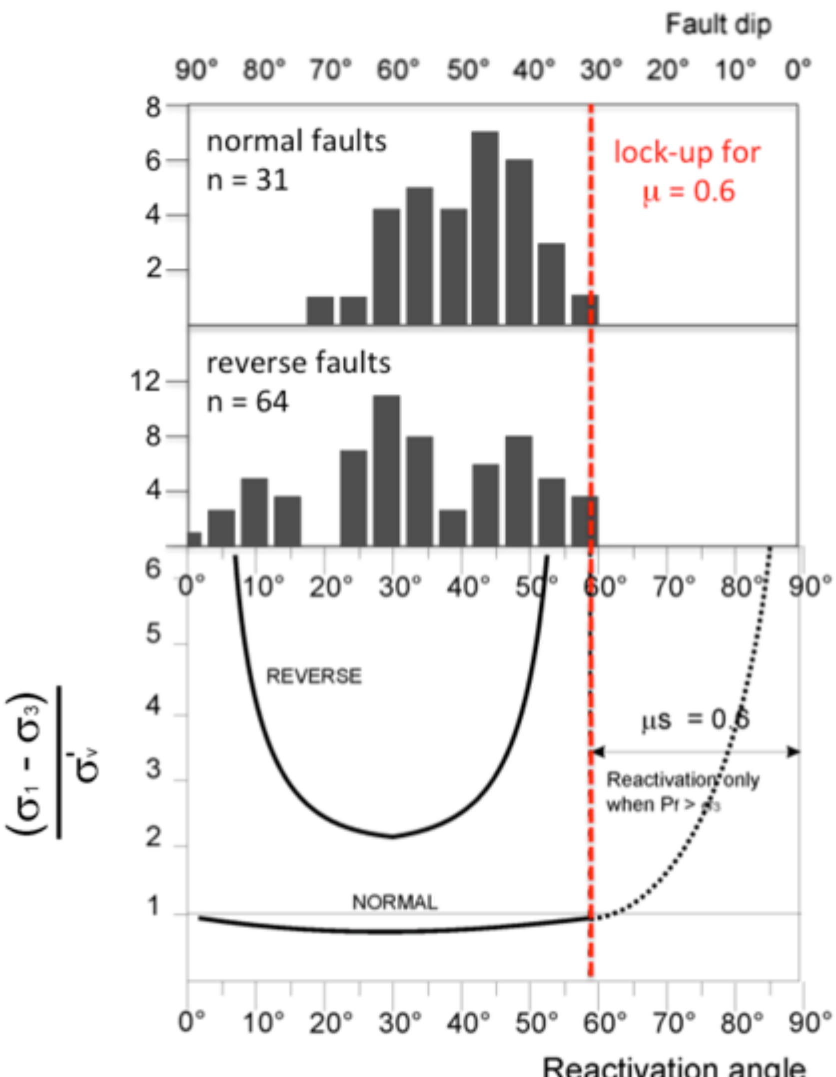
Deep stress measurements suggest that the brittle crust is critically stressed according to frictional fault reactivation, $\tau = \mu\sigma'_n$, under Byerlee's friction (e.g. $\mu = 0.6$ at depth > 3km)

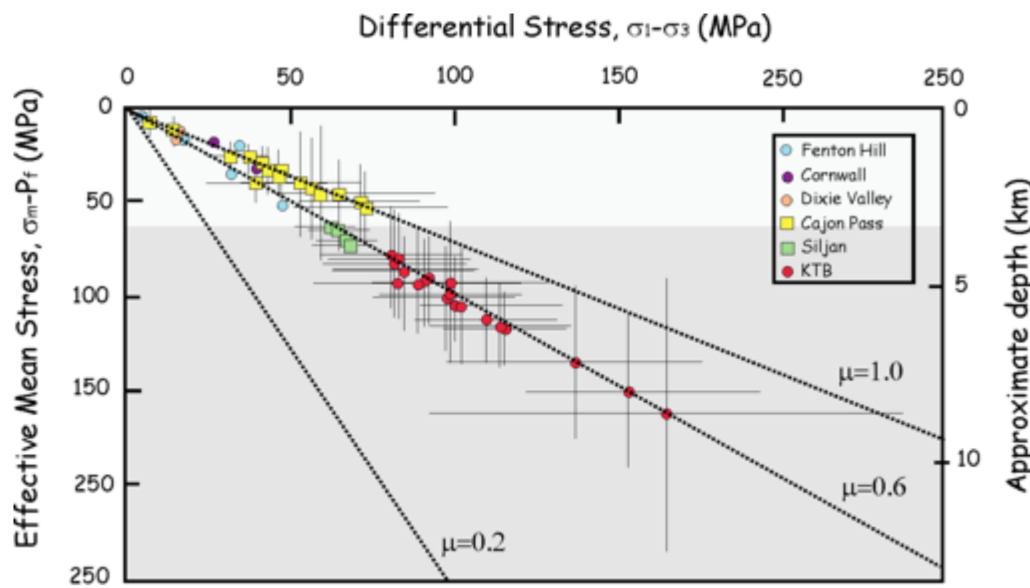


Zoback and Townend Tectonophysics 2001

2001

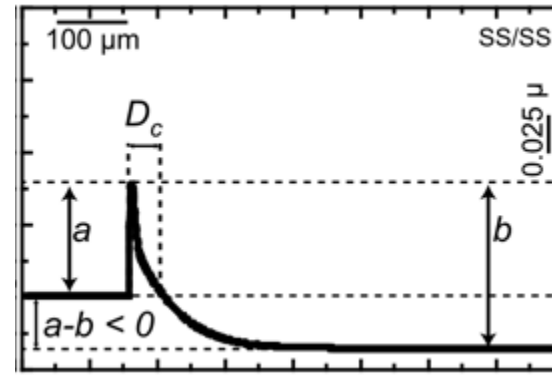
These two datasets point to faults controlled by Byerlee's friction, i.e. strong faults that in some cases can become transiently weak due to fluid overpressure.

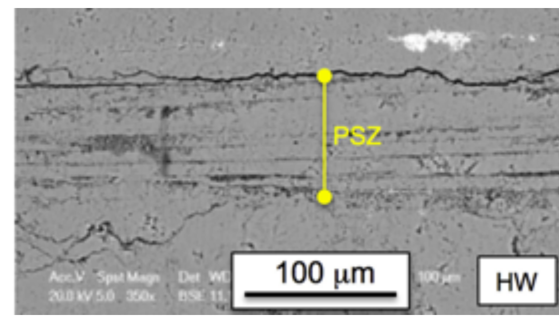


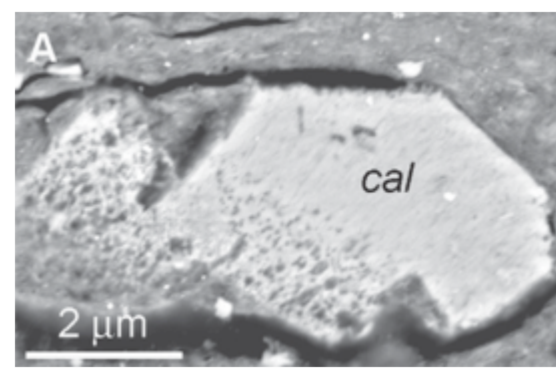


Zoback and Townend Tectonophysics 2001
Townend & Zoback, Geology, 2000
Collettini and Sibson Geology 2001
Sibson and Xie BSSA, 1998
Scholz's book

An example of a strong fault with localization, velocity weakening, fast healing and the record of ancient earthquakes with thermal decomposition.







Collettini et al., Geology, 2013, Carpenter et al., JGR, 2014.

Is the San Andreas the only weak fault?

Research Articles

New Evidence on the State of Stress of the San Andreas Fault System

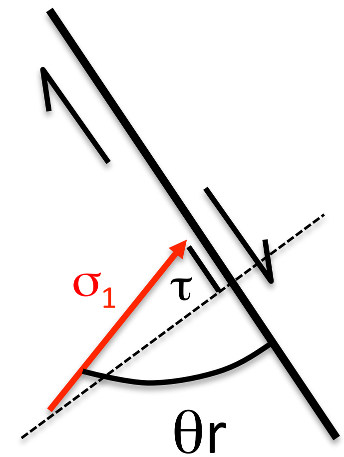
Mark D. Zoback, Mary Lou Zoback, Van S. Mount, John Suppe, Jerry P. Eaton, John H. Healy, David Oppenheimer, Paul Reasenberg, Lucile Jones, C. Barry Raleigh, Ivan G. Wong, Oona Scotti, Carl Wentworth

Contemporary in situ tectonic stress indicators along the San Andreas fault system in central California show northeast-directed horizontal compression that is nearly perpendicular to the strike of the fault. Such compression explains recent uplift of the Coast Ranges and the numerous active reverse faults and folds that trend nearly parallel to the San Andreas and that are otherwise unexplainable in terms of strike-slip deformation. Fault-normal crustal compression in central California is proposed to result from the extremely low shear strength of the San Andreas and the slightly convergent relative motion between the Pacific and North American plates. Preliminary in situ stress data from the Cajon Pass scientific drill hole (located 3.6 kilometers northeast of the San Andreas in southern California near San Bernardino, California) are also consistent with a weak fault, as they show no right-lateral shear stress at ~2-kilometer depth on planes parallel to the San Andreas fault.

deformation along plate boundaries and within the plates, require resolution of this issue.

Although in situ stress measurements near the San Andreas and other faults are generally consistent with classical faulting theory and laboratory-derived friction values (*12*), the measurements are at relatively shallow depths (<0.9 km) and are difficult to extrapolate to the upper 15 to 20 km of the crust. Also, the shallow conductive heat flow measurements (most of the data come from boreholes that are only ~300 m deep) may be contaminated by near-surface thermal convection, which would obviate their significance (*13*). Although arguments have been made that significant convective heat flow is not occurring near the fault (*3*) the debate about the level of shear stress on the fault has continued (*14*). To help resolve this paradox, continental scientific drilling is currently under way at a site 3.5 km from the San Andreas fault at Cajon Pass, California, with the goal of measuring in situ stress and heat flow at seismogenic depth (*15*).

There is considerable data indicating that the San Andreas is essentially a pure right-lateral strike-slip transform fault with hundreds of kilometers of displacement along it. However, since the



Is the San Andreas the only weak fault?....maybe

Evidence for a strong San Andreas fault

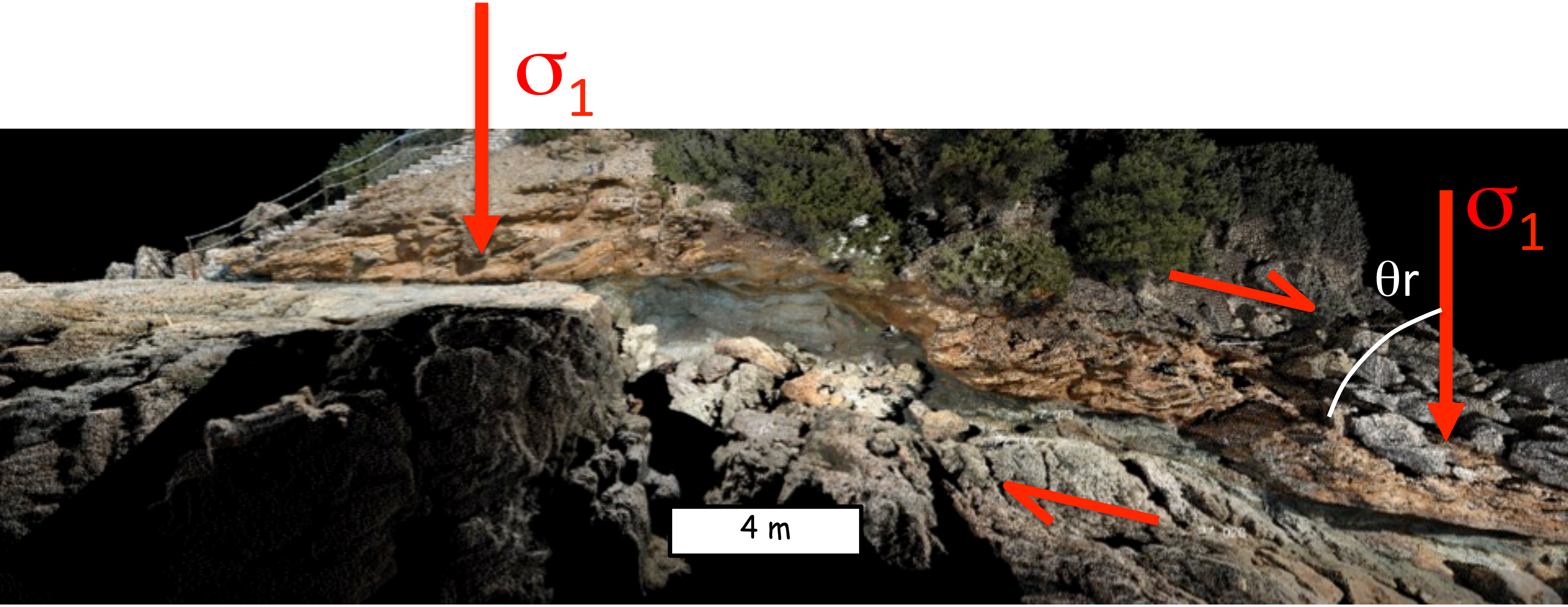
Christopher H. Scholz
Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York 10964, USA

Geology; February 2000; v. 28; no. 2; p. 163–166; 4 figures.

ABSTRACT

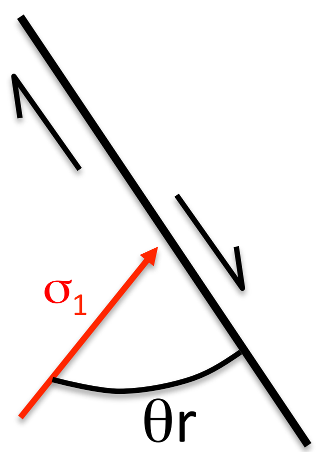
Stress measurements in deep boreholes have universally shown that stresses in the Earth's crust are in equilibrium with favorably oriented faults with friction coefficients in the range 0.6–0.7 and with nearly hydrostatic pore-pressure gradients. Because of the lack of any fault-adjacent heat-flow anomaly as predicted by a conductive model of frictional heating, the San Andreas fault has long been thought to be an exception, i.e., far weaker than this standard case. Borehole stress measurements near the San Andreas fault have failed to confirm this weak-fault hypothesis, being either inconclusive or in conflict with it. Directions of maximum horizontal stresses reported to be nearly fault normal in central California are now known not to be regional stresses but a result of active folding within folds that have been rotated 20°–30° clockwise from their original orientations. Everywhere in southern California it is observed that the maximum stress directions rotate to smaller angles (30°–60°) with the San Andreas, within 20 km of it. The sense of this rotation is opposite to that expected from the weak-fault hypothesis and indicates that the shear stress on the San Andreas is comparable in magnitude to all other horizontal stresses in the system. In the "big bend" section of the fault, this rotation is predicted from a transpressional plate-boundary model in which the San Andreas is loaded by a deep shear zone with a locking depth of 10 km. If the adjacent minor thrust faults are assumed to obey Byerlee friction, the crustal-average shear stress on the San Andreas in that region must be in the range 100–160 MPa, regardless of the pore pressure in the fault. These stresses are many times greater than permitted by the weak-fault hypothesis. In the more transcurrent regions farther south, the San Andreas shear stress will be smaller than this estimate, but similar stress rotations observed there indicate that the San Andreas cannot be weak relative to minor faults in that region. These stress rotations can only be consistent with the weak-fault hypothesis if it were assumed that all faults in California were equally weak, which is known to be untrue. The conclusion is that the heat-flow model is flawed, probably in its assumption that all heat transfer is governed by conduction.

Another exception given by low-angle normal faults?



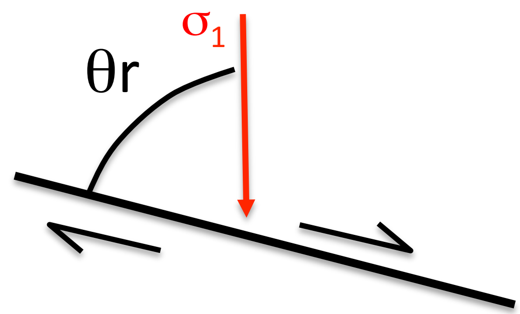
Are the San Andreas and low-angle normal faults the only weak faults?

Map view



San Andreas

Cross section



Low-angle normal faults

Are the San Andreas and low-angle normal faults the only weak faults?

My answer is no and I will support it by:

1) Examples of weak faults in different tectonic environments
2) Reaction softening
3) Laboratory experiments on friction

Are the San Andreas and low-angle normal faults the only weak faults?

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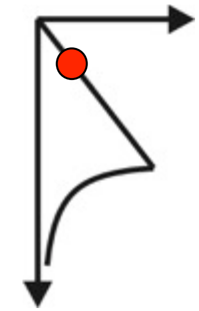
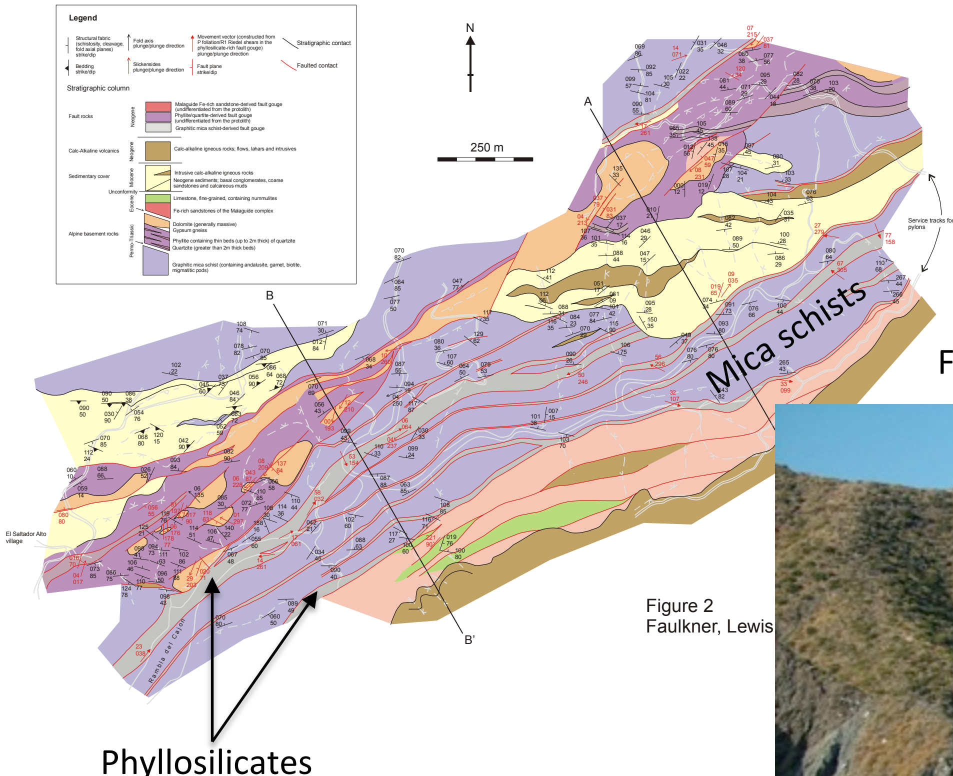
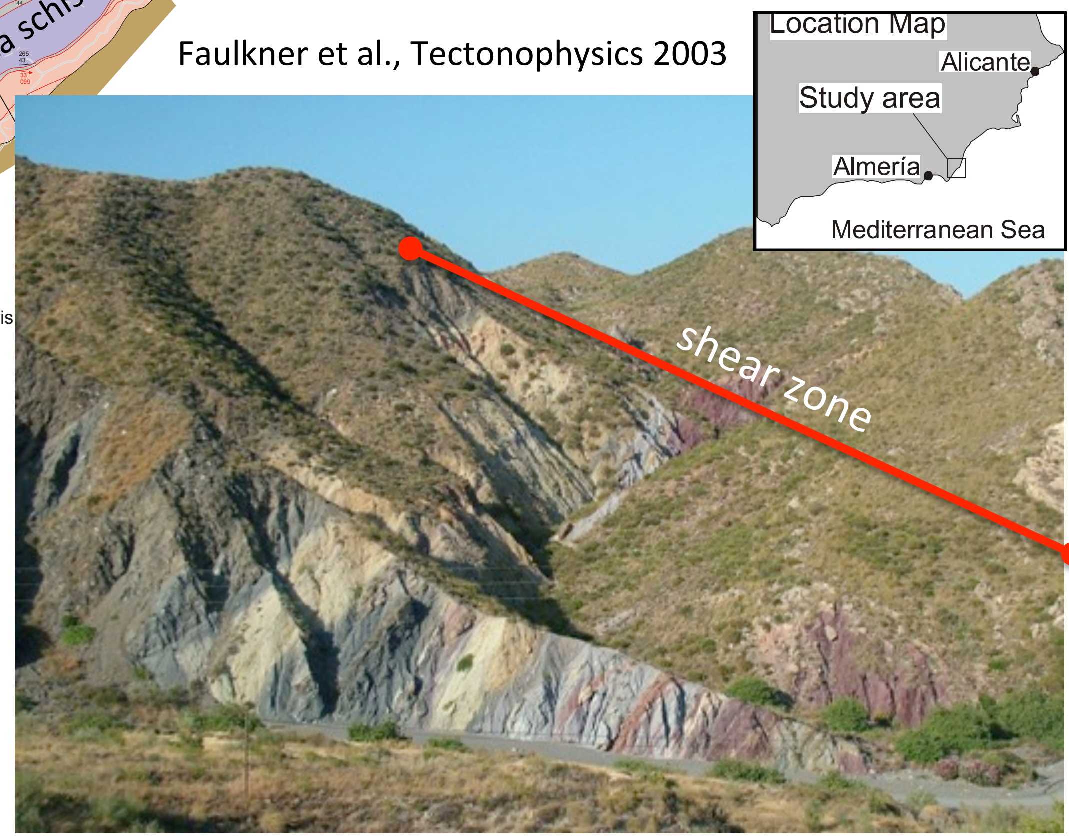
Carboneras fault: 1 km wide fault made of continuous layers of phyllosilicates (illite and chlorite) surrounding blocks of mica-schists & dolostones

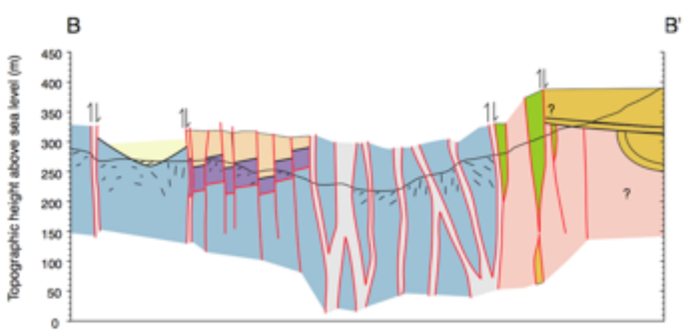
40 km of displacement
2-4 km of exhumation





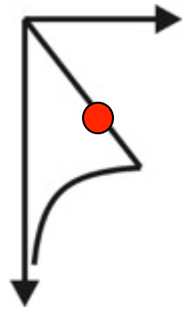
Faulkner et al., Tectonophysics 2003

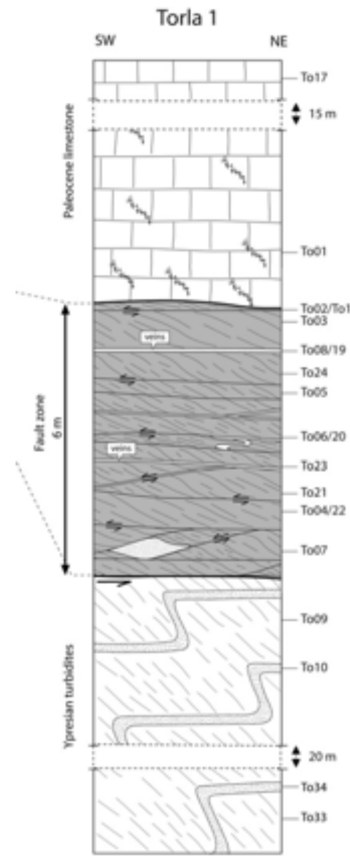




Torla thrust: thick horizons of phyllosilicates (illite & chlorite) surrounding strong lenses of competent sandstones.

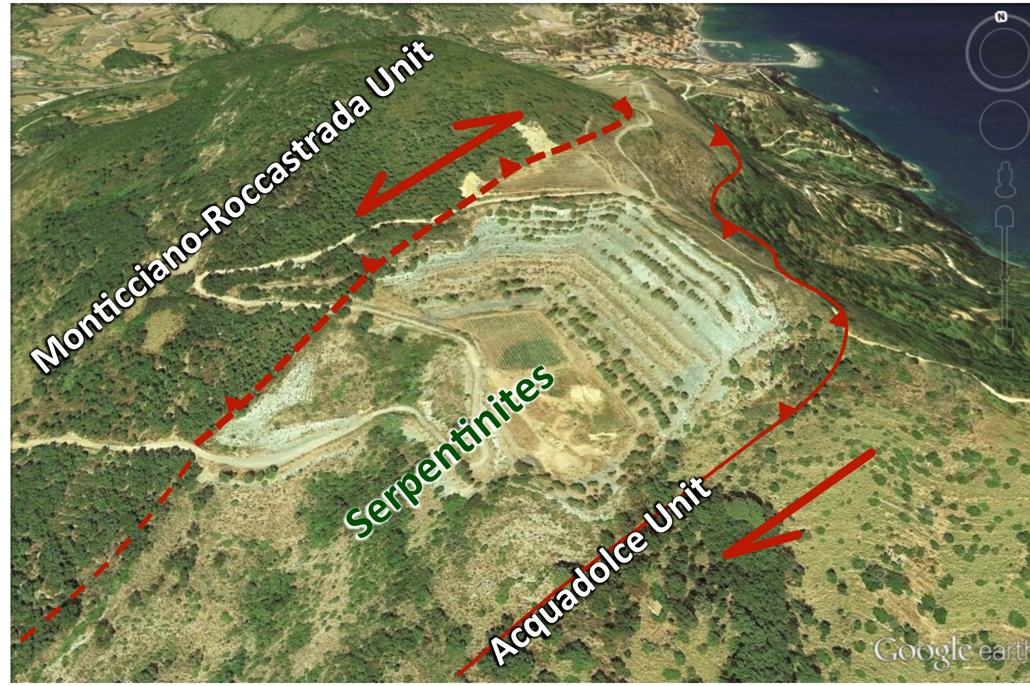
several km of displacement
6-7 km of exhumation





Lacroix et al., JSG, 2011

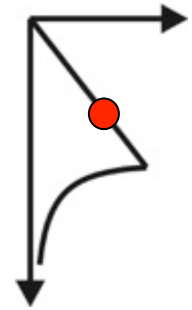
Monte Fico thrust: network of serpentine-rich shear zones surrounding competent lenses.



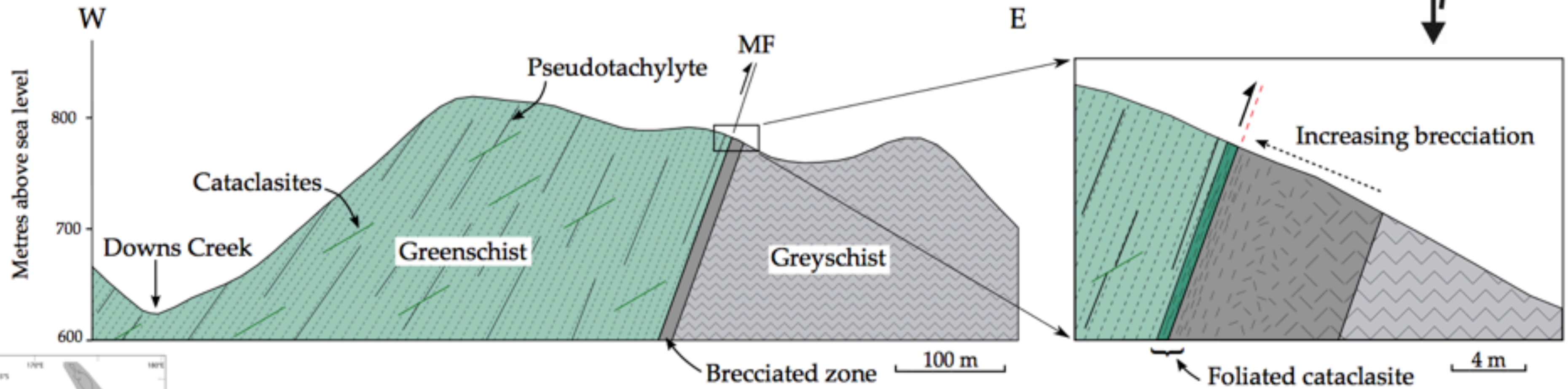
tens of km of displacement
250°C 2-3 kbar of exhumation

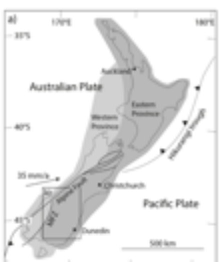
Tesei et al., in prep.

Moonlight fault: cataclasis of quartz and feldspar and concentration of phyllosilicates (chlorite and muscovite) along foliated surfaces.

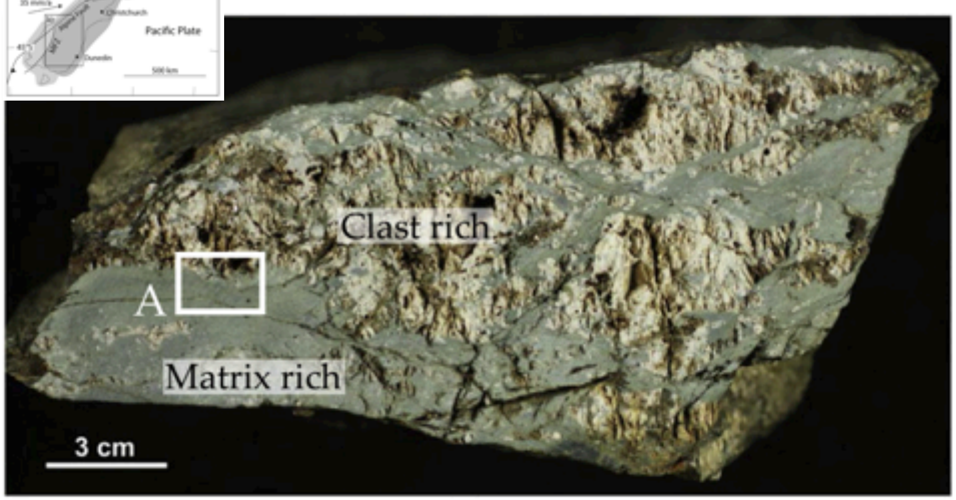


several km of displacement
9 km of exhumation

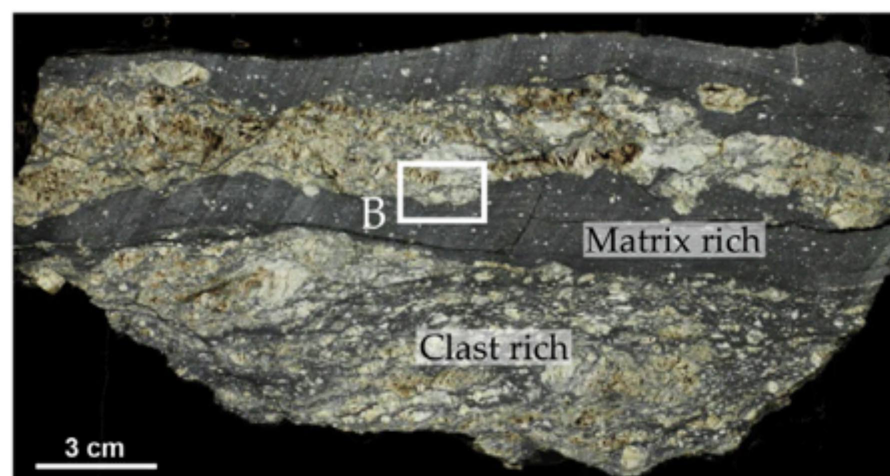




Chlorite foliation

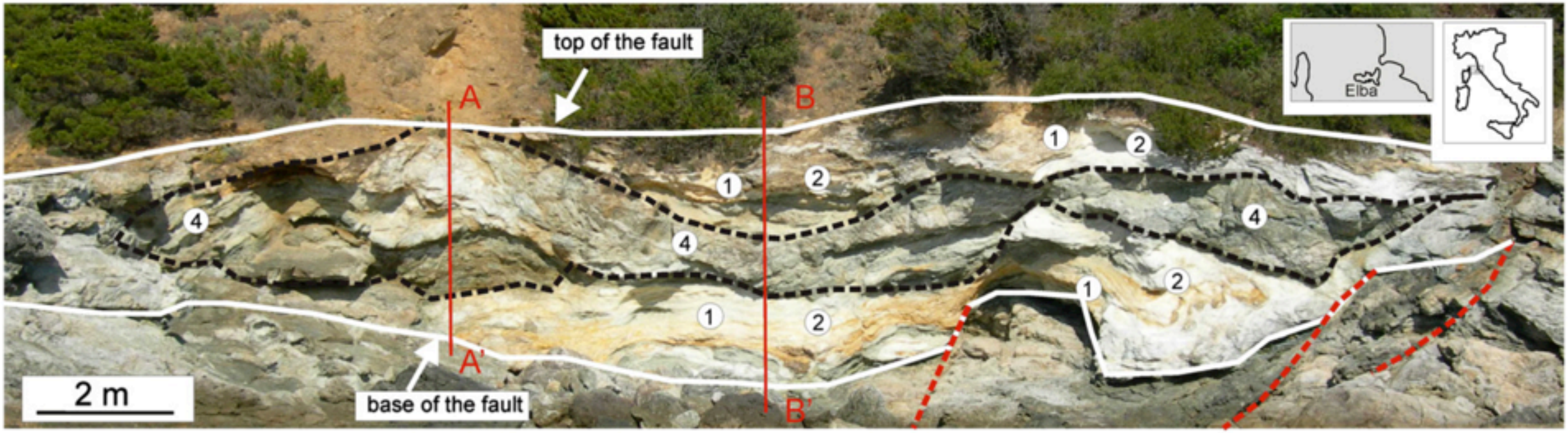


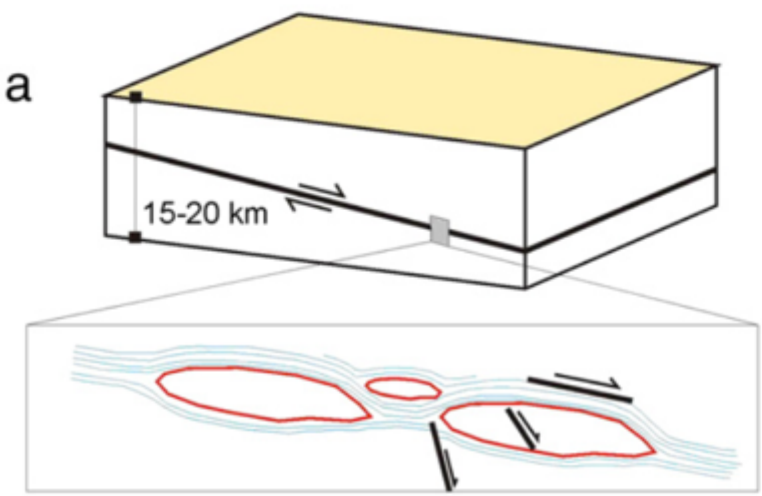
Muscovite foliation



Alder et al., JSG, 2016

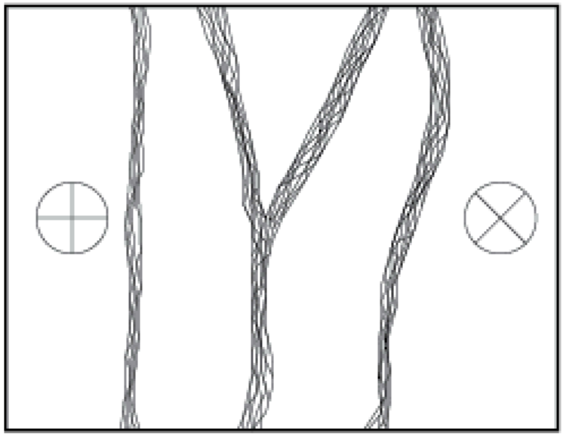
Zuccale low-angle normal fault: foliated rocks (talc & smectite) surrounding more competent materials (carbonate, ultramafic).

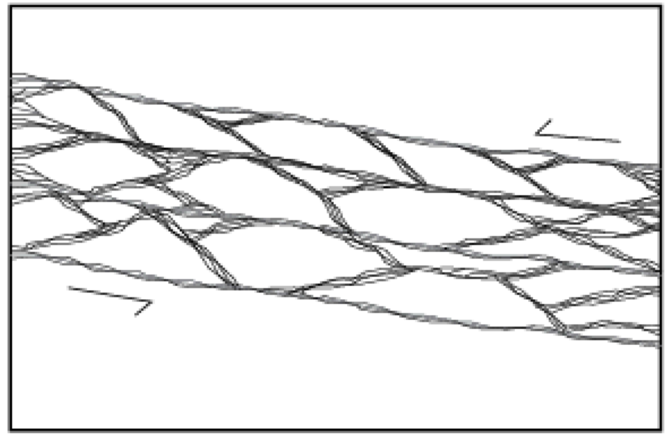


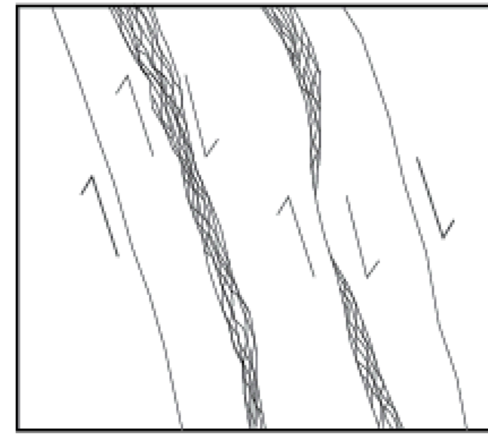


Collettini et al., EPSL, 2011

Fault zone structure: thick faults composed by interconnected networks of phyllosilicates







Carboneras Faulkner et al., 2003;
San Andreas, Holdsworth et al., 2011;
Midian Tectonic line, Jefferies 2006;
North Anatolia, Kaduri et al., JGR2017

Pyrenees, Lacroix JSG 2011;
C. Apennines, Tesei JSG 2013;
Serpentinites, Tesei et al., 2017
New Zeal., Fagereng/Sibson, Geology, 2010;
Shimanto belt, Kimura et al., Tect., 2011 ;
California, Meneghini More, BGSA, 2007
N. Apennines, Vannucchi et al., 2007
Outer Hebrides, Imber et al., Tectonics, 2001

Apennines, Bullock et al., Jsg, 2014
Wasatch, Bruhn et al., PAG. 94;
Alps, Manatchal, JSG 1999;
Death Valley, ayman, JSG, 2006;
Zuccale, Collettini Geology, 2009;
Moonlight, NZ, Alder JSG, 2016.

Are the San Andreas and low-angle normal faults the only weak faults?

My answer is no and I will support it by:

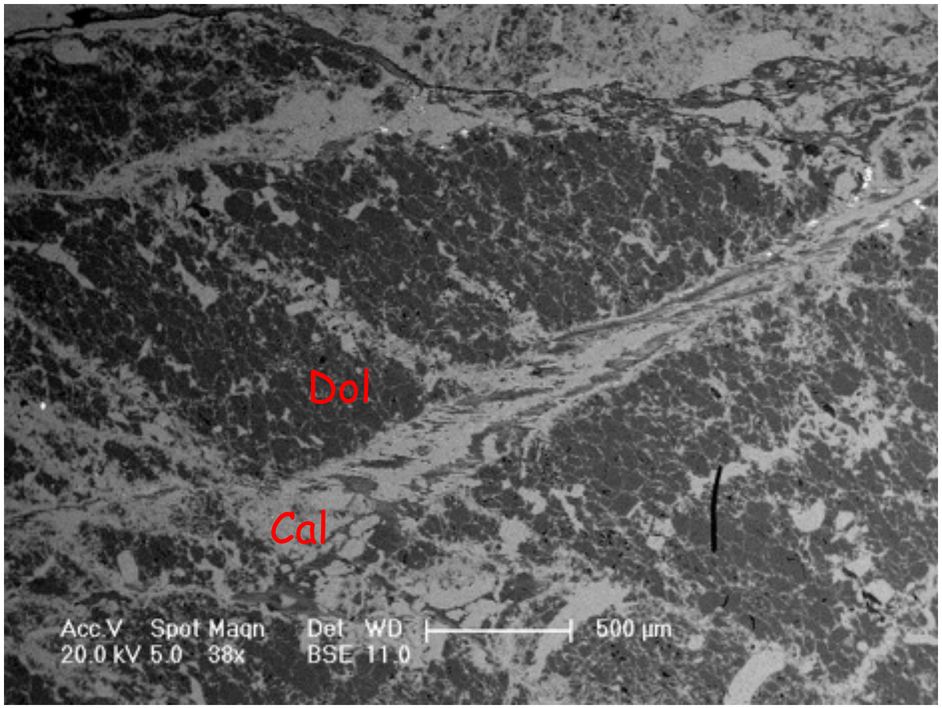
1) Examples of weak faults in different tectonic environments

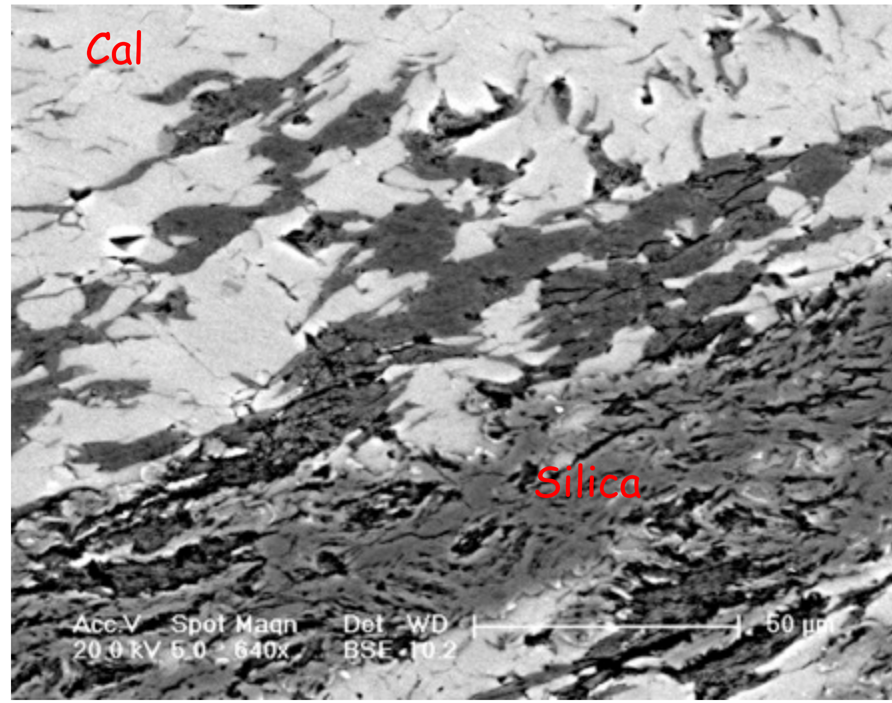
2) Reaction softening

3) Laboratory experiments on friction

Fault Weakening: reaction softening, i.e. replacement of strong with weak mineral phases.

Fault Weakening: at low strain fracturing and cataclasis + silica precipitation





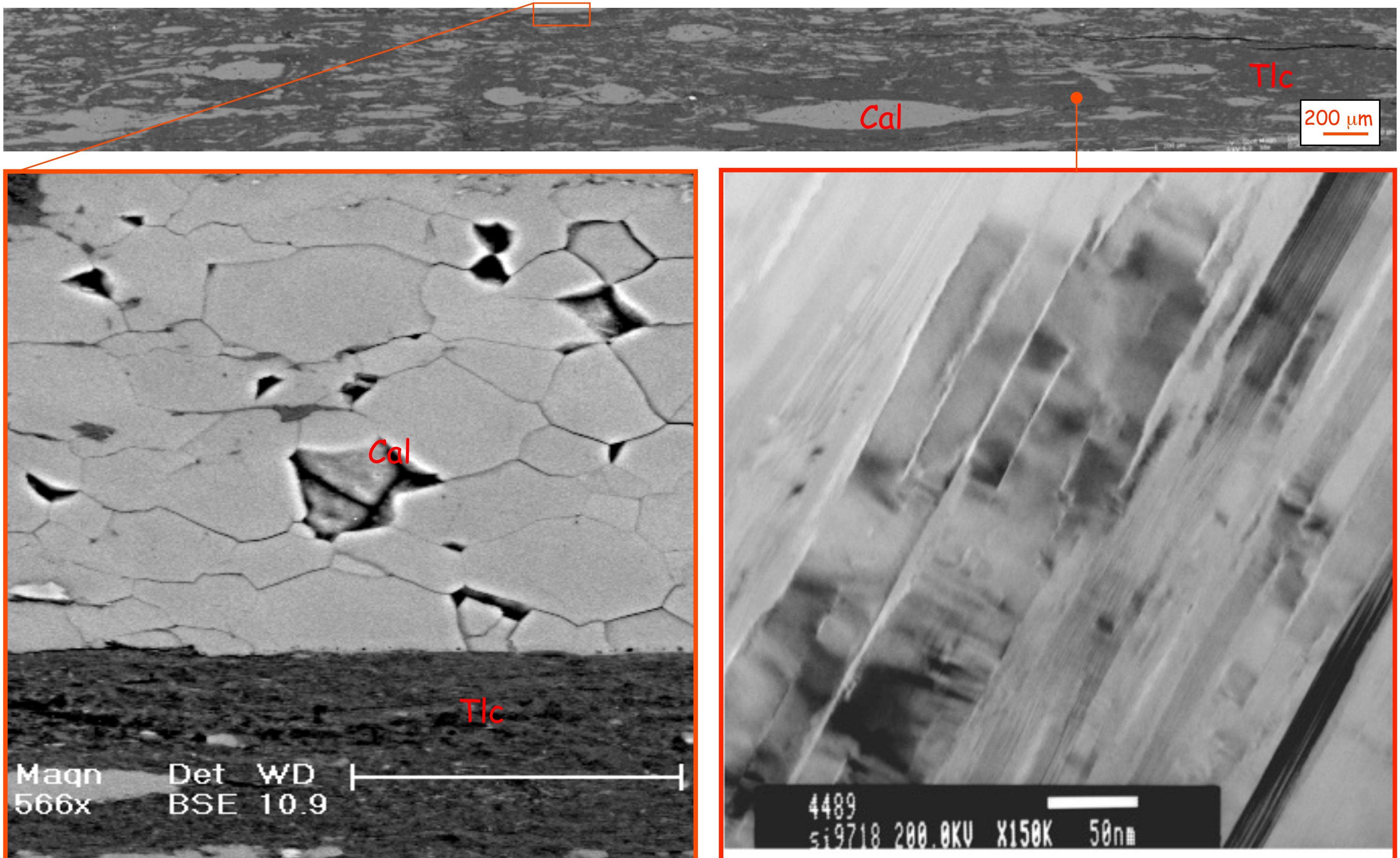
Calcite concentration along major fractures and syn-tectonic precipitation of calcite and talc along veins. Silica-rich fluids during deformation.

DOLOMITE + SILICA + H_2O = TALC + CALCITE + CO_2

$$3\ MgCa(CO_3)_2 + 4\ SiO_2 + H_2O = Mg_3Si_4O_{10}(OH)_2 + 3\ CaCO_3 + 3\ CO_2$$

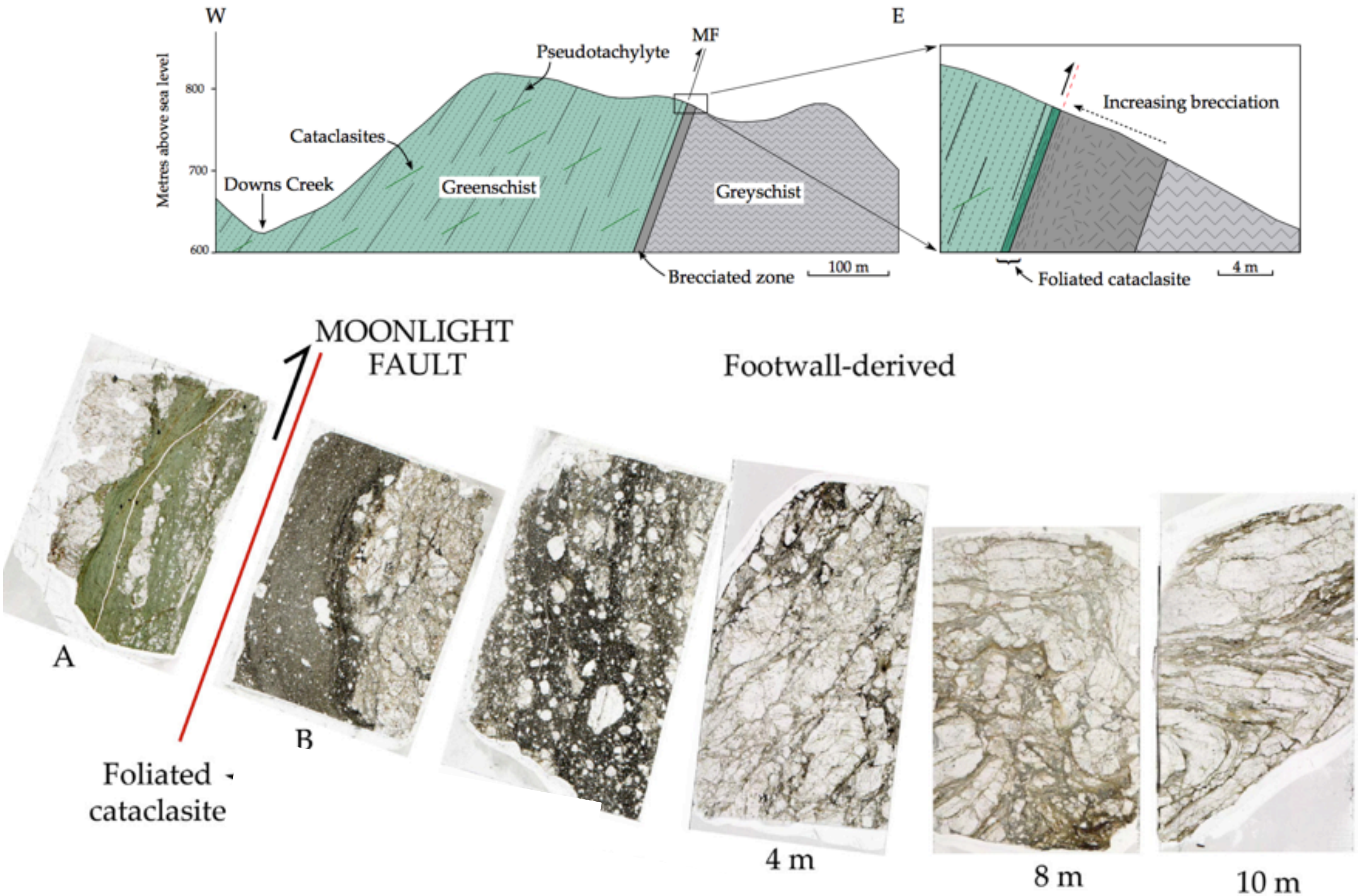
Collettini et al., Geology, 2009

Fault Weakening at high strain dissolution of carbonates and precipitation of talc + frictional sliding along talc.



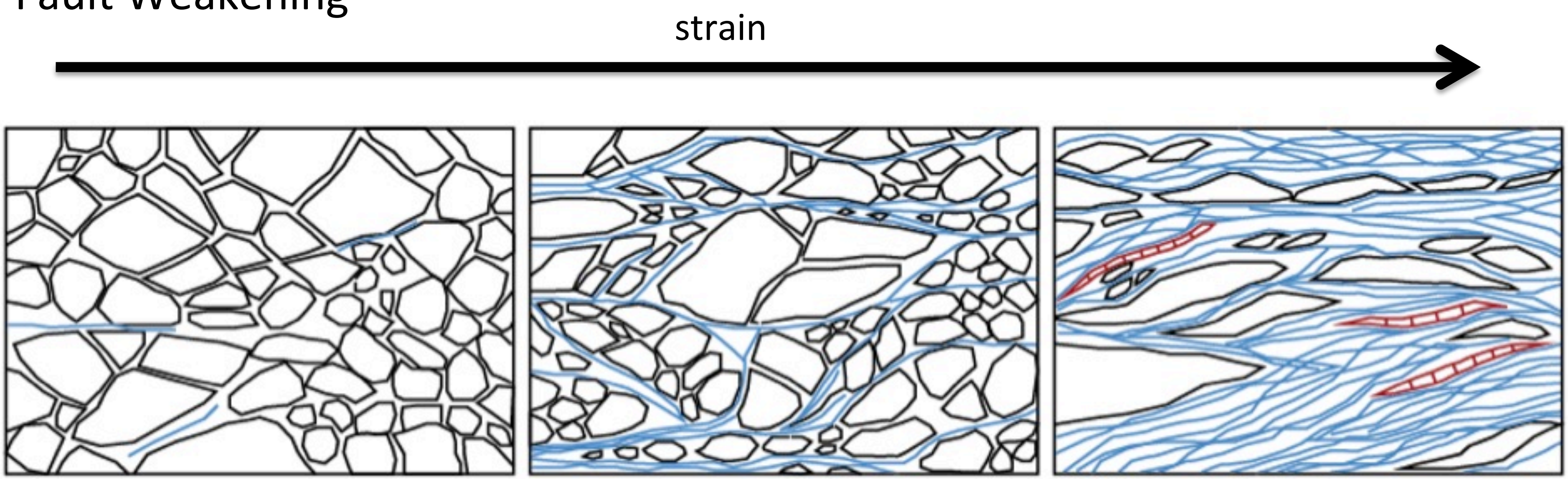
Collettini et al., Geology, 2009

Fault Weakening: reaction softening, i.e. replacement of strong with weak mineral phases.



Alder et al., JSG, 2016.

Fault Weakening



Cataclasis increases permeability and favors the influx of fluids.

Fluids promote dissolution of strong and precipitation of weak mineral phases .. to form a foliation....

...where a significant amount of deformation occurs by frictional sliding along the phyllosilicate

protolith	strong minerals	weak minerals
carbonates	calcite, dolomite	talc, illite, smectite
schists	quartz-feldspar	chlorite, muscovite
sandstone	quartz, calcite	chlorite, illite
granites	quartz-feldspar	chlorite, muscovite
mafic rocks (T <300°C)	olivine, pyroxene	chrysotile, lizardite, pol. ser.

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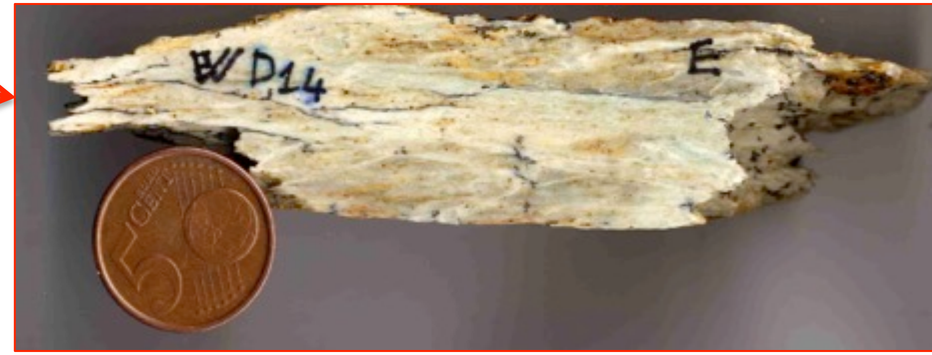
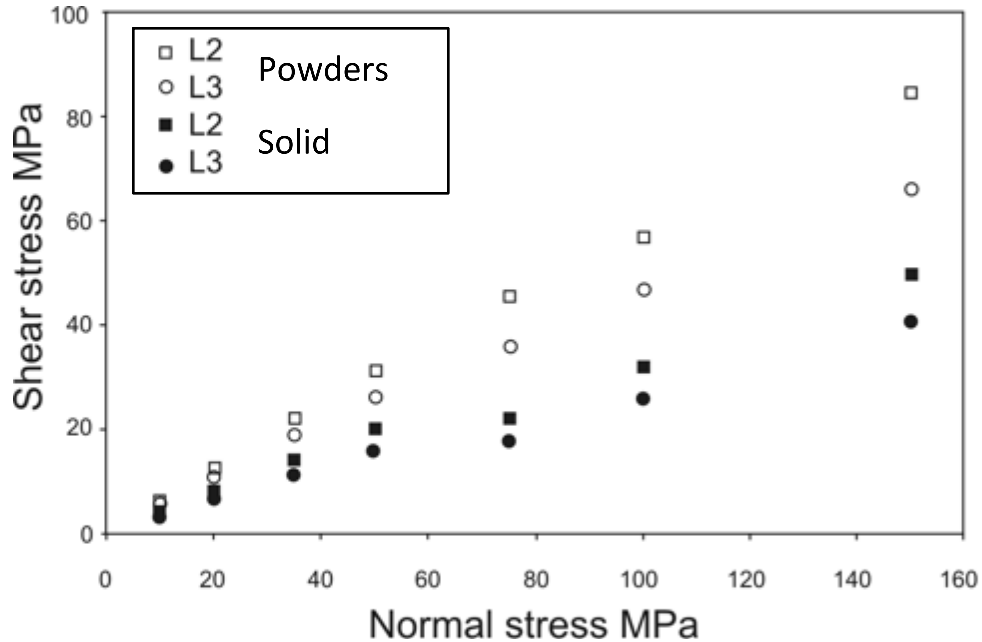
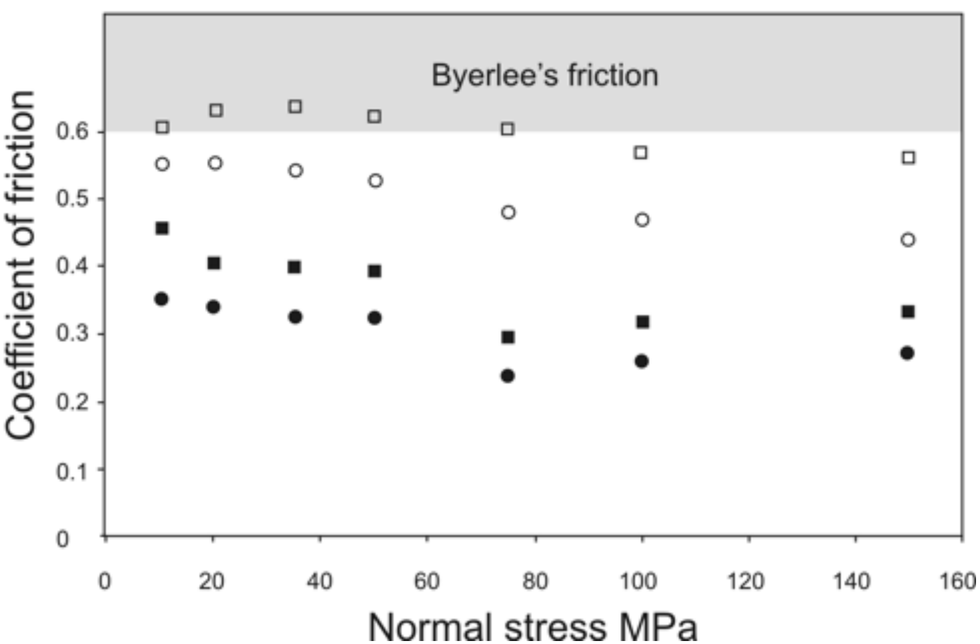
3) Laboratory experiments on friction

The role of fabric in fault weakness



The role of fabric in fault weakness





Frictional properties:
solid-foliated vs. powdered

Each rock-type plots along a line consistent with a brittle failure envelope, BUT the foliated solid wafers are much weaker than their powdered analogues.

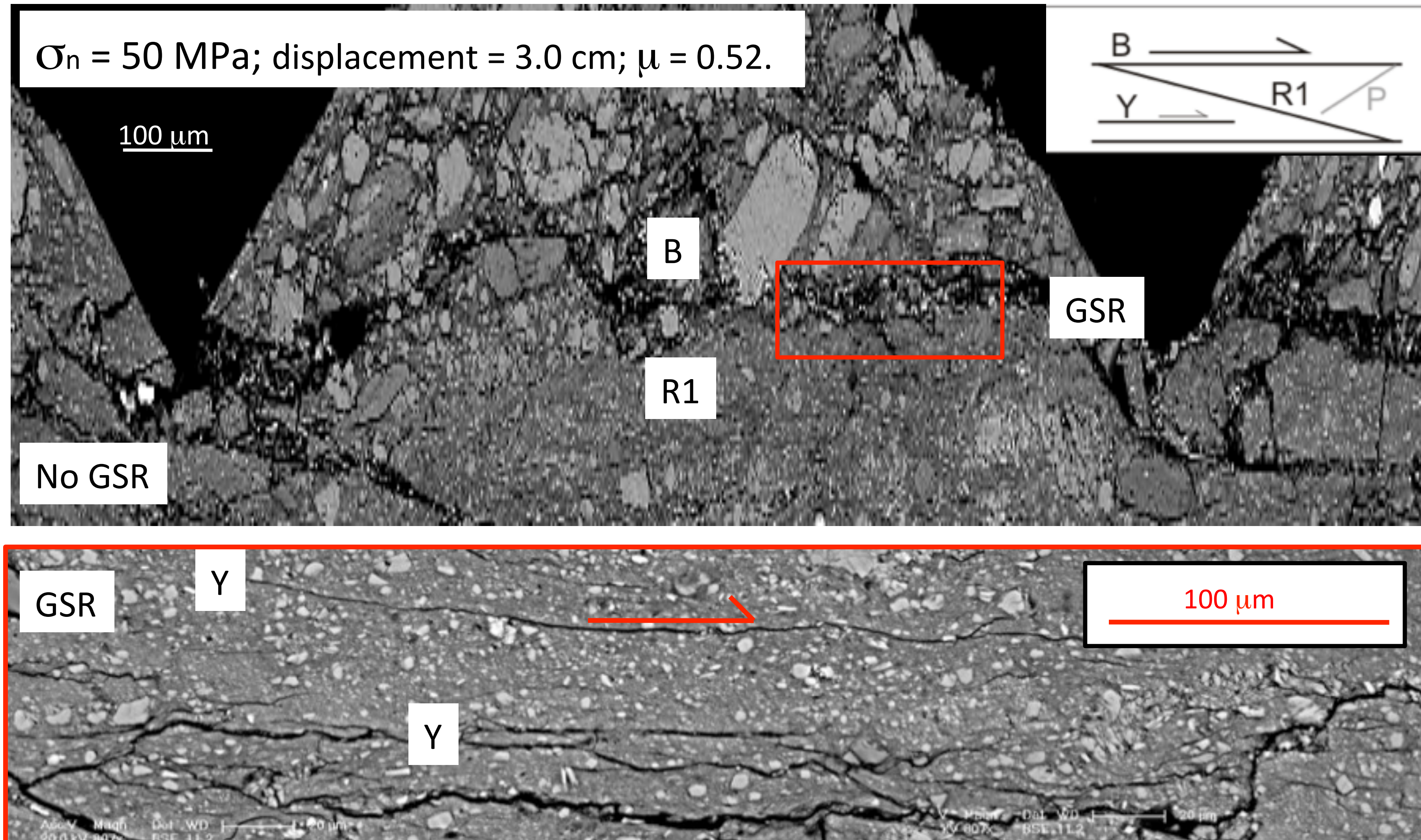
Powders show a friction close to Byerlee's values whereas the foliated rocks posses values significantly lower, 0.45-0.23.

Collettini, Niemeijer, Viti, Marone, Nature 2009

The role of fabric in fault weakness

Powders: deformation occurs along a zone characterised by cataclasis with grain-size reduction and affected by shear localization along R1, Y, B shears (e.g. Logan, 1978; Beeler et al., 1996; Marone et al., 1998).

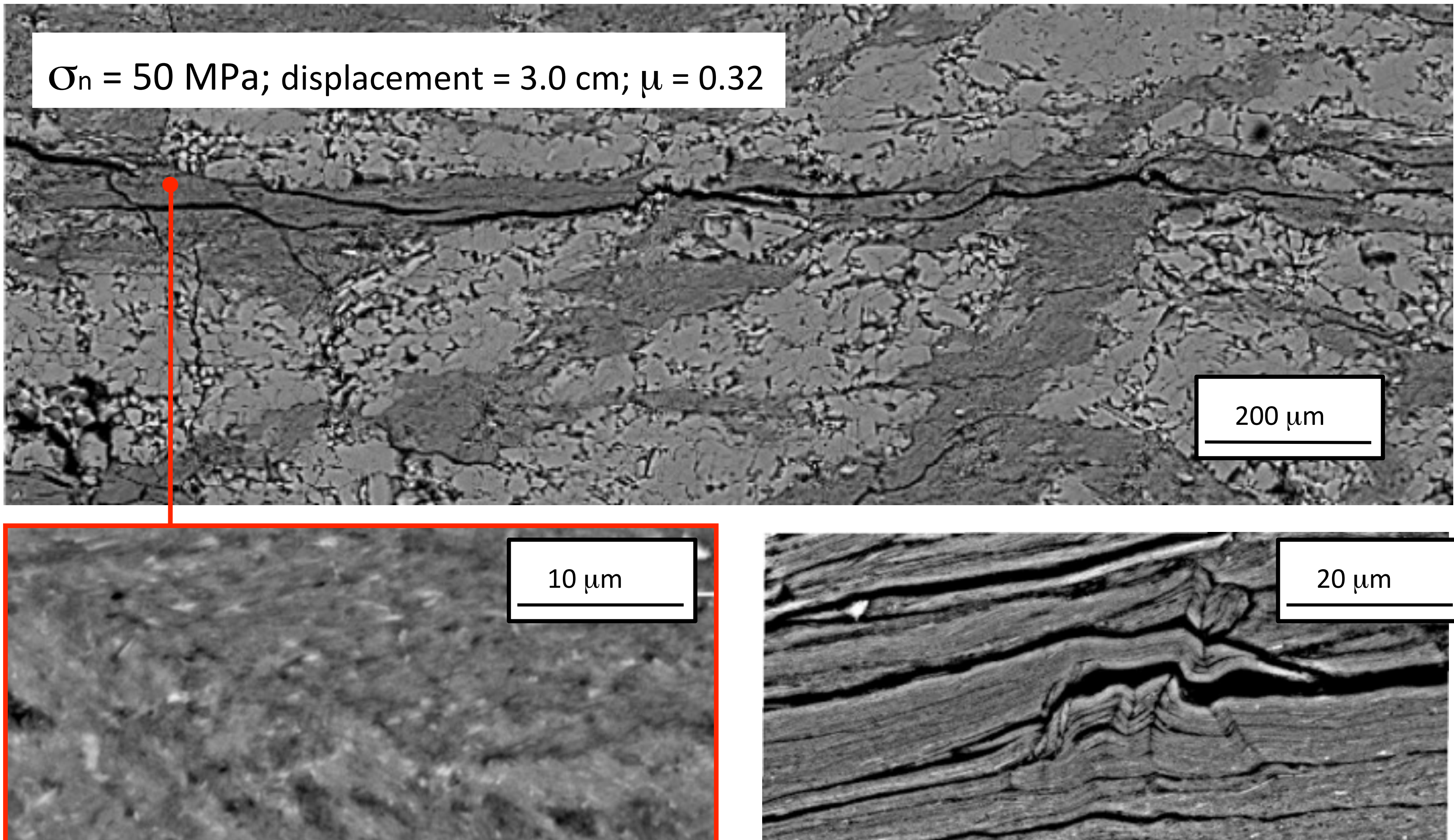
Microstructures solid-foliated vs. powdered



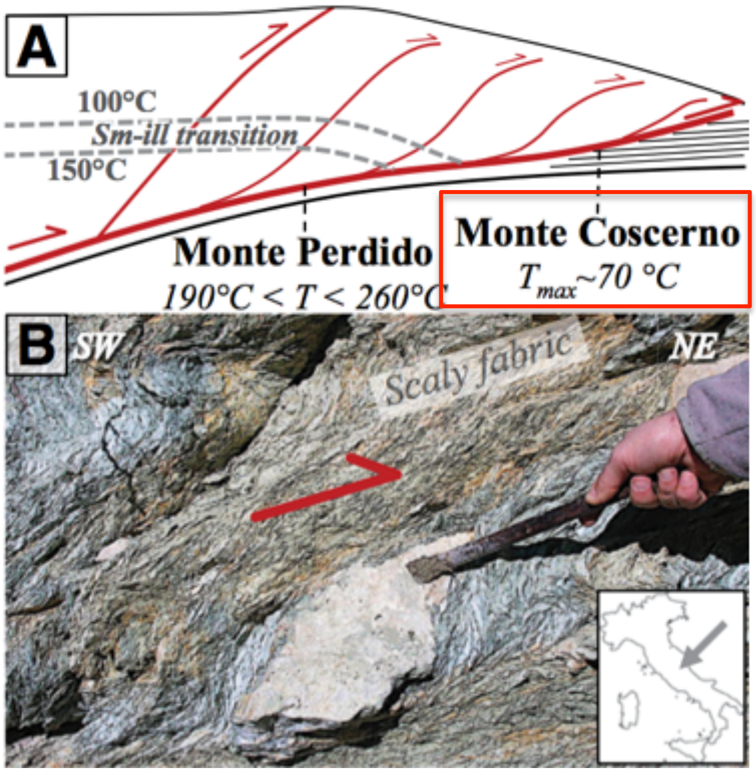
The role of fabric in fault weakness

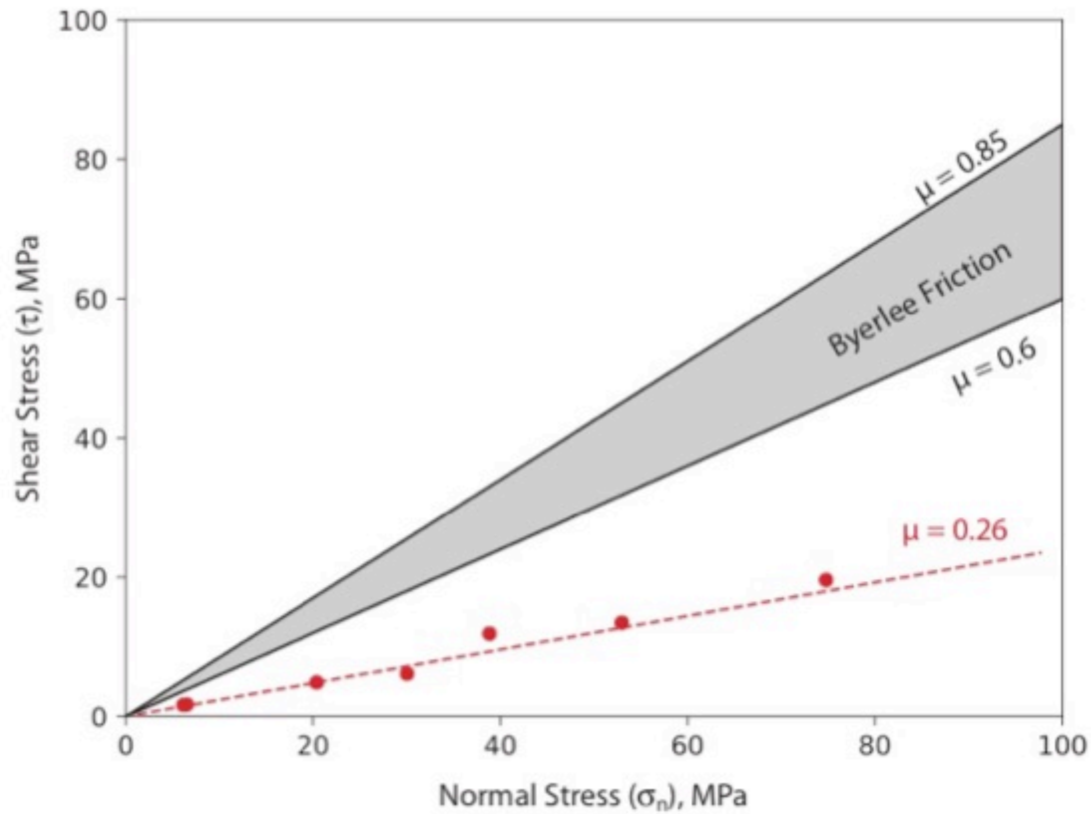
Solid-foliated sliding surfaces located along the pre-existing very fine grained, <2mm.

Microstructures
solid-foliated vs. powdered



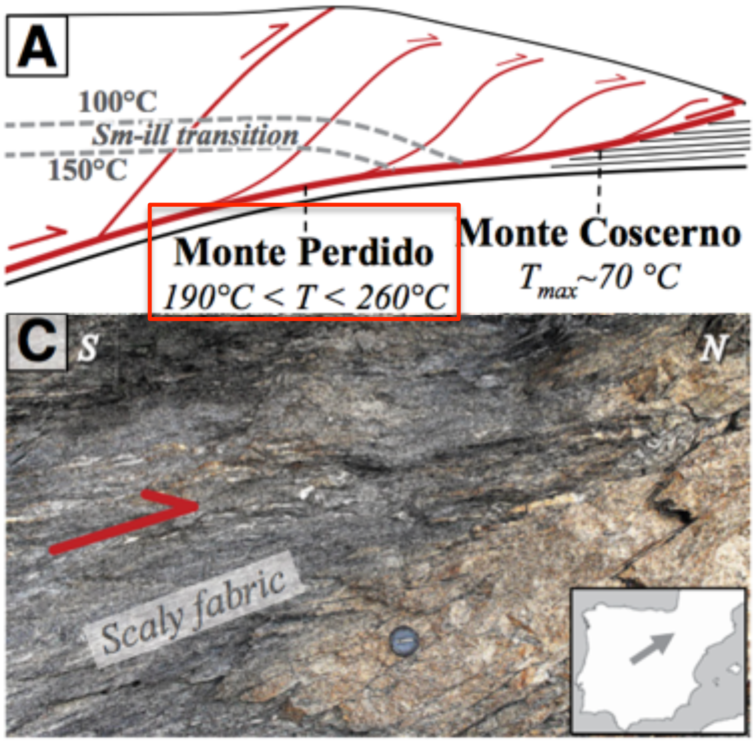
Monte Coscerno: protolith carbonates, foliation with smectite

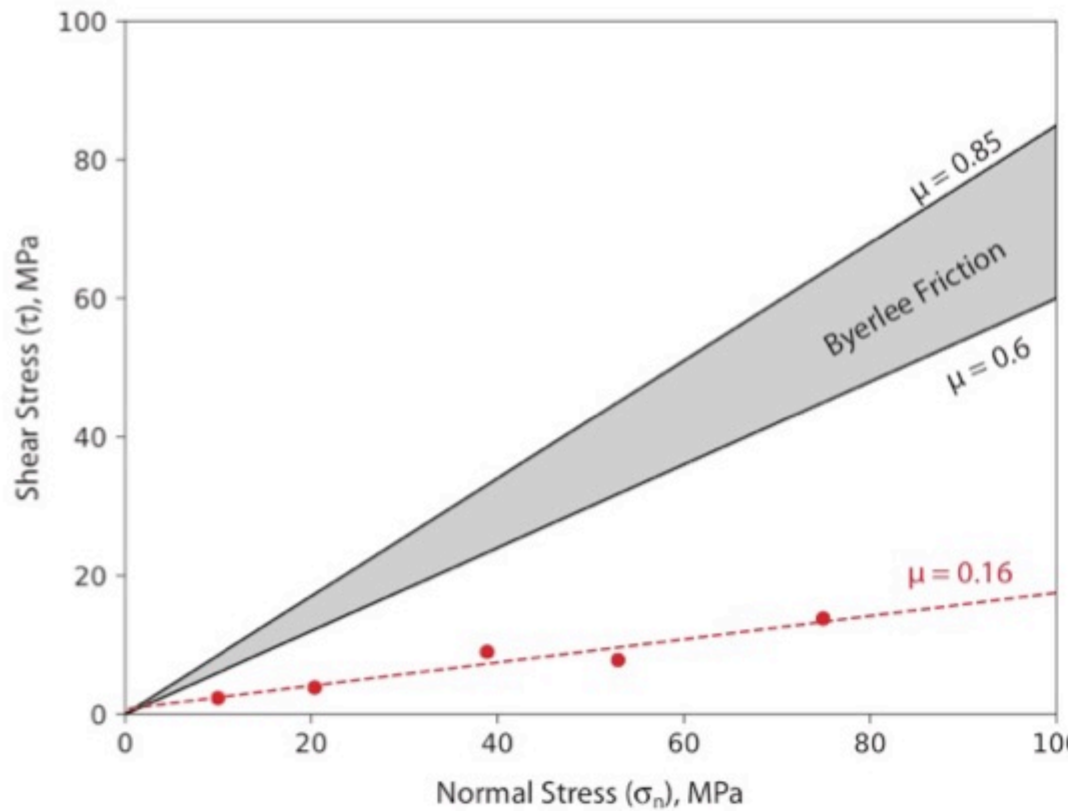


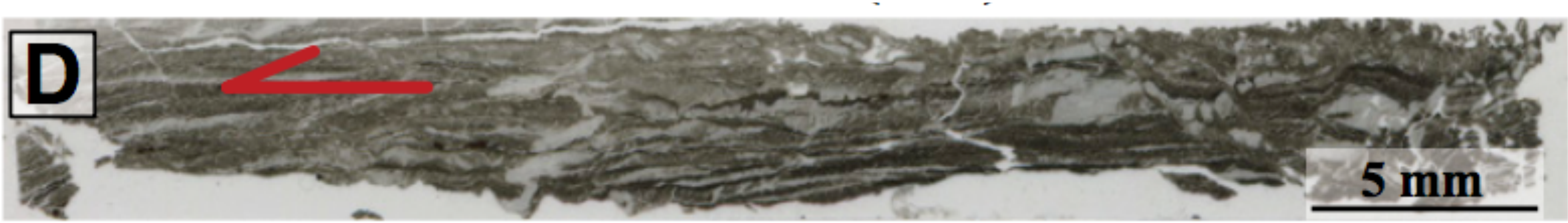


Tesei et al., Geology, 2015.

Monte Perdido: protolith sandstone, foliation with illite, smectite

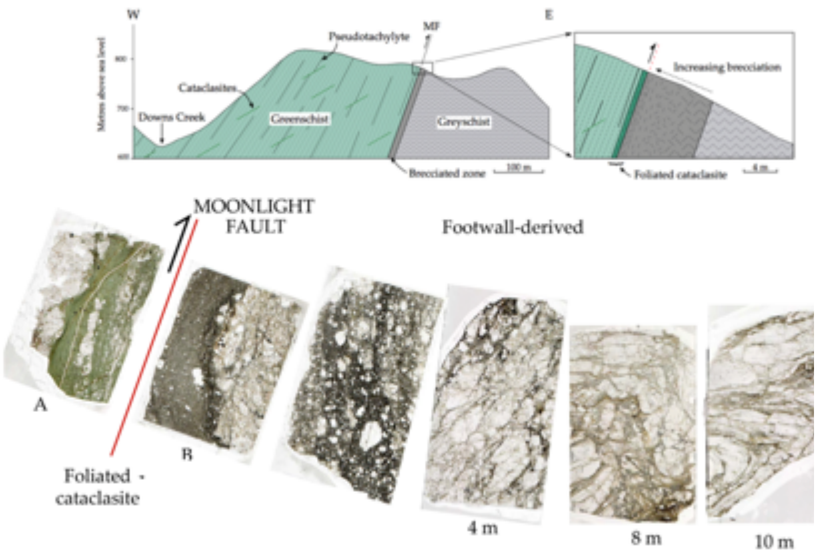


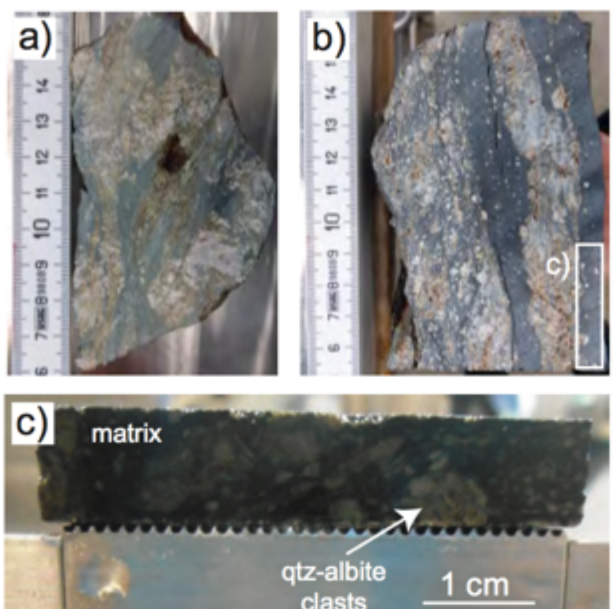


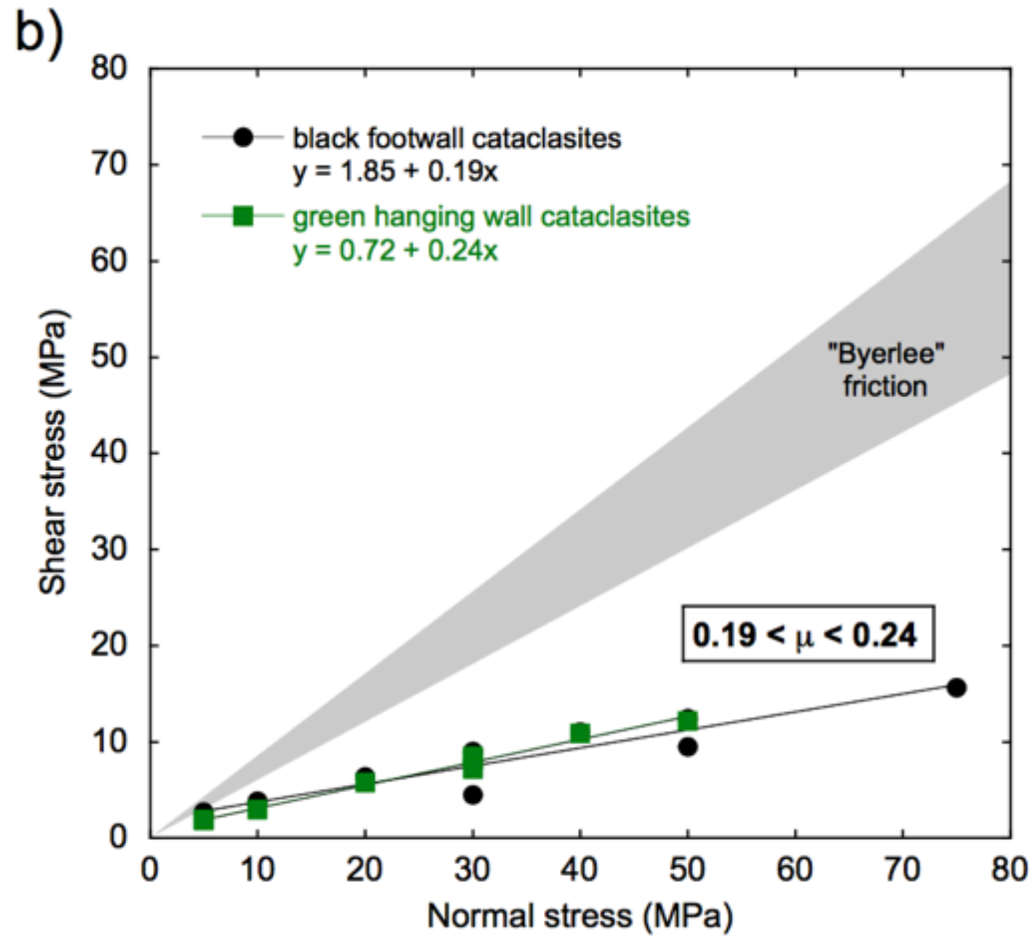


Tesei et al., Geology, 2015.

Moonlight fault: protolith schists, foliation with muscovite (FW) and chlorite (HW)

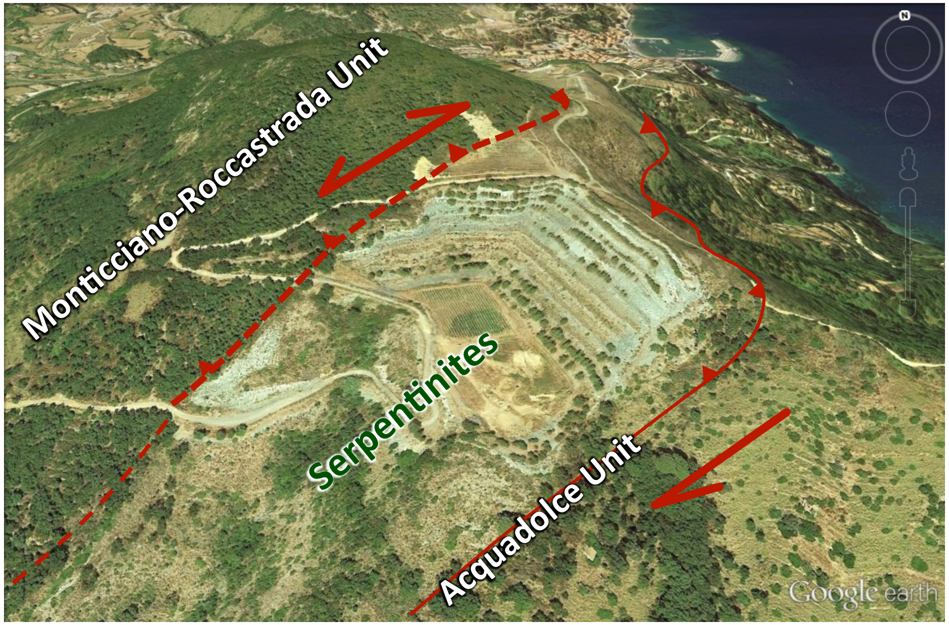






Smith et al., in review

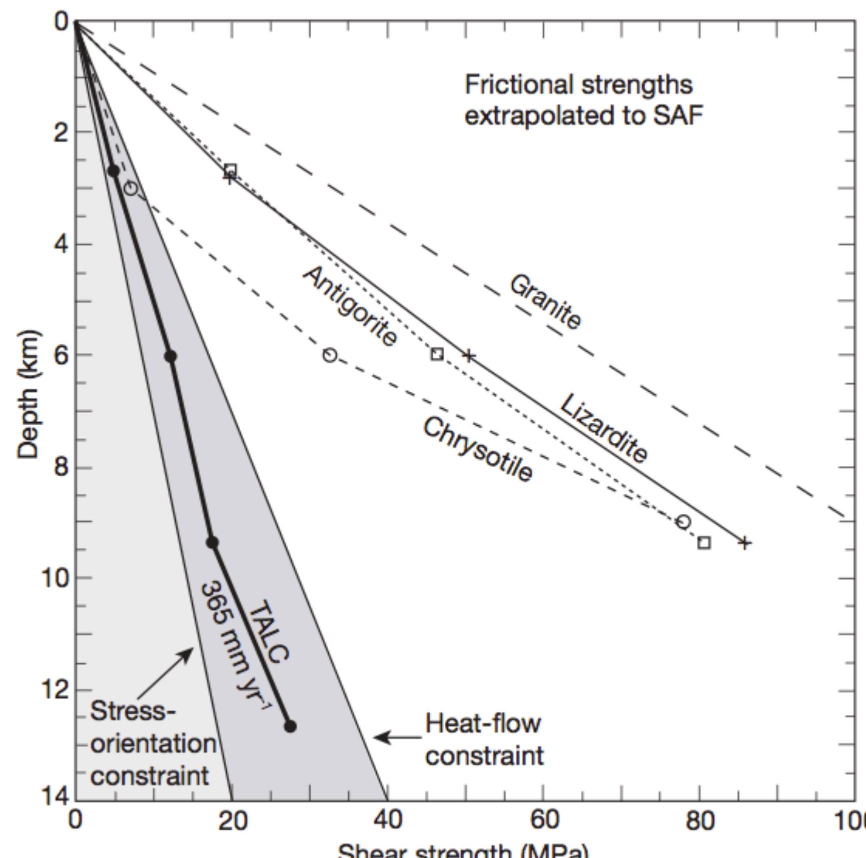
Monte Fico thrusts (serpentinites).



Serpentine minerals are chrysotile (fibrous), lizardite (platy) and antigorite (corrugated structure), together with a wide variety of intermediate structures.

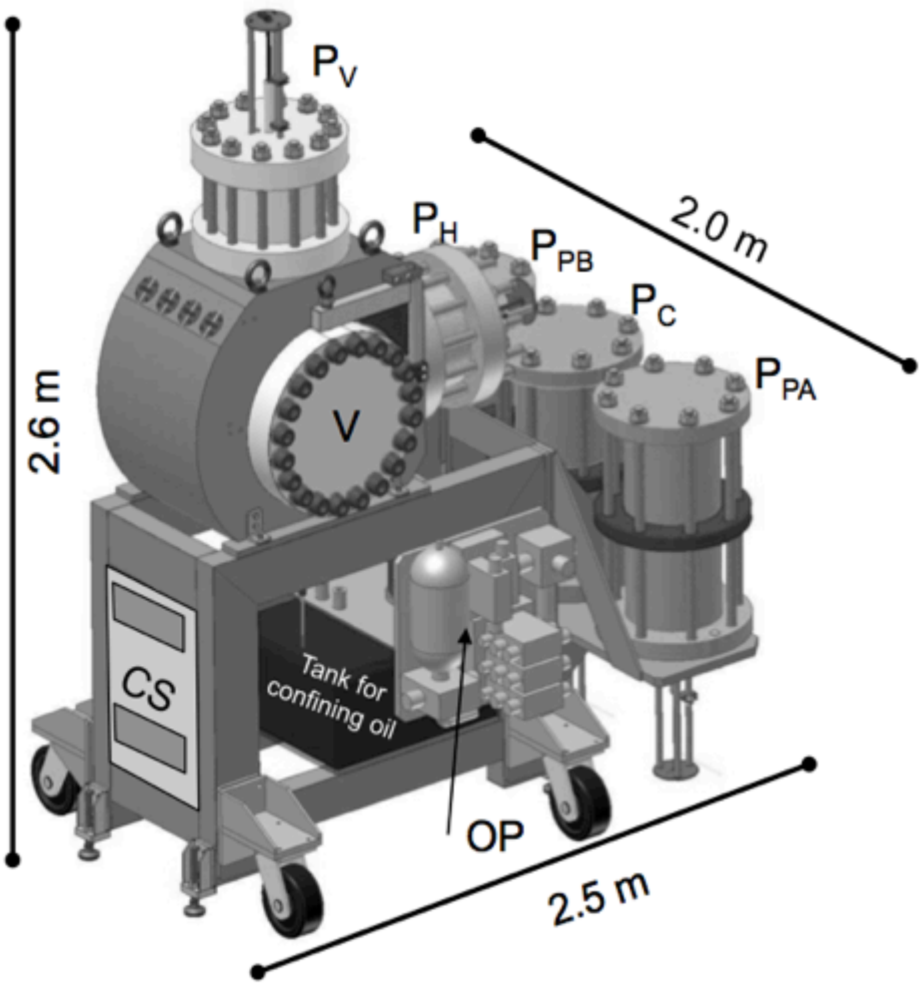
Chrysotile, lizardite and intermediate serpentine are the low T polymorphs T < 300 °C.

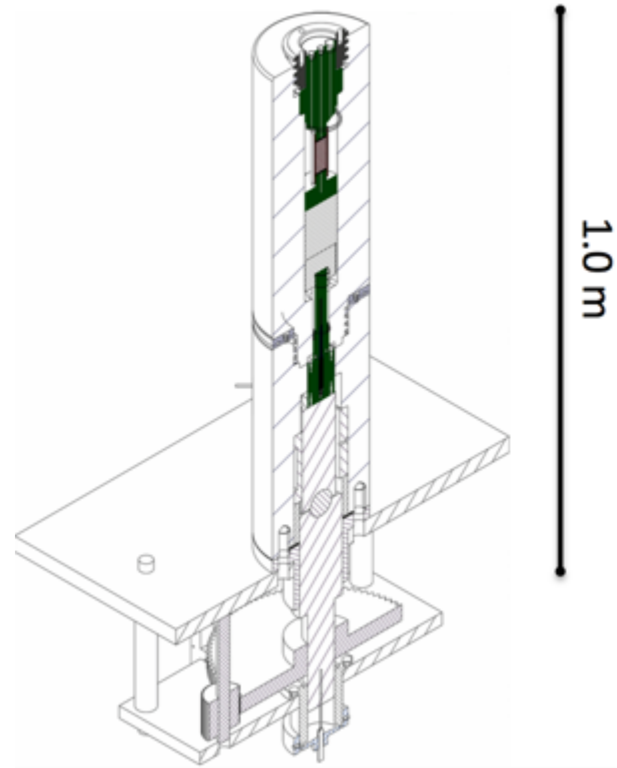
The frictional properties of these mineral phases, in general, are not invoked to support fault weakness.



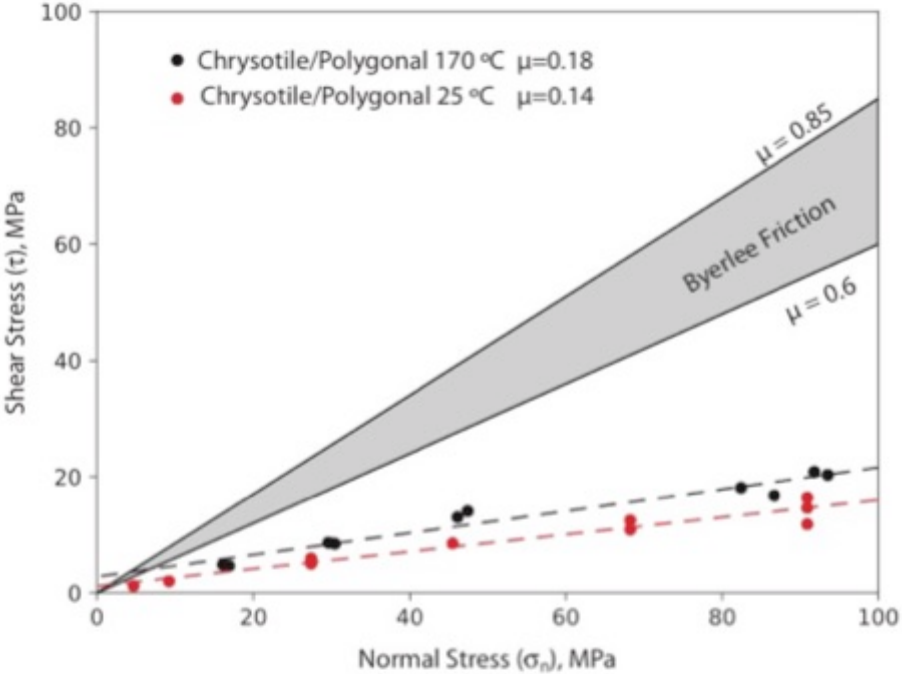
Moore and Rymer, 2007

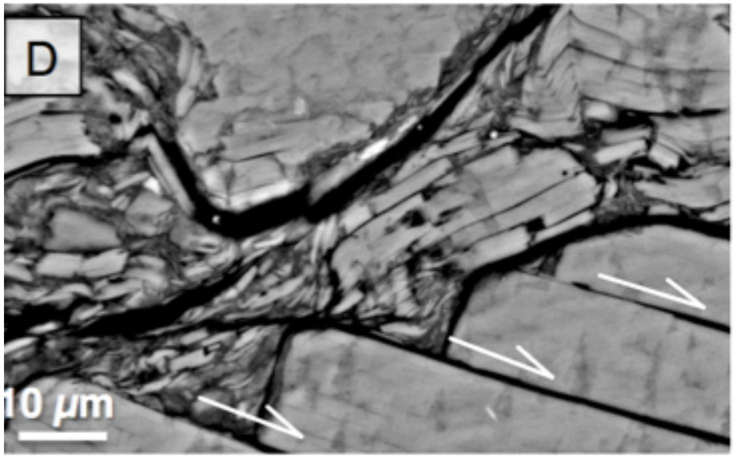
Friction experiments on chrysotile/poligonal serpentine and lizardite at both room temperature and 170°C.

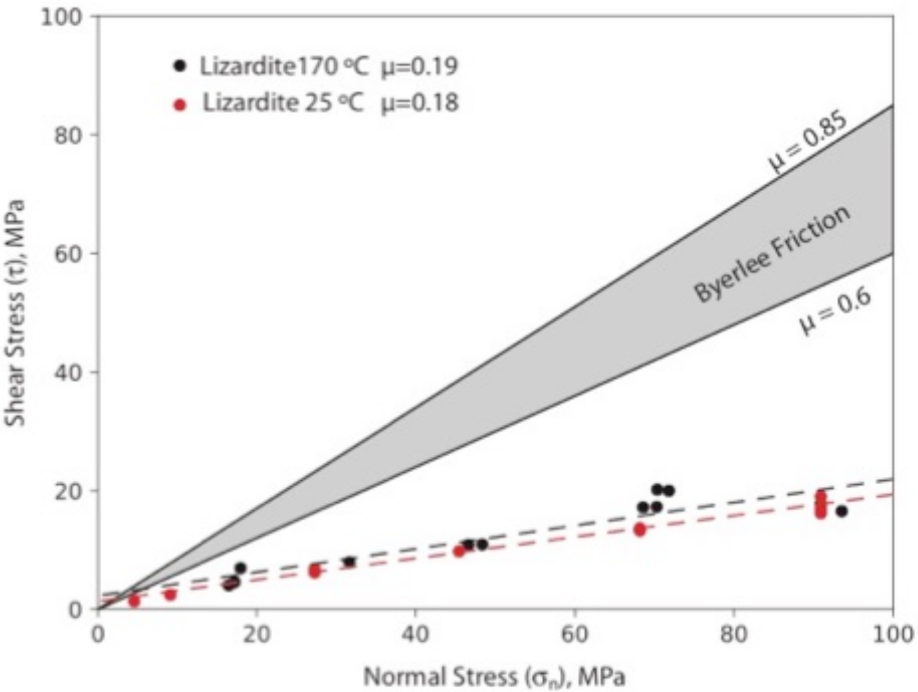


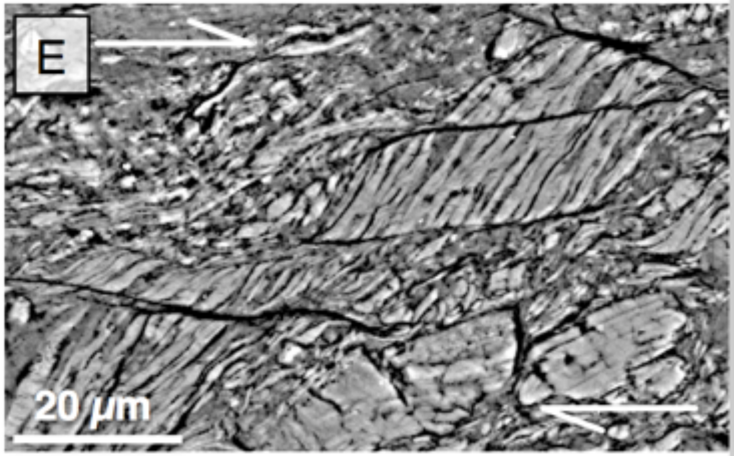


Tesei et al., in review



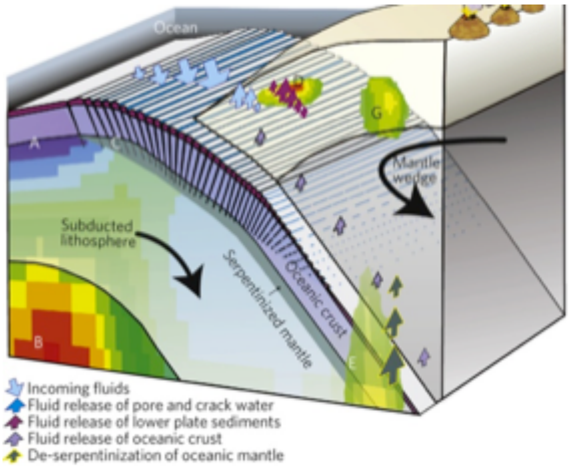


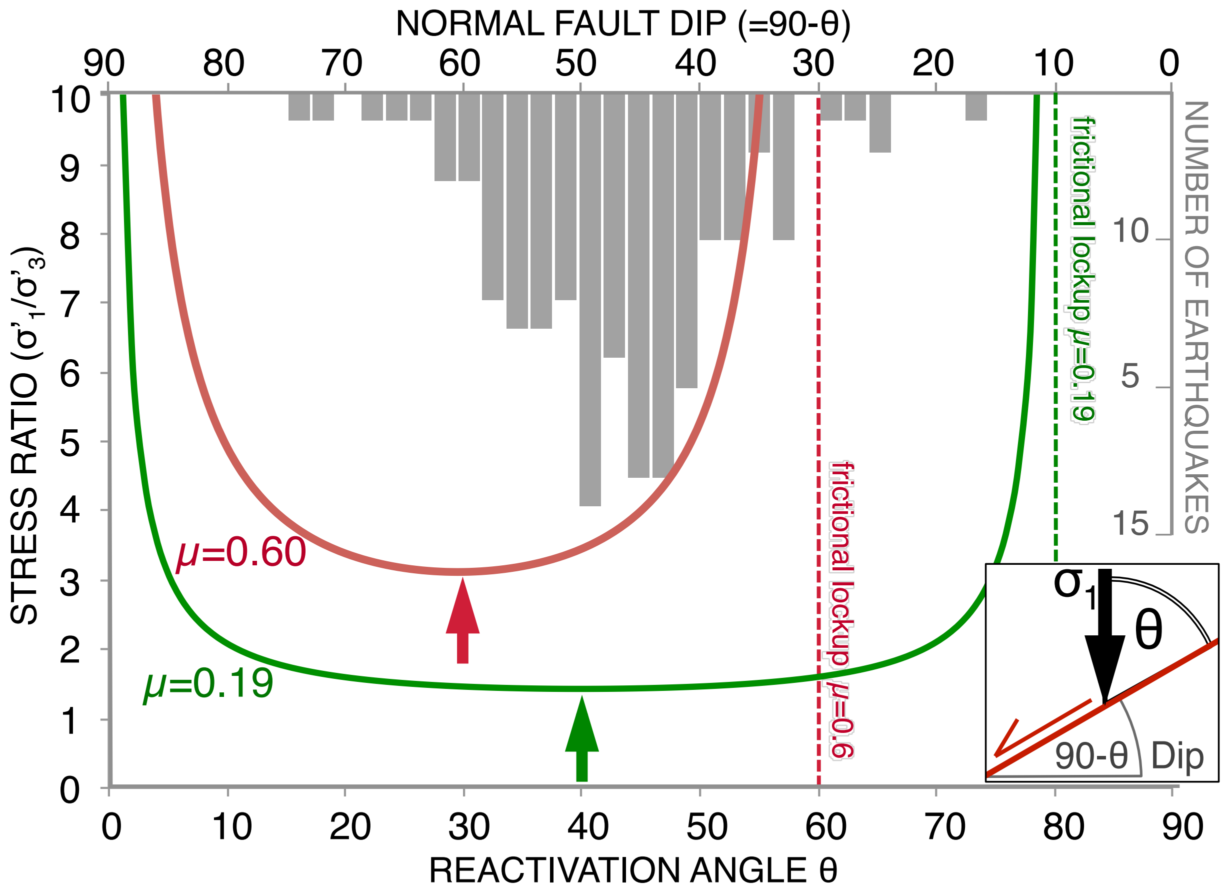




Tesei et al., in review

Comparison of frictional fault reactivation predicted by our experiments on friction and the dip distribution of the earthquakes occurring along the oceanic outer rise (focal mechanisms from Craig et al., EPSL 2014).



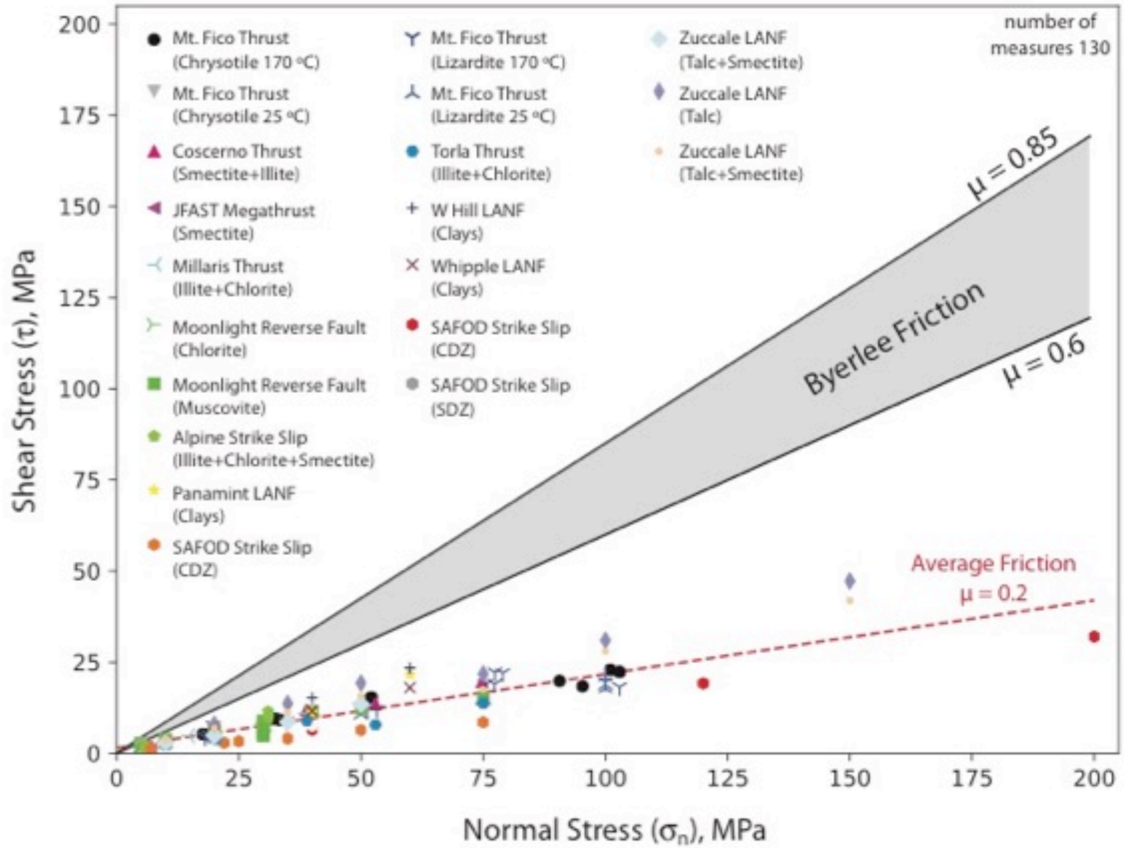


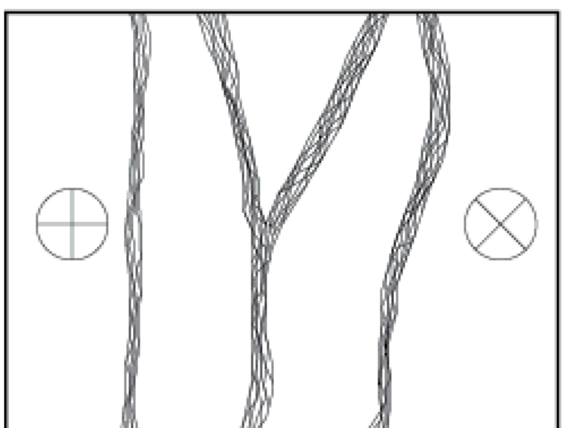
Tesei et al., in review

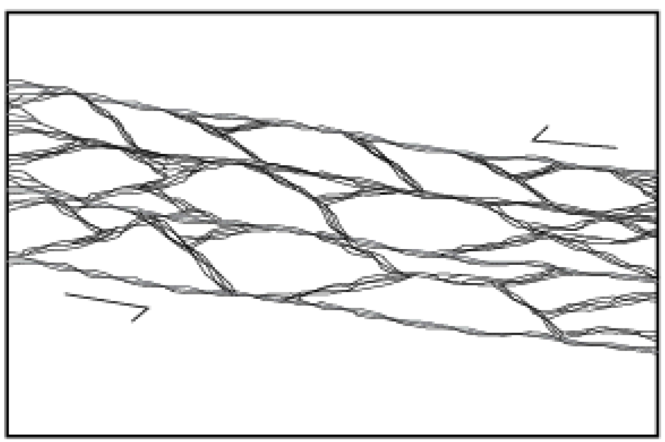
1) Examples of weak faults in different tectonic environments

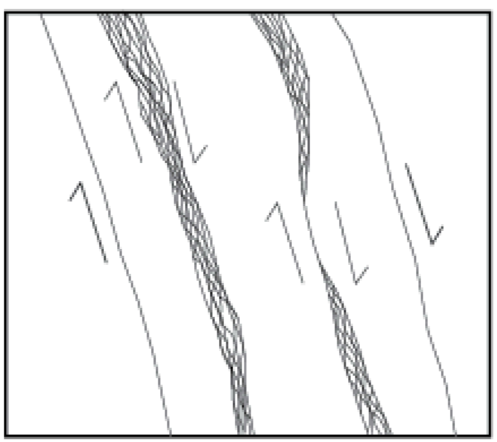
2) Reaction Softening

3) Laboratory experiments on friction

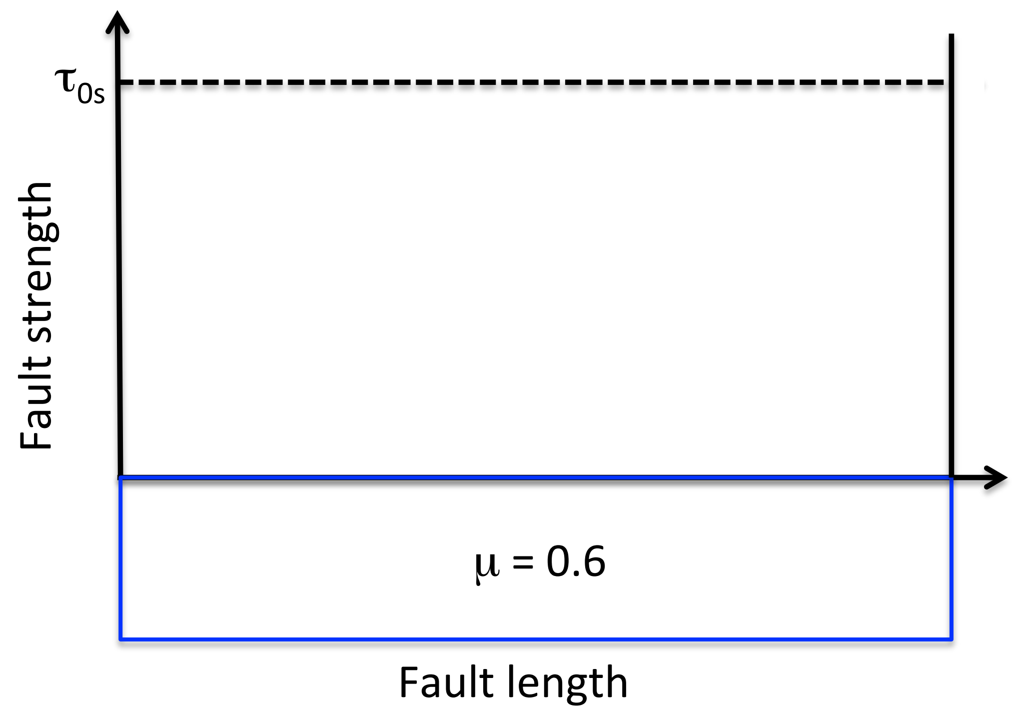




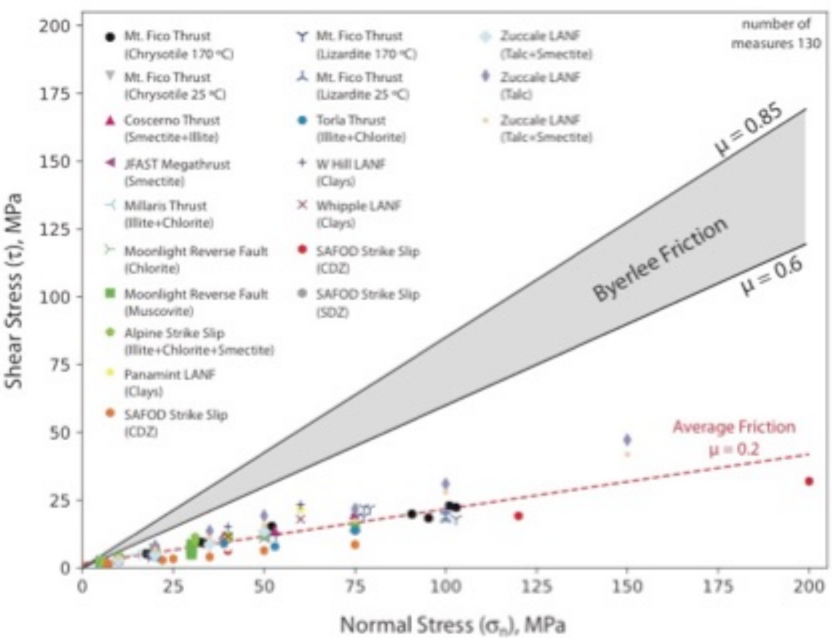


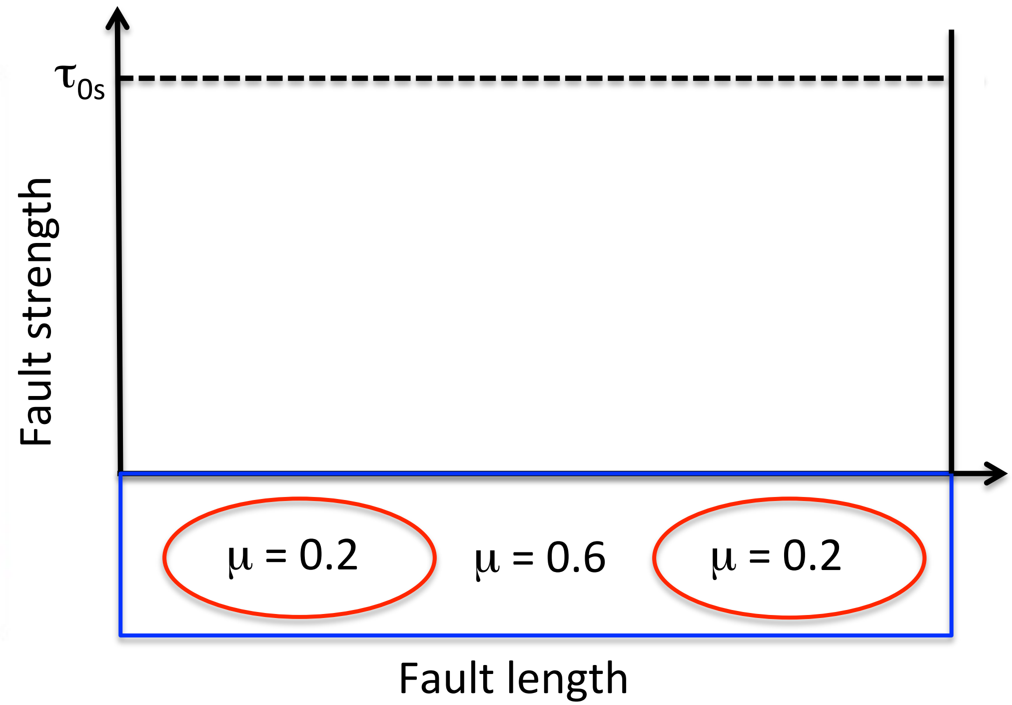


Strong fault with Byerlee's friction

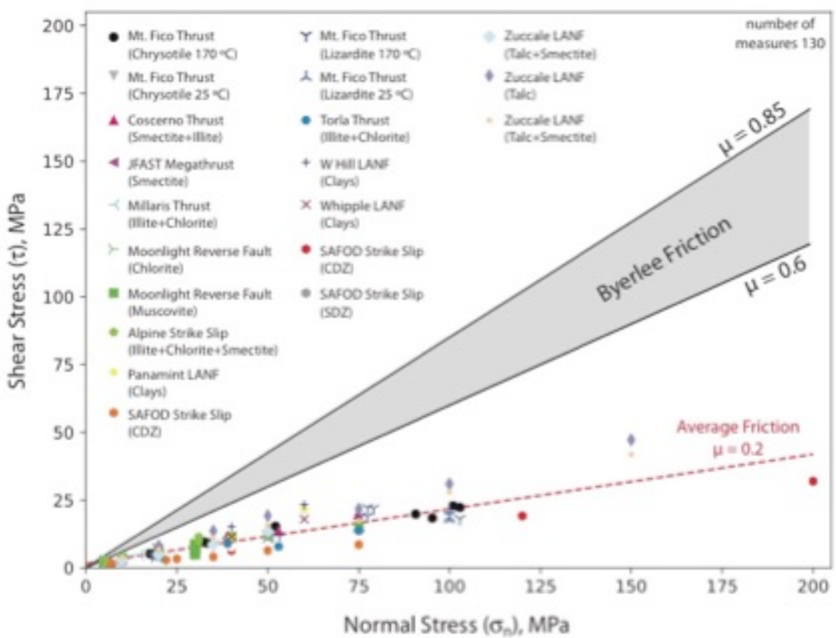


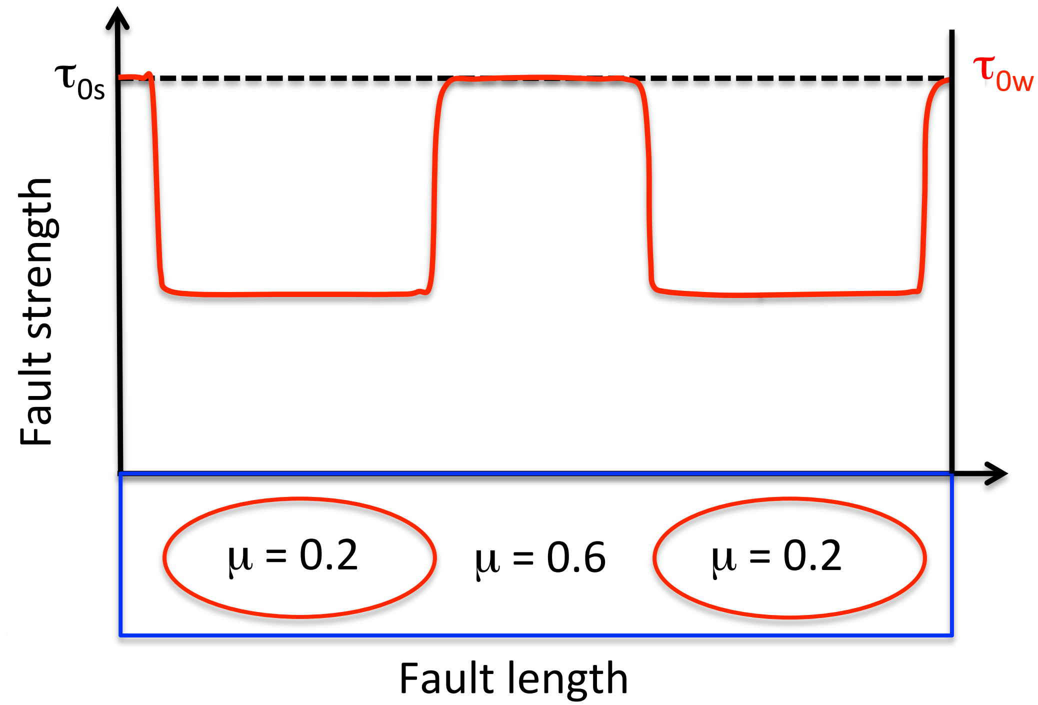
If we take into account that a significant number of faults might be weak





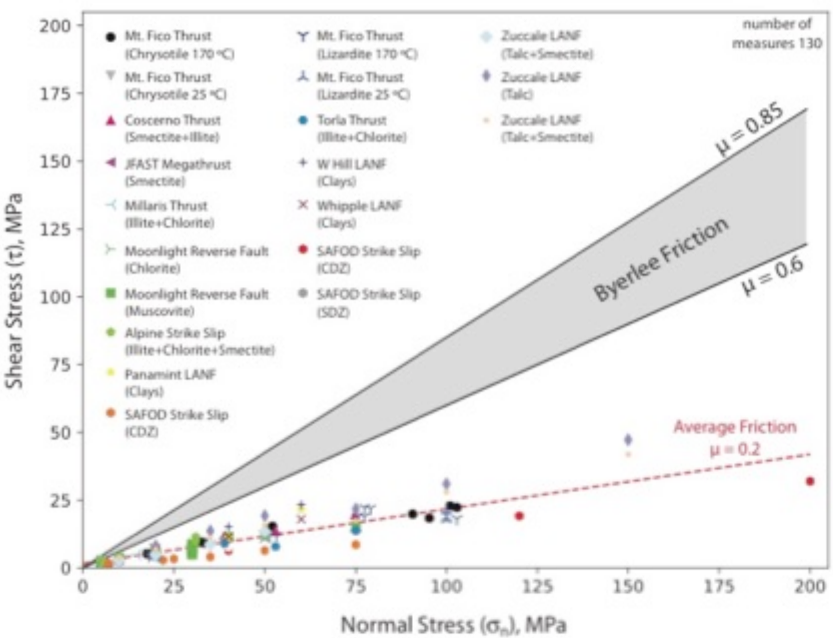
A significant number of faults are weak

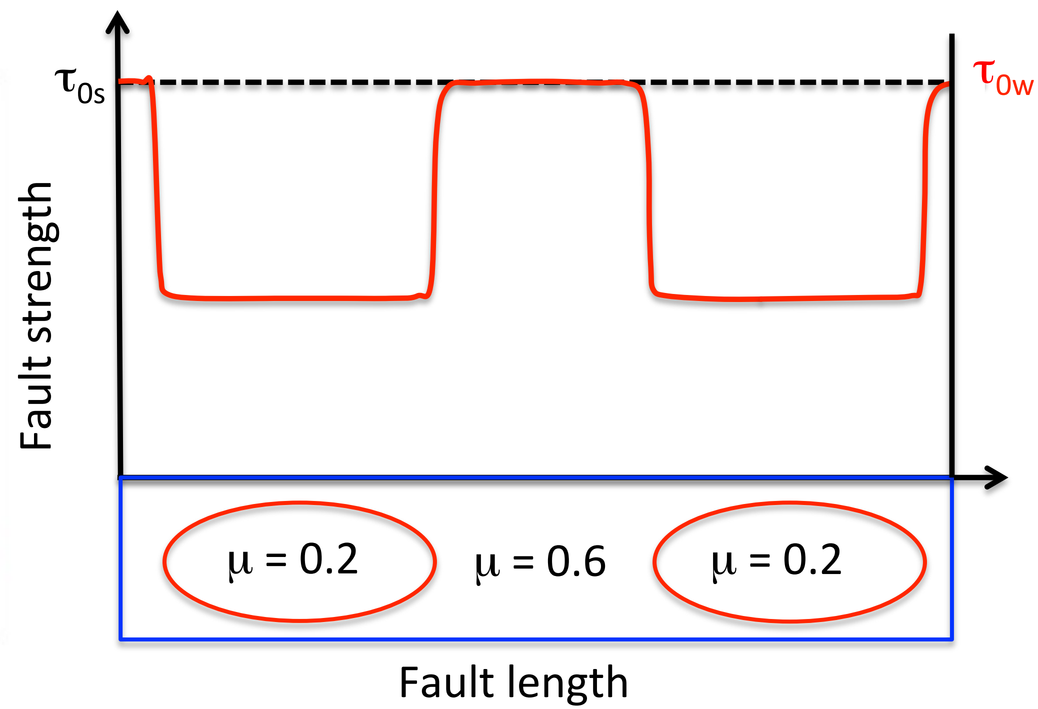




The low shear strength of weak faults can contribute in explaining

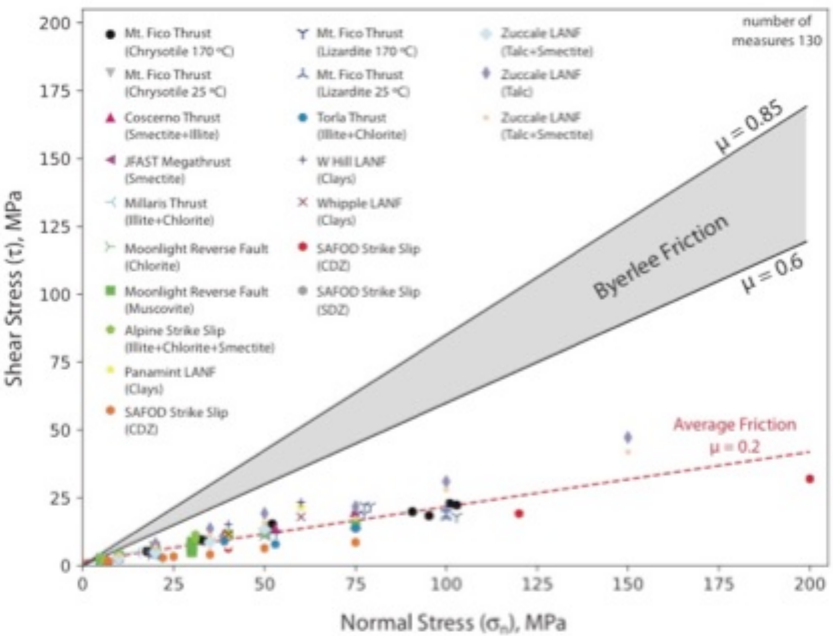
1) the lack of frictional heat associated with active faults

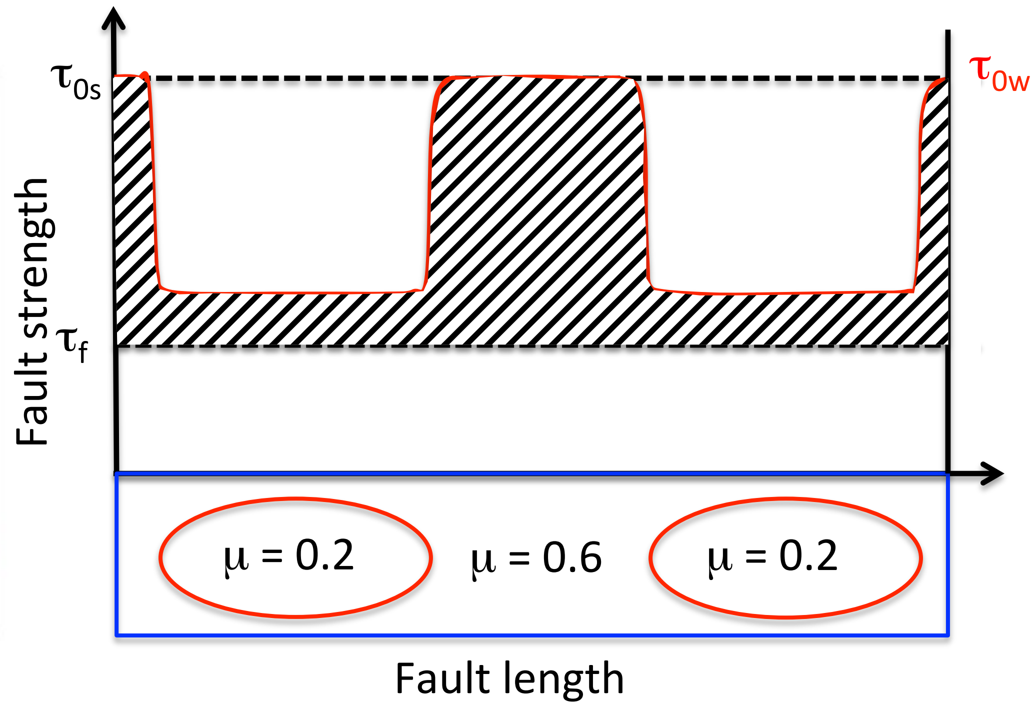




The low shear strength of weak faults can help in explaining

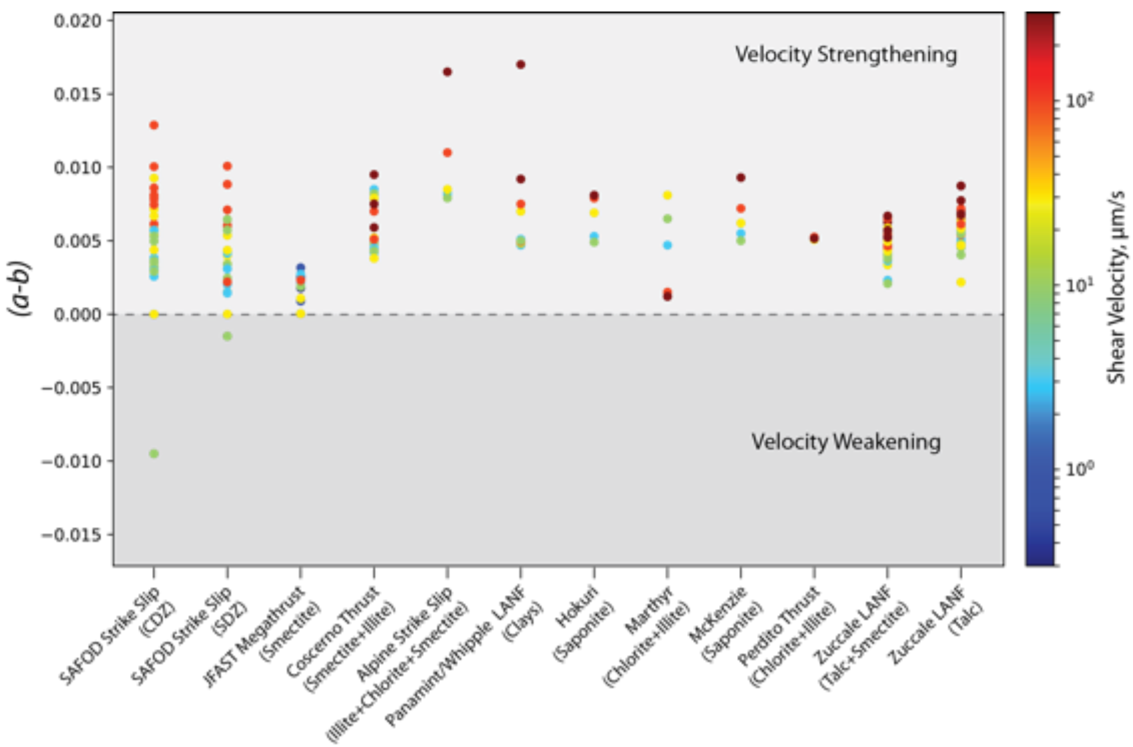
2) the low average earthquakes stress drop (together with dynamic weakening, e.g. Rice et al., 2009, or fault roughness e.g. Zielke et al., 2017).

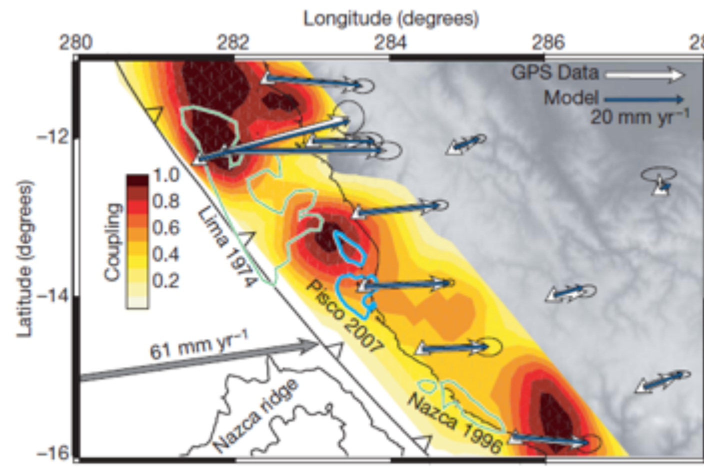




In addition, since most of the weak minerals are velocity weakening,

3) this can contribute in explaining the significant amount of deformation accommodated not via earthquakes within the seismogenic layer.





On average aseismic slip in the interseismic period accounts for about 38% to 59% of interplate slip at depth shallower than 40 km.

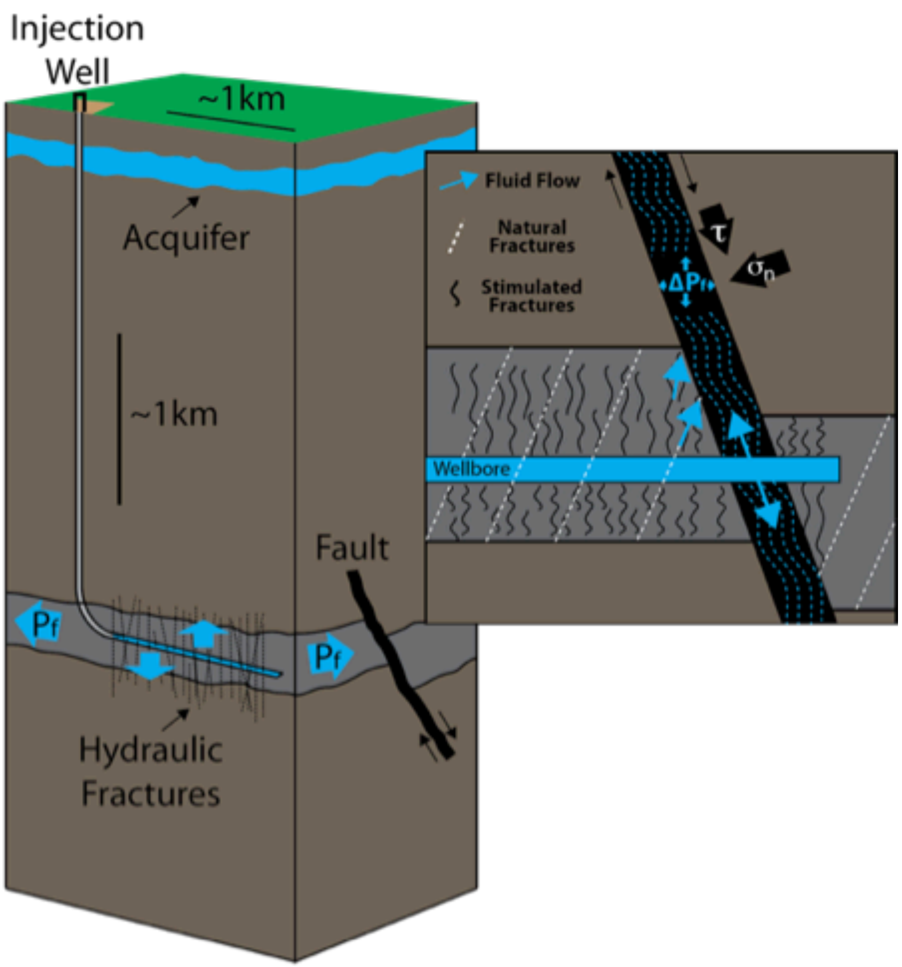
Perfettini et al., Nature 2010.

Fault strength

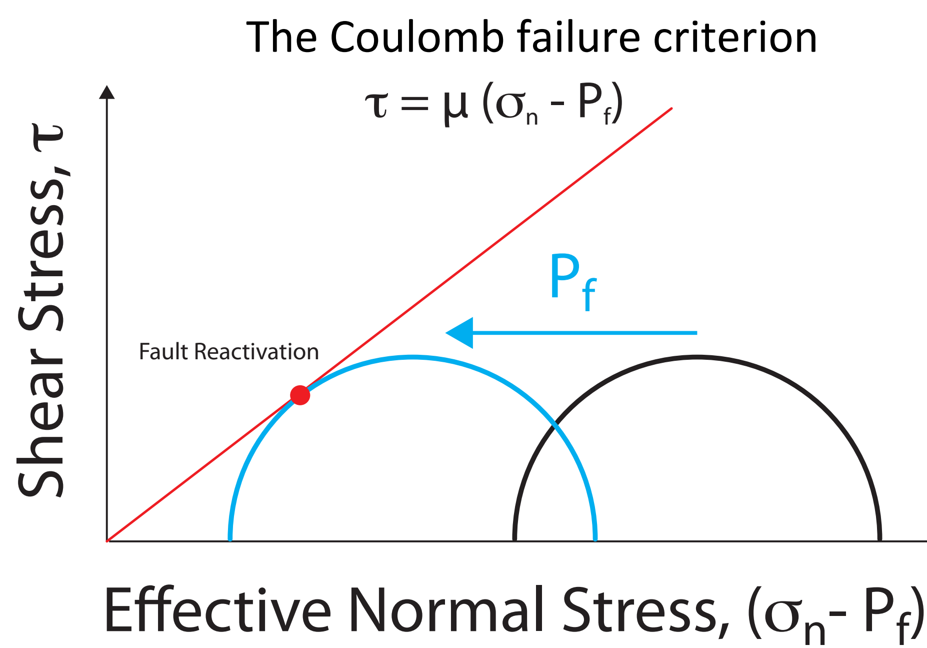
- Intro
- Examples of weak faults in different tectonic environments
- Reaction softening
- Frictional properties
- Implications for seismic & aseismic slip

Slip behaviour of fluid pressurized experimental weak faults

The basic physical mechanism for induced seismicity is well understood. Following injection, fluid overpressure reduces the effective normal stress, that holds the fault in place, promoting fault reactivation (e.g. Hubbert and Rubey, 1959 Bull. Geol. Soc. Am.).



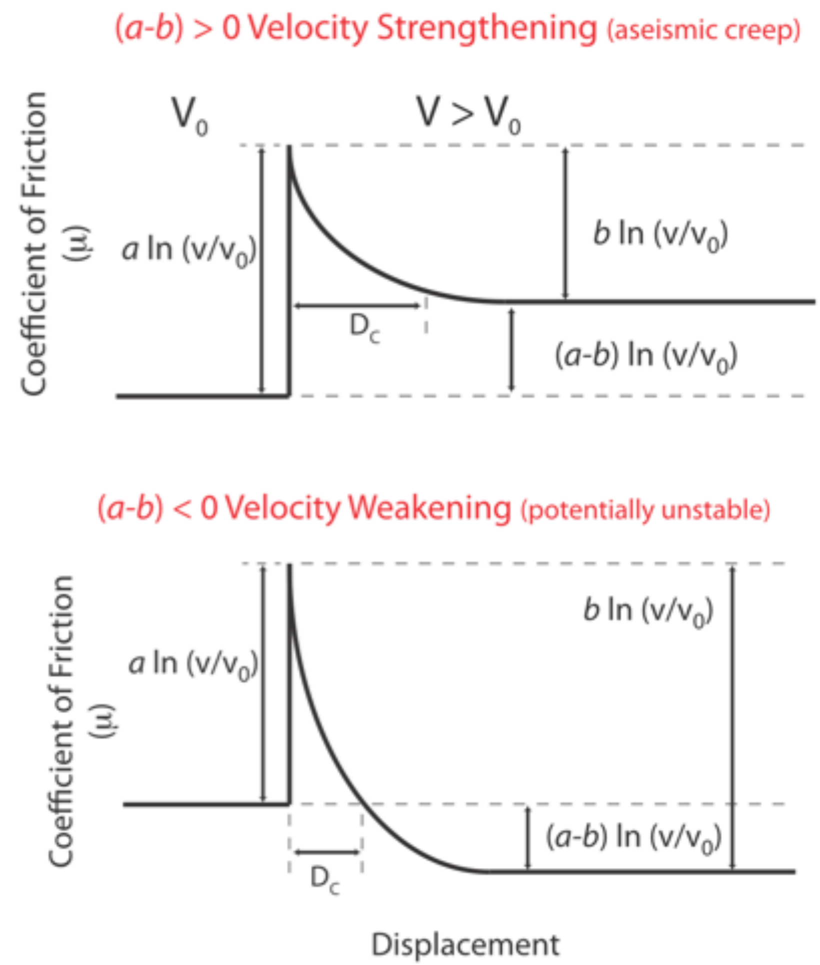
Modified from Davies, 2013



Fault reactivation vs. Frictional slip stability

Rate- and State- frictional constitutive equations (RSF) to evaluate frictional stability

$$\frac{\tau(\theta, v)}{\sigma_n} = \mu_o + a\ ln\left(\frac{v}{v_o}\right) + b\ ln\left(\frac{v_o\theta}{D_c}\right)$$



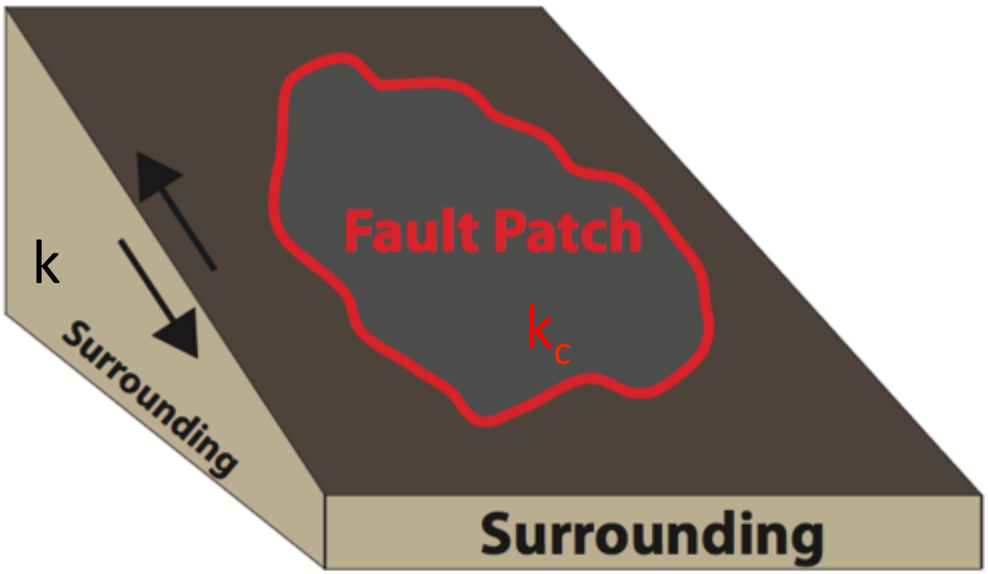
Dieterich, 1979 (JGR); Ruina, 1983 (JGR); Marone, 1998 (AREPS).

Fault reactivation vs. Frictional slip stability

Criterion for fault stability

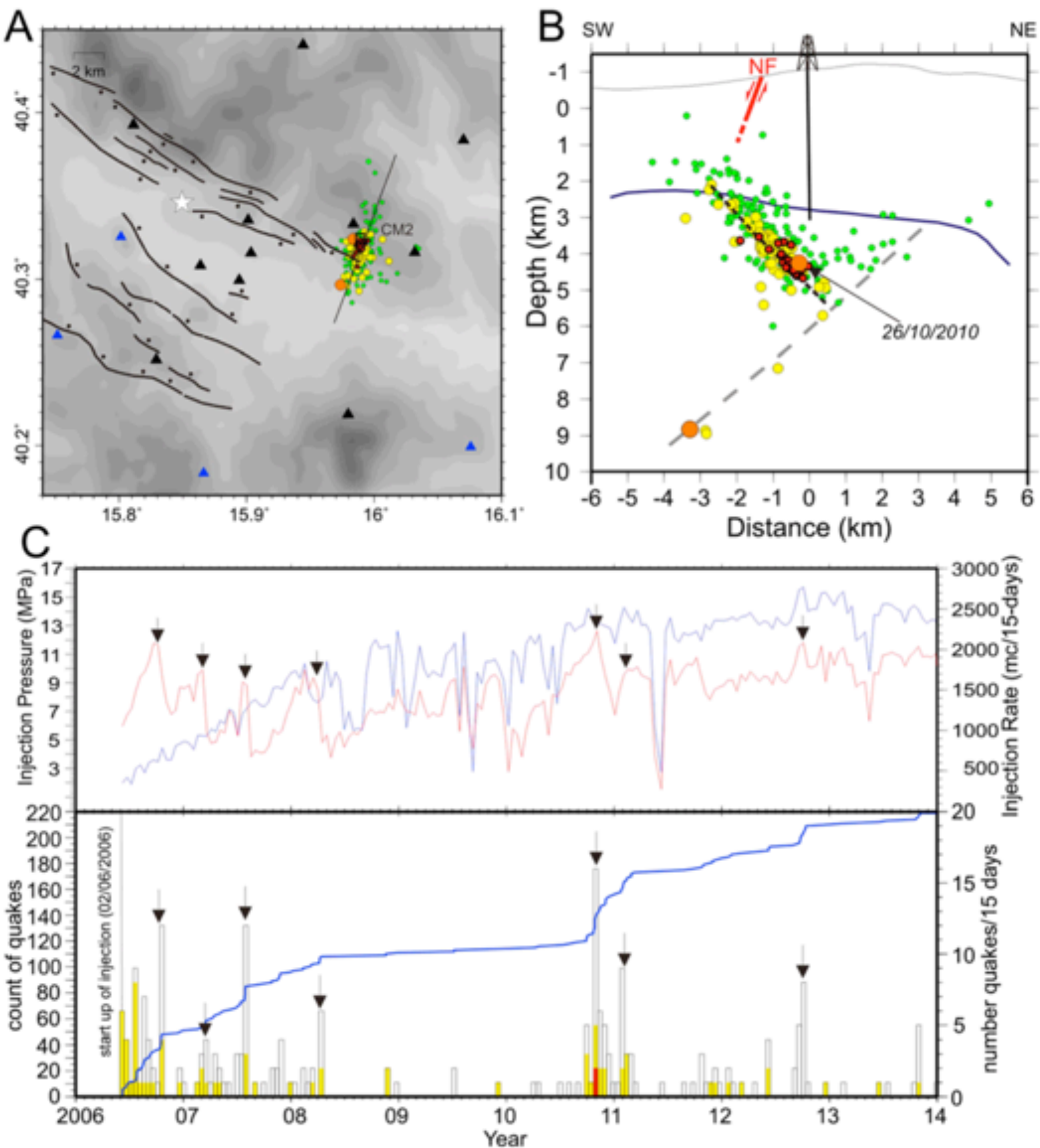
defined by the critical stiffness

$$k_c = (\sigma_n - P_f)\,(b\text{-}a) / D_c$$



- $k > k_c$ — *Stable*
- $k \sim k_c$ — *Conditional Stability*
- $k < k_c$ — *Unstable*

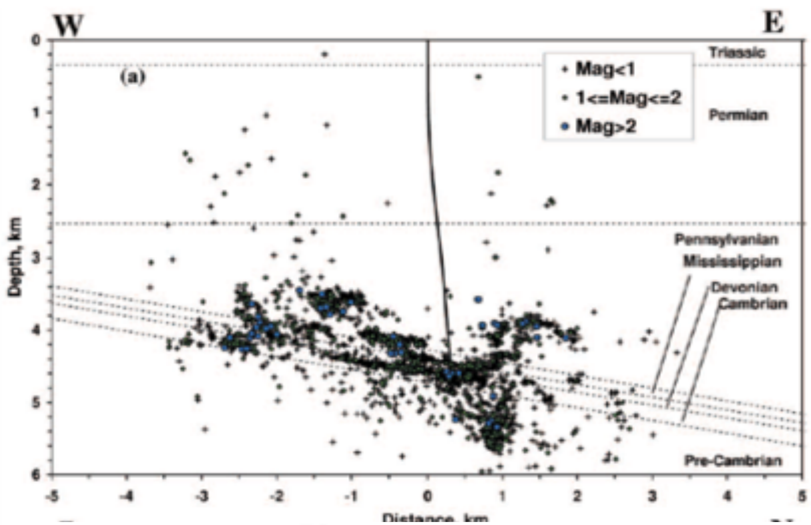
In Val D'Agri oil filed (Southern Italy), positive correlation between the level of injection pressure and earthquake occurrence (Improta et al., 2015). Rock type: carbonates.

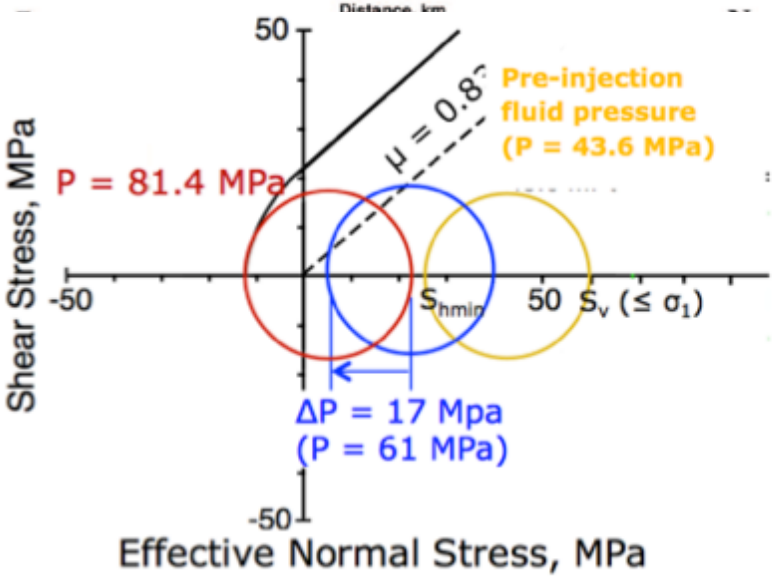


Instability if $k < k_c$

$$k_c = (\sigma_n - P_f)\,(b-a) / D_c$$

At Paradox, Colorado (Ake et al., 205, BSSA; Block st al., SRL, 2014) first earthquakes when the stress reached the failure envelope, then most of earthquakes occurred during large volume injection. Rock types: carbonates, schists, sandstone, granites.

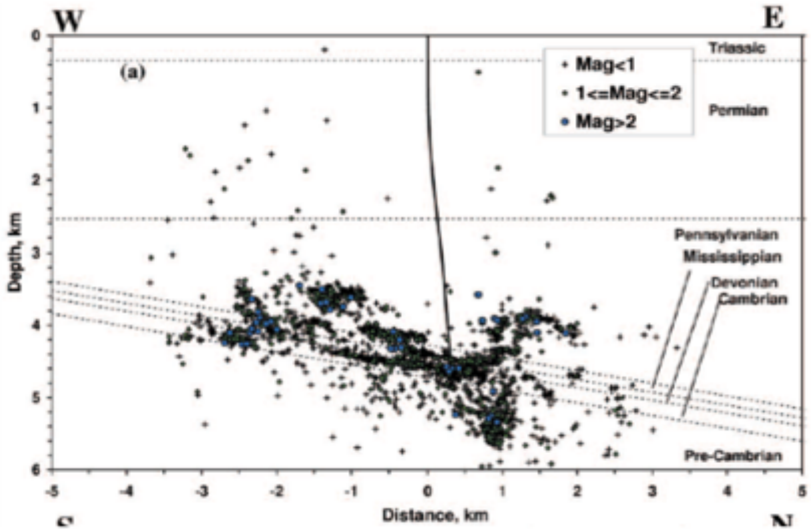


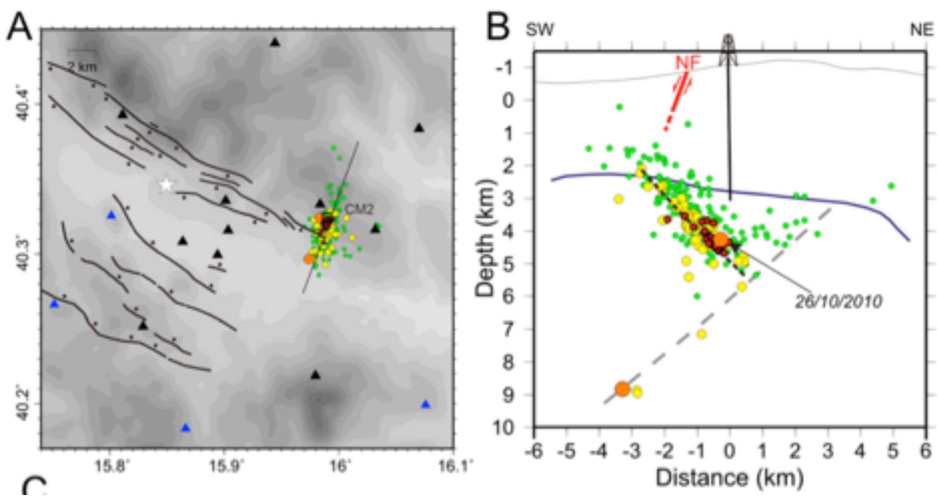


Instability if $k < k_c$

$$k_c = (\sigma_n - P_f)(b\text{-}a) / D_c$$

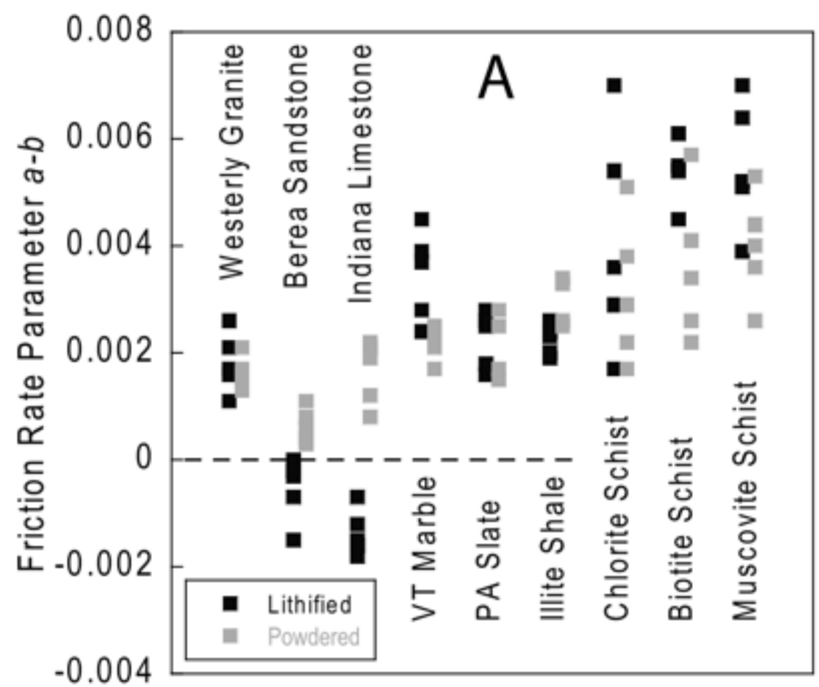
In addition the criterion for fault instability predicts earthquake slip only if the material is velocity weakening, while laboratory experiments show a wide variety of velocity strengthening fault gouge.





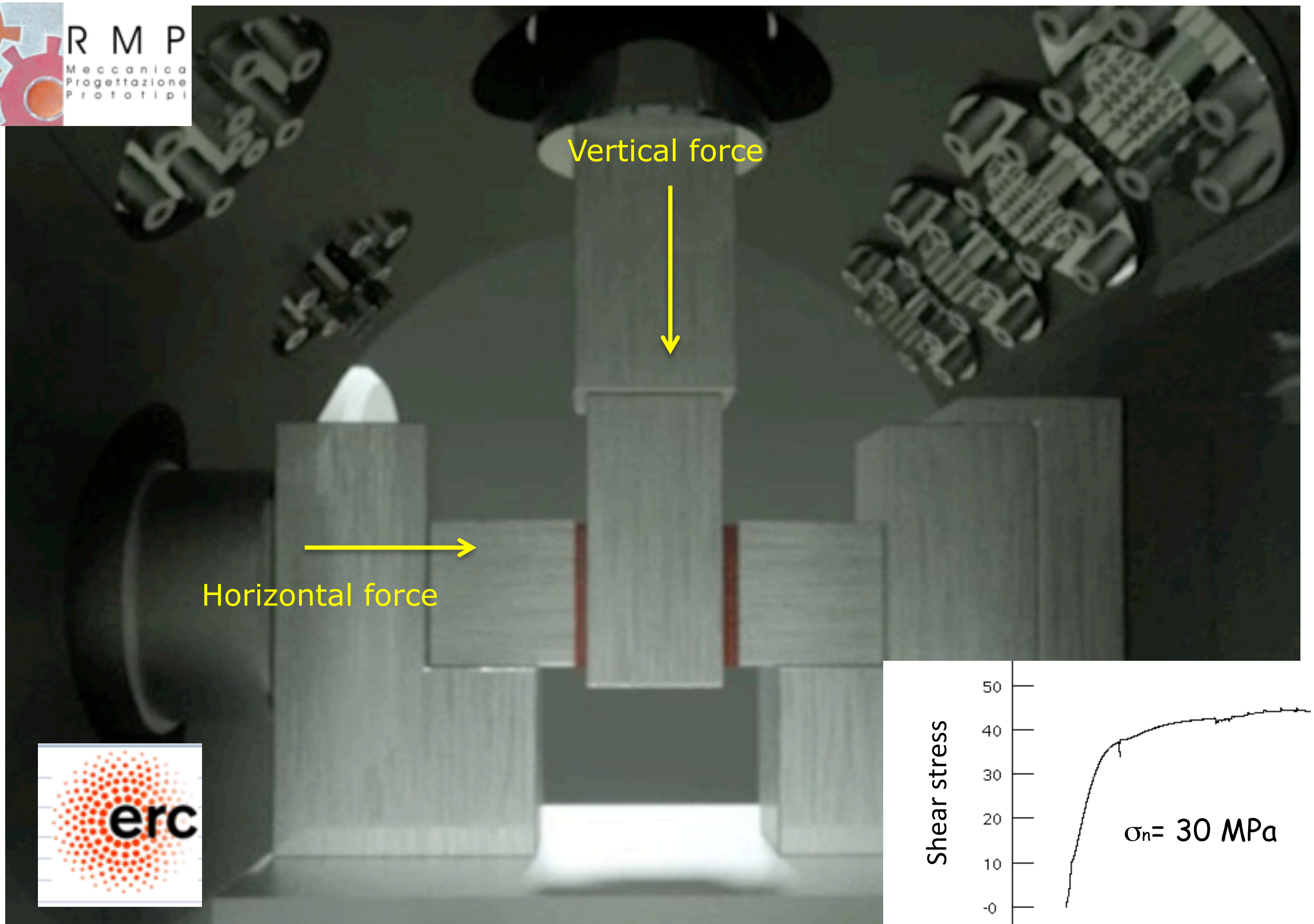
Instability if k < k_c

$$k_c = (\sigma_n - P_f)\,(b\text{-}a) / D_c$$



At stress/temperature conditions typical of the occurrence of induced seismicity, i.e. < 5 km, a wide variety of fault gouge materials show a velocity strengthening behavior (e.g. Ikari 2011).

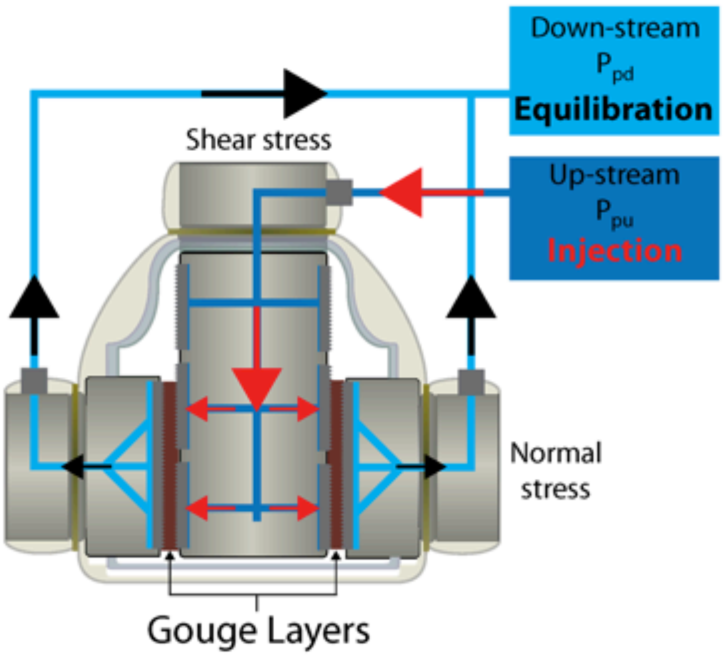
To address this conundrum we developed laboratory experiments at boundary conditions more similar to those of induced seismicity.

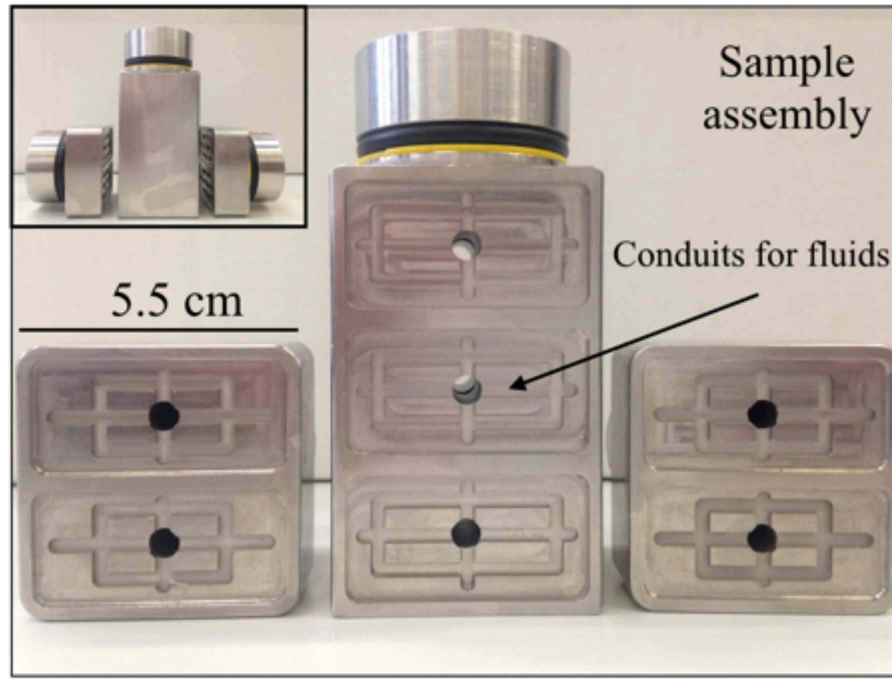


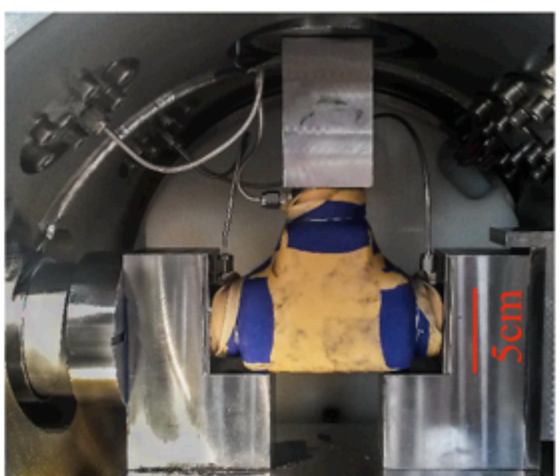
BRAVA apparatus Collettini et al., IJRM, 2014

Biaxial configuration with fluid flow to run experiments with fluid pressure.

Scuderi & Collettini, Sci. Rep., 2016





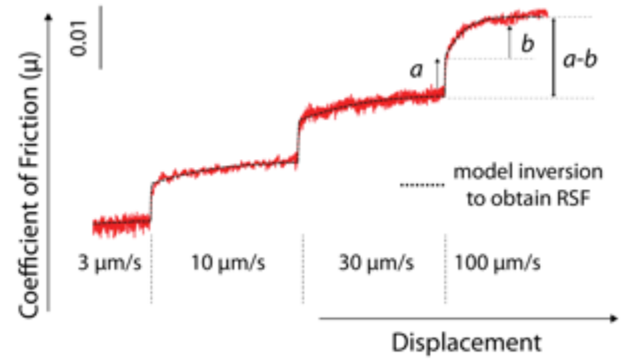


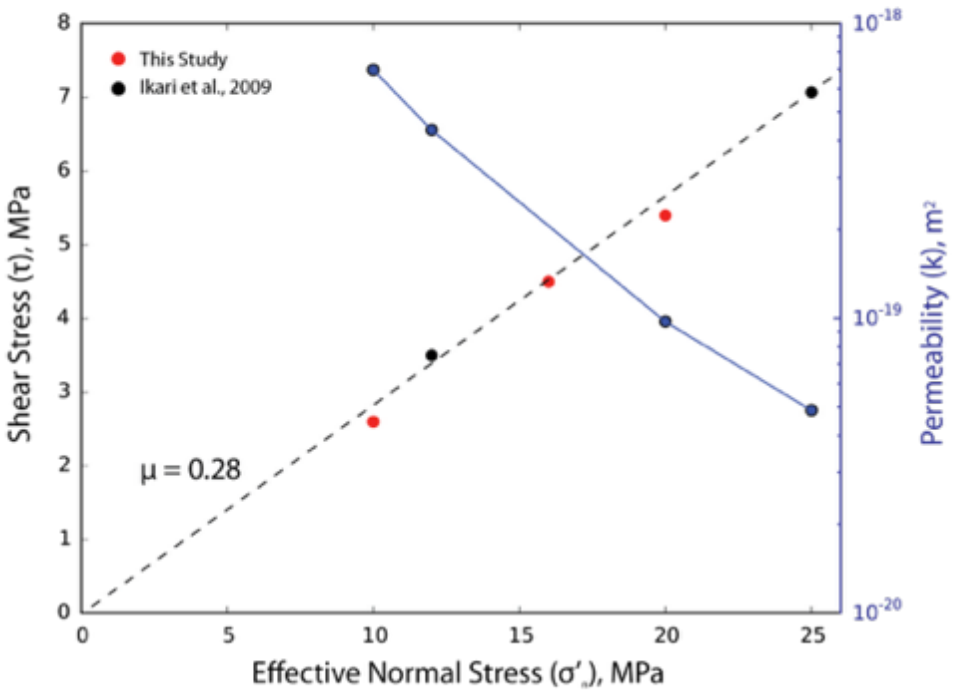
Latex jacket

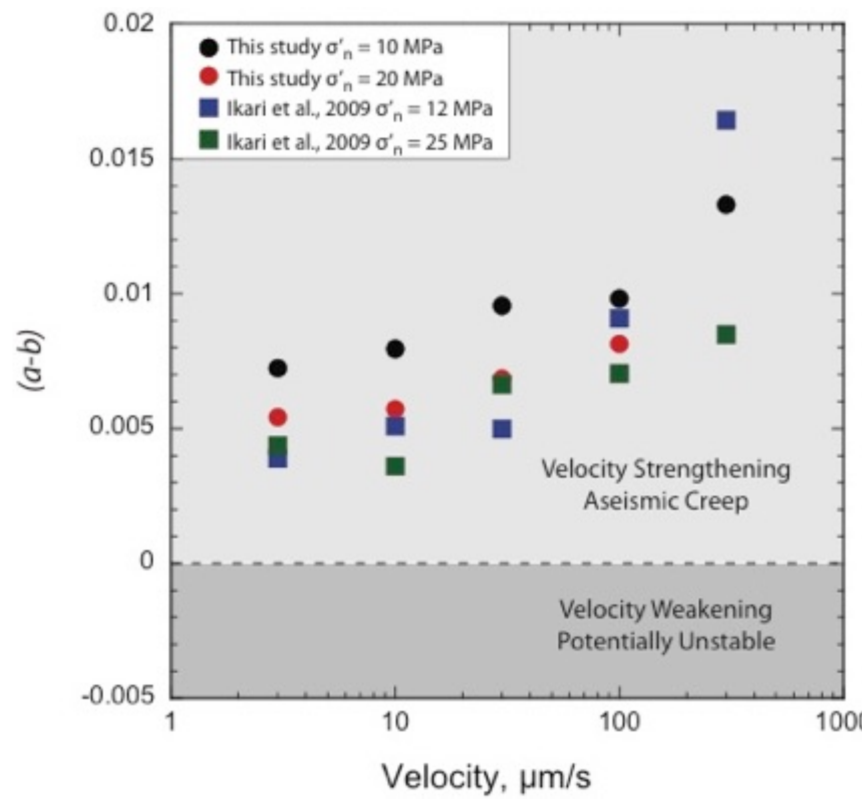
Porous Frits

A) Frictional and fluid flow properties of Shale: Rochester Shale (59% Illite, 9% Kaolinite 27% Quartz)

Low friction, low permeability and velocity strengthening behaviour

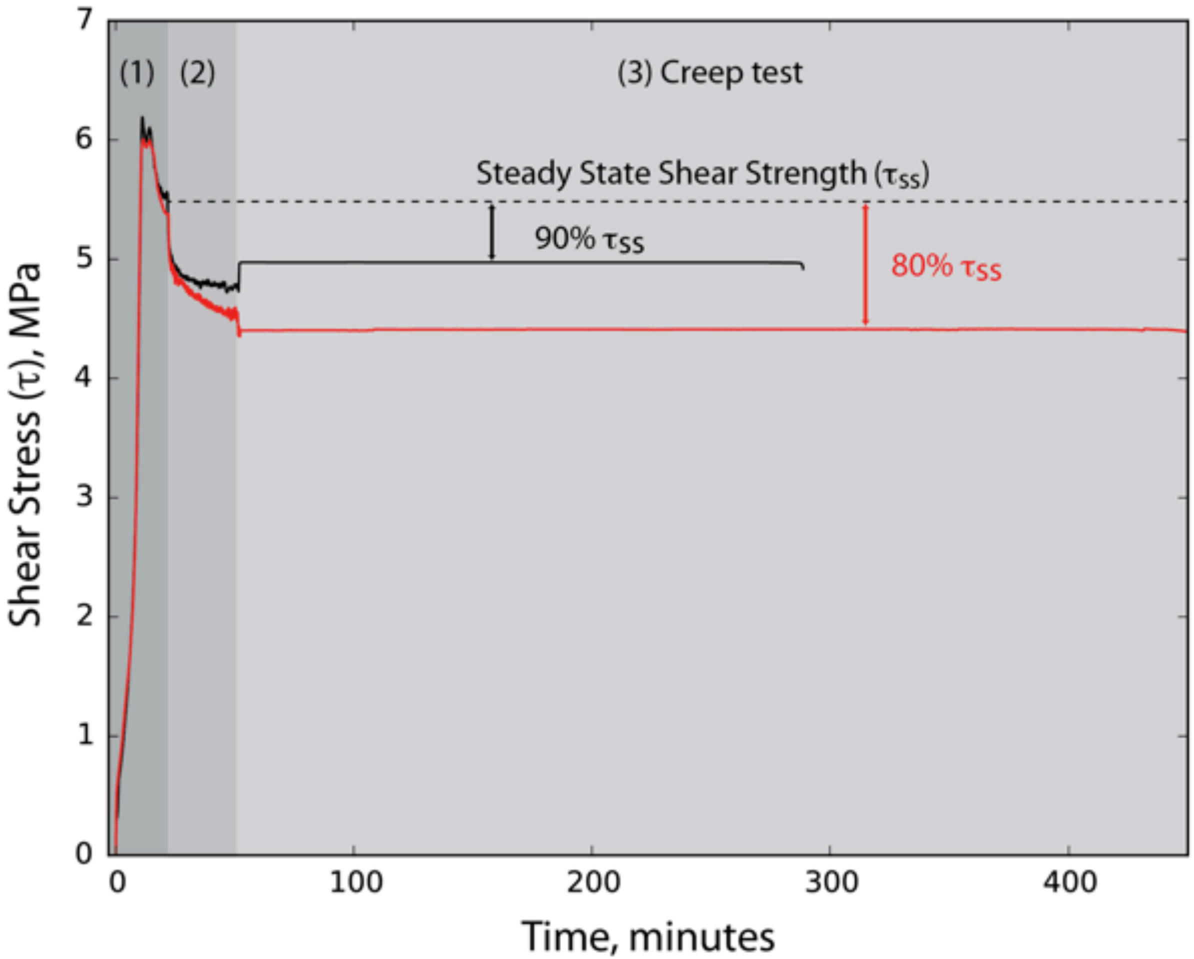


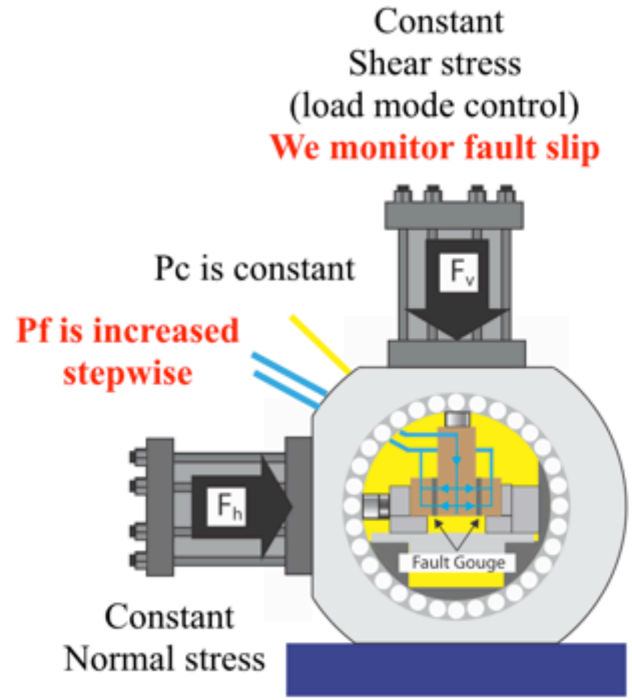




Scuderi et al., in prep.

B) Creep experiments to monitor fault slip behaviour during pressurization

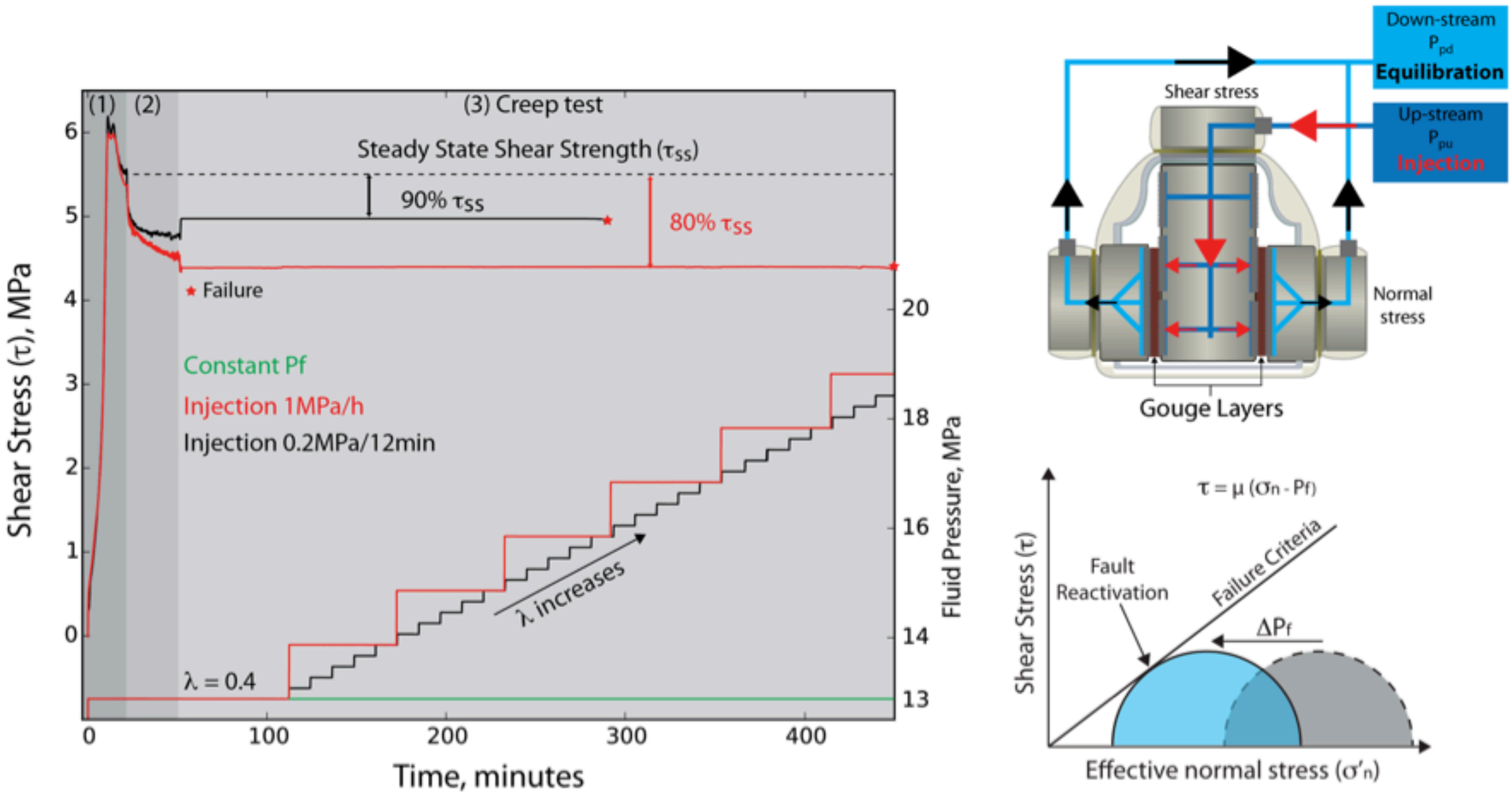




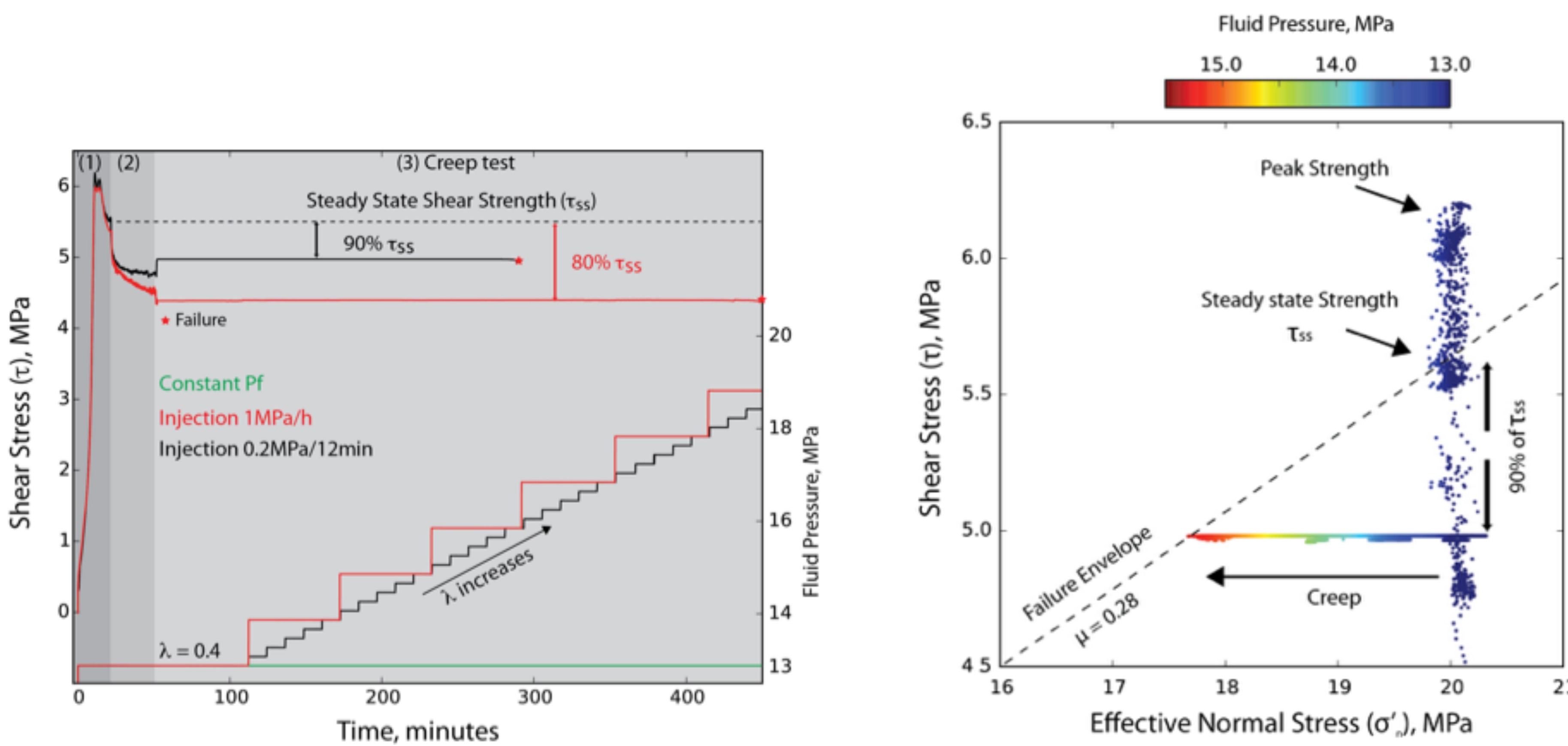
(1) Constant displacement rate of 10 µm/s to localize shear
(2) Fault relaxation to residual strength
(3) Set the shear stress at the desired value in load control to monitor fault slip

Scuderi et al., EPSL 2017.

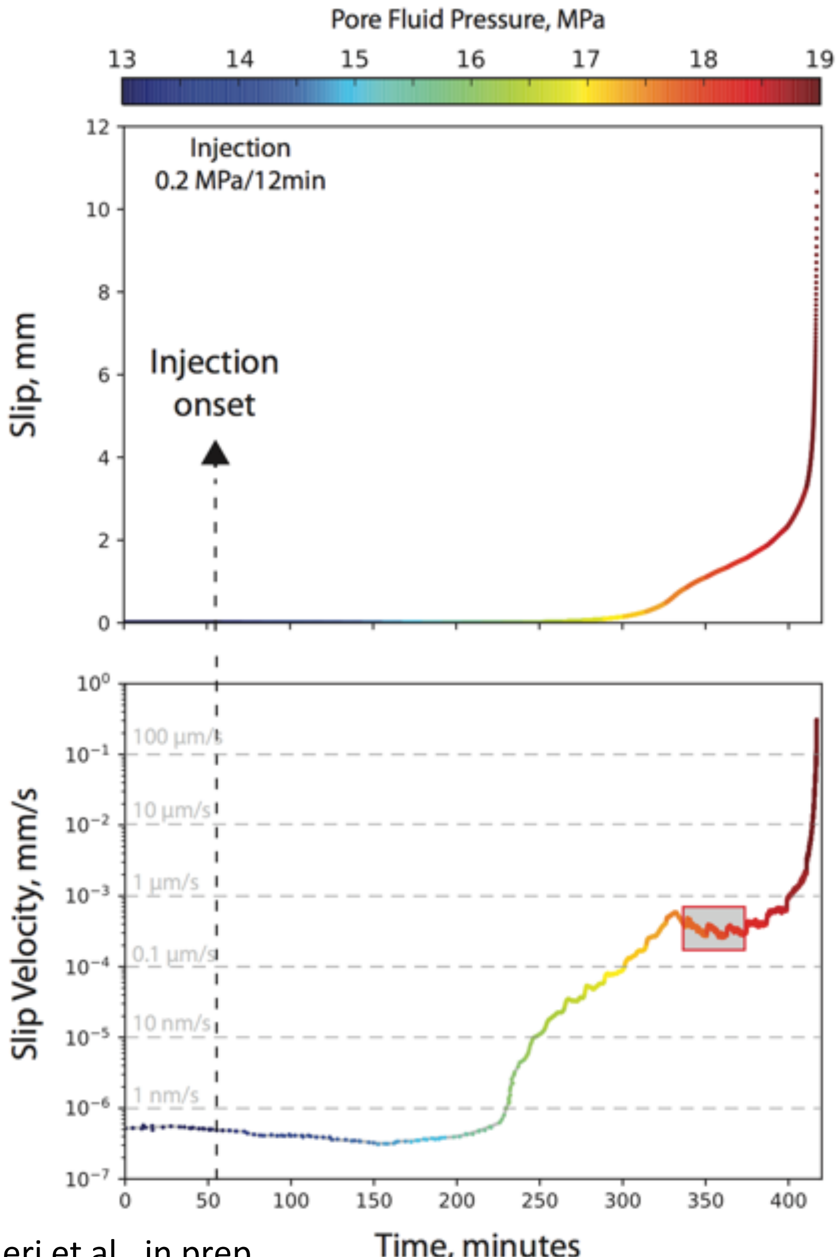
B) Creep experiments to monitor fault slip behaviour during pressurization



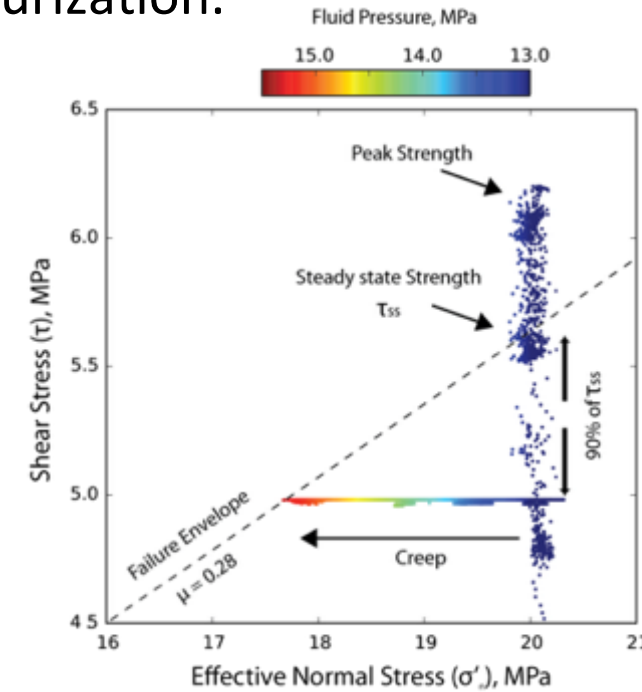
B) Creep experiments to monitor fault slip behaviour during pressurization

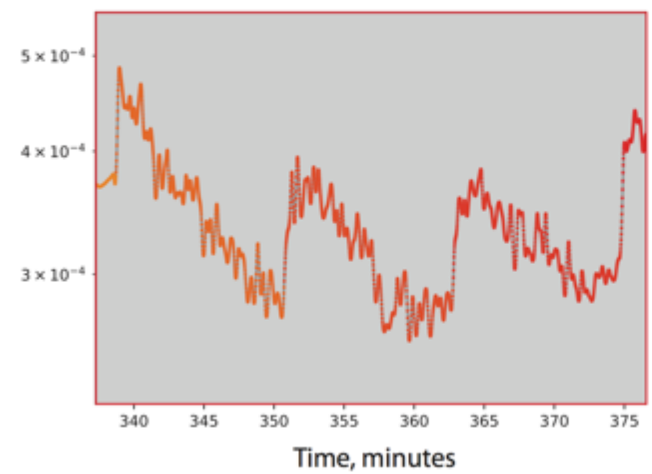


Slip and slip velocity evolution during fluid pressurization.



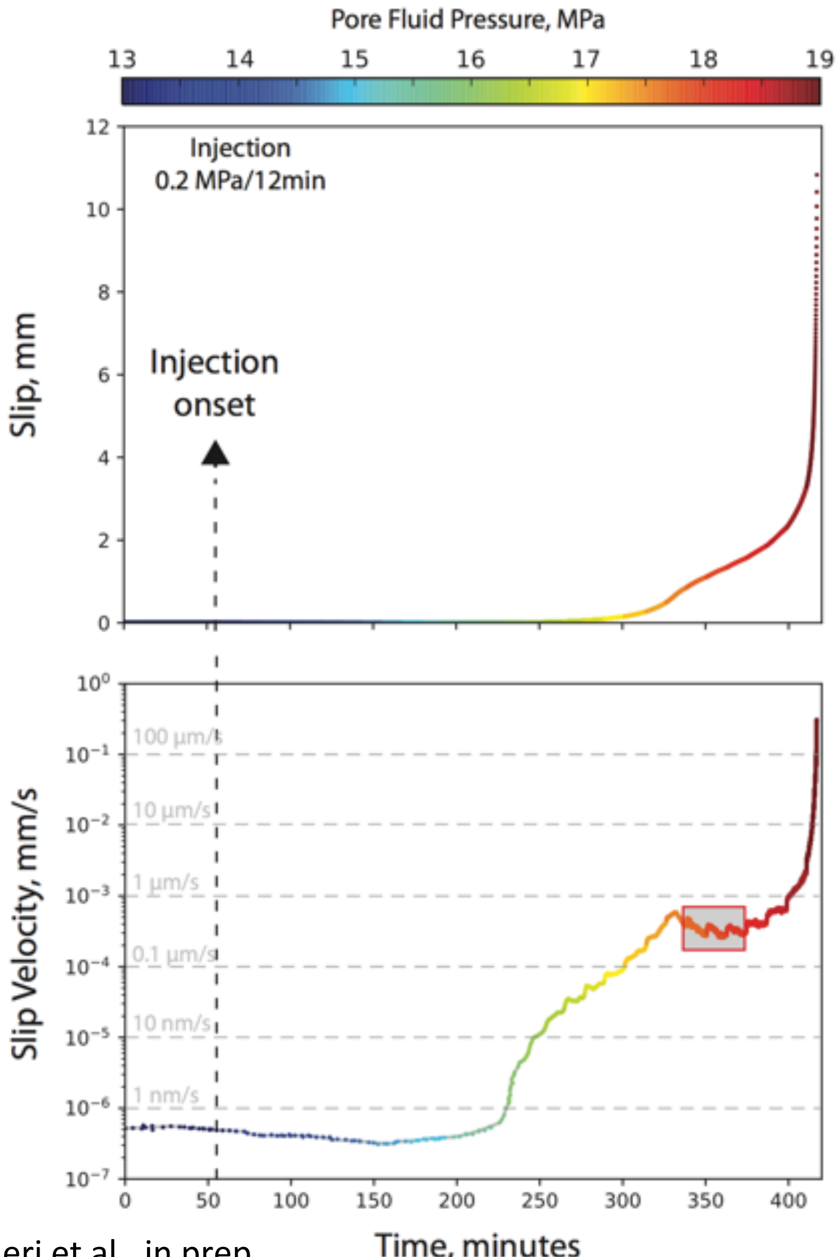
Scuderi et al., in prep.

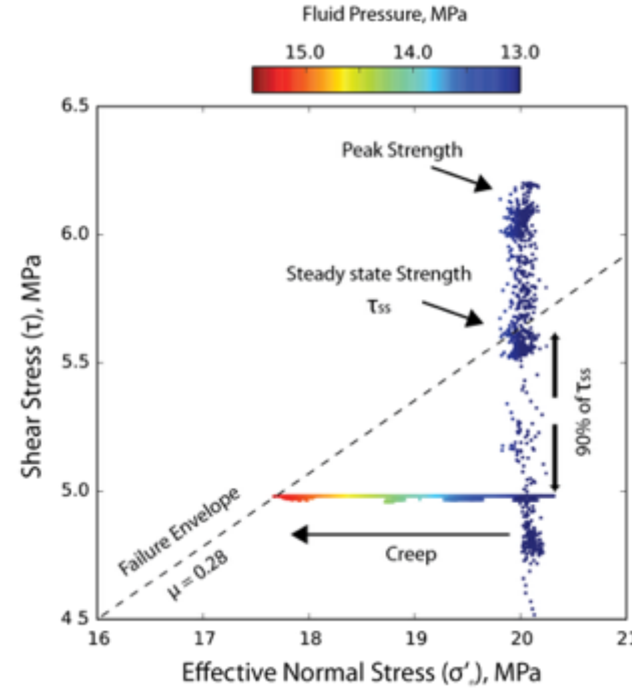


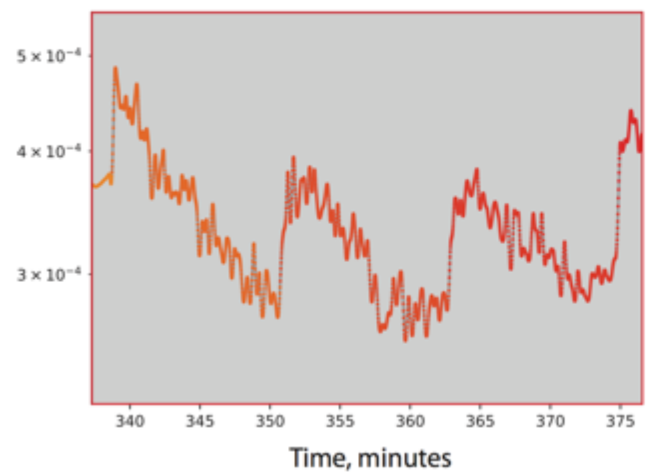


Acceleration and deceleration modulated by fluid pressure steps

Why these accelerations and self decelerations?



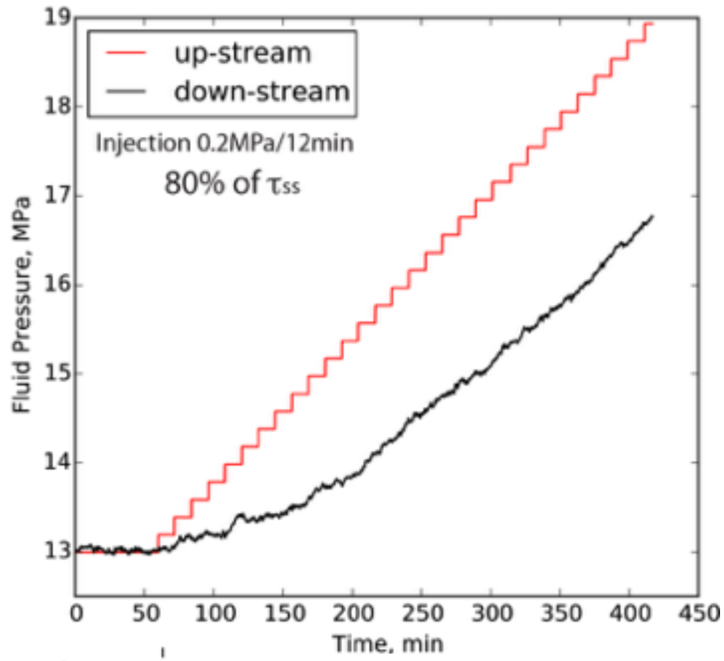


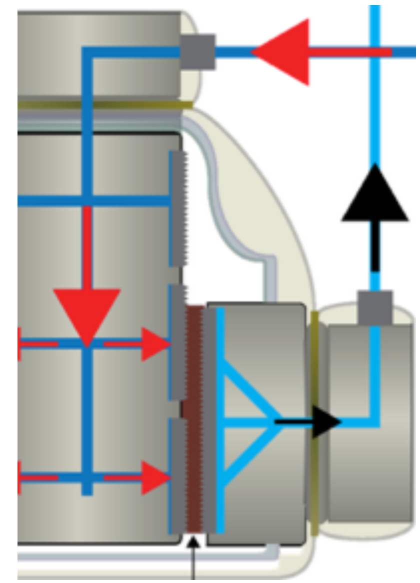


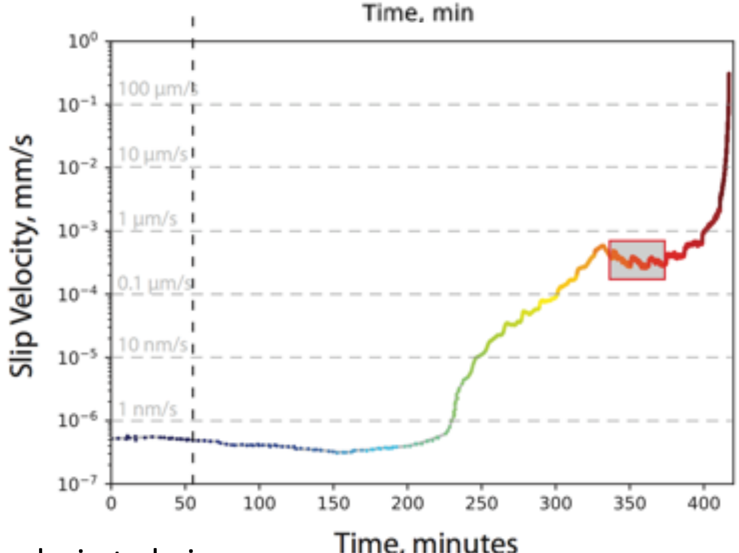
Acceleration and deceleration modulated by fluid pressure steps

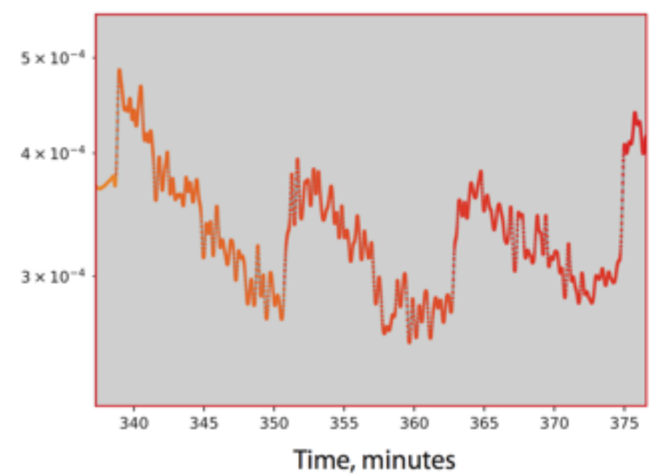
Scuderi et al., in prep.

Due to the low permeability of clay, during pressurization Pf is always higher in the proximity of the injection point.





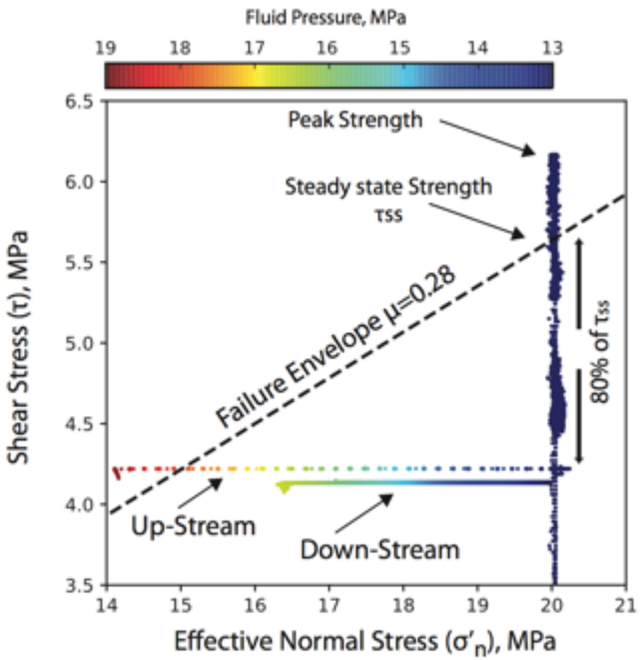


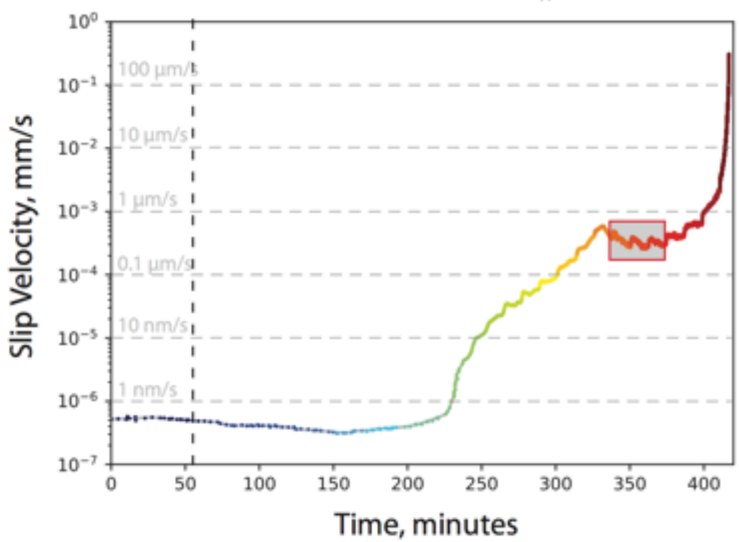


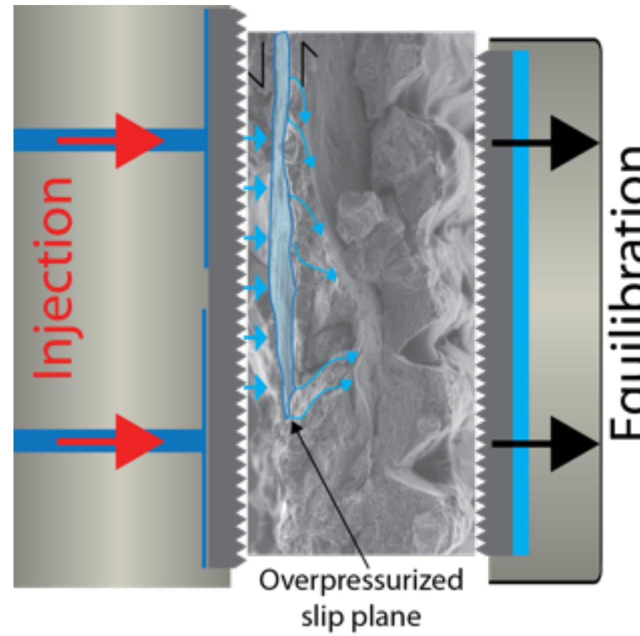
Scuderi et al., in prep.

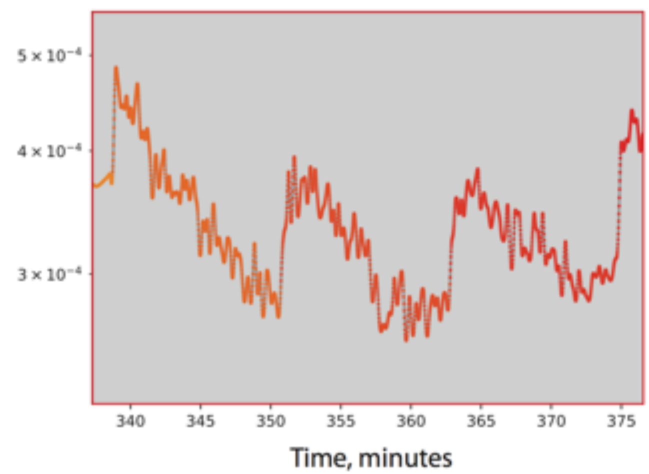
Why these accelerations and self decelerations?

1) Fluid pressure build-up allows fault slip. Slip increases permeability favoring fluid pressure release and fault deceleration.





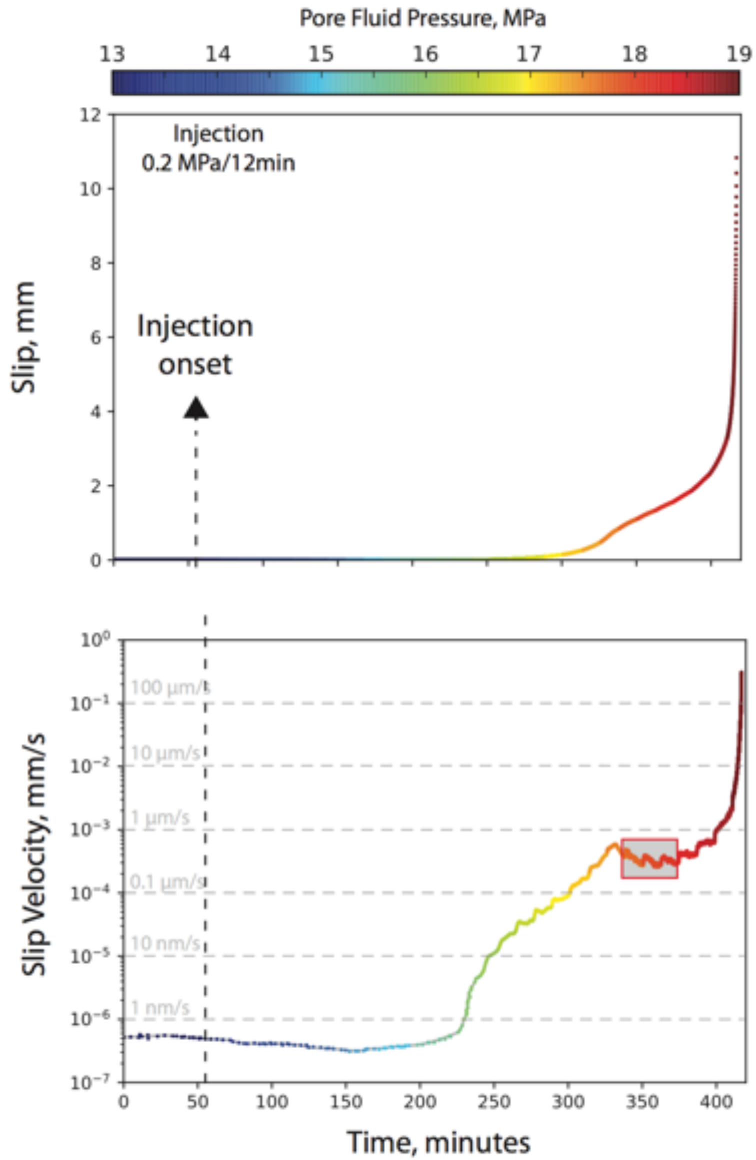


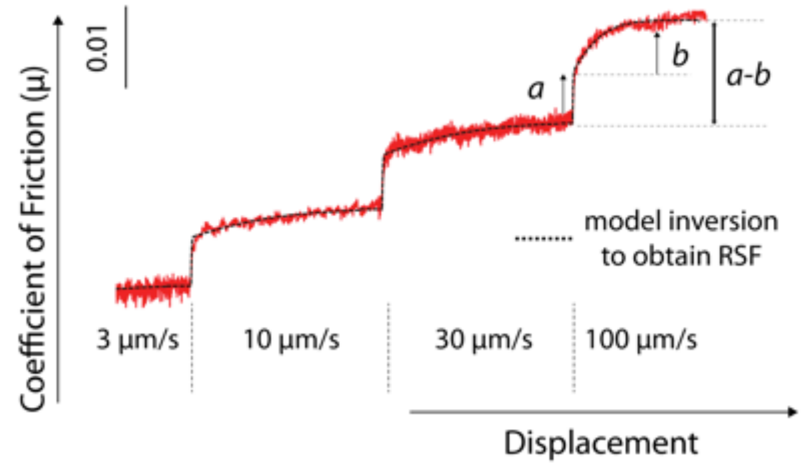


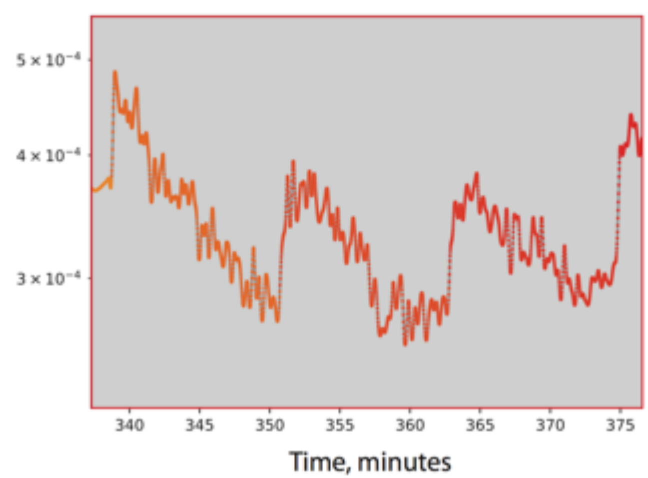
Scuderi et al., in prep.

Why this final slow acceleration?

2) The weakening induced by fluid overpressure is counteracted by the strong velocity strengthening behaviour of clay inhibiting a fast dynamic rupture.







Scuderi et al., in prep.

Thank you

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