Mechanics of Earthquakes and Faulting

Lecture 19 , April 6 2021

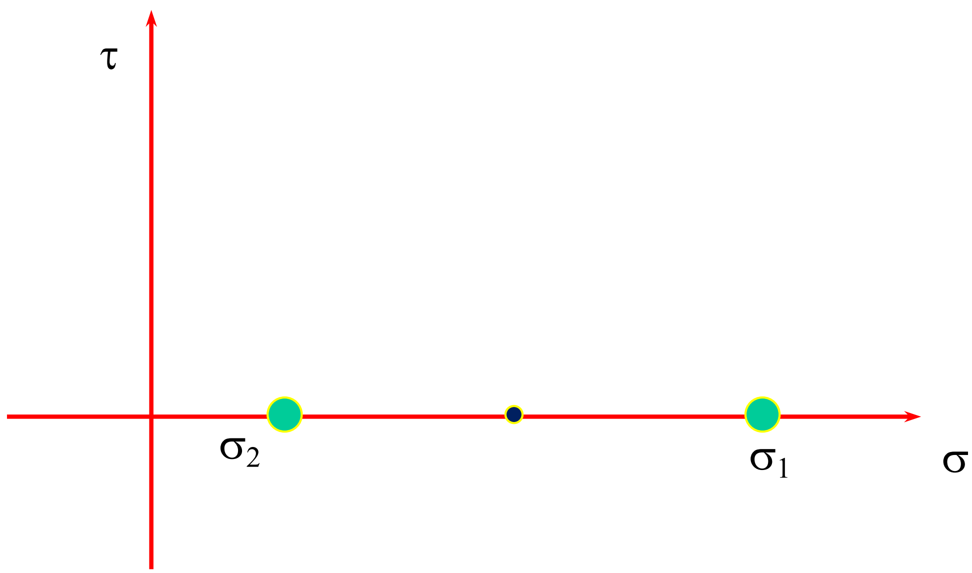
www.geosc.psu.edu/Courses/Geosc508

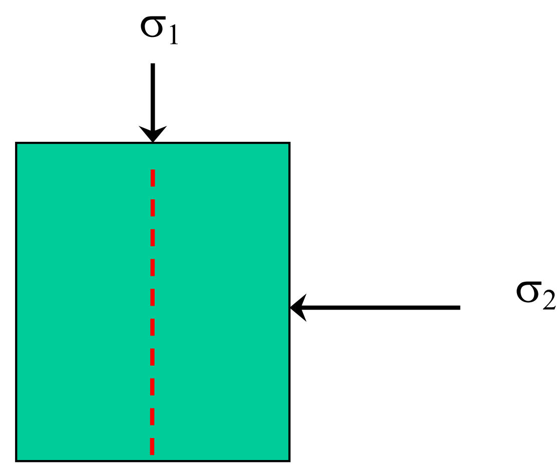
- Project presentations on Apr 22,27, 29
- Shear heating, fault strength and the state of stress in Earth's crust
- Moment, Magnitude and scaling laws for earthquake source parameters
- Seismic Spectra & Earthquake Scaling laws.

Imagine that you're in a restaurant with some friends. The owner stops by to say hello and after hearing that you're a geophysicist she challenges you to write down the Shear and Normal Stress on a Plane of Arbitrary Orientation given the principal stresses.

She calls the waiter over and he gives you a couple extra napkins .....

Ok, get to work! You've got to finish before he brings the drinks





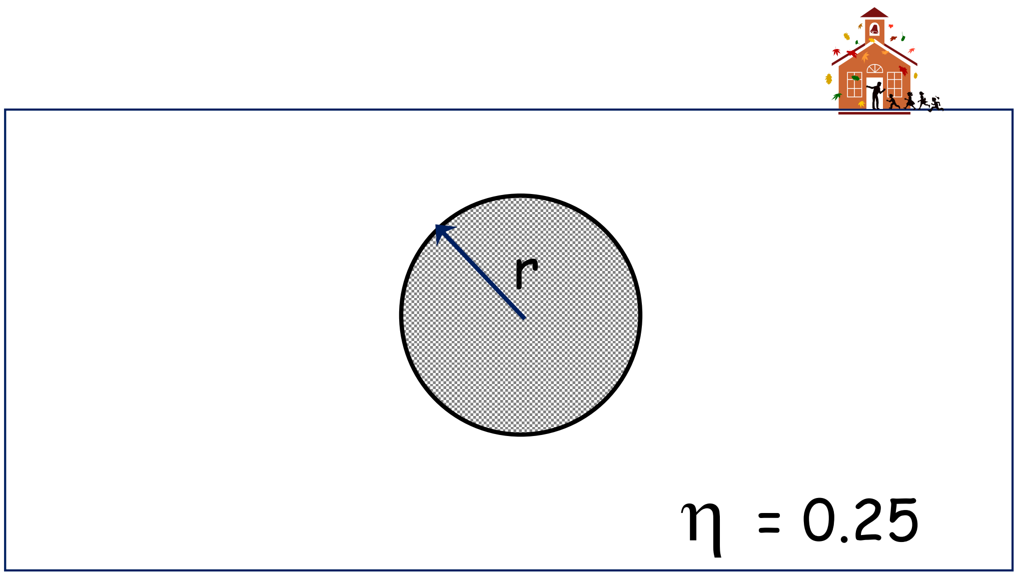
$$\sigma(\alpha) =$$

$$\tau(\alpha) =$$

Imagine that the owner is even more persistent today.....

After seeing how well you did with stress transformation, she asks you about earthquake nucleation.

According to friction stability theory and using rate/state friction, what is the critical patch size for rupture nucleation?



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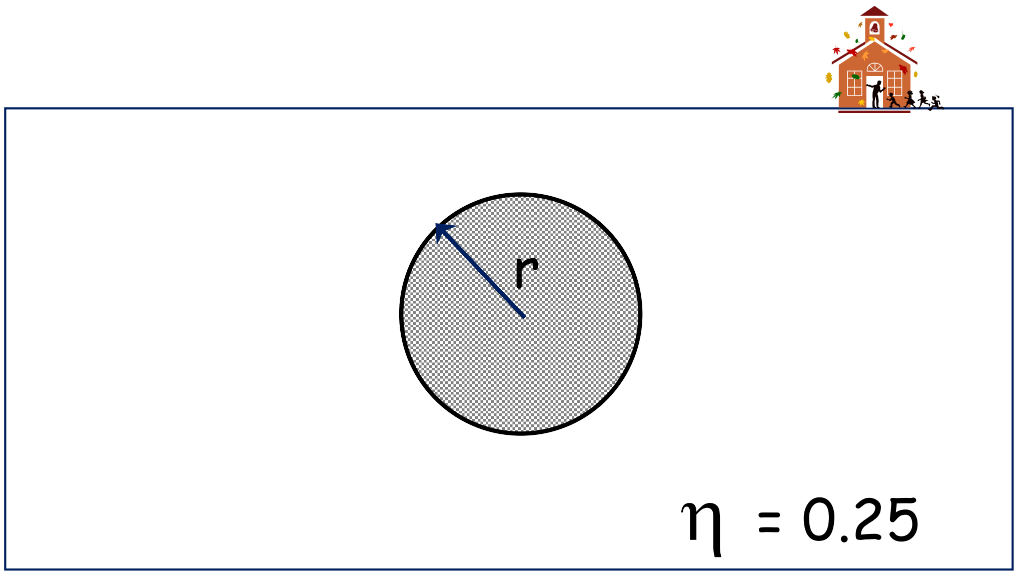


$$\Delta\sigma = \frac{7\pi}{16} G \frac{\bar{u}}{r}$$

$$K = \frac{\Delta\sigma}{\bar{u}} = \frac{7\pi}{16}\frac{G}{r}$$

$$K_c \approx \frac{\sigma_n(b-a)}{D_c}$$

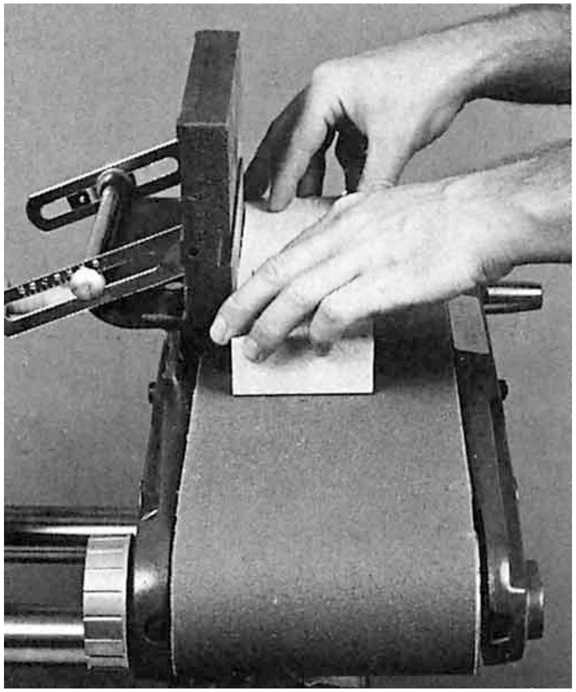
Earthquake Nucleation occurs when the patch size exceeds r_c

$$r_c = \frac{G D_c}{\sigma_n(b-a)}$$

Thermo-mechanics of faulting

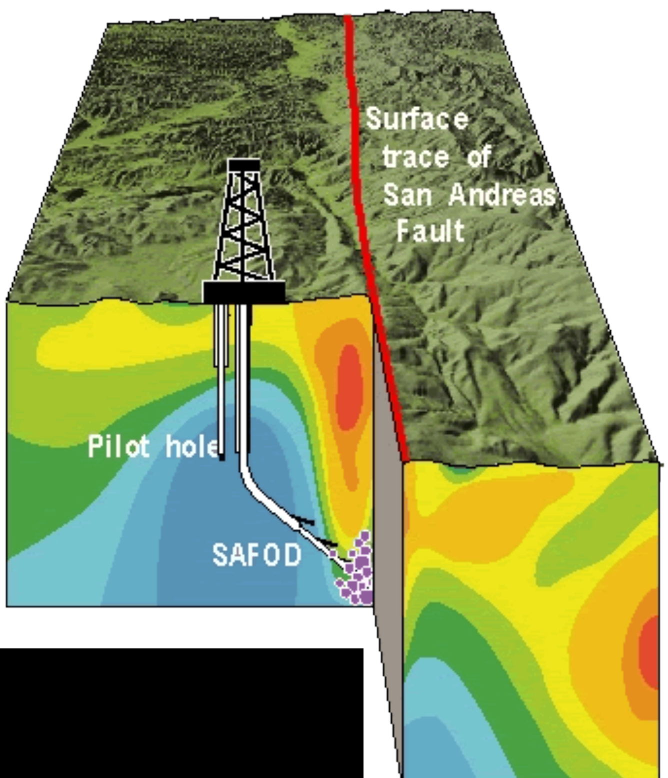
Shear heating, fault strength, state of stress in Earth's crust

- San Andreas fault strength, heat flow.
- Consider shear heating: $W_f = \tau v \geq q$

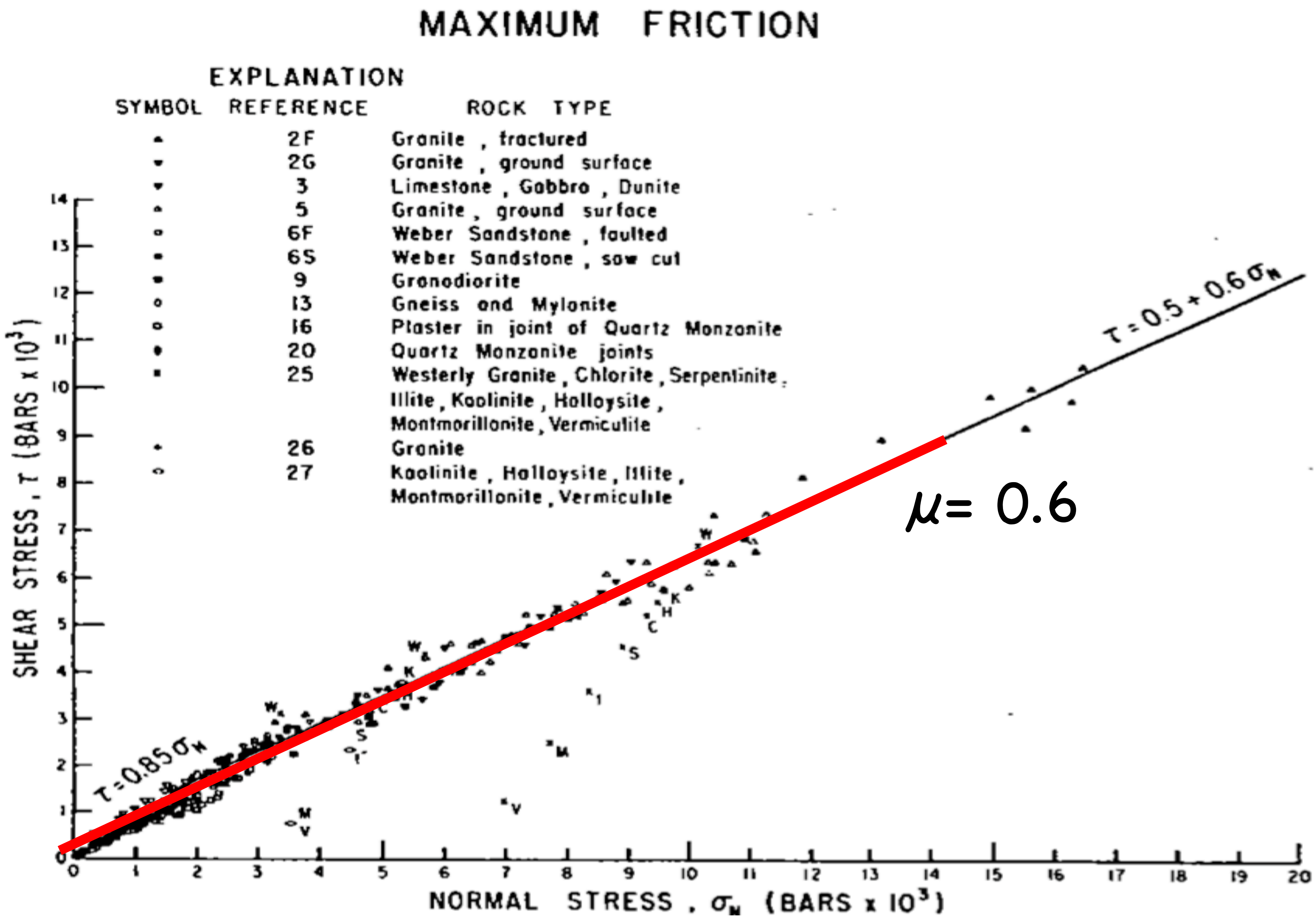


What is the strength of a plate boundary fault at seismogenic depth?

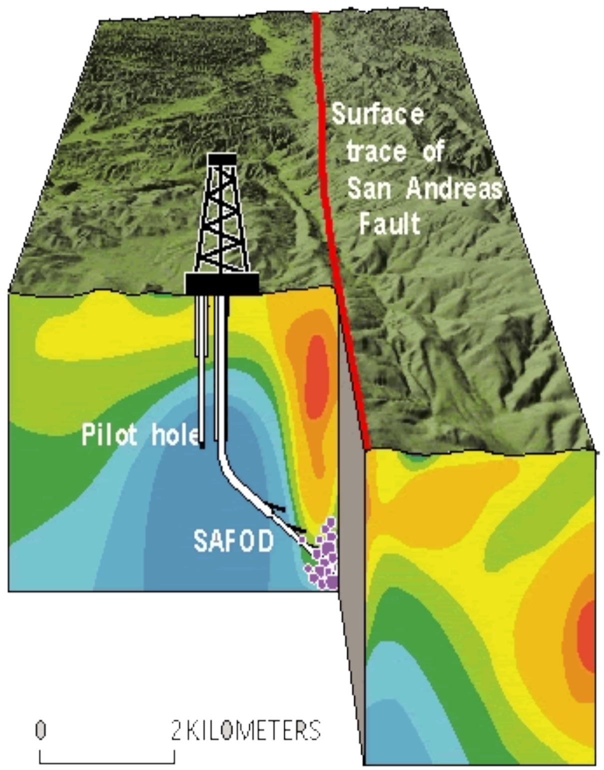
Is it 100-200 MPa, $\mu \approx 0.6$,
or 10-20 MPa, $\mu \leq 0.2$?



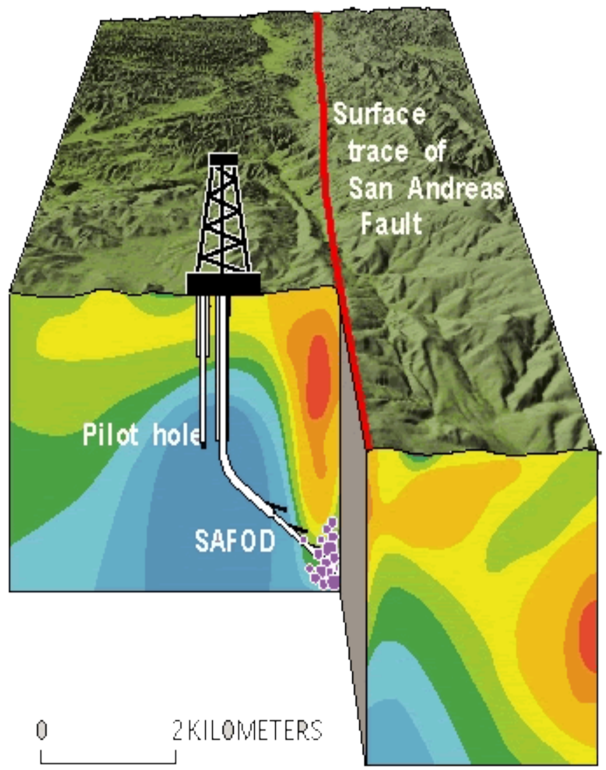
Byerlee's Law



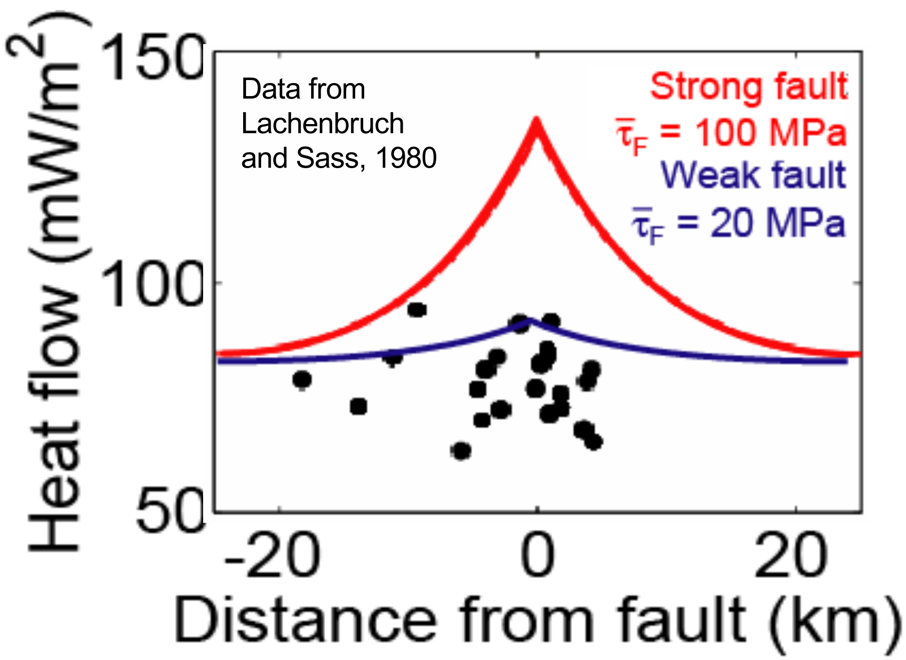
- **Thermo-mechanics of faulting...**
- Fault strength, heat flow. What do we expect for heat flow?
- Consider shear heating: W_f



- **Thermo-mechanics of faulting…**
- Fault strength, heat flow. What do we expect for heat flow?
- Consider shear heating: $W_f = \tau v \geq q$
- If $\tau \sim 100$ MPa and v is ~ 30 mm/year, then q is:
- 1e8 (N/m^2) 3e-2 (m/3e7s) = 1e-1 ($J/s\ m^2$) ≈ 100 mW/m^2

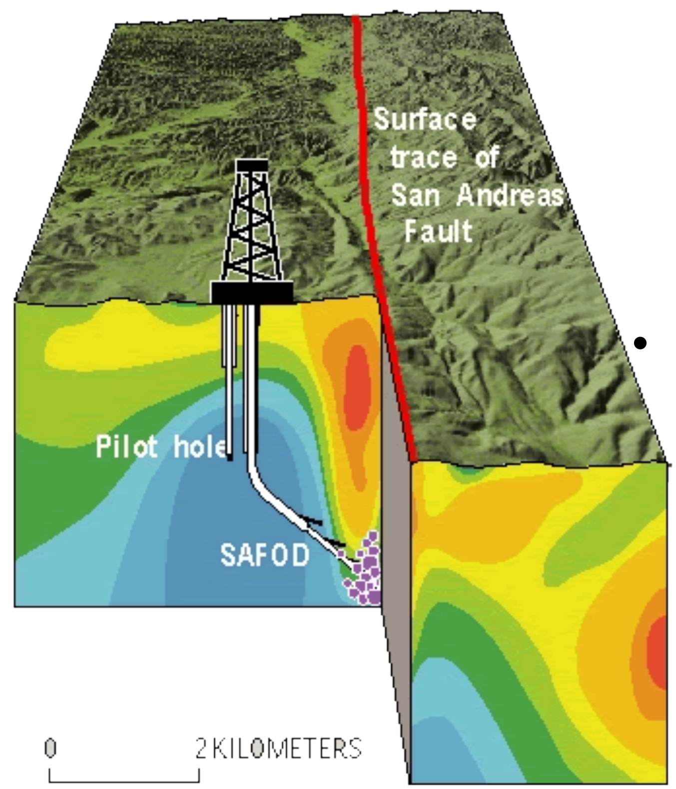


What do we see for heat flow?



Data from Lachenbruch and Sass, 1980

Read: Collettini, Tectonophys. 2011



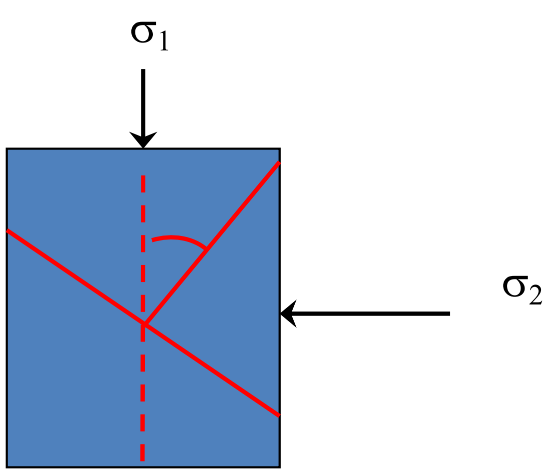
- S A F

e.g. Townend & Zoback, 2004; Hickman & Zoback, 2004

Fault Strength and State of Stress

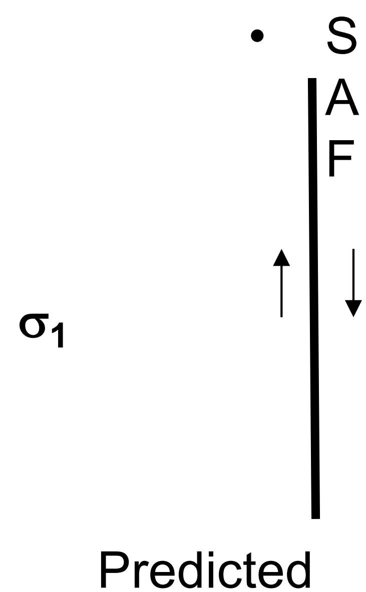
$$\sigma = \frac{(\sigma_1 + \sigma_2)}{2} + \frac{(\sigma_1 - \sigma_2)}{2} \cos 2\alpha$$

$$\tau = \frac{\sigma_1 - \sigma_2}{2} sin(2\alpha)$$



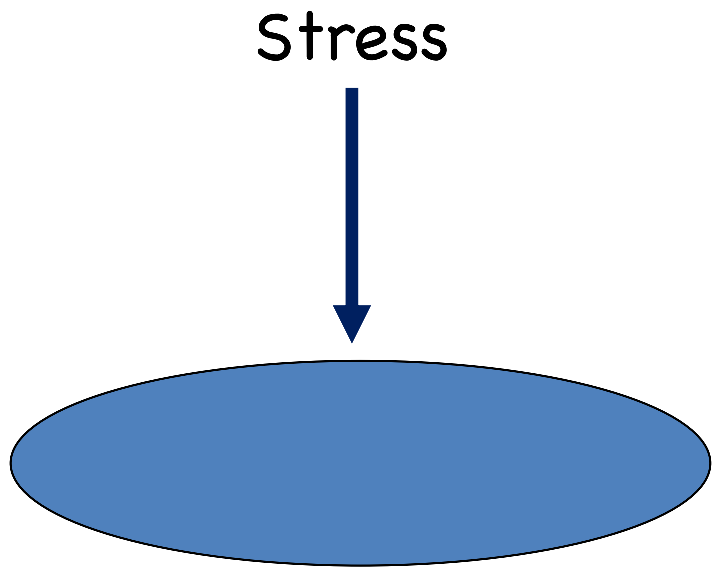
Also stress orientation

This has been used to suggest that the SAF is weak, $\mu \approx 0.1$.



Concept of a free surface –that is, a surface that cannot support shear stress

In this case, one of the principal stresses must be perpendicular



Nine components of the stress tensor

And for the principal stresses

Concept of a free surface –that is, a surface that cannot support shear stress

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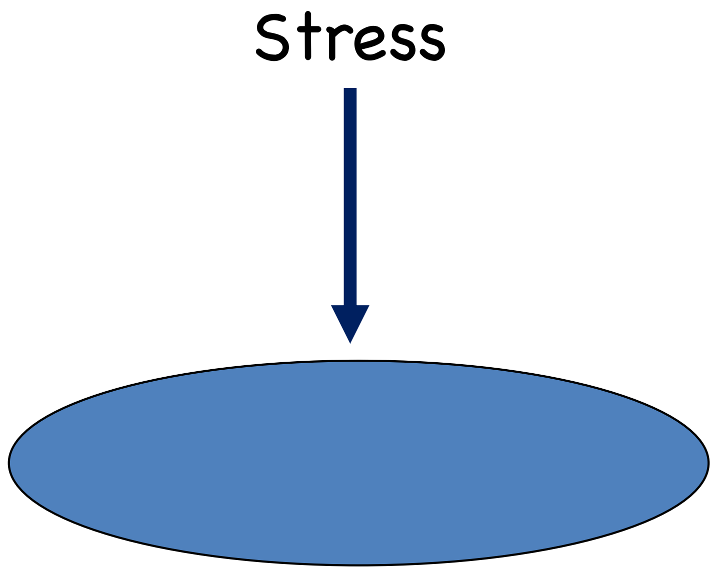


Nine components of the stress tensor

$$\begin{array}{ccc} \tau_{xx}, & \tau_{xy}, & \tau_{xz} \\ \tau_{yx}, & \tau_{yy}, & \tau_{yz} \\ \tau_{zx}, & \tau_{zy}, & \tau_{zz} \end{array}$$

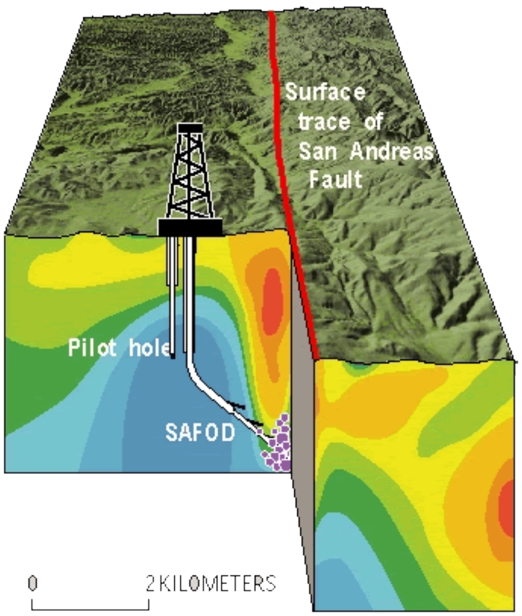
And for the principal stresses

$$\begin{array}{ccc} \sigma_{11}, & 0, & 0 \\ \tau_{yx}, & \sigma_{22}, & 0 \\ 0, & 0, & \sigma_{33} \end{array}$$

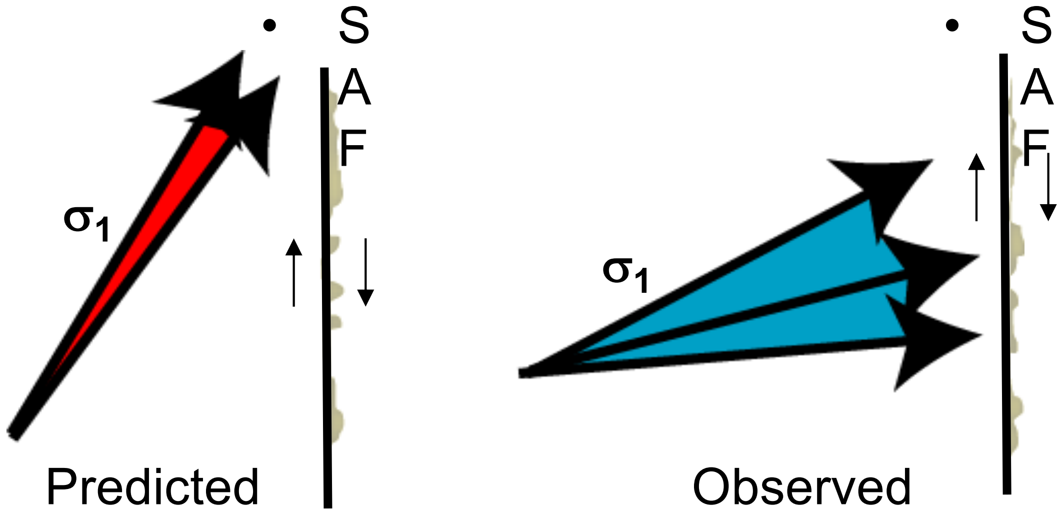
Concept of a free surface –that is, a surface that cannot support shear stress

In this case, one of the principal stresses must be perpendicular

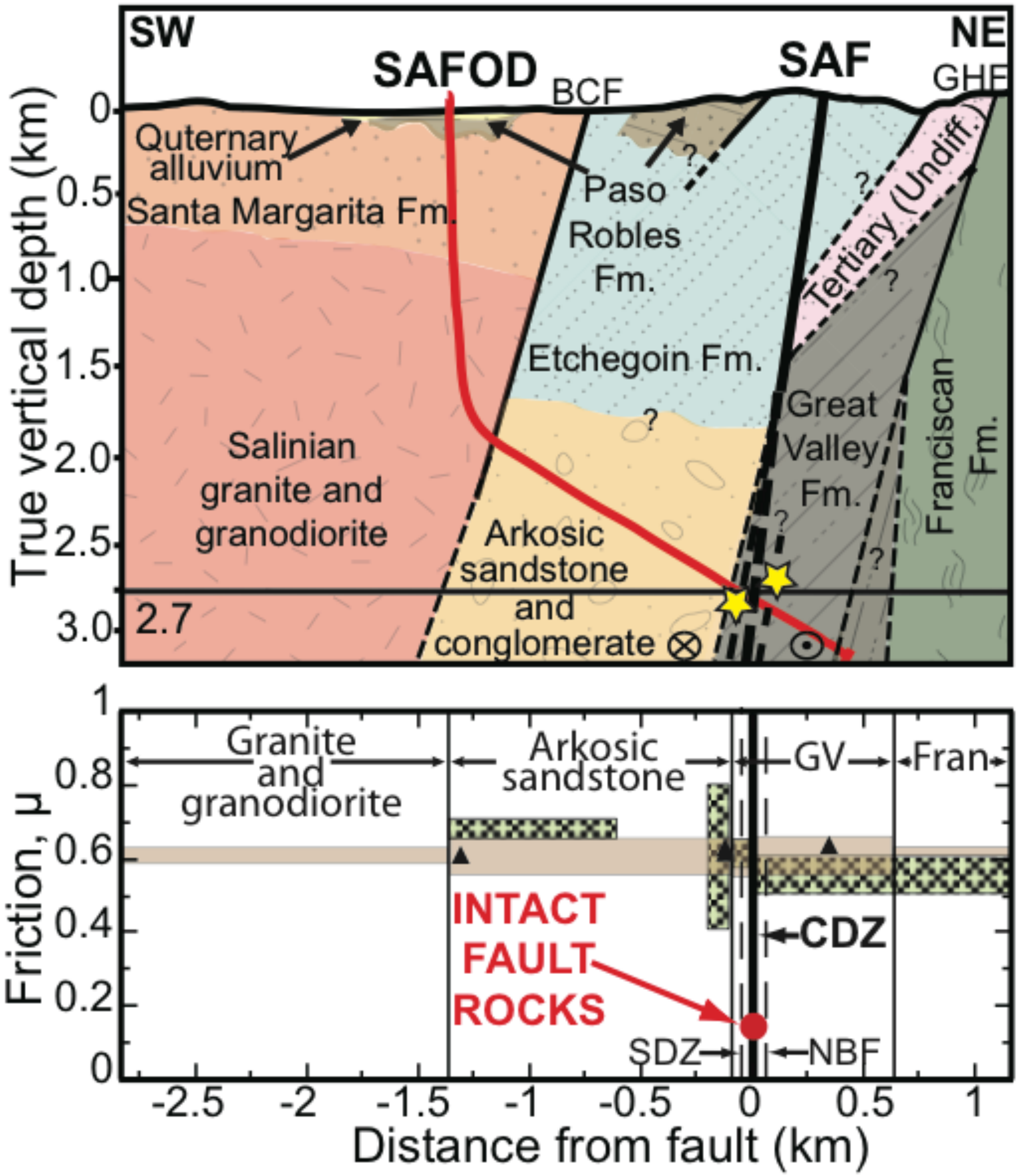
As applied to the SAF, it means the maximum horizontal stress is perpendicular is the fault strength is near zero



- Inferred stress directions



e.g. Townend & Zoback, 2004; Hickman & Zoback, 2004



What about lab measurements?

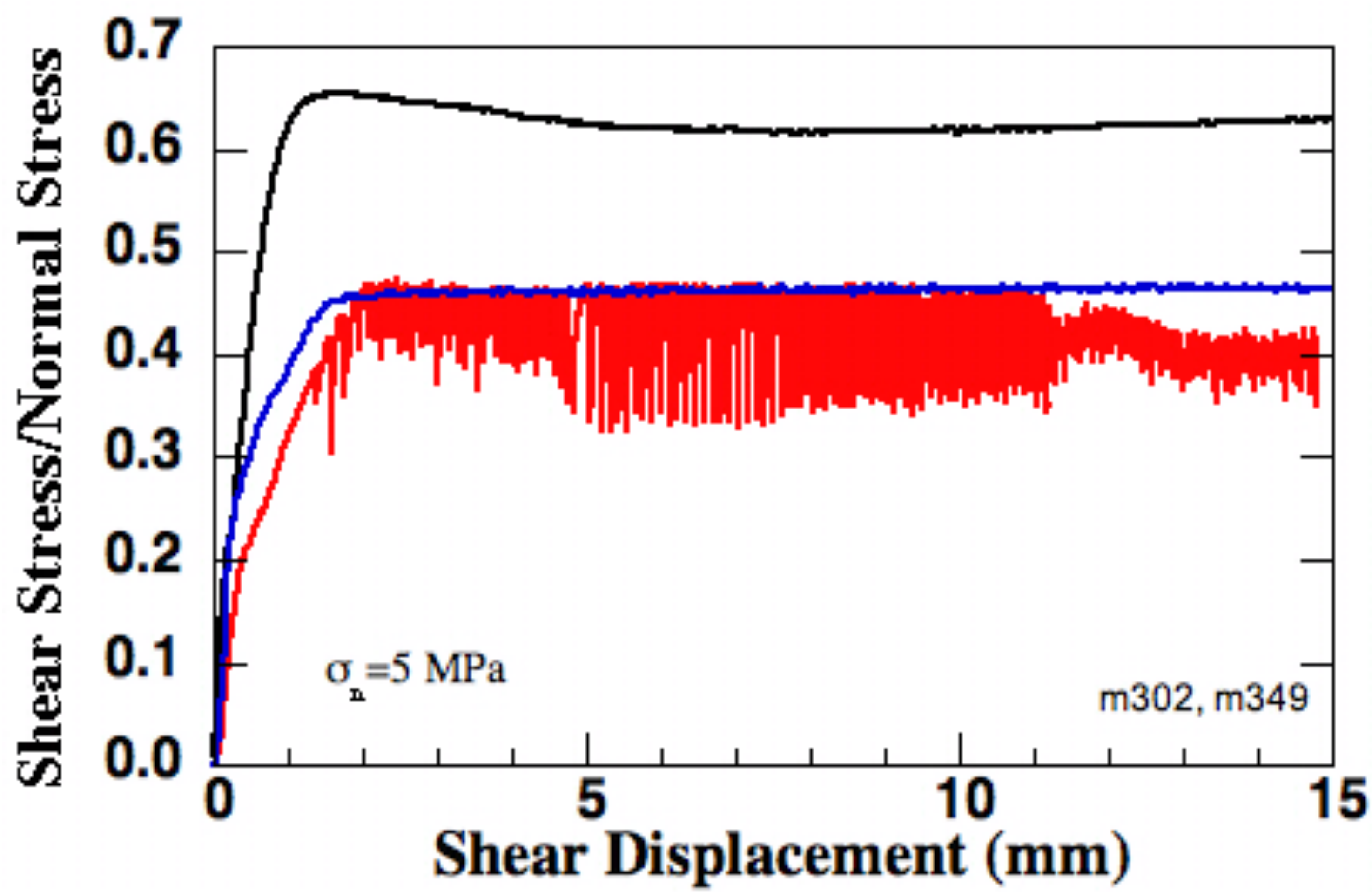
Carpenter, Saffer, and Marone.
Geology, 2012

Fault Strength, State of Stress in Earth's Crust, Fault Weakness

- Lab measurements of fault rock (Strong)
- Heat flow around faults (Weak)
- Stress orientations around faults (Weak)
- Earthquake triggering
- Fault slip behavior: Seismic vs. Aseismic Slip; Earthquake Stress Drop

Earthquakes occur on Strong Faults, Creep and Aseismic Slip on Weak Faults

- Seismic vs. Aseismic Slip; Earthquake Stress Drop
- ~~CREEPING, ASEISMIC FAULTS ARE WEAK….~~



Strong, Stable creep

Weaker, Stable or Unstable Stick slip

Mair, Frye & Marone, JGR, 2002

At least in some locations: **Major Tectonic Faults are Weak and Tend to Creep**

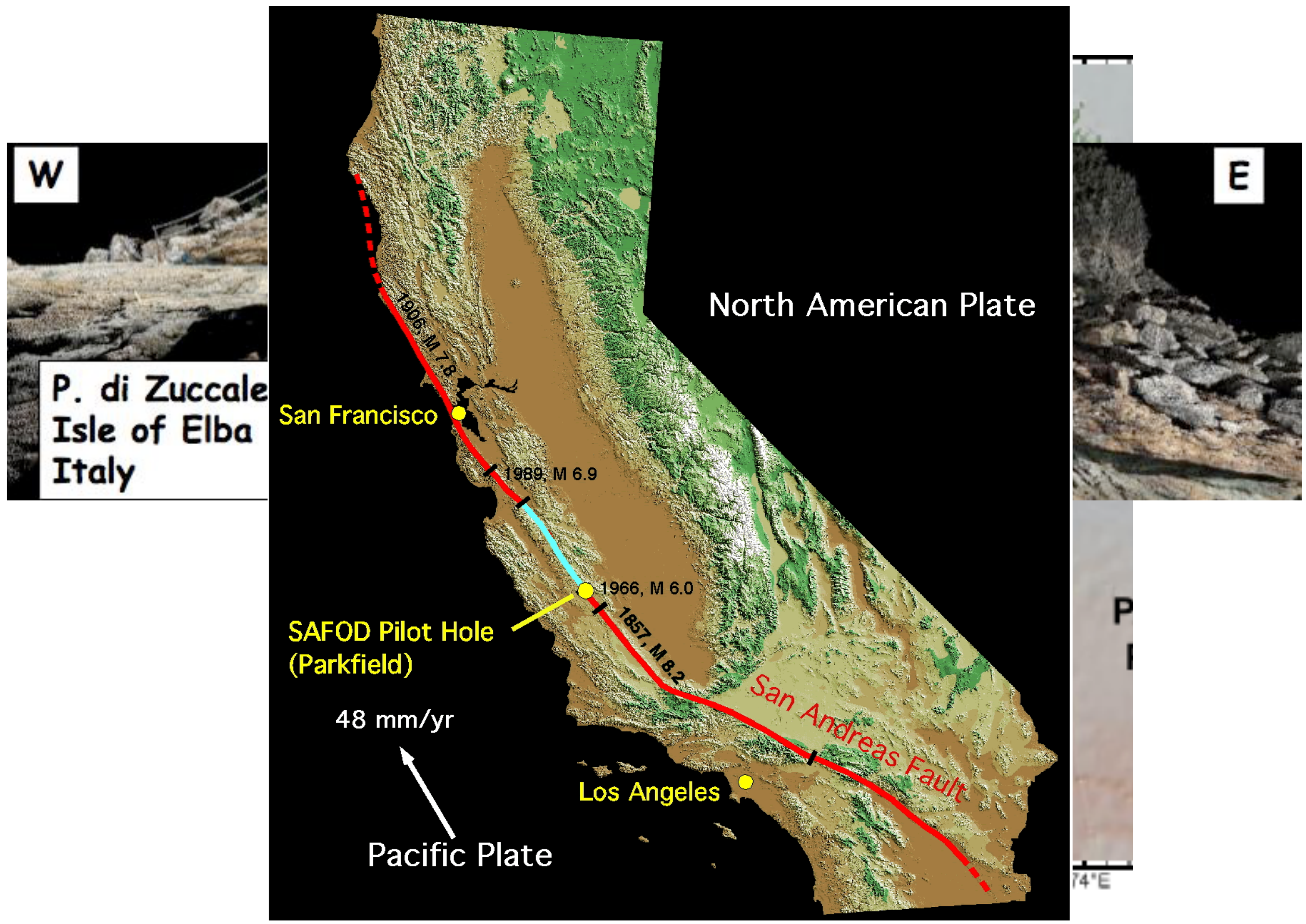
1. Fault Strength: Strong faults or weak faults, some background

2. Lab friction data. Fault zone samples San Andreas, Alpine Fault, Zuccale Fault (central Italy)

3. Role of fabric, clay and surface coatings

4. Post failure recovery of frictional strength. Frictional healing, stability and fault rheology

5. Summary and why we had this wrong for so long



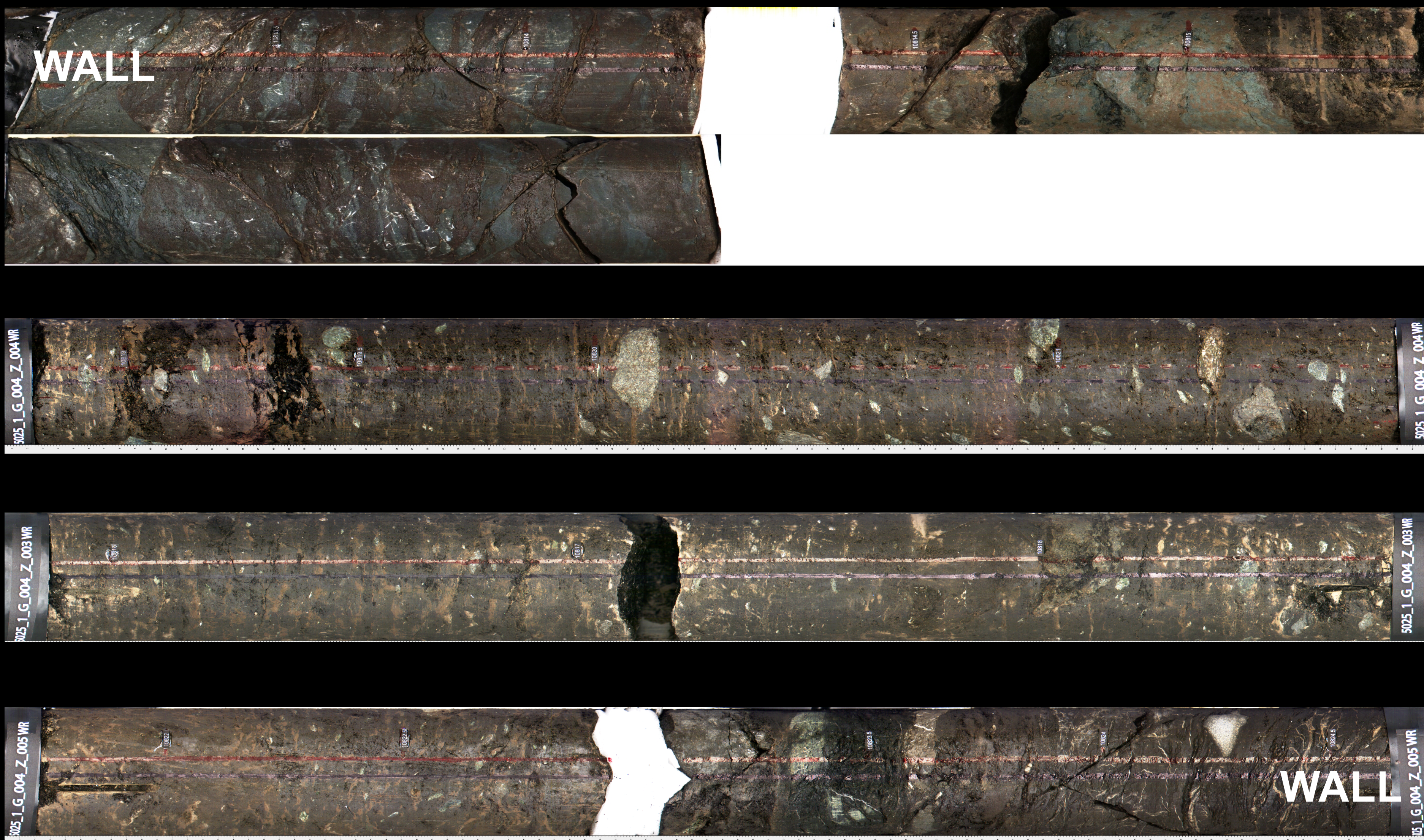
SAFOD Drilling

Sample Collection
(Brett Carpenter)

SAFOD Drilling

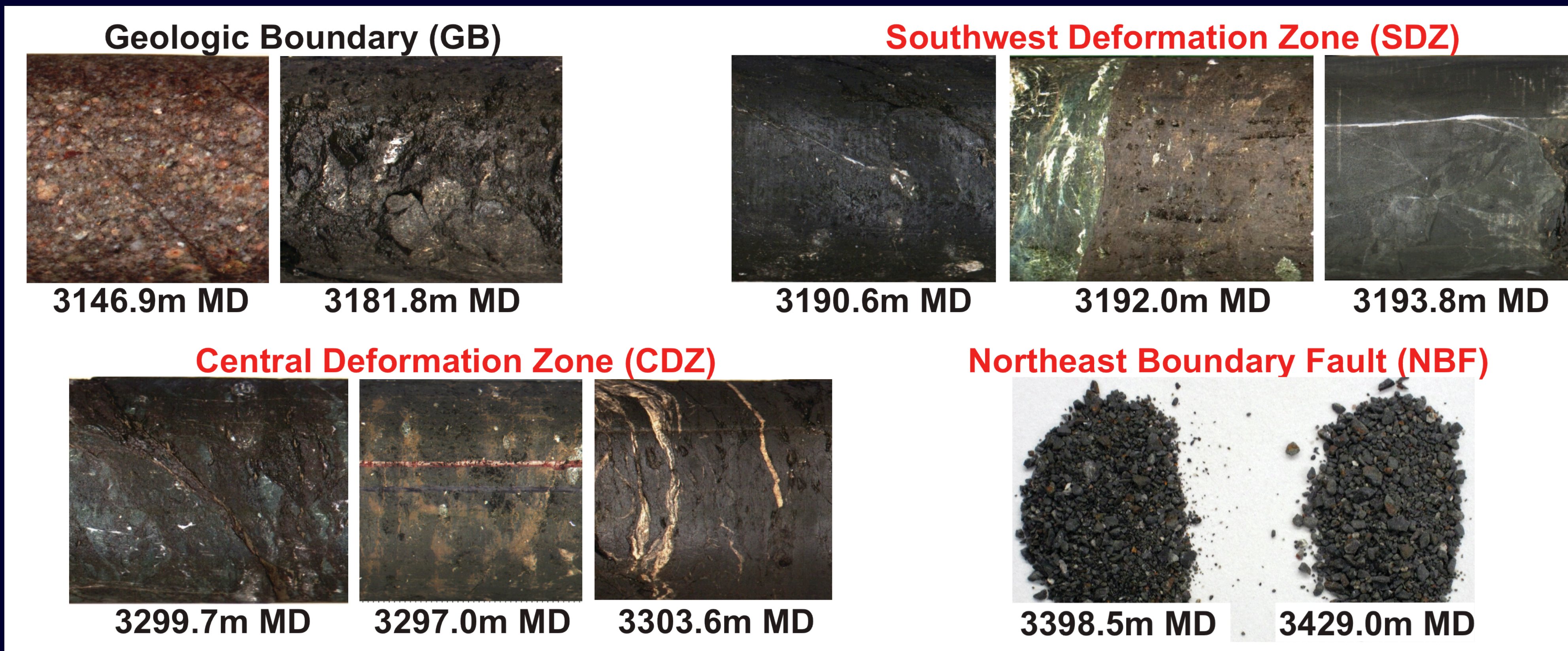
Core Processing

SAFOD Drilling

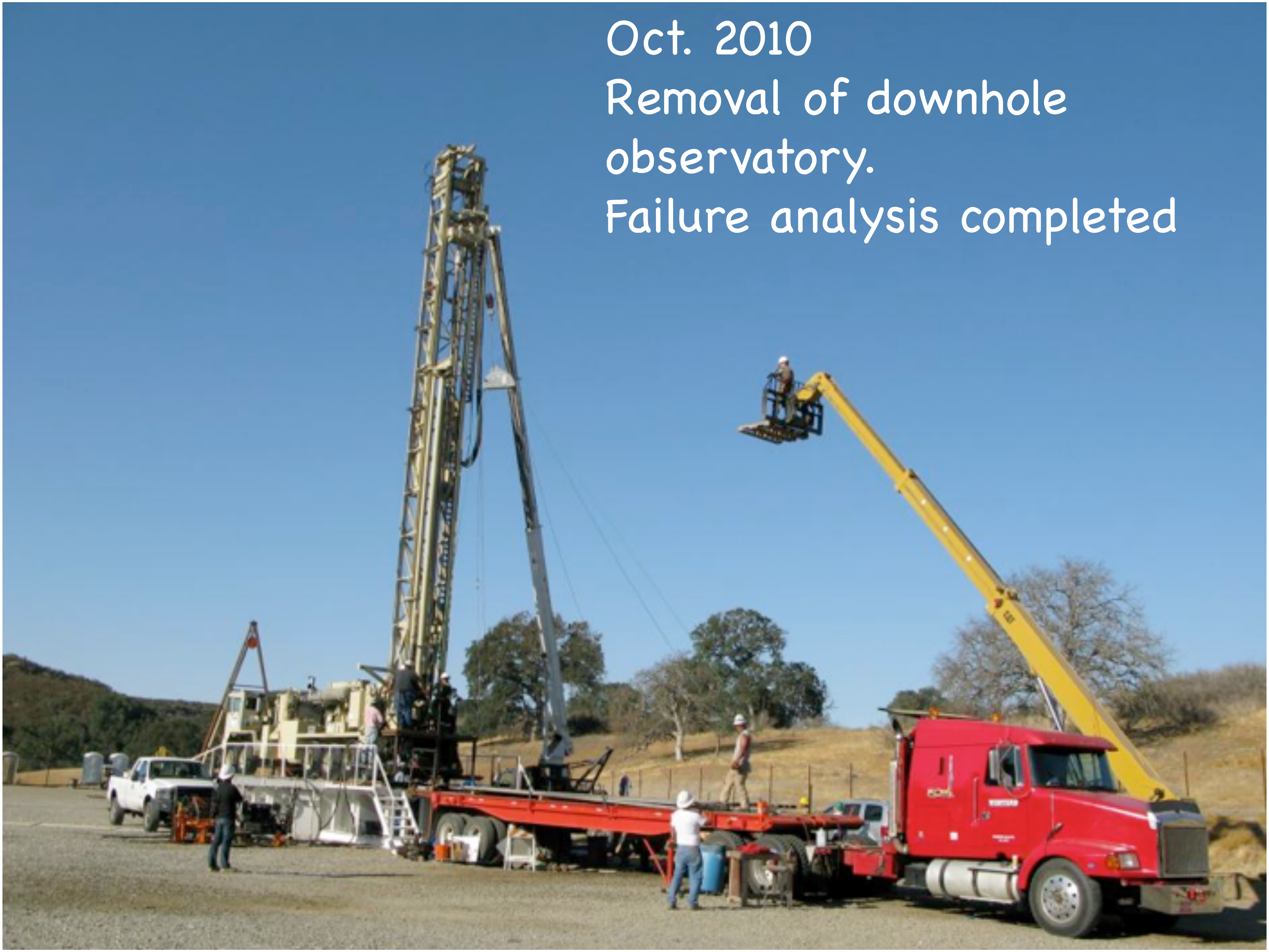


Fault Core

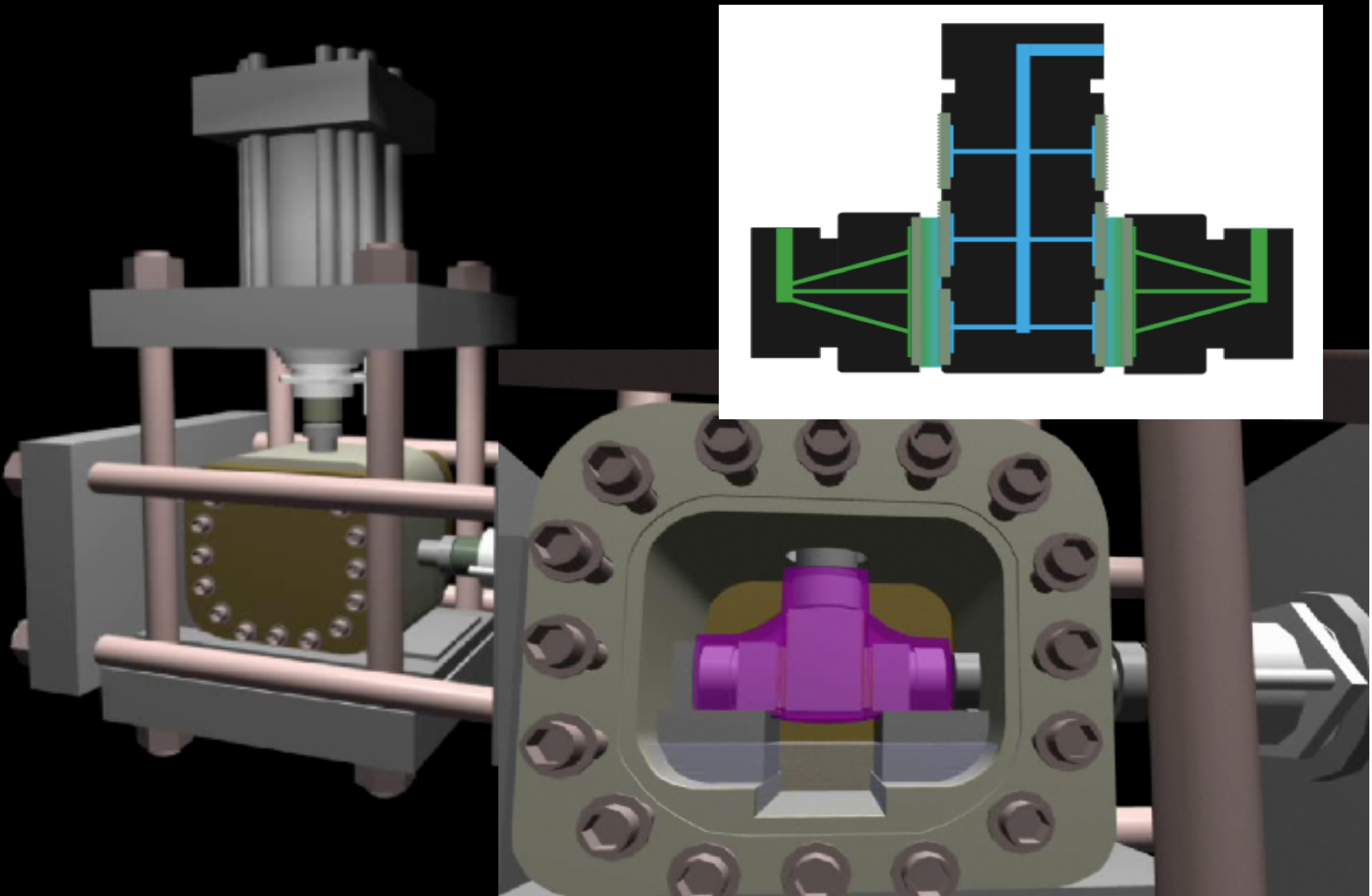
SAF Samples



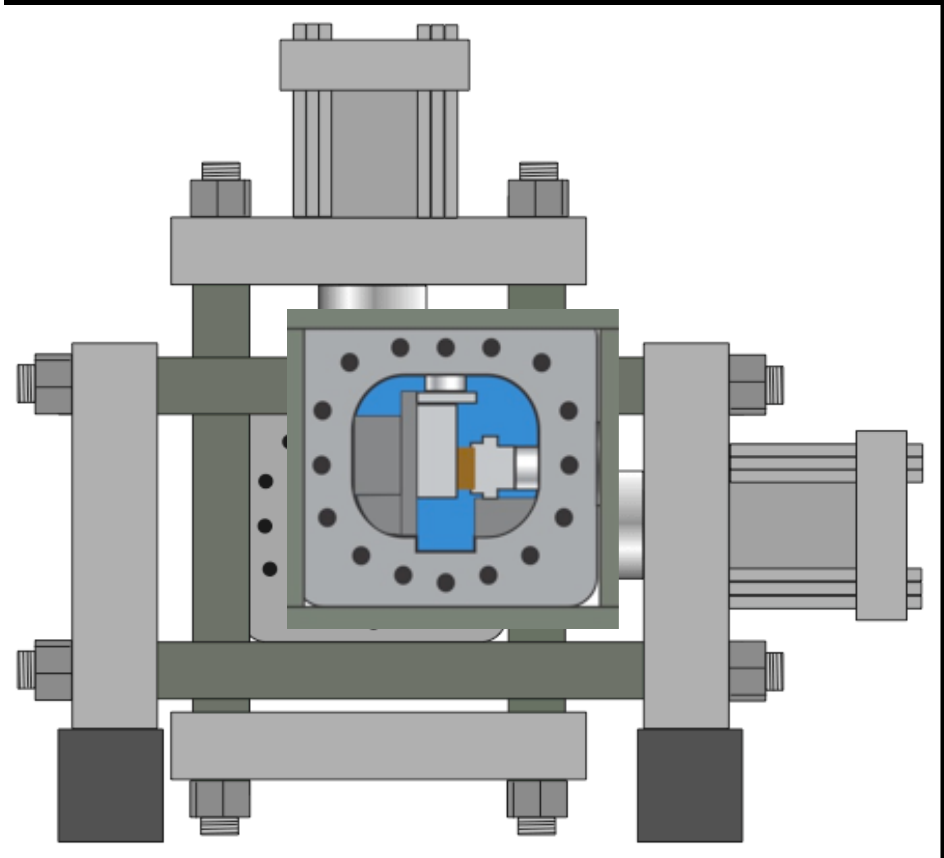
Carpenter et al., in prep


Oct. 2010
Removal of downhole
observatory.
Failure analysis completed

True Triaxial Stress State, Direct Shear, Pore fluid



San Andreas Fault Samples: Intact wafers and powdered gouge



Single-direct shear

True-triaxial Stresses

Effective normal stresses 10 to 100 MPa

Mock Pore water

<u>Measured</u>:

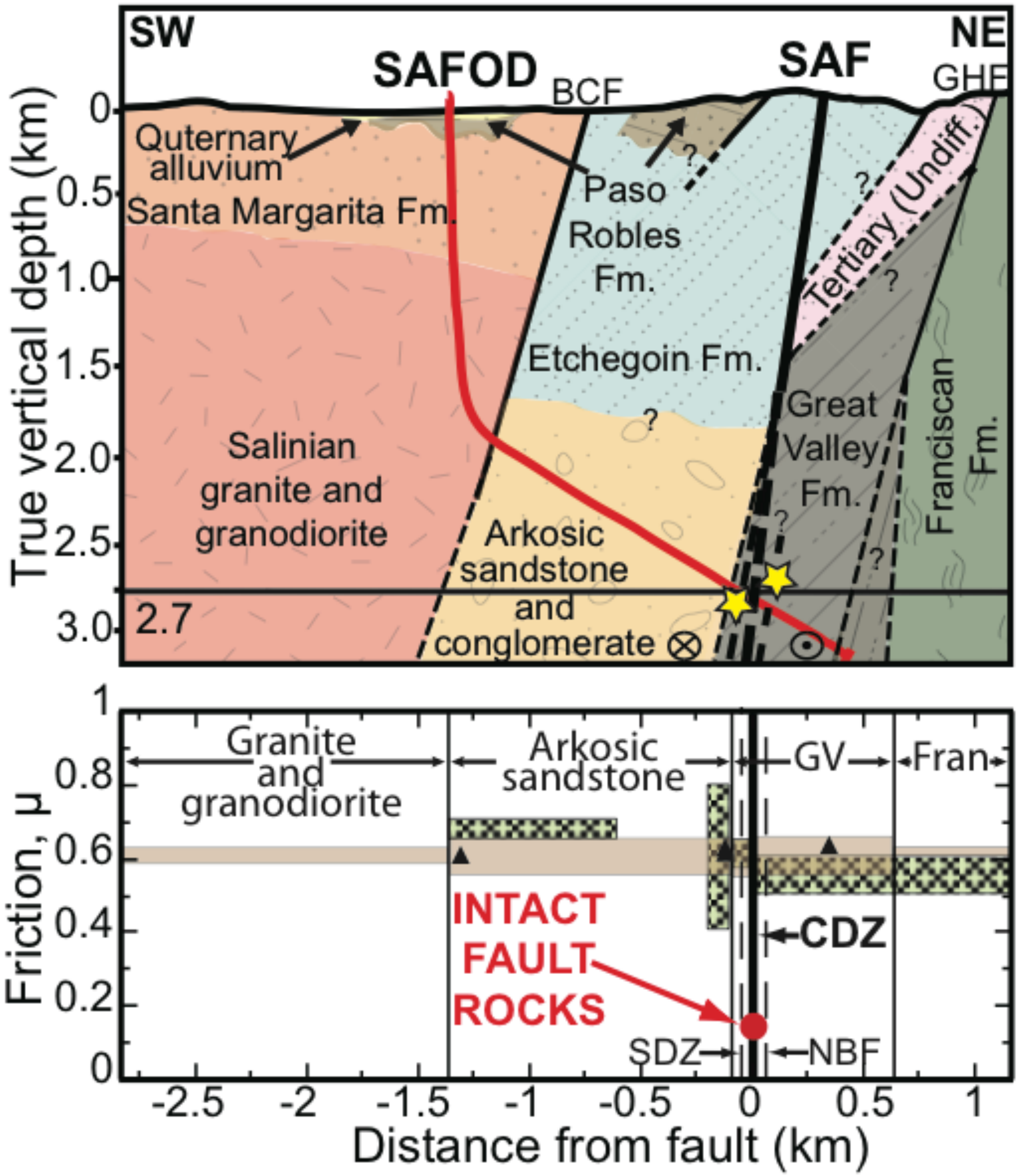
Permeability

Frictional Strength

Friction Velocity Dependence

Frictional Healing

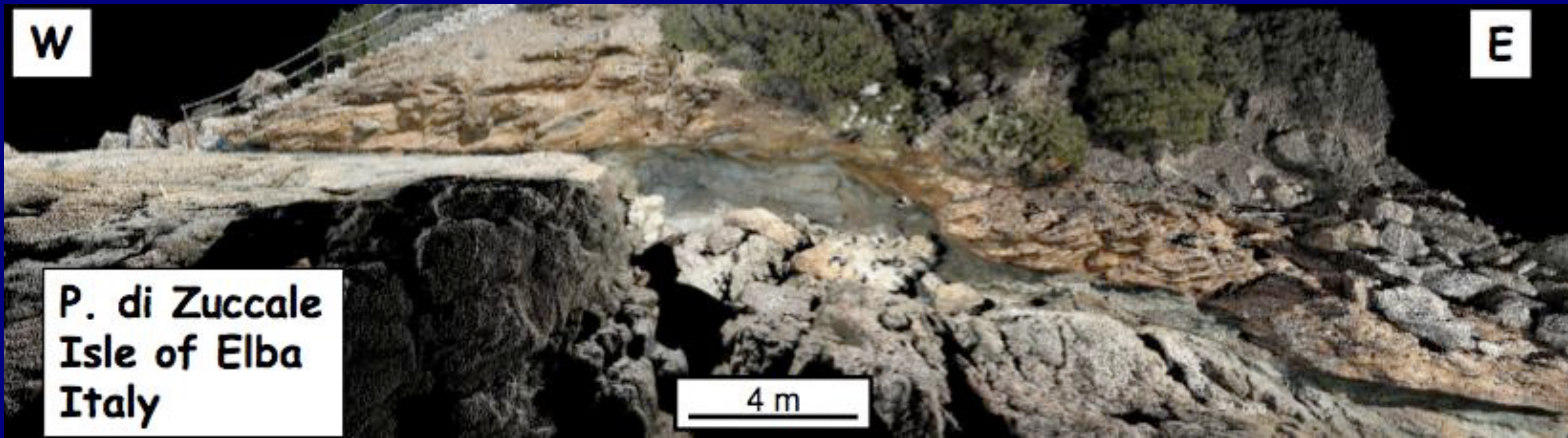
Intact Fault Rock vs. Powdered Gouge



What about lab measurements?

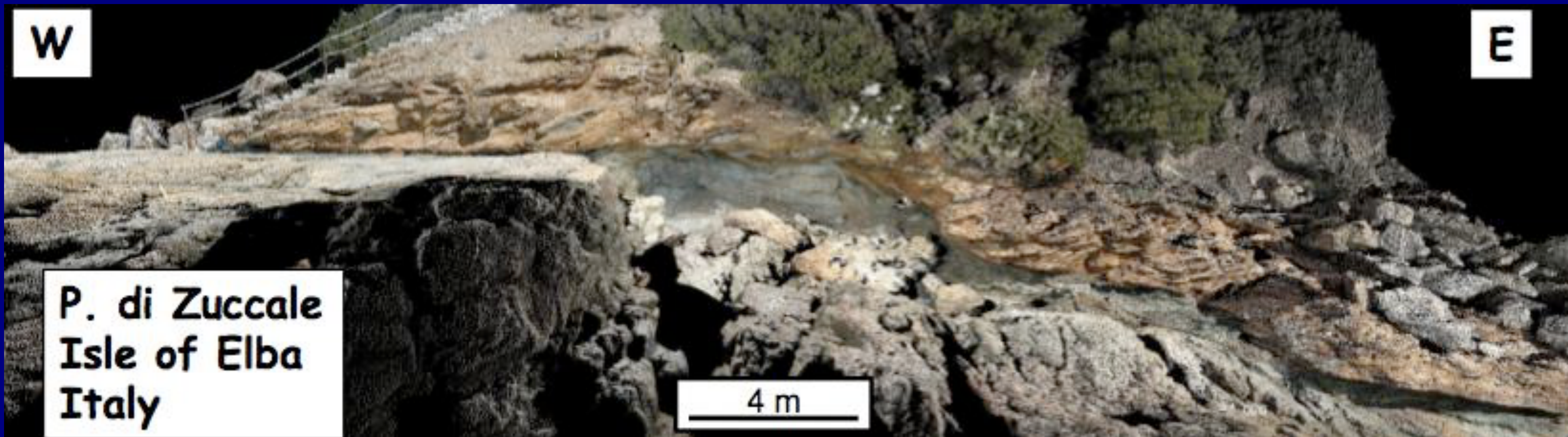
Carpenter, Saffer, and Marone.
Geology, 2012

LANF's Fault zone fabric and weakness

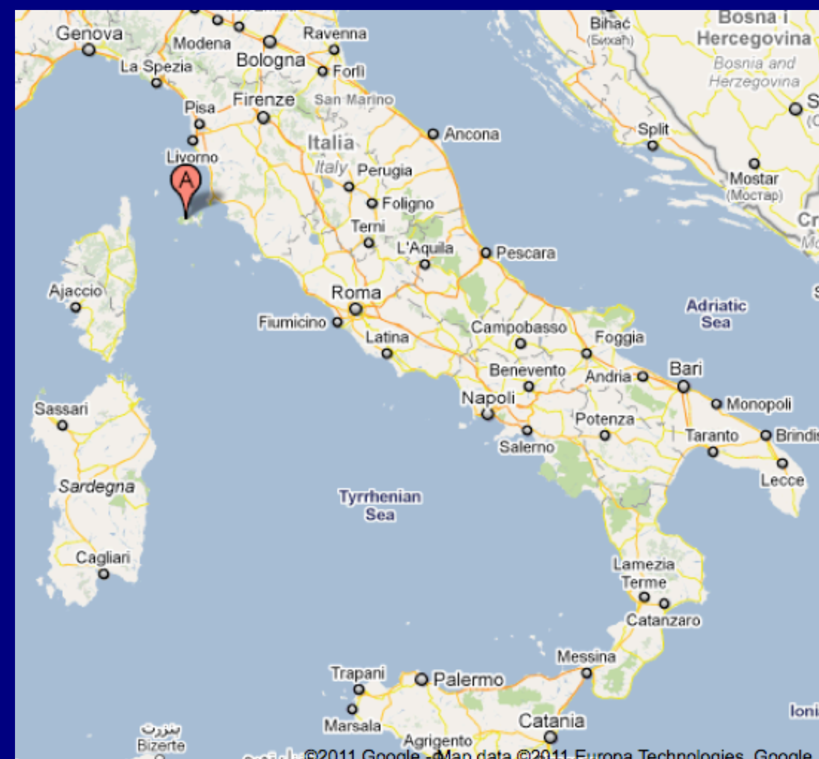


Collettini, Niemeijer, Viti and Marone, Fault zone fabric and fault weakness, *Nature, 462,* 907, 2009

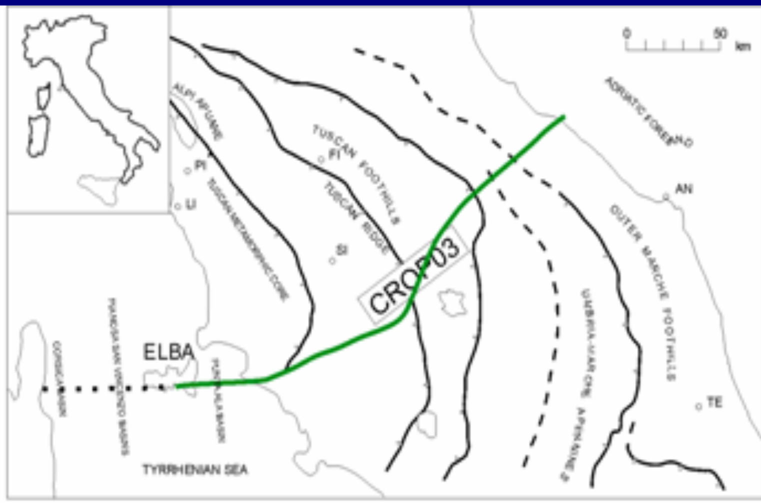
Low Angle Normal Faults…

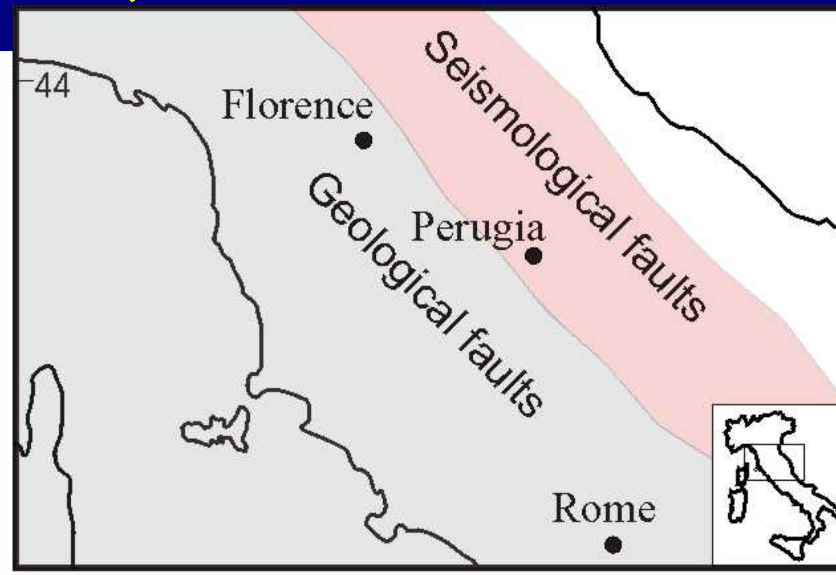


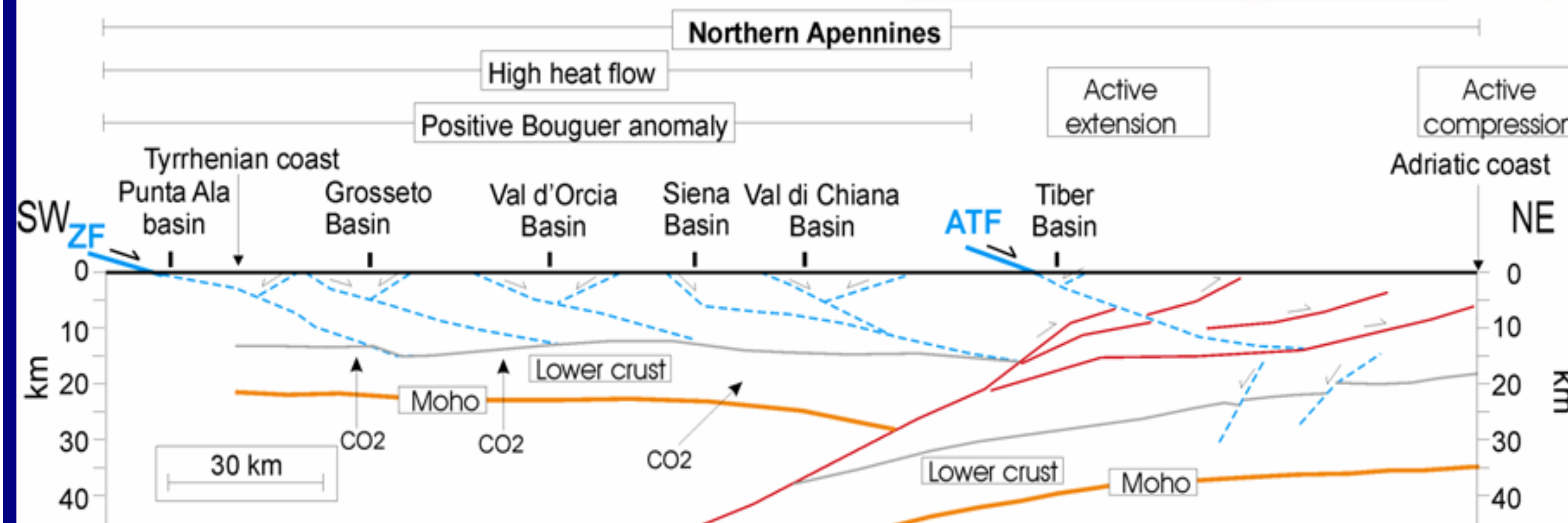
Collettini, Niemeijer, Viti and Marone, Fault zone fabric and fault weakness, *Nature, 462,* 907, 2009



The Zuccale Fault is part of a system of low angle normal faults in central Italy

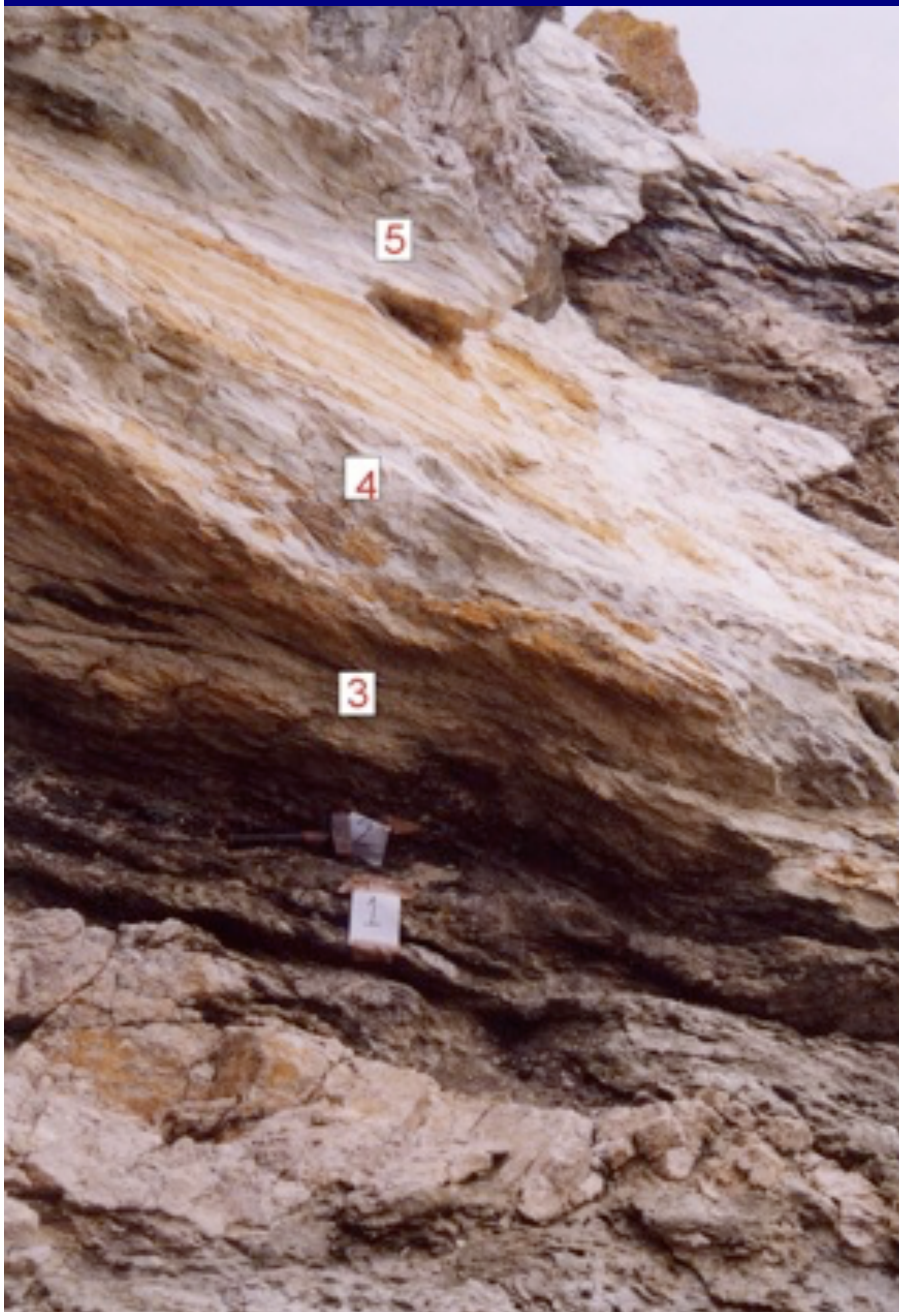




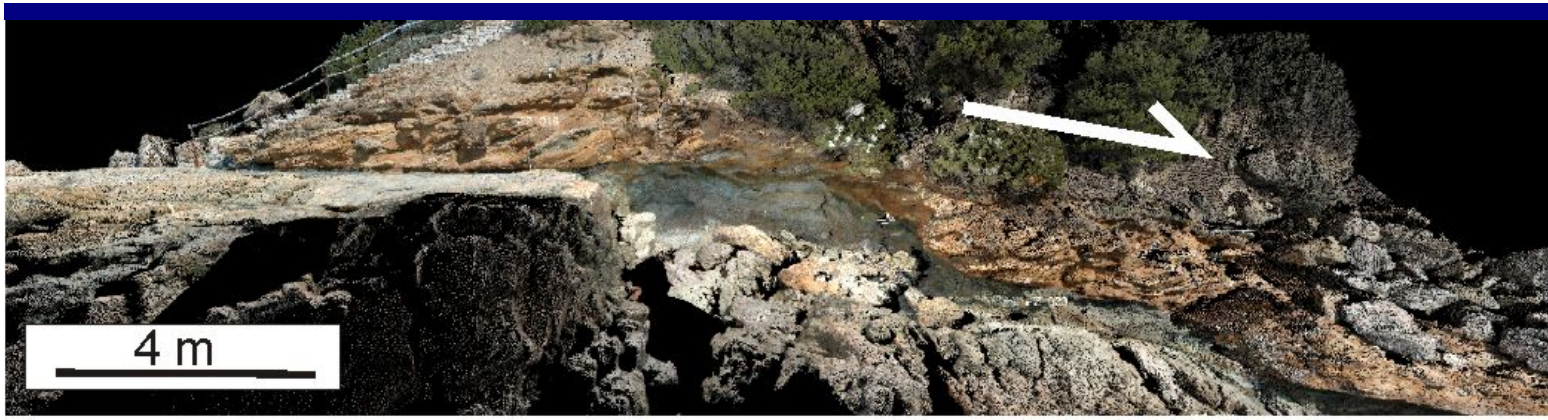


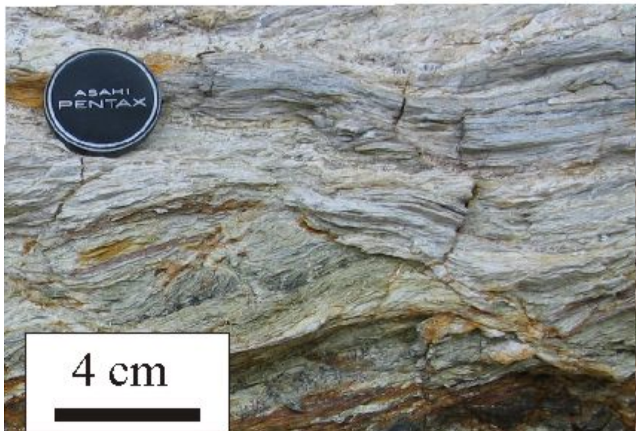
Collettini, Niemeijer, Viti and Marone, Fault zone fabric and fault weakness, *Nature, 462,* 907, 2009

Collecting Samples from the Zuccale Fault, Isle of Elba



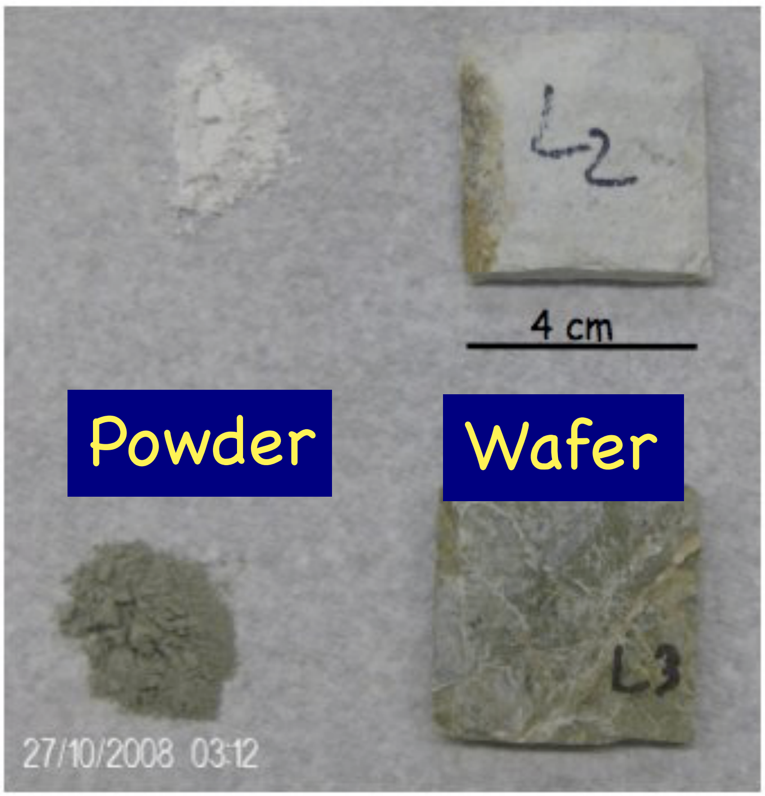
Tino Marone & Claudio Collettini





Finding good samples of Zuccale Fault Rocks

~~Cutting~~ Sculpting Samples for friction tests, in-situ shear geometry



	L2	L3
calcite	43%	39%
tremolite	36%	26%
talc	6%	15%
smectite	15%	20%
phyllosilicates	21%	35%

Differential thermal analysis coupled with mass spectrometer;

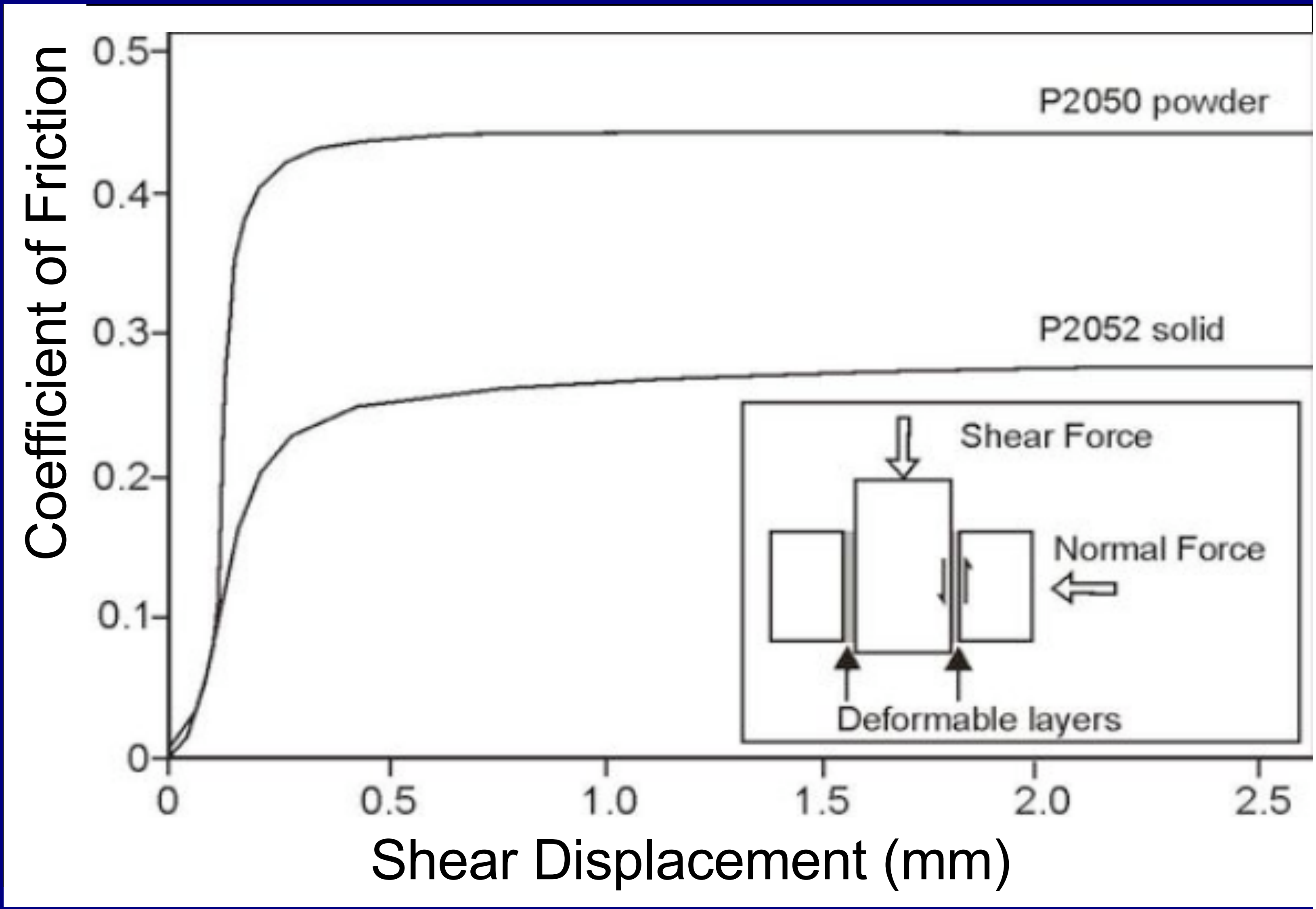
XRPD on bulk starting sample;

XRPD on the fine fraction (< 2 μm).

Collettini, Niemeijer, Viti and Marone, Fault zone fabric and fault weakness, *Nature, 462,* 907, 2009

Comparison of fault rock and powdered gouge

Foliated fault rocks, sheared in their in-situ geometry, are weaker than their powdered equivalents



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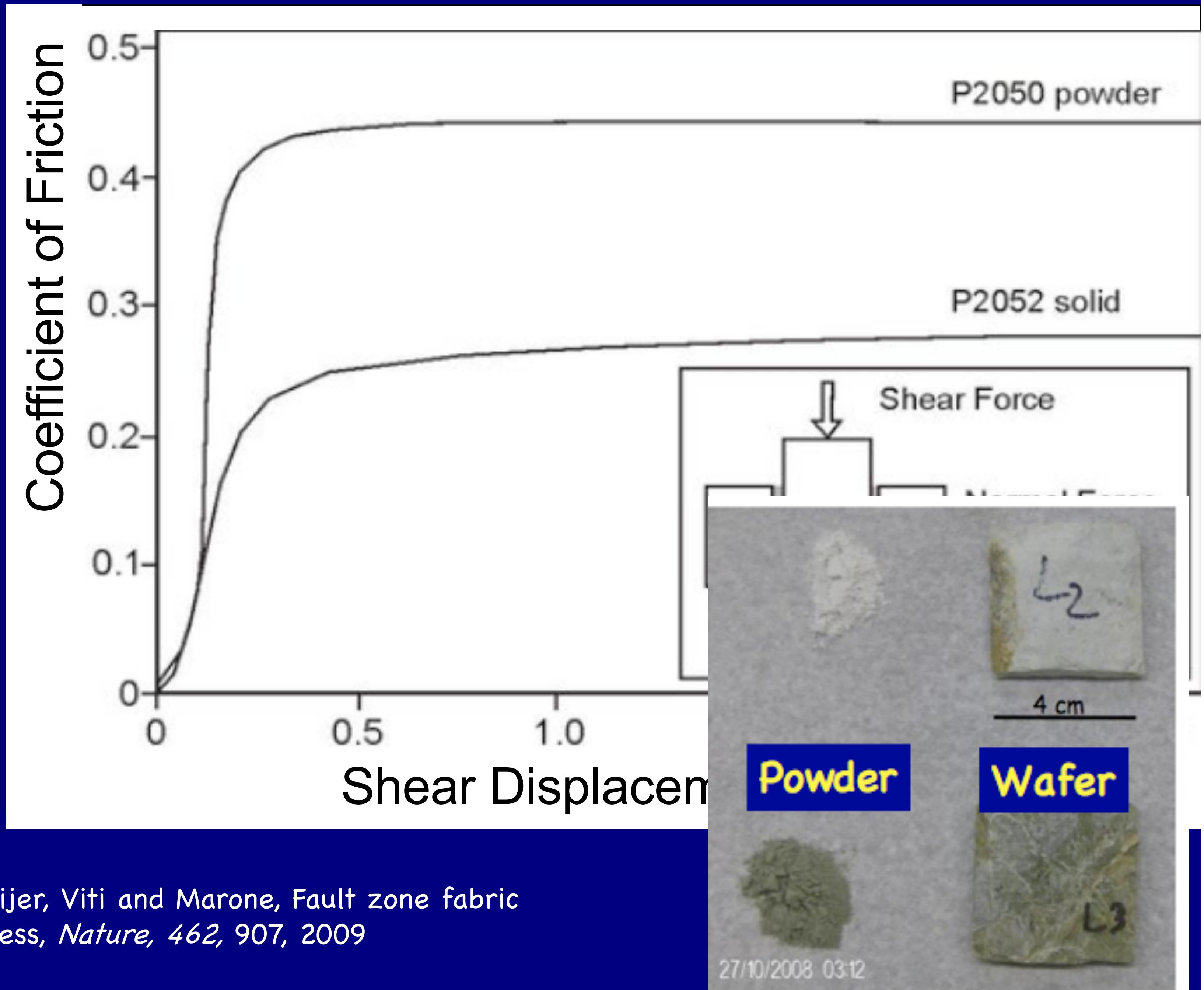
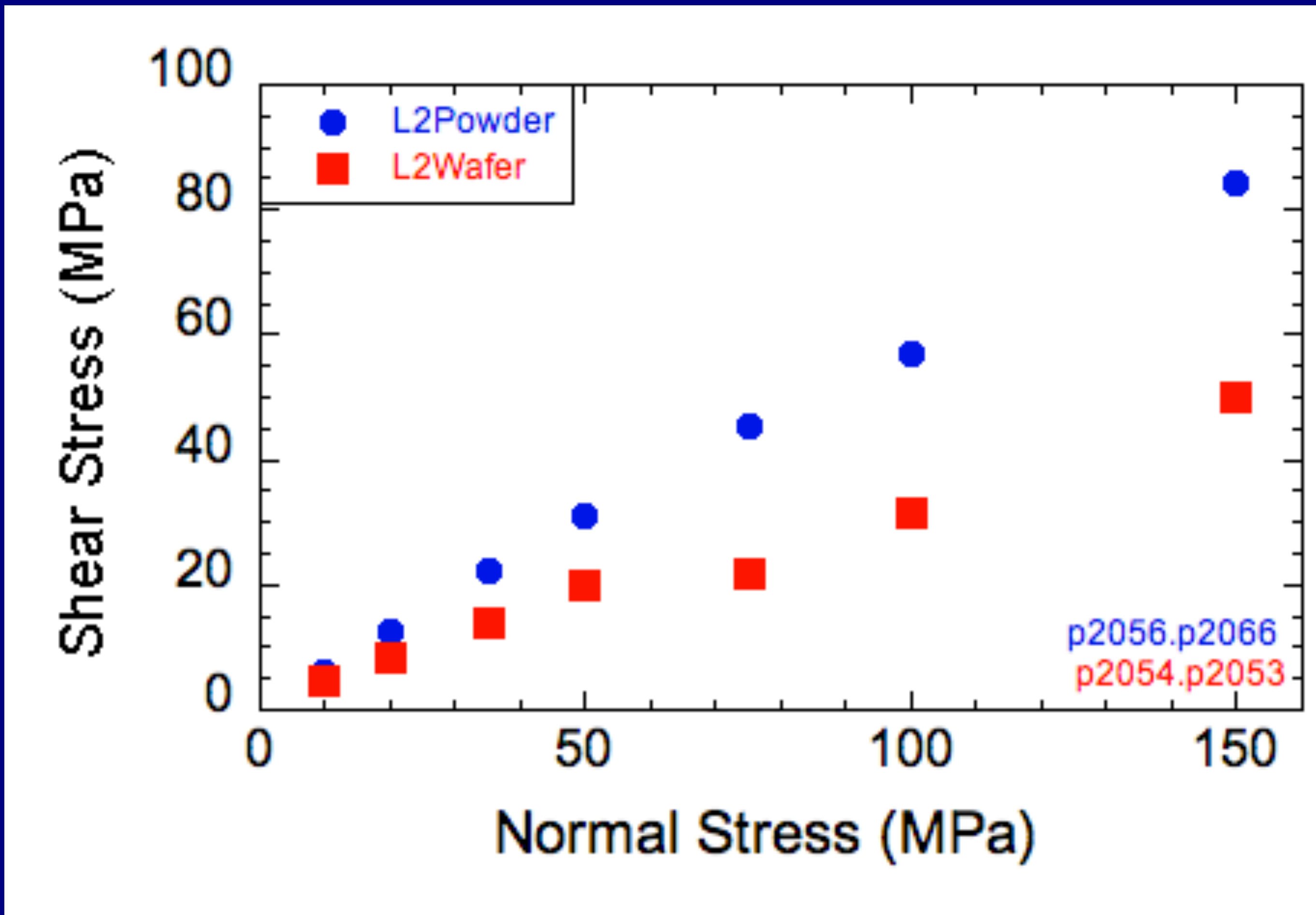


Collettini, Niemeijer, Viti and Marone, Fault zone fabric and fault weakness, *Nature, 462,* 907, 2009

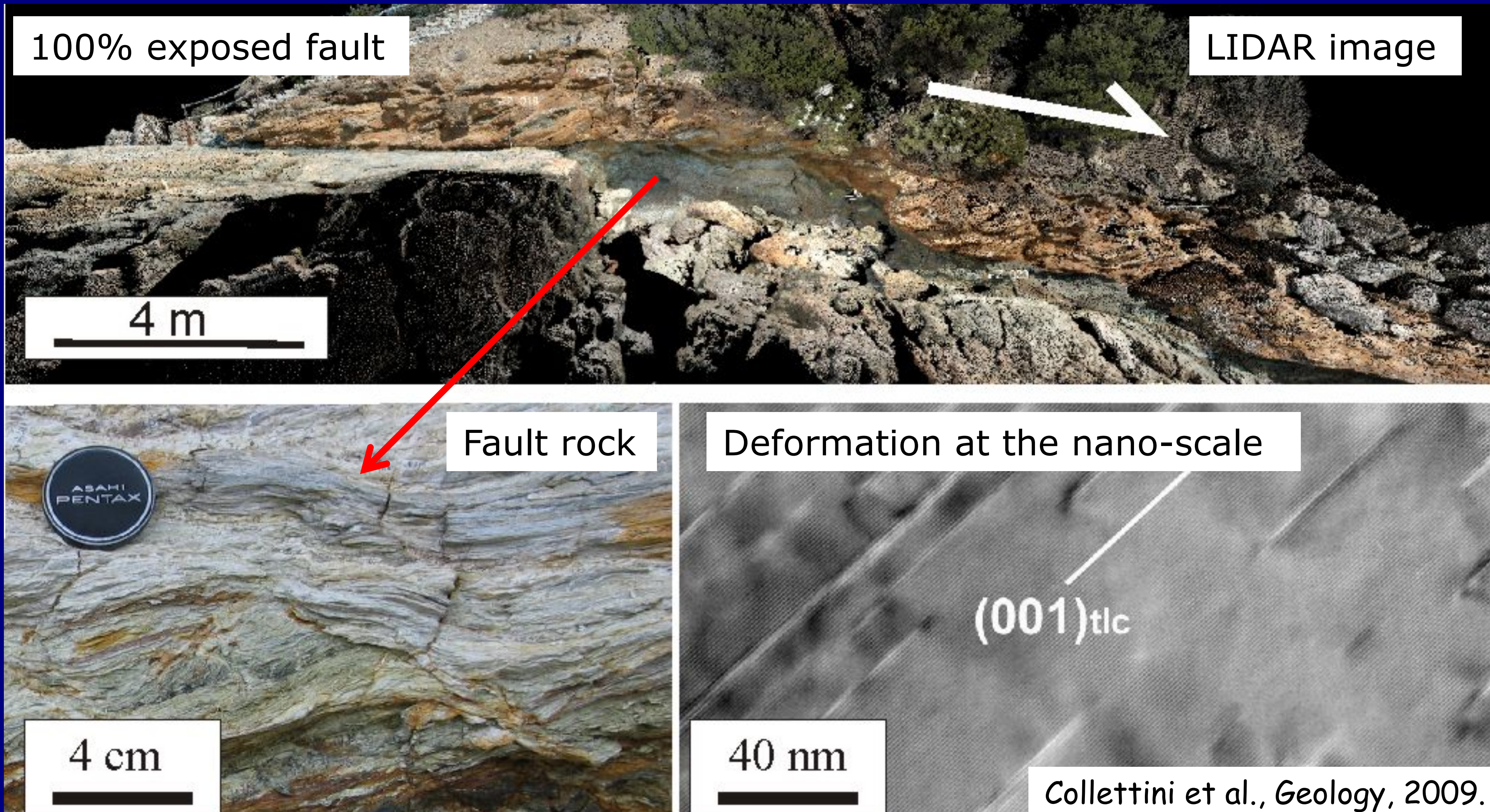
Foliated fault rocks are weaker than their powdered equivalents



Powder

Foliated Fault Rock

Collettini, Niemeijer, Viti and Marone, Fault zone fabric and fault weakness, *Nature, 462,* 907, 2009

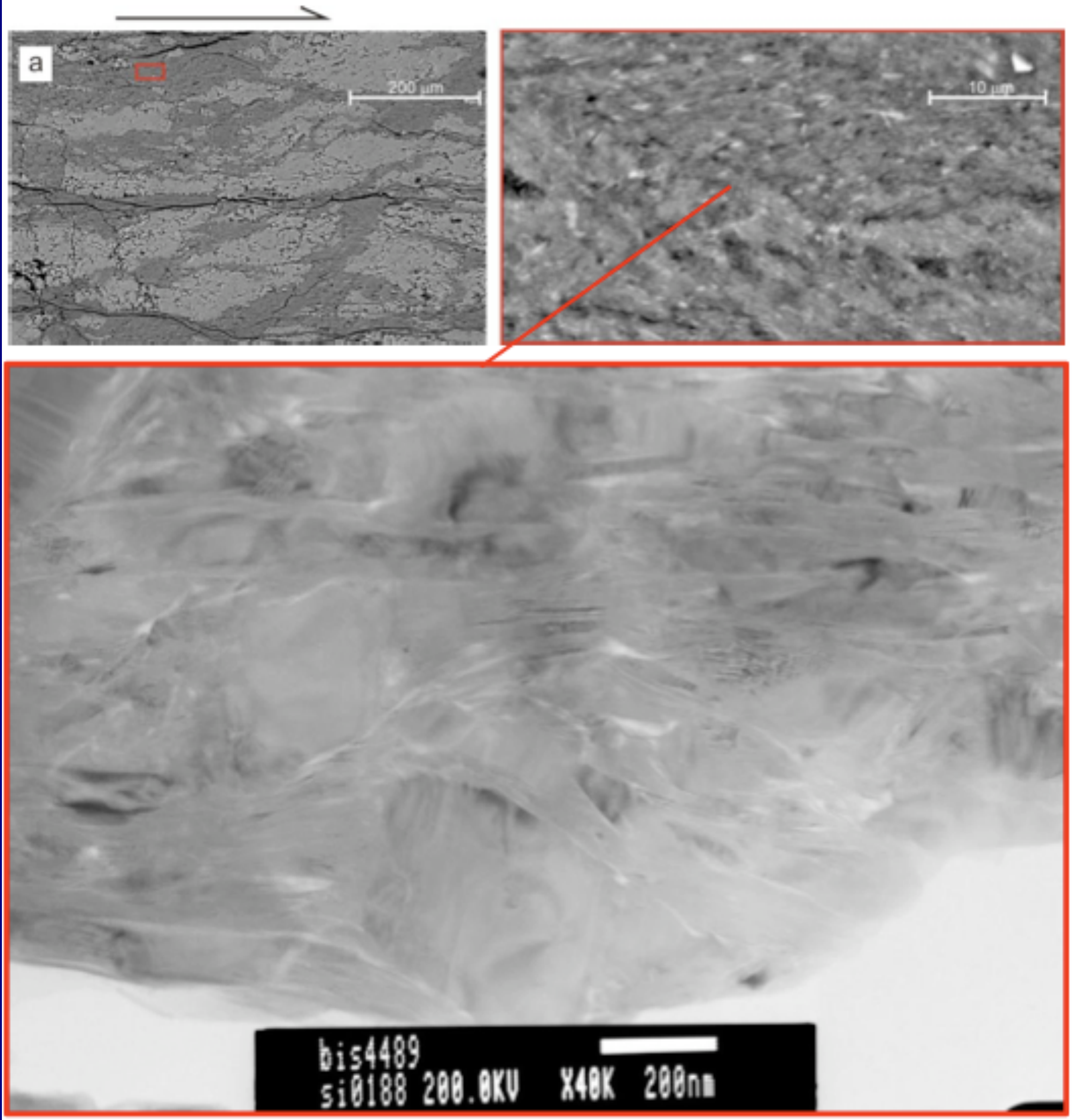


Collettini et al., Geology, 2009.

DOLOMITE + SILICA + H_2O = TALC + CALCITE + CO_2

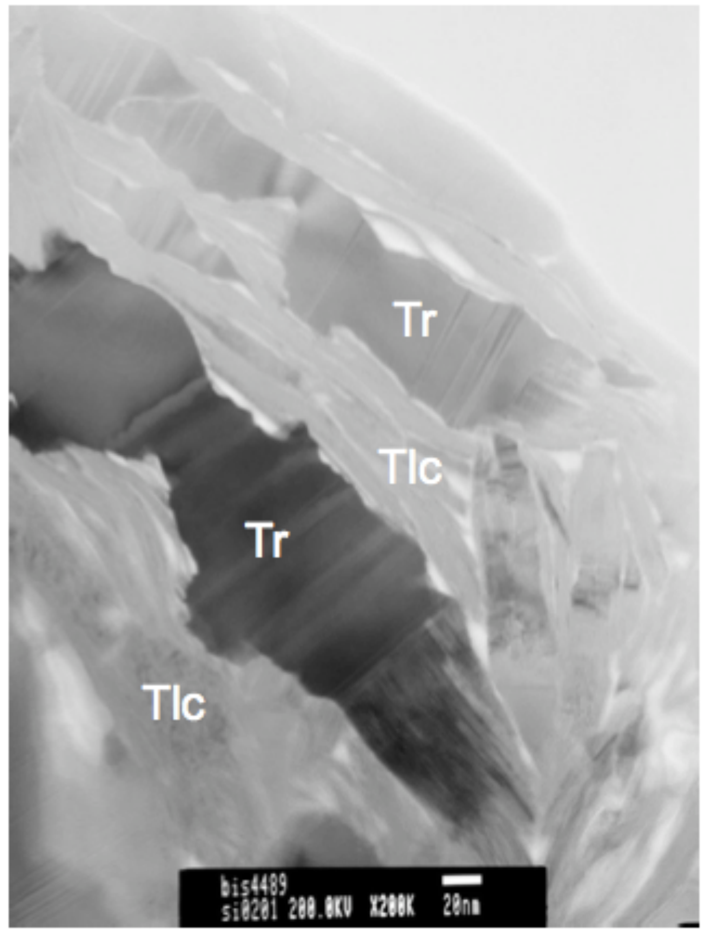
$3\ MgCa(CO_3)_2 + 4\ SiO_2 + H_2O = Mg_3Si_4O_{10}(OH)_2 + 3\ CaCO_3 + 3\ CO_2$

Fault Zone Fabric Defined By Anastamosing Surfaces Coated With Weak Minerals



Microstructures
fine grained foliation

Interconnected phyllosilicate-rich network (talc, smectite) embedding isolated crystals of tremolite



Collettini, Niemeijer, Viti and Marone, *Nature, 2009*

Nanocoatings of clay and creep of the San Andreas fault at Parkfield, California

A.M. Schleicher[1], B.A. van der Pluijm[1], and L.N. Warr[2]
[1]Department of Geological Sciences, University of Michigan, 1100 North University Avenue, Ann Arbor, Michigan 48109, USA
[2]Ernst-Moritz-Arndt Universität Institut für Geographie und Geologie, F. Ludwig-Jahn-Strasse 17A, D-17487 Greifswald, Germany

Geology, July 2010

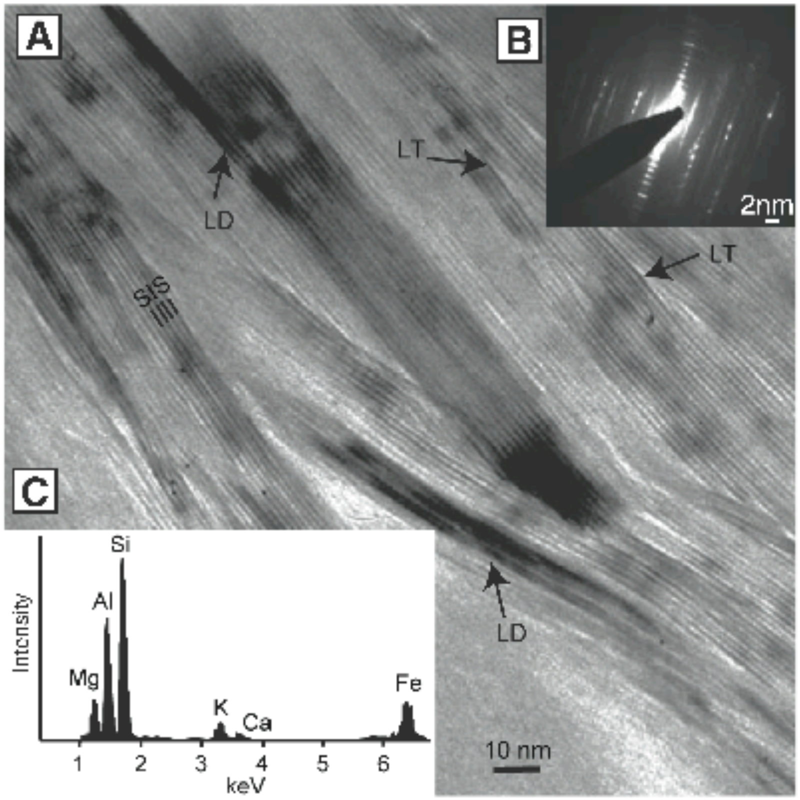
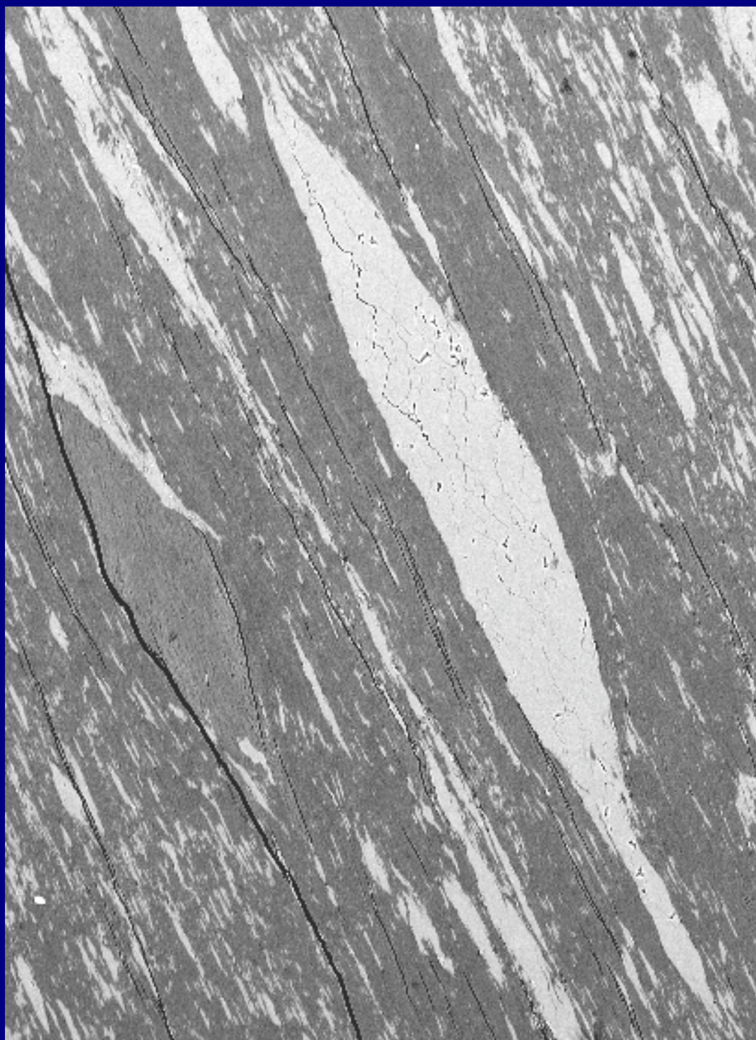
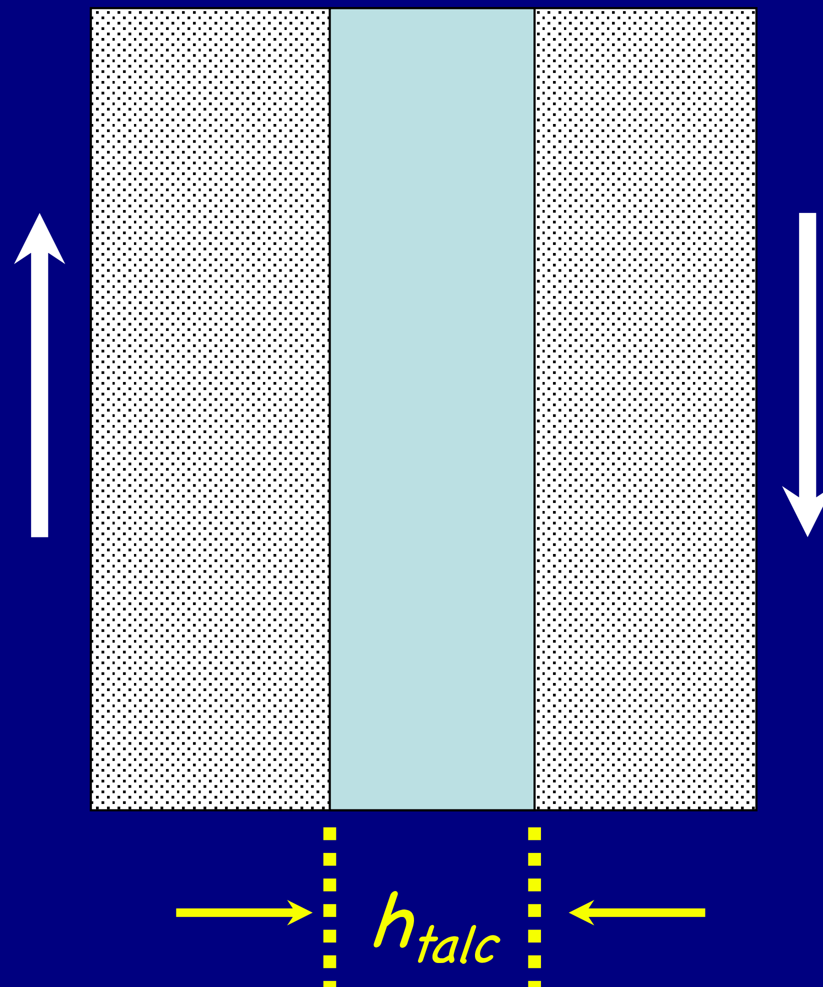


Figure 2. A: High-resolution transmission electron microscopy image of nanoclay coatings. Low-angle arrays of 5–20-nm-thick, ordered illite-smectite particles are arranged in <100-nm-thick mineralized sheets. I—llite; S—smectite layers; LD—lattice distortion; LT—lattice termination. B: Diffraction pattern of illite particles (1Md polytype) with streaking of nonbasal (hkl) planes. C: Chemical composition of authigenic I-S, with notable Mg and Ca in smectite interlayers.

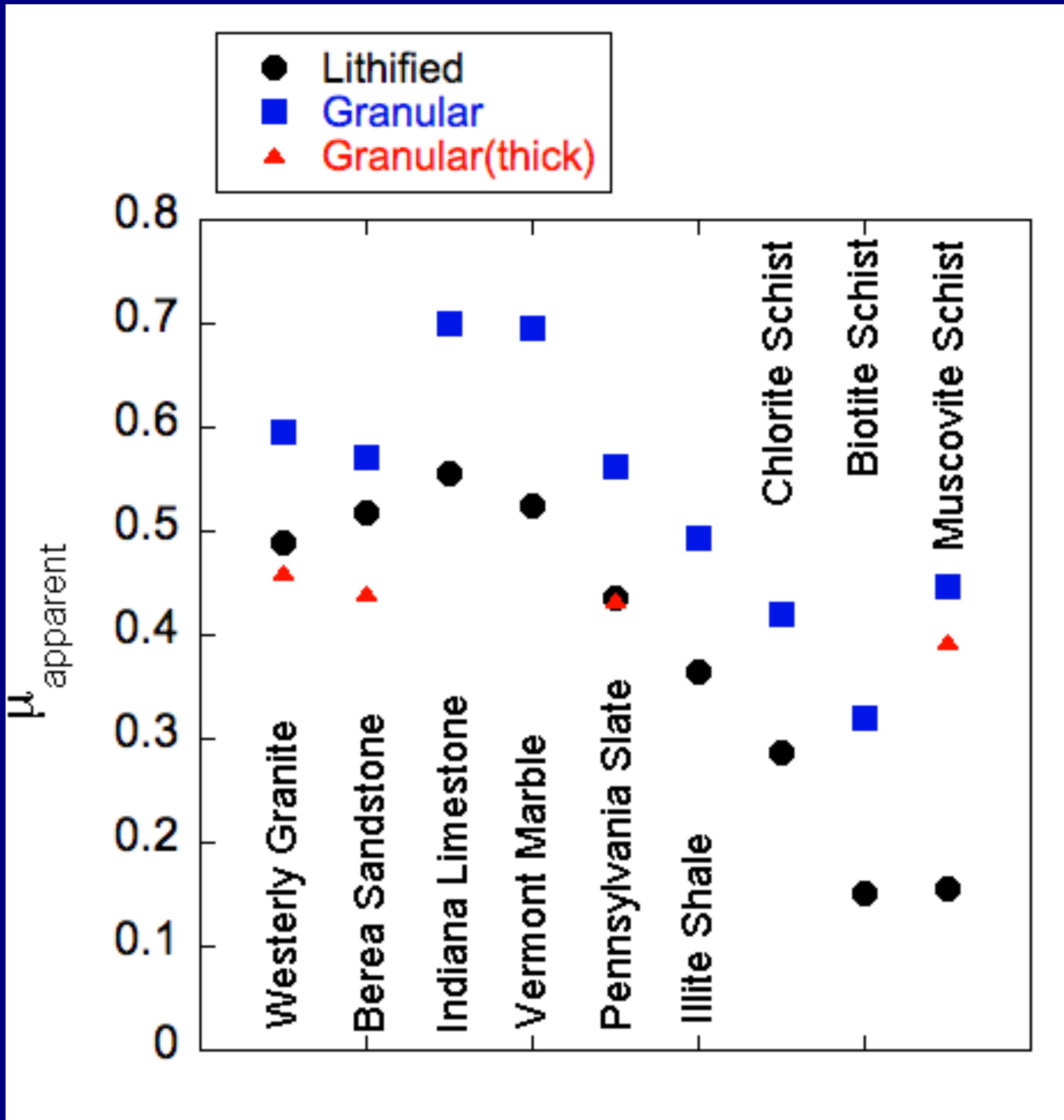
How much of the weak phase do you need to make the whole thing weak?



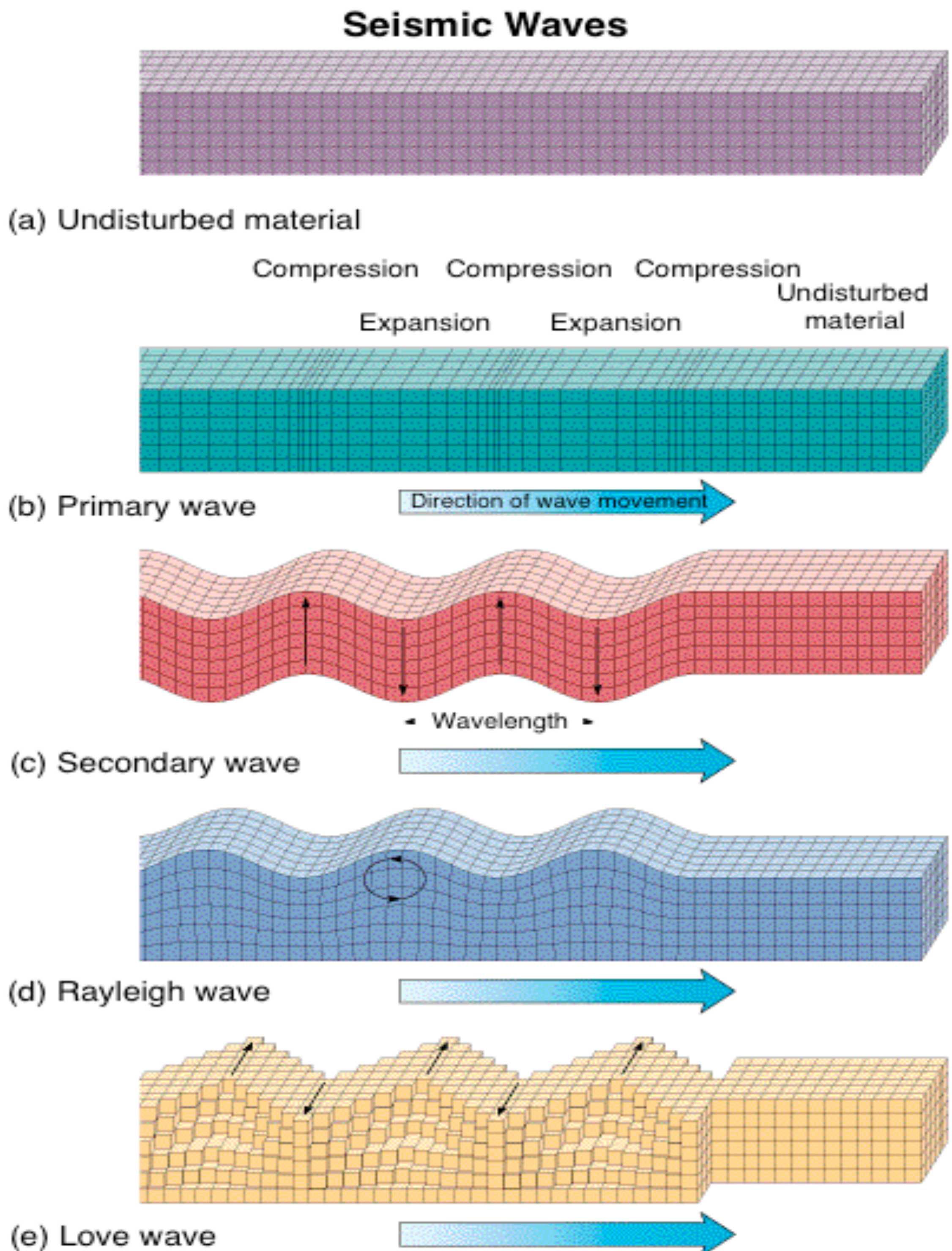


Niemeijer, Marone, and Elsworth, *Geophys. Res. Lett.*, 37, L03304 2010

Not all foliated fault rocks are equal...



Ikari, Niemeijer and Marone, JGR, 2011



P waves

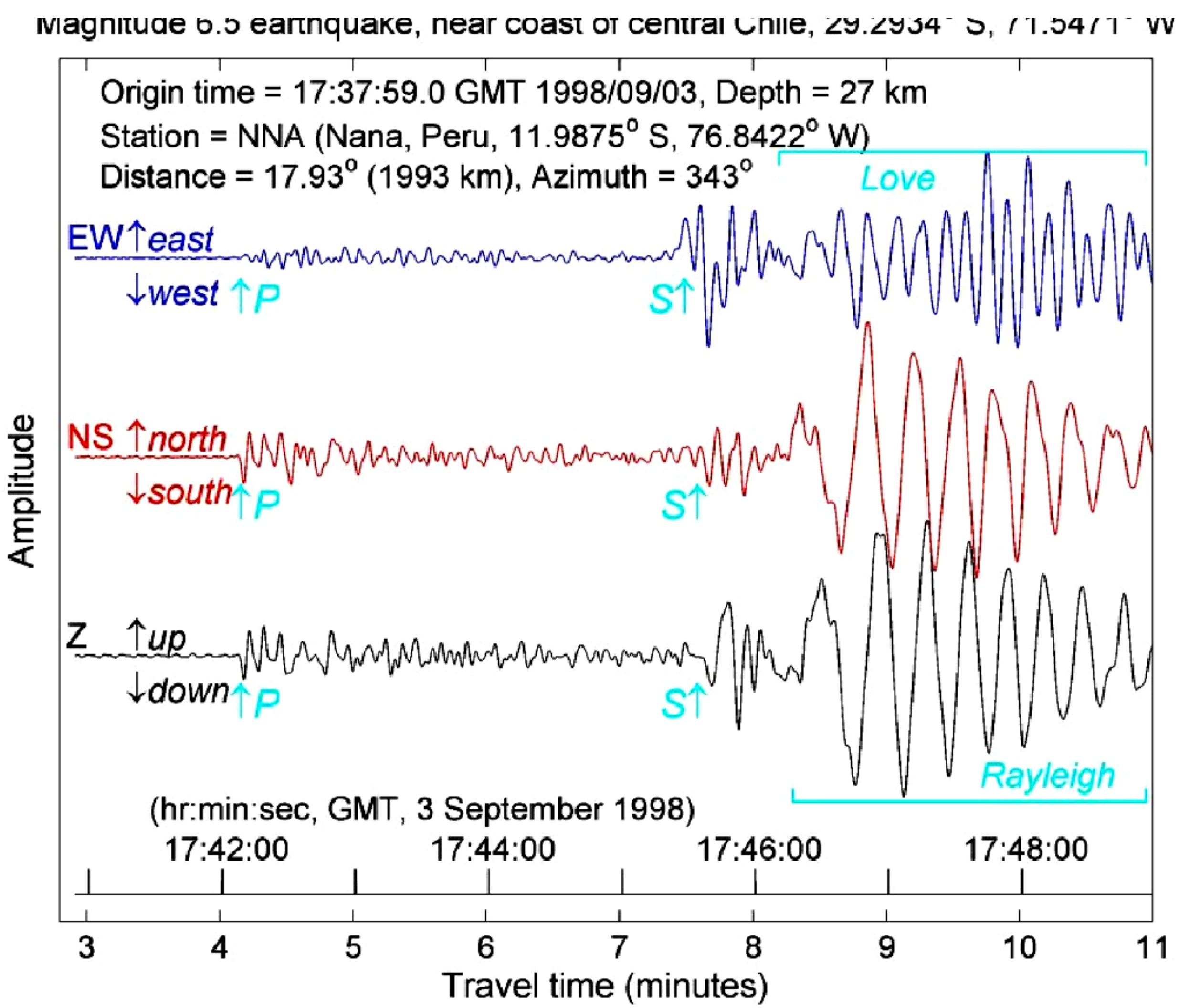
S waves

Surface waves -- waves resulting from the interaction of P and S waves with Earth's surface.

Surface waves propagate to depths approx. equal to their wavelength, so 5-10 km or so

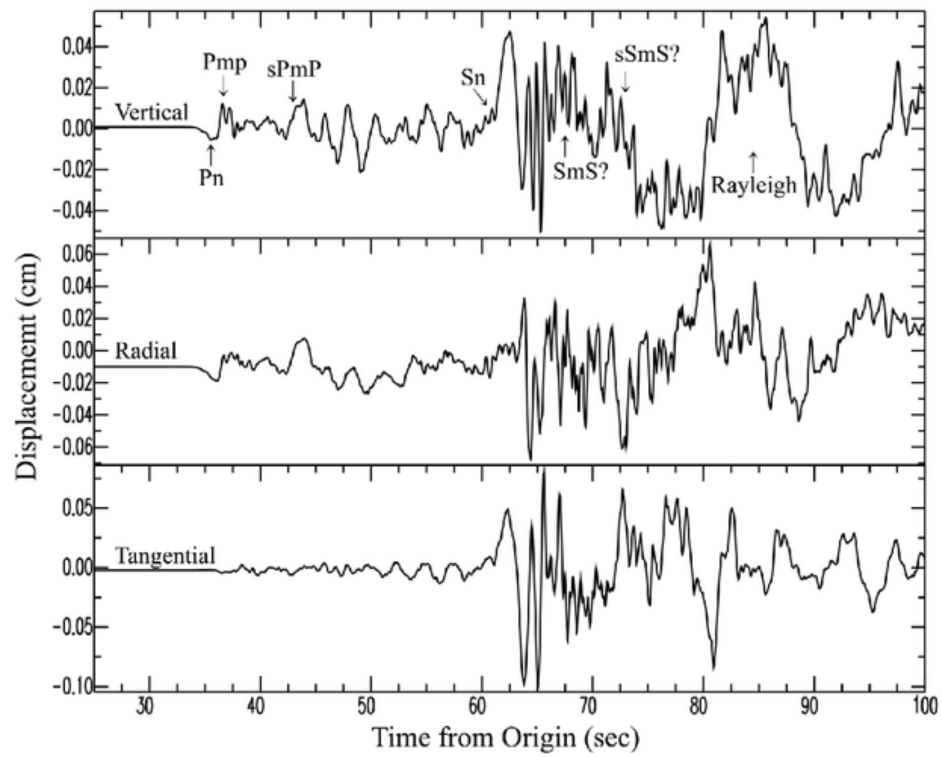
Magnitude is a measure of earthquake size based on:

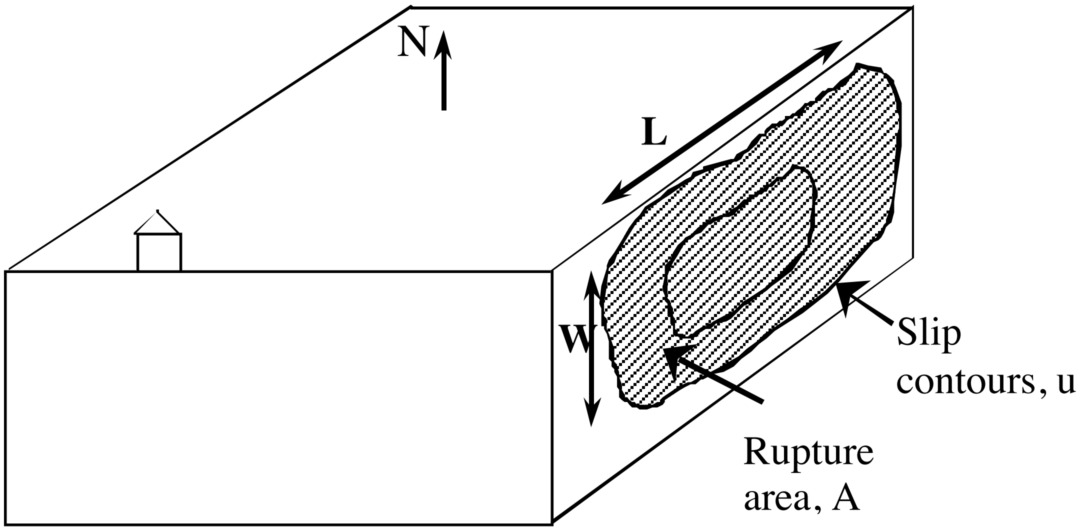
- Ground shaking
- Seismic wave amplitude at a given frequency



3 components of motion

Transforming the horizontal components to radial and transverse





Magnitude is a measure of earthquake size based on:

- Ground shaking
- Seismic wave amplitude at a given frequency

Magnitude accounts for three key aspects:

- Huge range of ground observed displacements --due to very large range of earthquake sizes
- Distance correction –to account for attenuation of elastic disturbance during propagation
- Site, station correction –small empirical correction to account for local effects at source or receiver

$$M_L = \log_{10}\left(\frac{u}{T}\right) + q(\Delta, h) + a$$

Magnitude is a measure of earthquake size based on:

- Ground shaking
- Seismic wave amplitude at a given frequency

$$M_L = \log_{10}\left(\frac{u}{T}\right) + q(\Delta,h) + a$$

M_L (Richter --*local*-- Magnitude) & M_S, based on 20-s surface wave

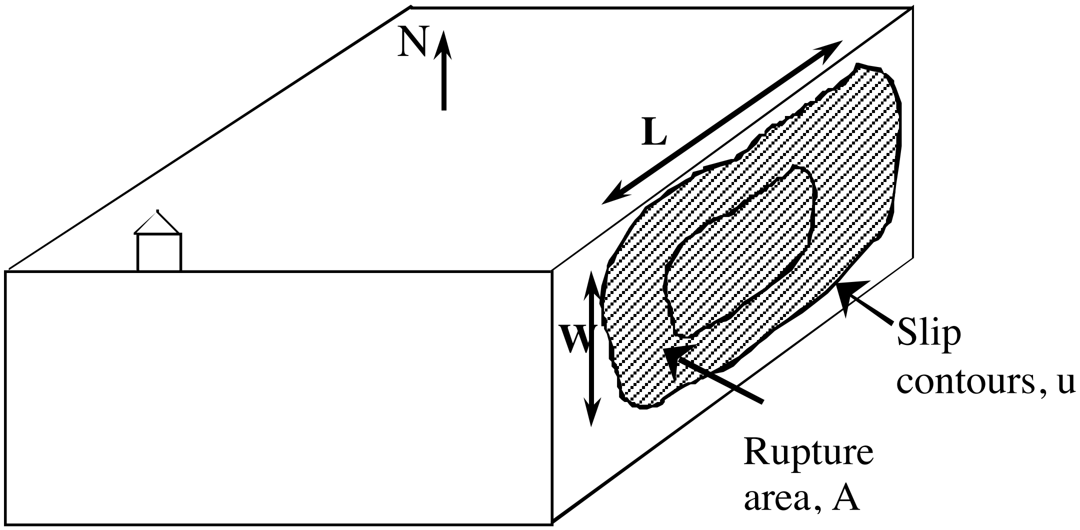
M_B, Body-wave mag. Is based on 1-s wave p-wave

M_W, Moment mag. (see Hanks and Kanamori, JGR, 1979)

Systematic differences between M_s and M_b --due to use of different periods.

Source Spectra is not flat.
Saturation occurs for large events, particularly saturation of M_s.

e.g: http://neic.usgs.gov/neis/nrg/bb_processing.html



Magnitude and Seismic Moment. Moment is a more robust measure of earthquake size because magnitude is a measure of size at only one frequency.

$M_o = \mu A u$, where μ is shear modulus, A is fault Area and u is mean slip.

Moment and Moment Magnitude (Hanks and Kanamori, JGR, 1979):

$M_w = 2/3 \log M_o - 6$ or

$M_o = 3/2\ M_w + 9$ (for M_o in N-m)

Earthquakes represent failure on geologic faults. The rupture occurs on a pre-existing surface.

Faults are finite features –*the Earth does not break in half every time there is an earthquake*.

Earthquakes represent failure of a limited part of a fault. Most earthquakes within the crust are shallow

Definitions of **Focus, Epicenter**
NOTE: *Epicenter* is also the Rancho Cucamonga Quakes' stadium –they are single-A team of the Anaheim (LA) Angles: http://www.rcquakes.com/

Earthquake Size (Source Properties)

Measures of earthquake size: Fault Area, Ground Shaking, Radiated Energy

Fault dimensions for some large earthquakes:

	L (km)	W (km)	U (m)	Mw
Chile 1960	**1000**	**100**	**>10**	**9.7**
Landers, CA 1992	**70**	**15**	**5**	**7.3**
San Fran 1906	**500**	**15**	**10**	**8.5**
Alaska 1964	**750**	**180**	**~12**	**9.3**