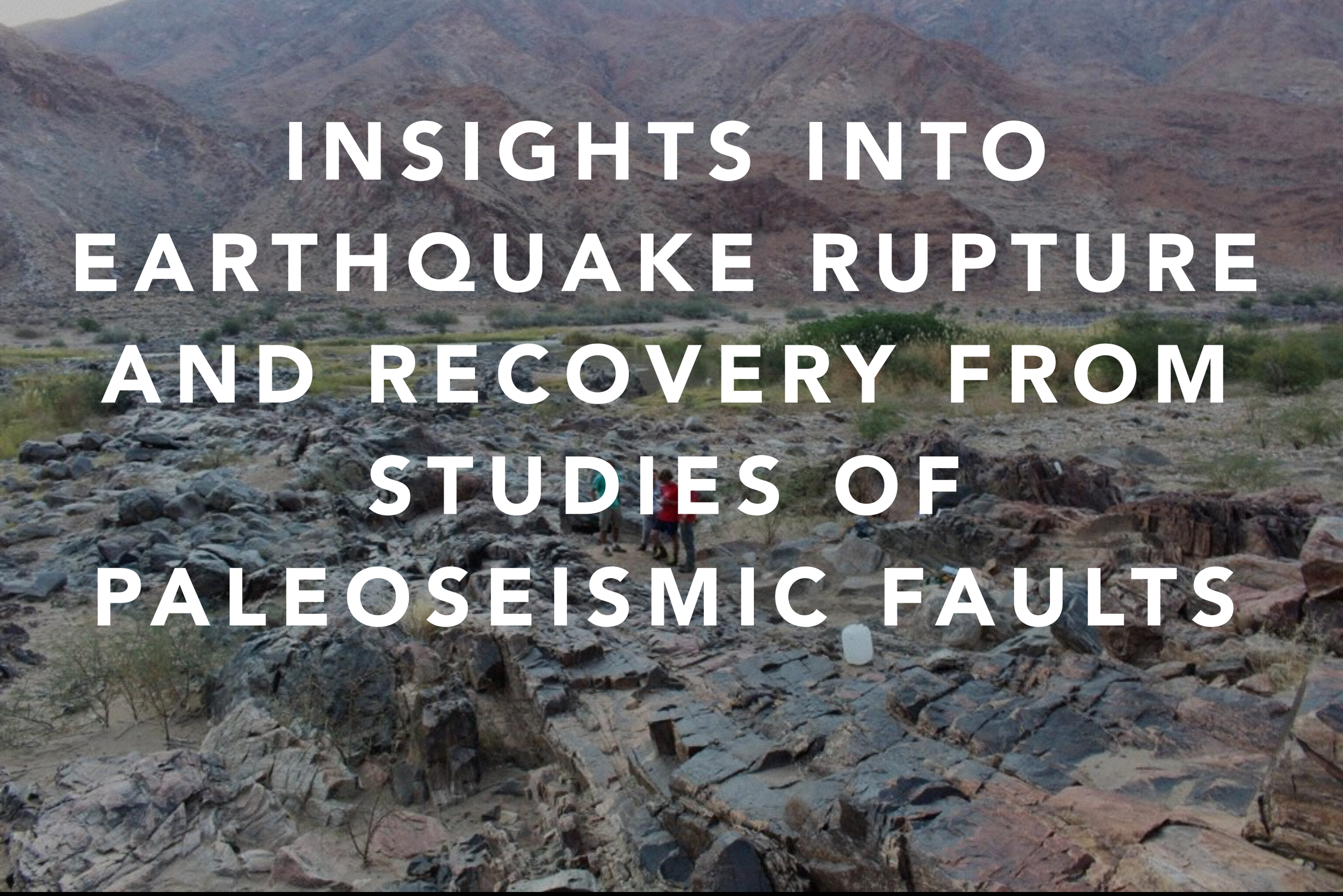


INSIGHTS INTO EARTHQUAKE RUPTURE AND RECOVERY FROM STUDIES OF PALEOSEISMIC FAULTS

CHRISTIE ROWE, MCGILL UNIVERSITY

DEFINITION OF AN EARTHQUAKE

1. **Fast fault slip (~1 m/s) generates heat**

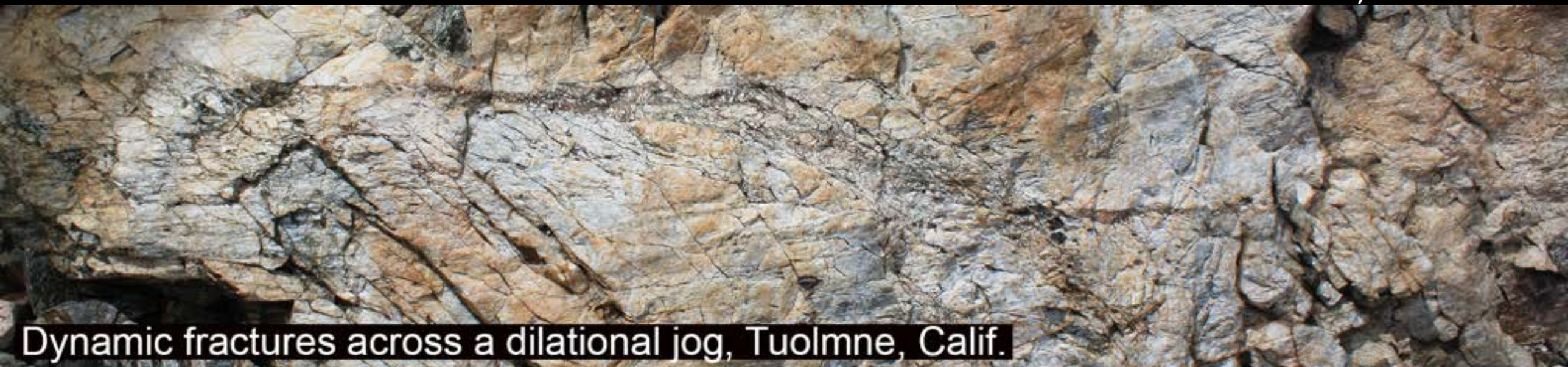
2. **Slip propagates dynamically (inertia is significant and stress can be transiently very high)**

3. Radiates short period seismic waves (10 Hz)

4. Stress drop (1-10 MPa) across all magnitudes

5. Initiation and cessation of rupture are controlled by stress conditions on the fault

Cowan, 1999 JSG



CO-SEISMIC HEATING FORMS PSEUDOTACHYLYTES

$$\Delta T = \frac{\tau_f v}{c_p \rho t_s}$$

- Faults get HOT if strong, fast
- Earthquakes = fastest fault motion
- deep = strong
- If temp reaches rock melting temp, layer of melt forms in fault

$$\text{temperature rise} = \frac{\text{shear stress * velocity}}{\text{heat capacity * density * thickness}}$$

Sibson, 1975

FIG. 3(a) and (b)

PSEUDOTACHYLYTES MARK EARTHQUAKE RUPTURE PLANES

- Record energy budget of earthquake slip
- Preserve geometry of co-seismic faulting
- Quenching and overprinting textures record fault healing

Pseudotachylyte veins, Glacier Lakes Shear Zone, Calif.

RARELY RECOGNIZED

- 90% of reported pseudotachylytes occur in light-coloured host rocks
- Most geologists have never seen in the wild - may not recognize or report

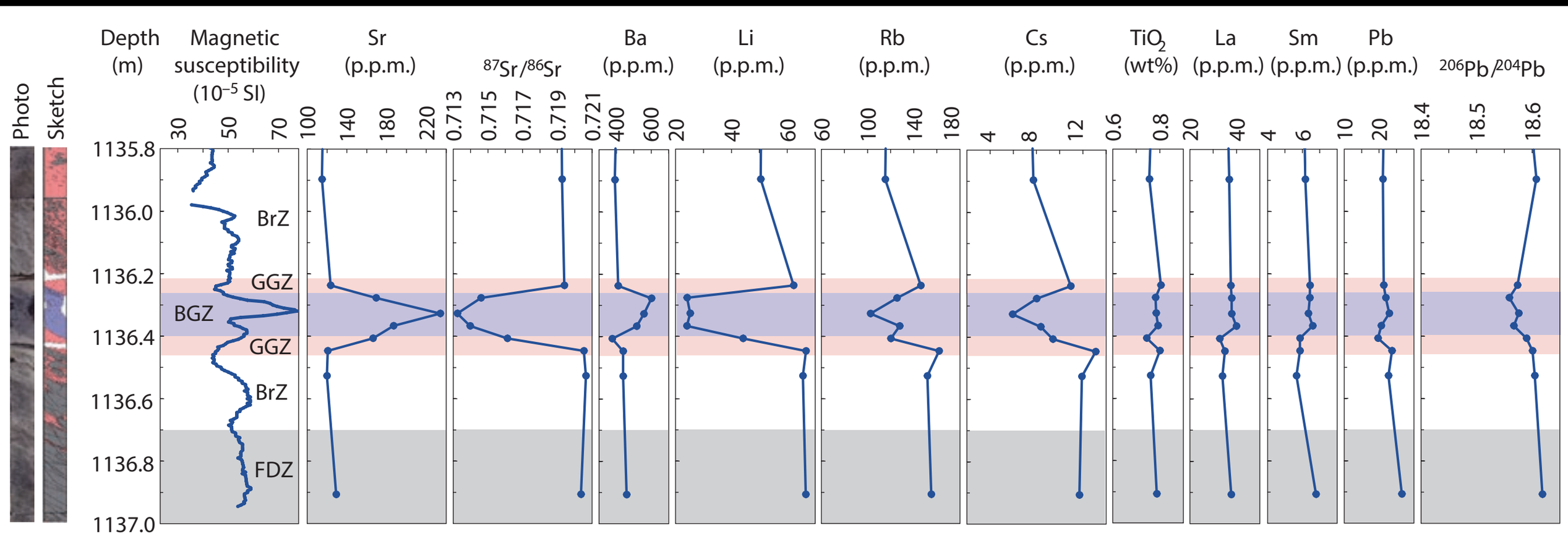
RARELY PRESERVED

- Pseudotachylytes quench to glass or fine-grained textures
- Easily hydrated (e.g. epidote alteration, right)
- Easily broken during post-seismic slip or creep
- Easily recrystallized back to metamorphic textures
- Preferentially mylonitize due to fine grain size

Price et al., 2012; Kirkpatrick & Rowe, 2013

Most earthquakes occur in ambient temps ~ 150-350°C.
Most rocks melt at 600-1000°C.
So, pseudotachylytes occur when dT ~300-800°C.

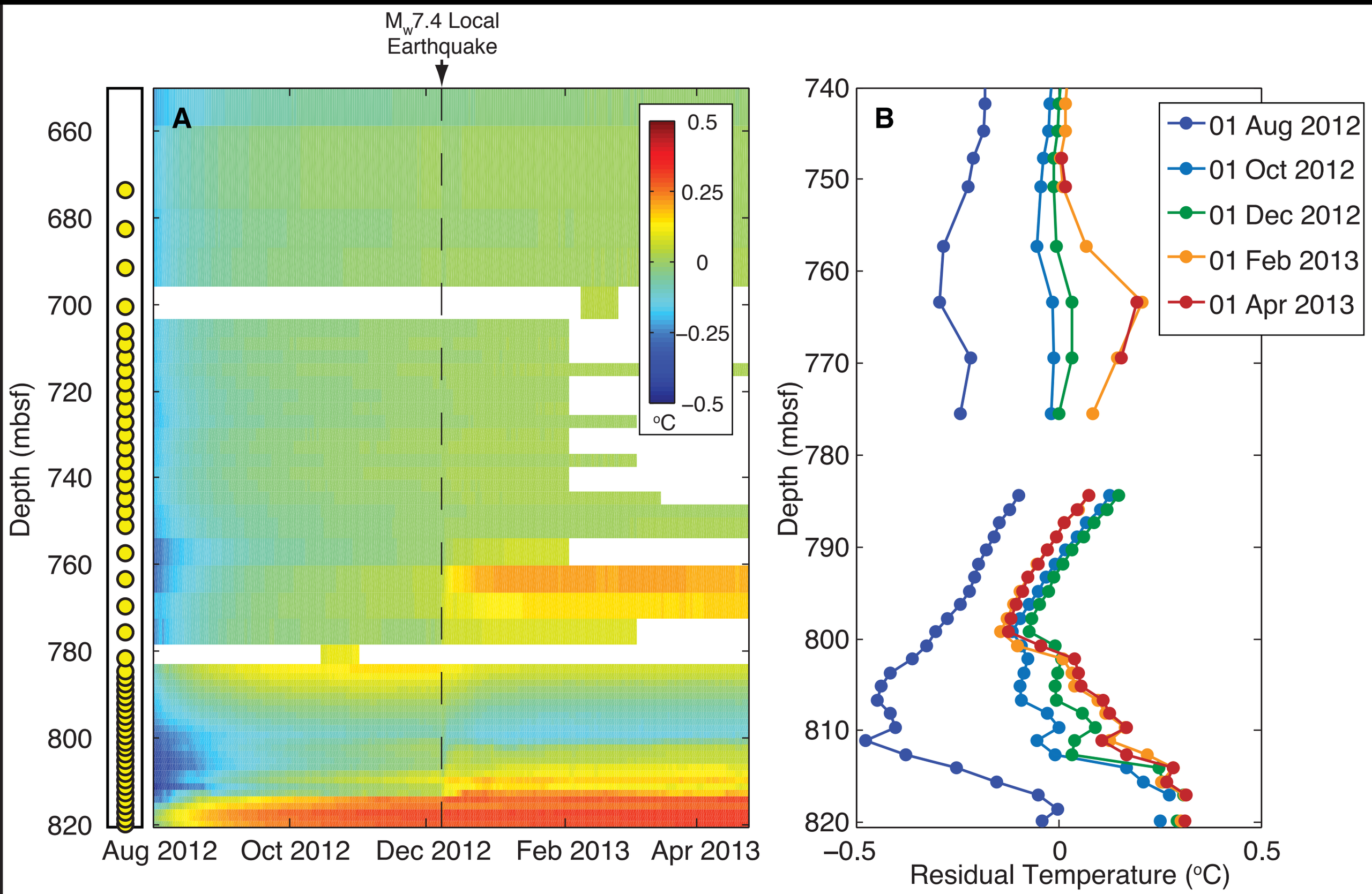
WHAT ABOUT COSEISMIC HEATING BELOW MELTING POINT?



Ishikawa et al., 2008

Temperature rise at JFAST borehole

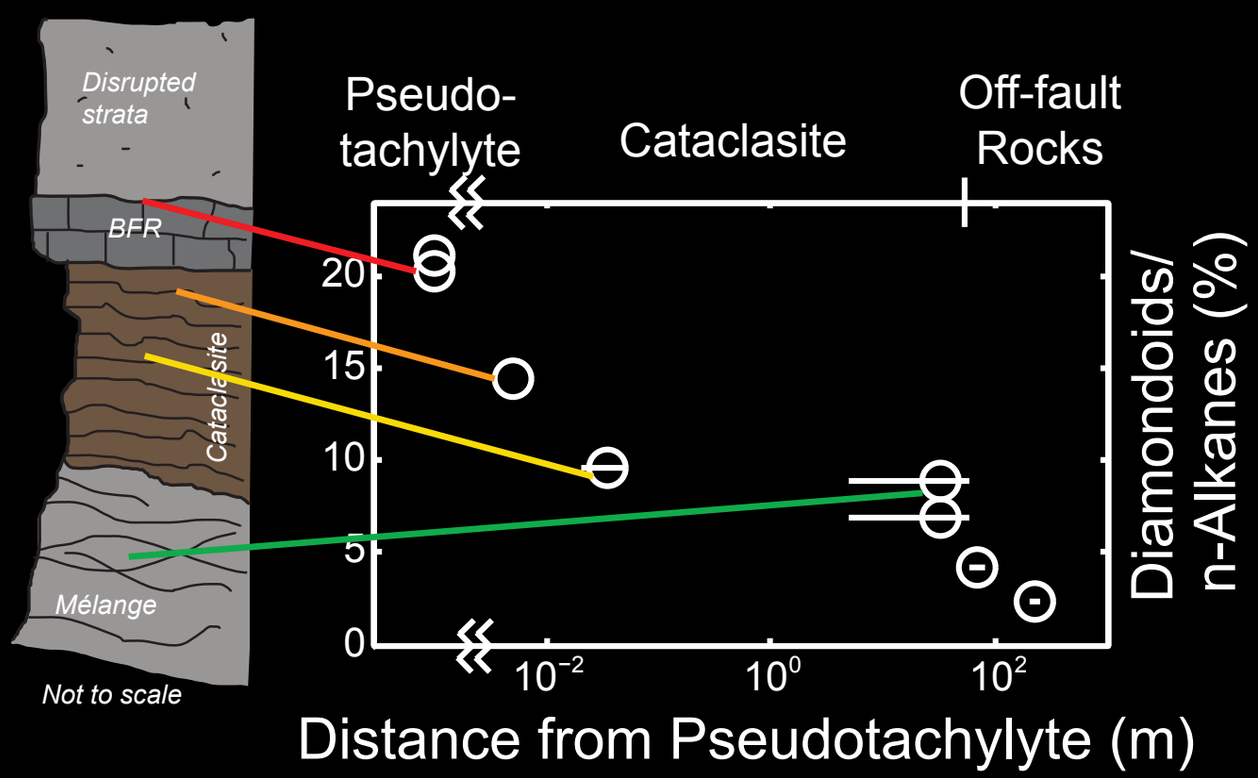
Fulton et al., 2013, Science

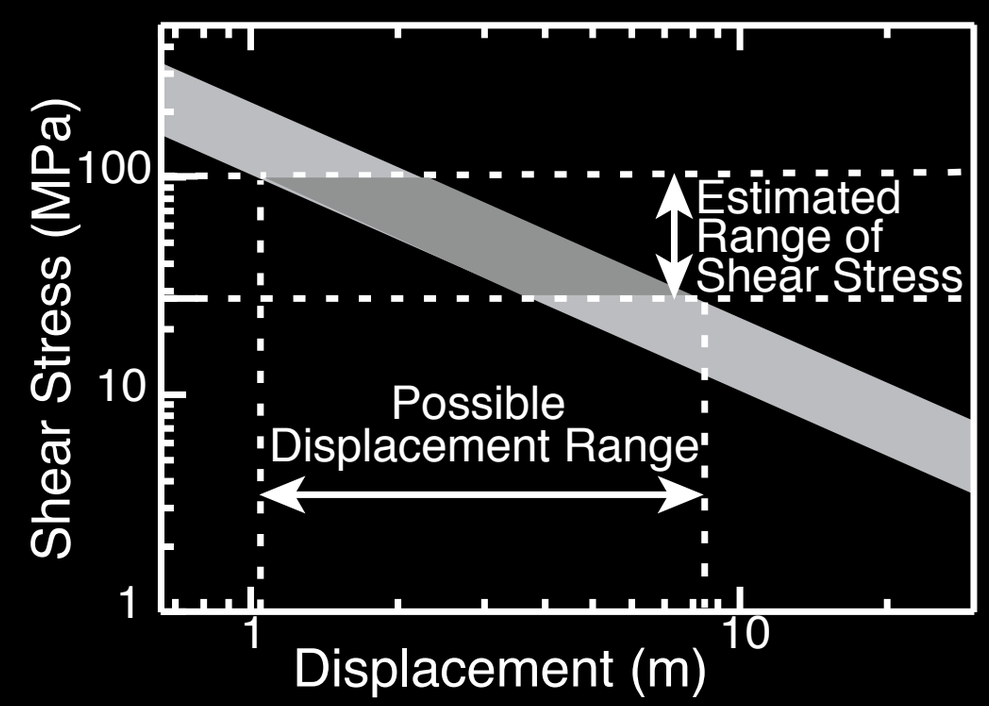


ORGANIC MOLECULE MATURITY

Sensitive to temp.

rise ~100-300°





Savage et al. 2014 Geology

SINCE 1999, ~13 INDICATORS OF CO-SEISMIC HEATING HAVE BEEN DESCRIBED

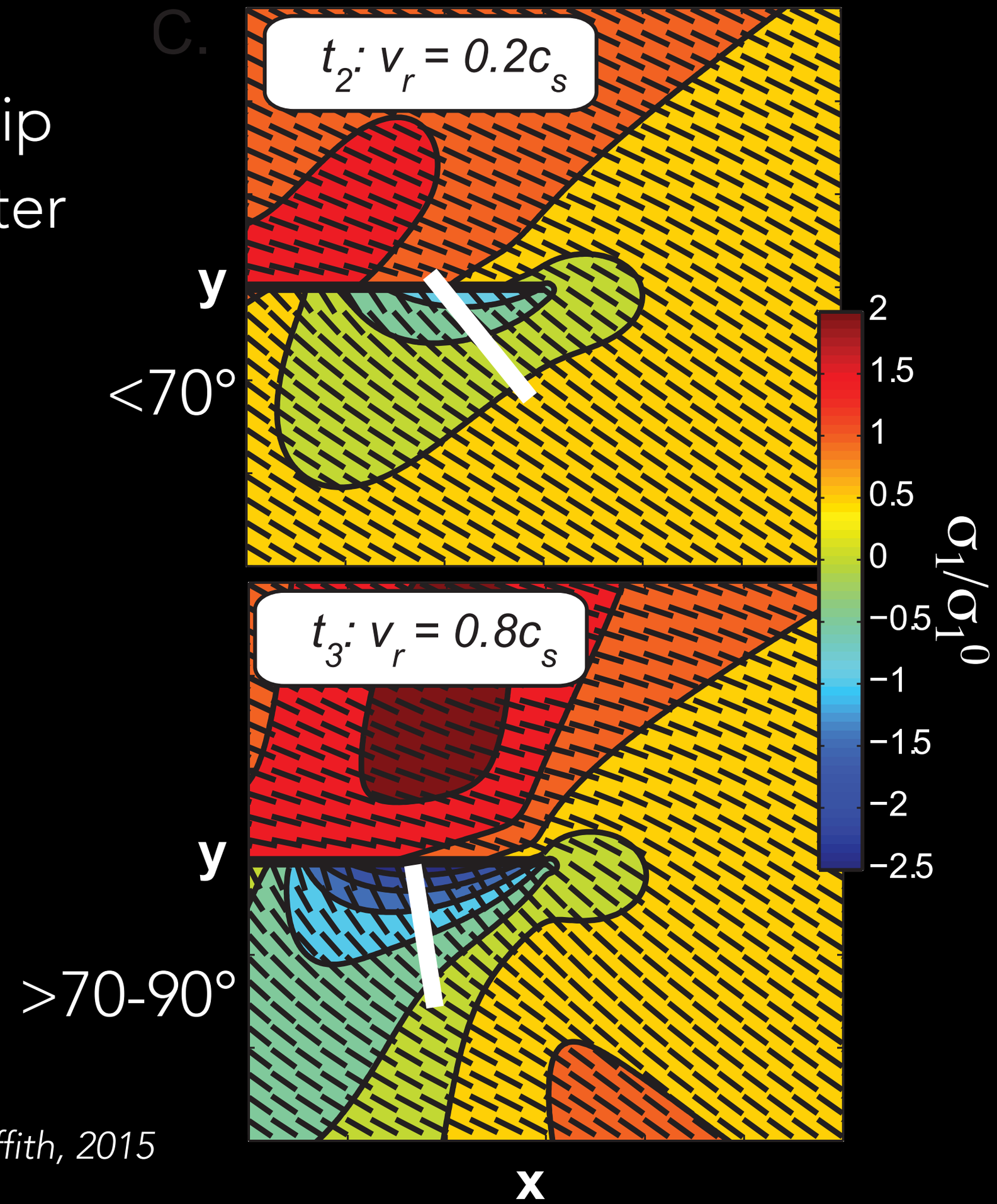
Table 1
Frictional heating proxies for peak temperatures below melt temperature. Sources:[1] Schleicher et al. (accepted),[2]Kameda et al. (2011),[3]Evans et al. (2014),[4]Ishikawa et al. (2008),[5]Mishima et al. (2006),[6]Collettini et al. (2013),[7]Grim and Bradley (1940),[8]Isambert et al. (2003),[9]McIntosh et al. (1990),[10]Sheppard et al. (2015),[11]Rabinowitz et al. (2014). Most or all of these reactions are Ahrrenius relationships where reaction progression depends upon time-temperature path, so time path has been roughly estimated based on heating rates on the order of 10s–100s °C/m.

Peak temp.	Mineralogy	Indicators
~250 °C	Smectite clay	Expulsion of interlayer water; resistance to re-hydration[1]
~250 °C	Smectite/chlorite interlayers, corrensite	Transformation of smectite to chlorite[2]
≥300 °C	Hematite fault veins	Reduction iridescence of hematite to magnetite transition[3]
≥200–350 °C	Any fault gouge	Trace element exchange (especially Li, Rb, Cs)[4]
~400 °C	Fe-bearing smectite clay	Breakdown of clay; formation of high magnetic susceptibility minerals such as magnetite[5] and amorphous remnants[6]
~350–600 °C	Illite	Loss of water and lattice collapse[7]
~400–600 °C	Sedimentary rocks	organic biomarker maturity[10,11]
≥480 °C	Siderite/ankerite	decarbonation[8]
~500 °C	Montmorillonite	Loss of water and lattice collapse[7]
~600 °C	Montmorillonite	melting, loss of crystal lattice[7]
~700–800 °C	Dolomite/dolostone	decarbonation[9]
~800–850 °C	Illite	melting, loss of crystal lattice[7]
~800–900 °C	Calcite/limestone	decarbonation[9]

Not Just Pseudotachylyte!

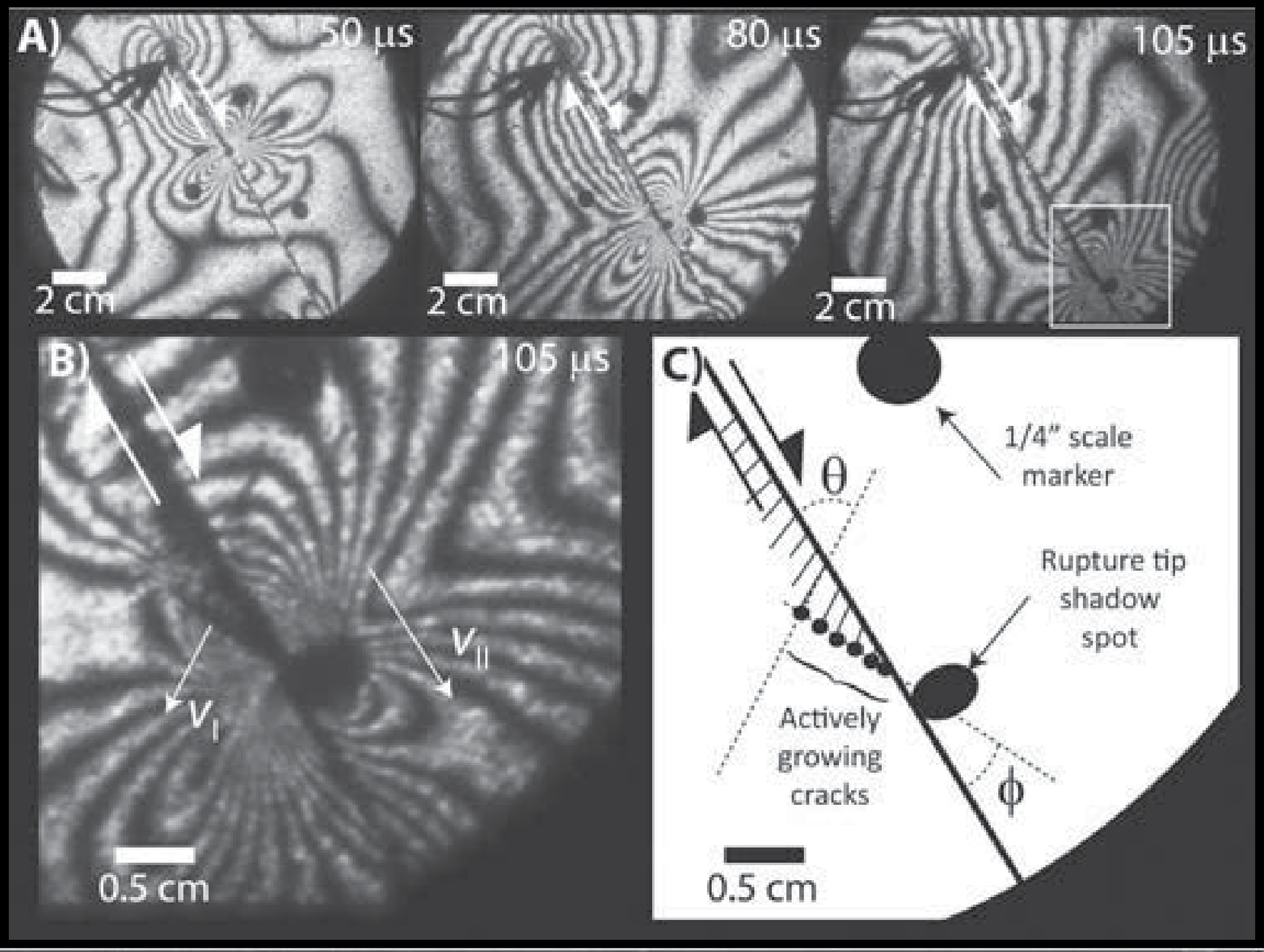
Stress at rupture tip increases with faster rupture

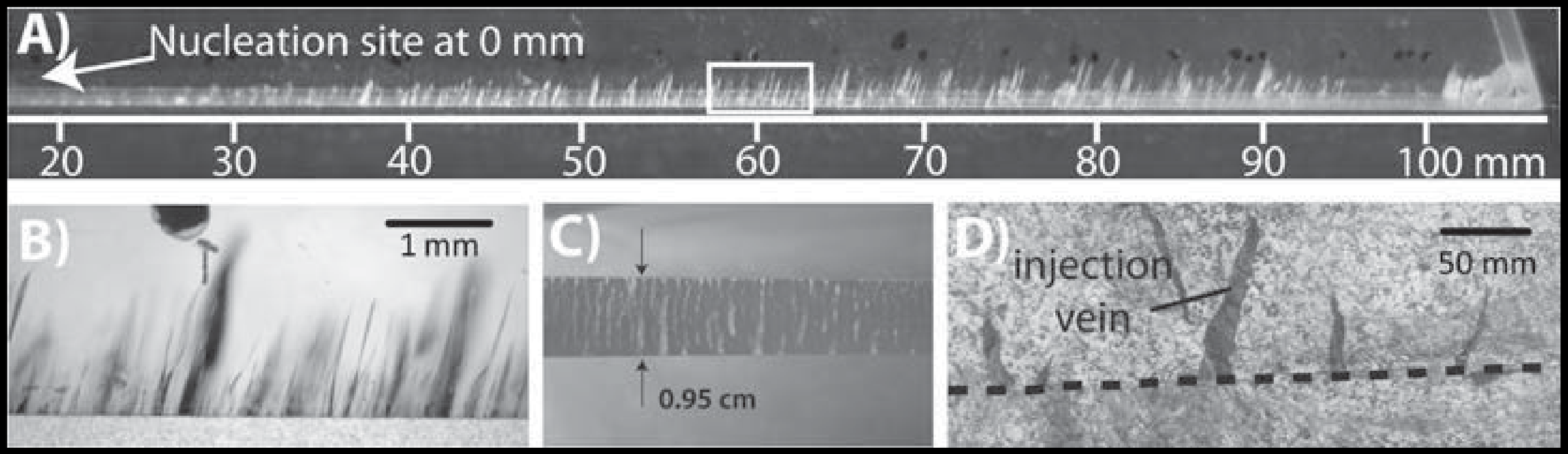
Stressing RATE comparable to propagation rate



Di Toro et al., 2005; Rowe & Griffith, 2015

Closely spaced tensile cracks on one side of the fault

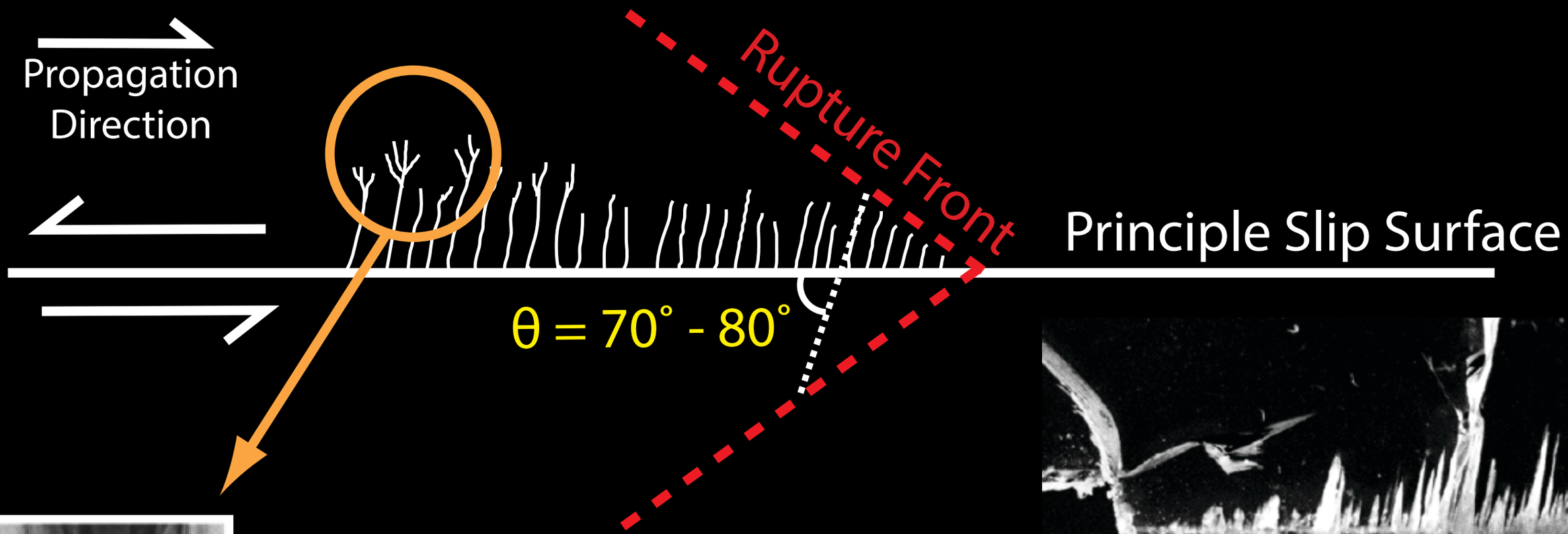




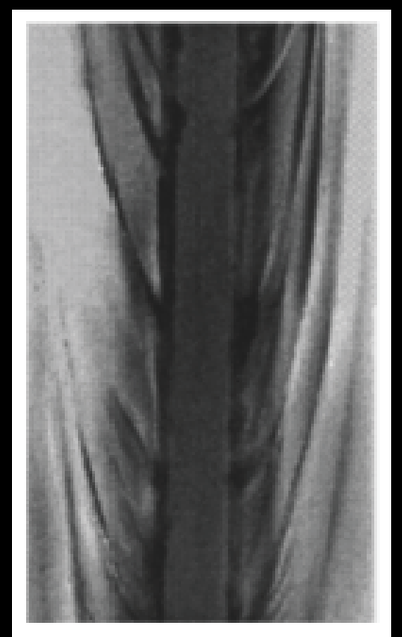
Griffith et al. 2009

DYNAMIC FRACTURING:

TWO SIGNATURE PATTERNS



Griffith et al., 2009
Rosakis, 2002



Sharon and Fineberg, 1996

0.25 mm

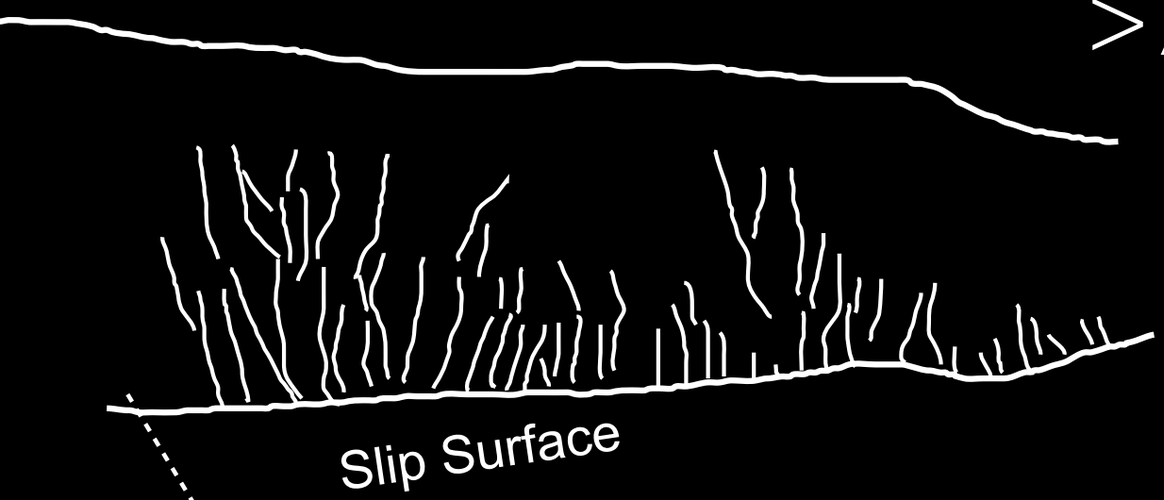
Melosh et al. 2014

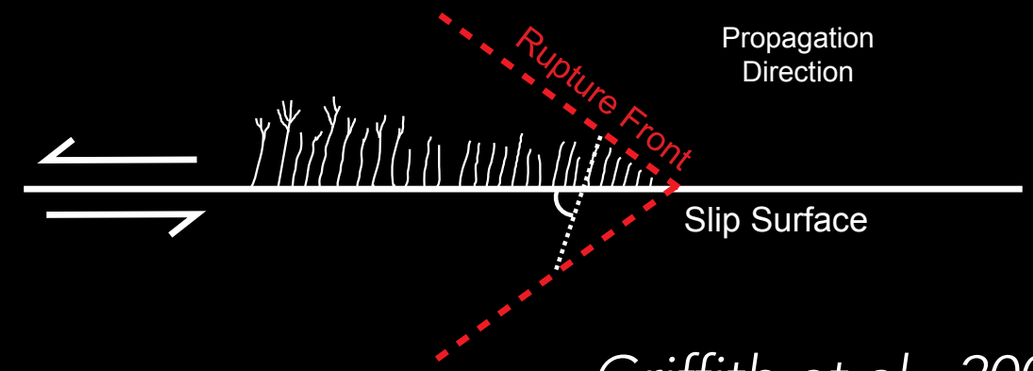
POFADDER SHEAR ZONE, S.AFRICA-NAMIBIA

Paul Macey, Conrad Groenwald, Chris Lambert (SA-CGS), Jodie Miller, Dey Cisneros Lazaro (Stellenbosch), Chris Gerbi (U. Maine)

Ben Melosh, Erik Young, *Noah Phillips, Jamie Kirkpatrick (McGill U.)*

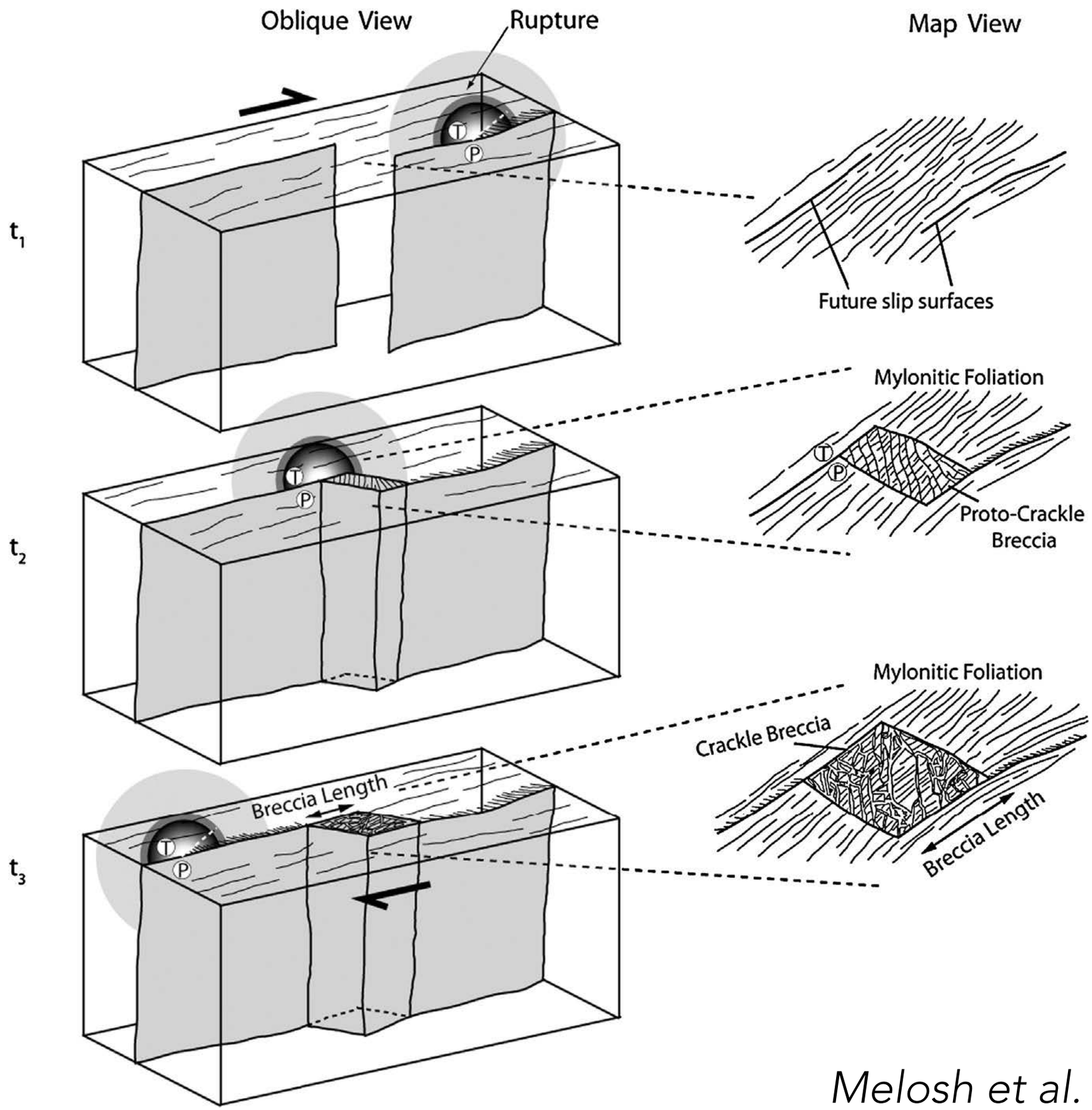
>70-90°



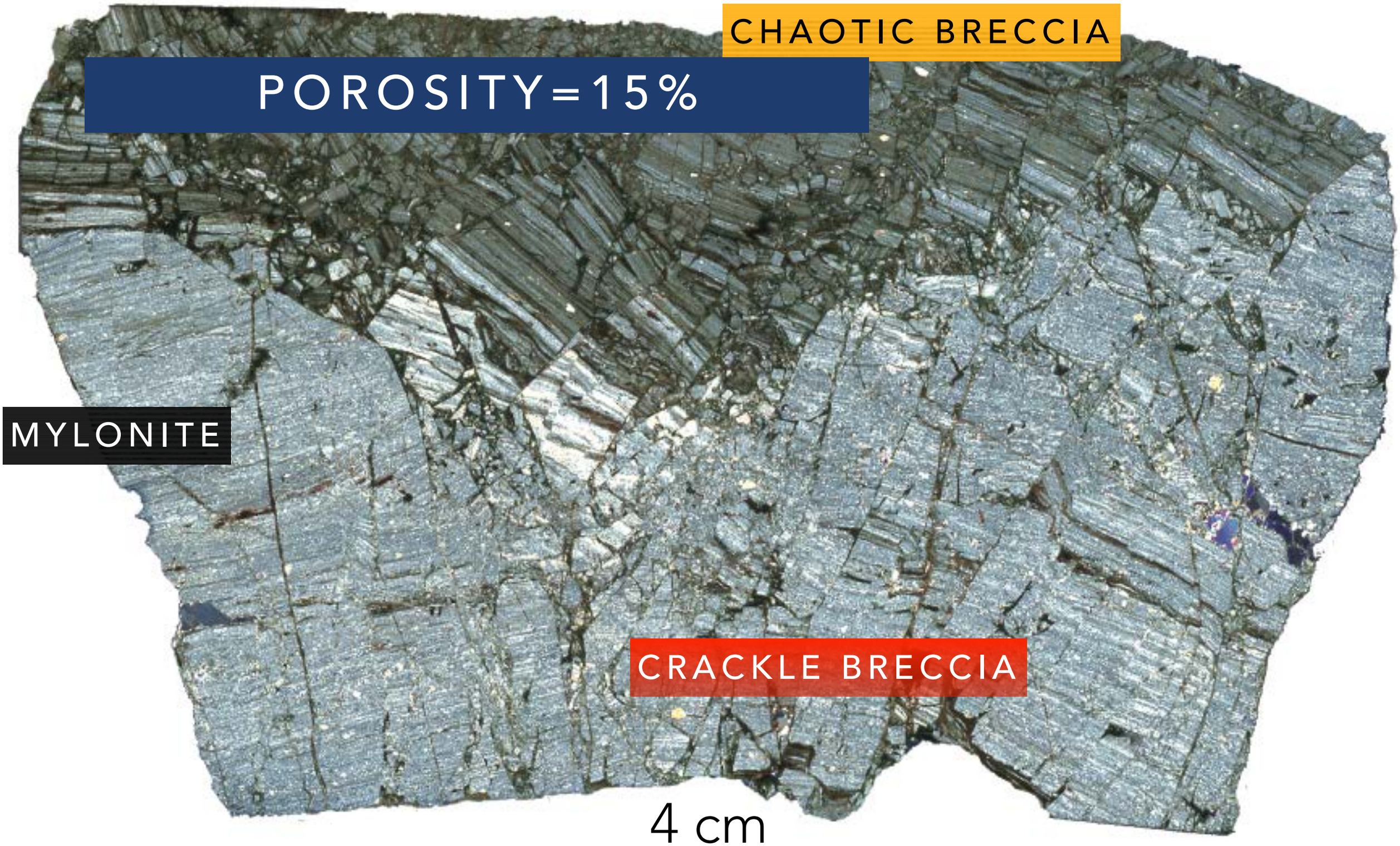


Griffith et al., 2009
Rosakis, 2002

Melosh et al. 2014
Melosh et al. 2016

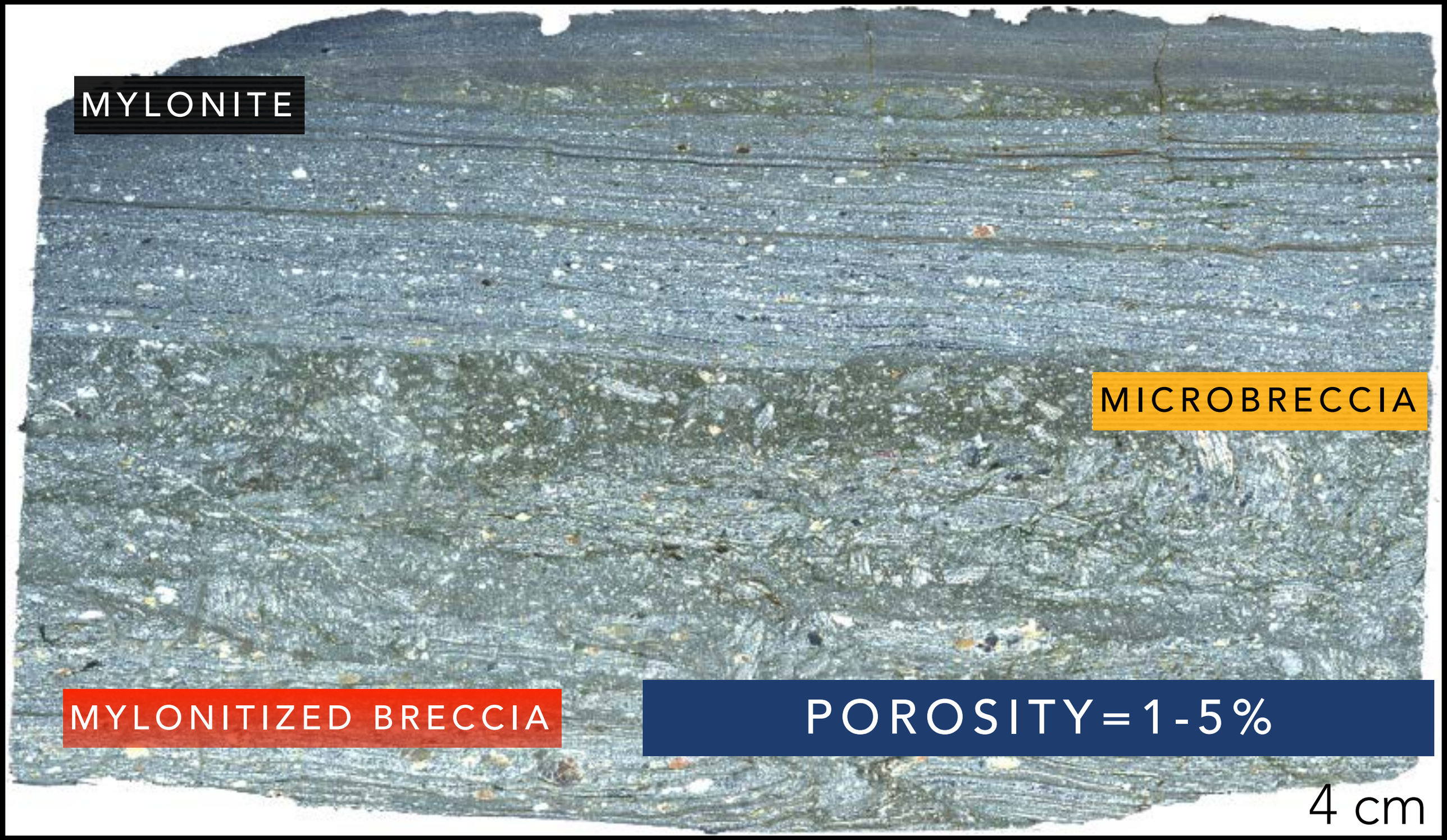


Melosh et al. 2014 EPSL



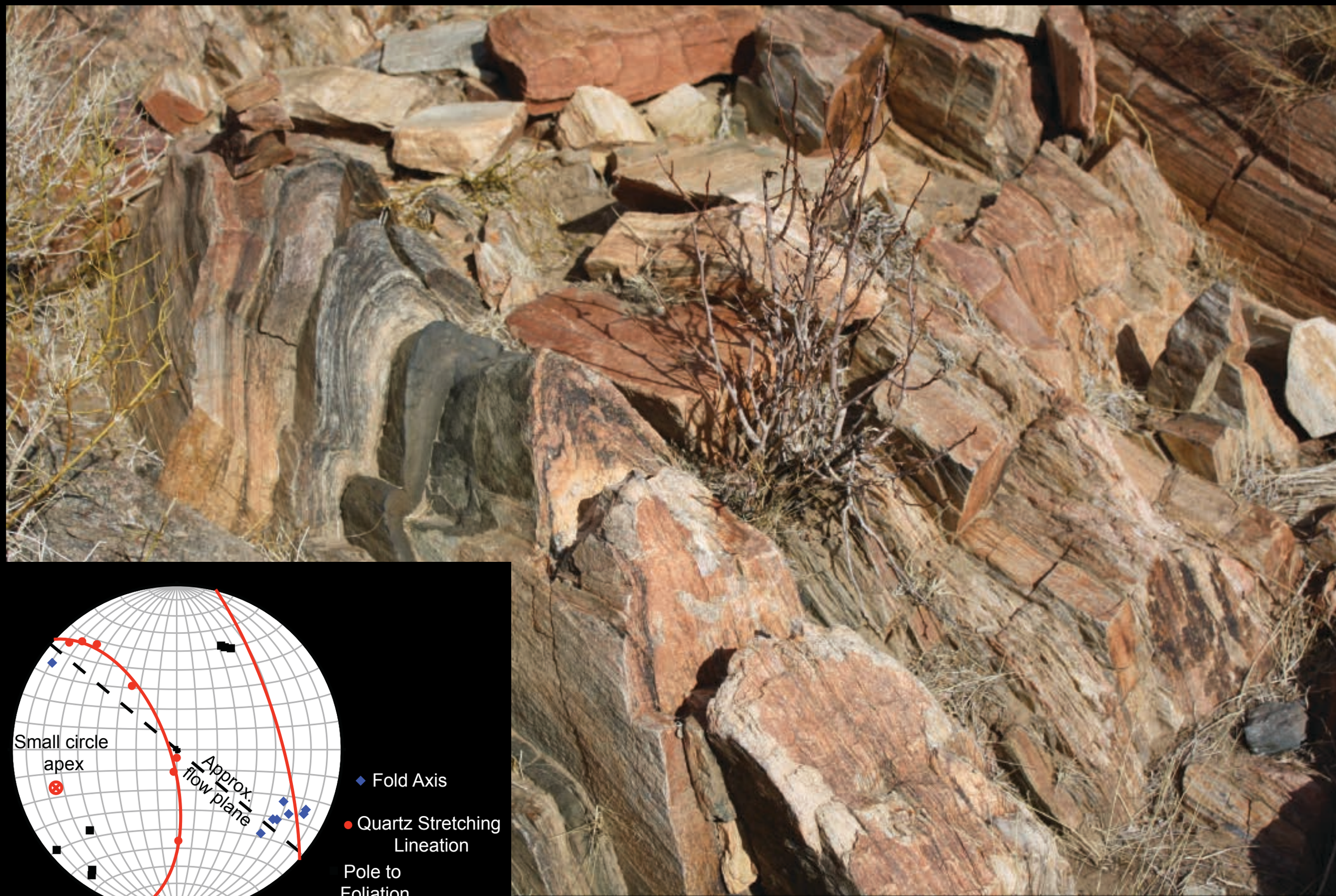
PS194

Melosh et al., 2016 JSG

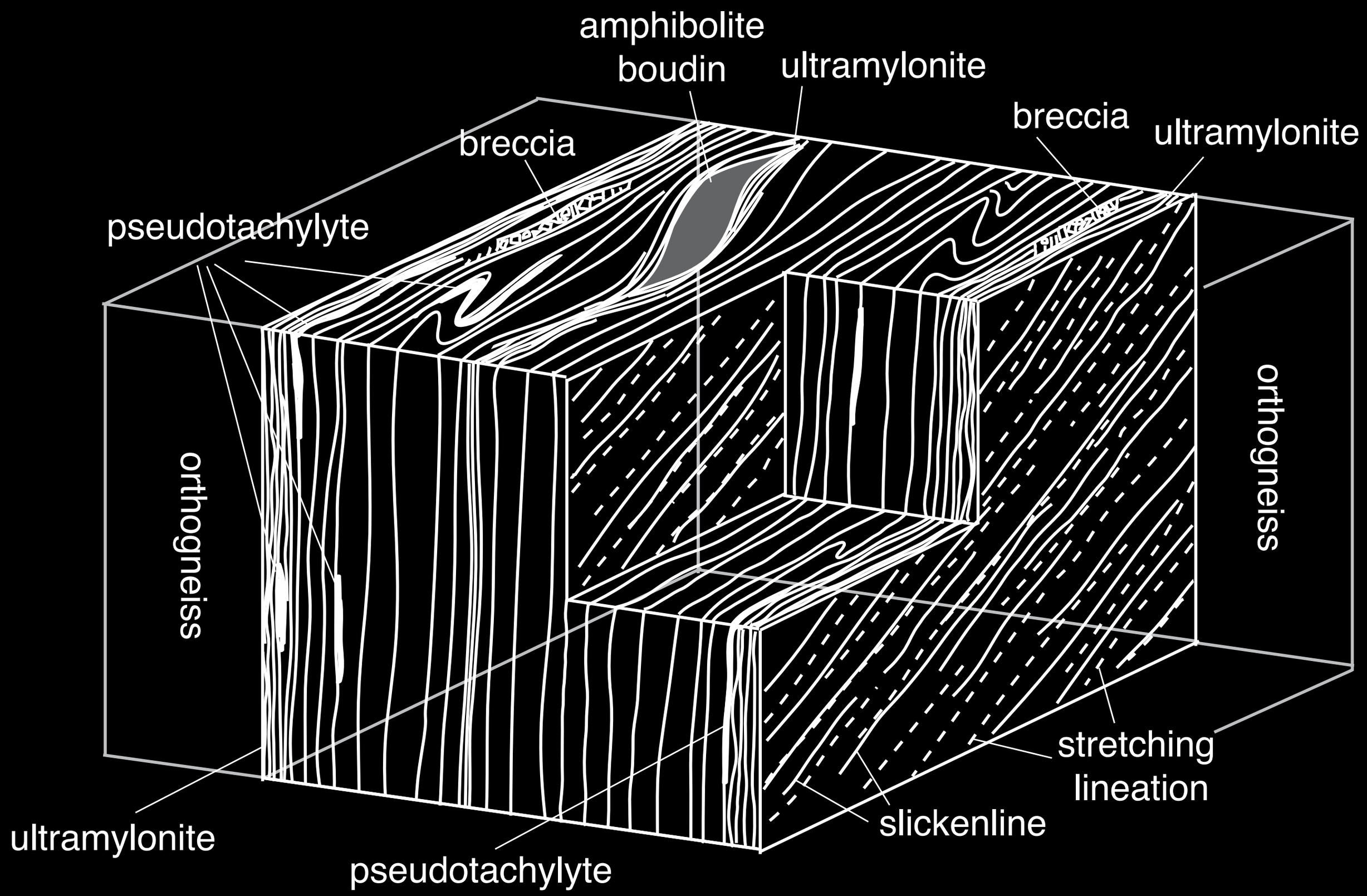


PS196

Melosh et al., 2016 JSG



Melosh et al. (submission imminent, I am told)


amphibolite
boudin
ultramylonite
breccia
breccia
ultramylonite
pseudotachylyte
orthogneiss
orthogneiss
stretching
lineation
slickenline
ultramylonite
pseudotachylyte

BRECCIATION-HEALING CYCLES

- Porous pathways along faults - preferential sites of post-seismic creep/healing?
- Rupture planes rarely reused / or / don’t persist very long in terms of earthquake cycles
- Folding of slip planes caused by viscosity gradients expected in banded rock - probably common.

TAKE AWAY THOUGHTS

- ✓ Signatures of frictional heating are common
- ✓ Structures recording dynamic stress around faults also record seismic slip
- ✓ Slip surfaces are reused, but not too many times (prevented by pseudotachylyte welding, folding, mylonitization)
- ✓ Rock record can reveal aspects of earthquake slip (geometry, mechanisms of deformation, and energy) which seismology cannot