How do rocks fail? Strain localization and microstructural transformations in the earthquake cycle

Matěj Peč

In collaboration with:

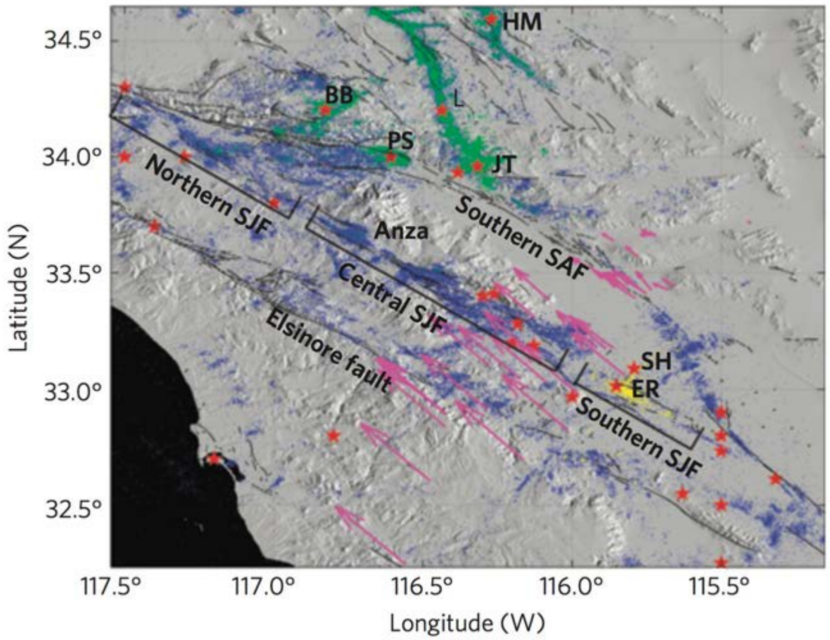
Daniel Ortega-Arroyo[1], Hoagy O'Ghaffari[1], Camilla Cattania[1], Hongyu Sun[1], Saleh Al Nasser[1] Sofia Cubillos[1], Roger Fu[2], Zheng Gong[2] ,Oliver Plümper[3], Markus Ohl[3],Holger Stünitz[4], Renée Heilbronner[4]

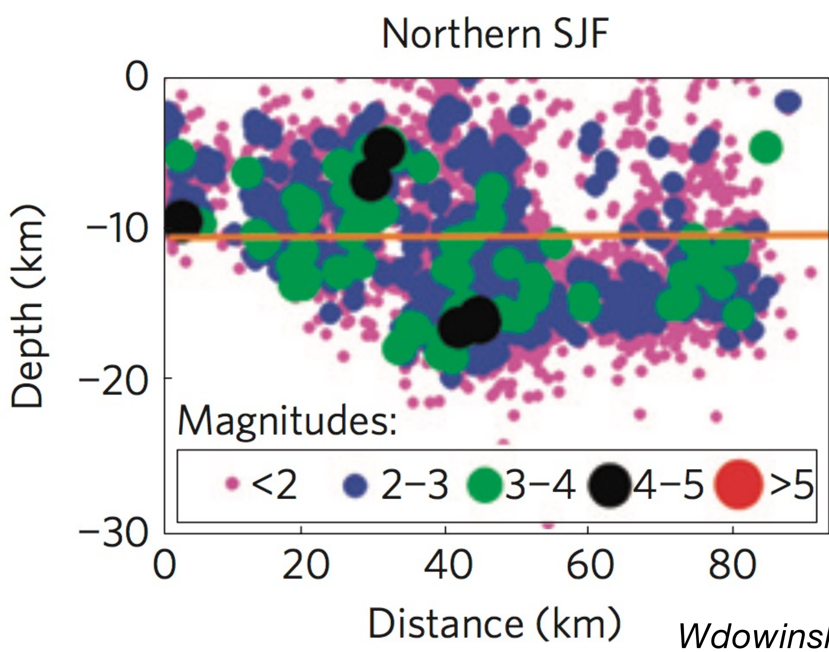
[1]: MIT, Department of Earth, Atmospheric and Planetary Sciences
[2]: Harvard University, Department of Earth and Planetary Sciences
[3]: Utrecht University, Department of Earth and Planetary Sciences
[4]: Universität Basel, Geosciences

Excite Network

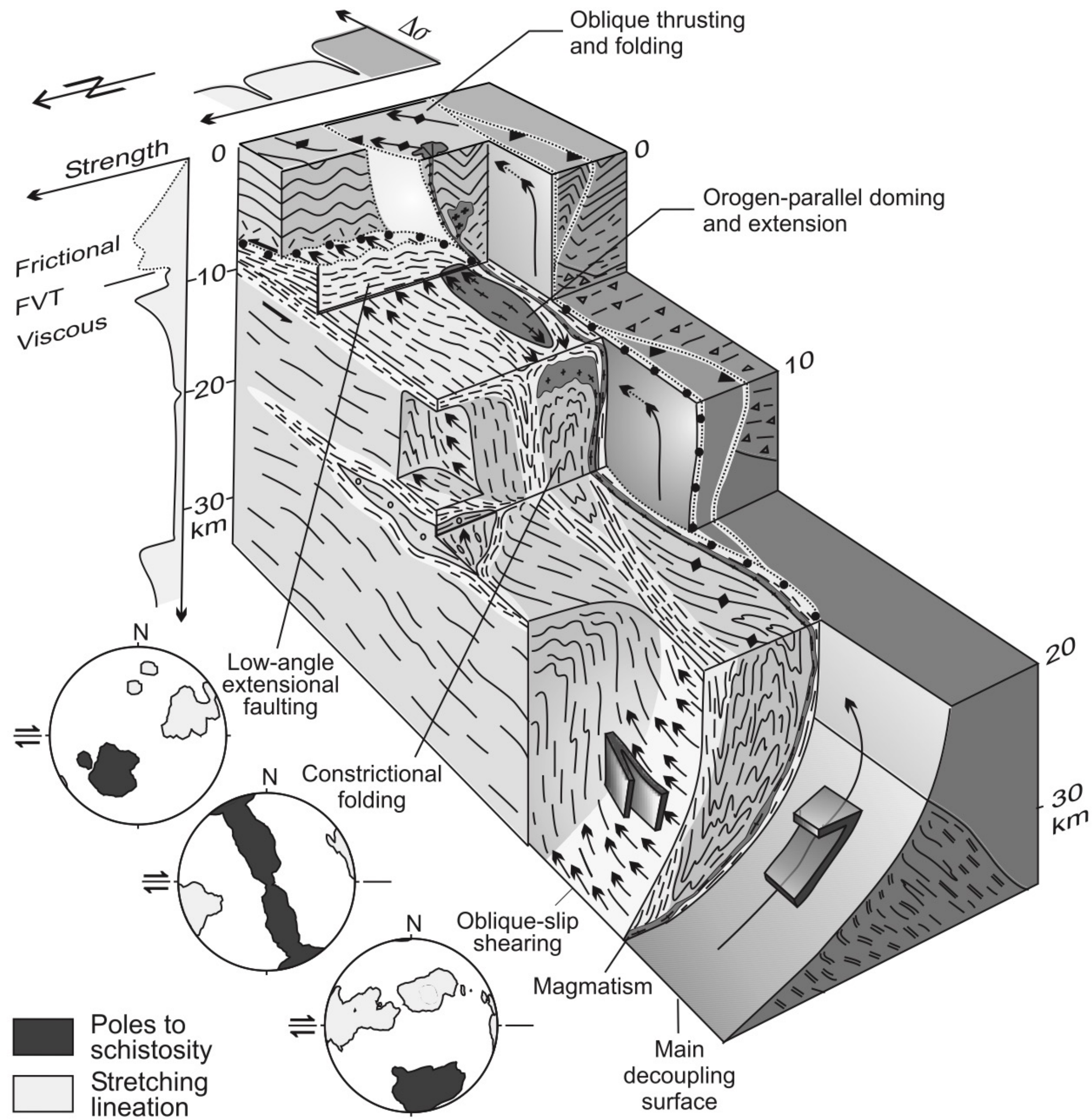
Funded by the European Union

Fault Zones





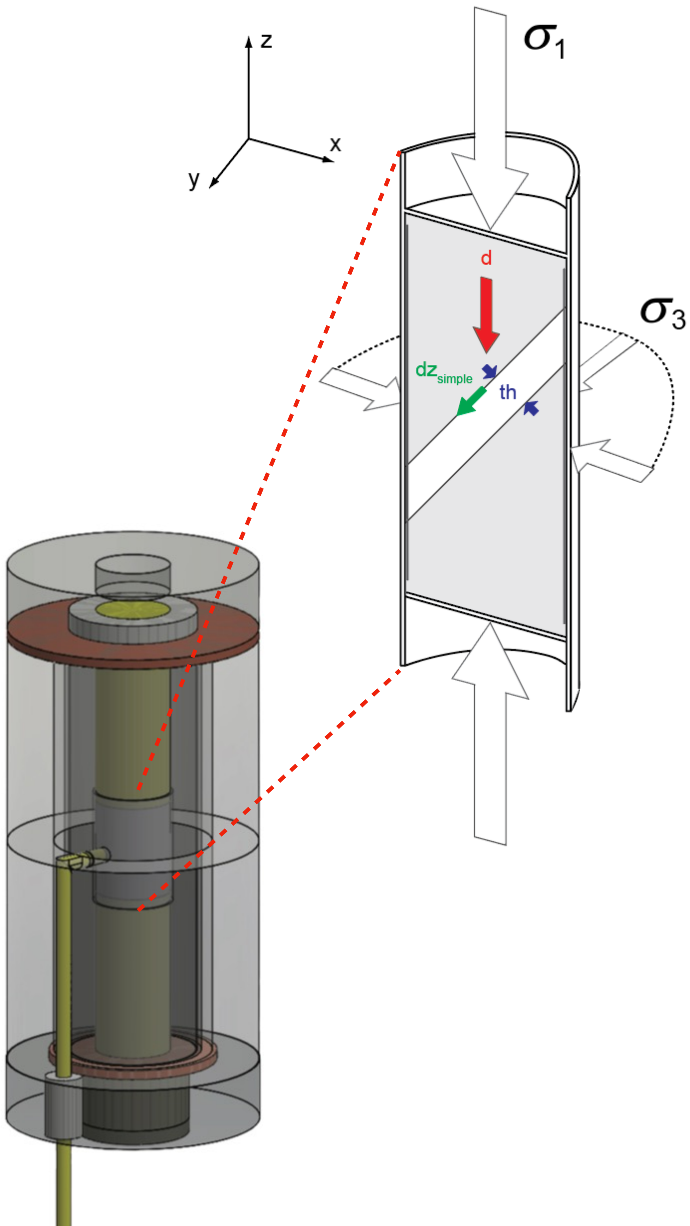
Wdowinski 2009



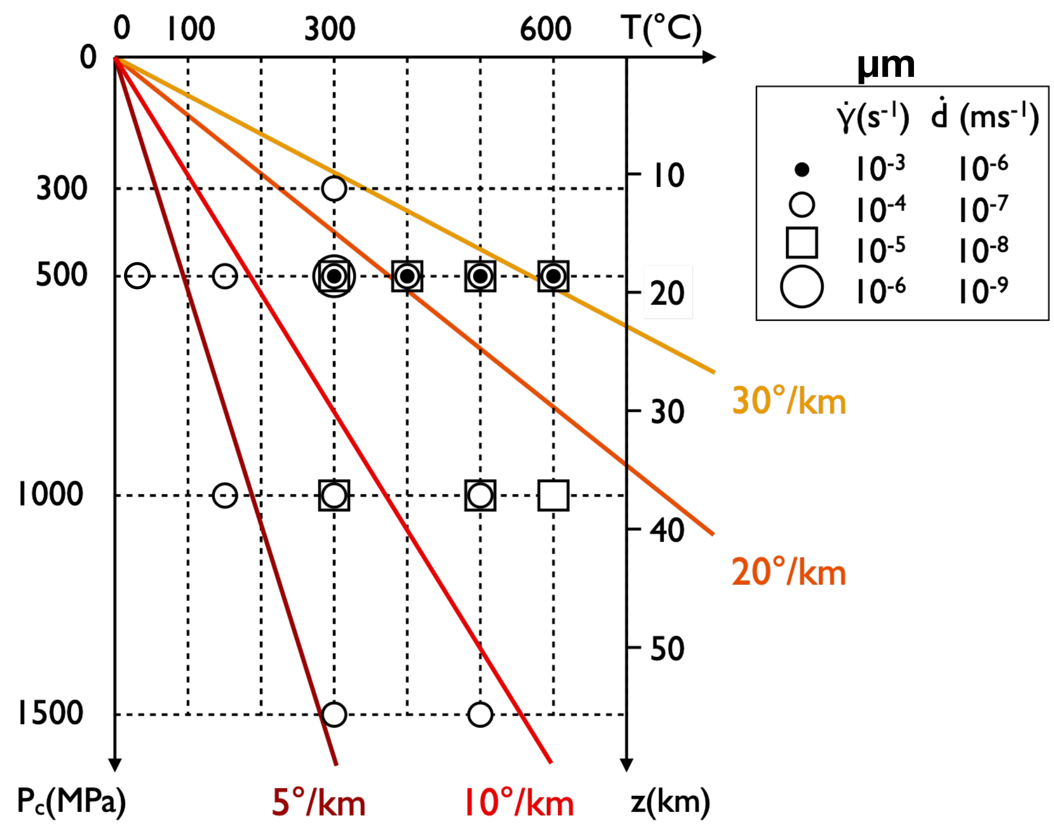
Handy, Hirth, Bürgmann 2007

Experiments on cataclasites

- **Verzasca gneiss granitoid**
  - ~ 37% **Qtz**, 33% **Plg**, 28% **Kfs**, 2% **micas**
  - Initial grain size, **d ≤ 200 μm, 0.2 wt% H_2O** added
  - Newest additions: **AE** monitoring, **local T** measurements

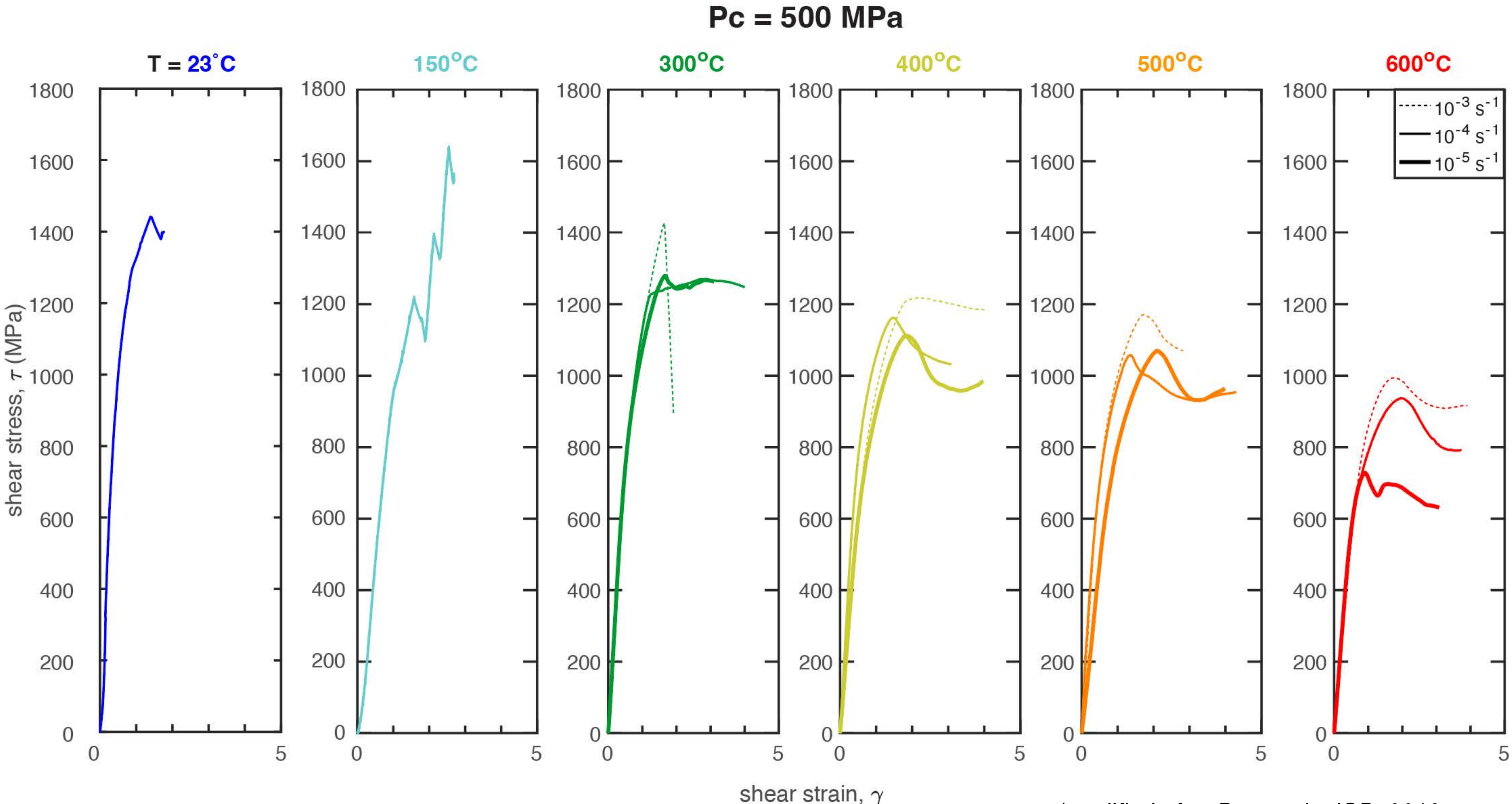


Modified after Précigout et al. 2018



(modified after *Pec et al., JGR, 2016)*

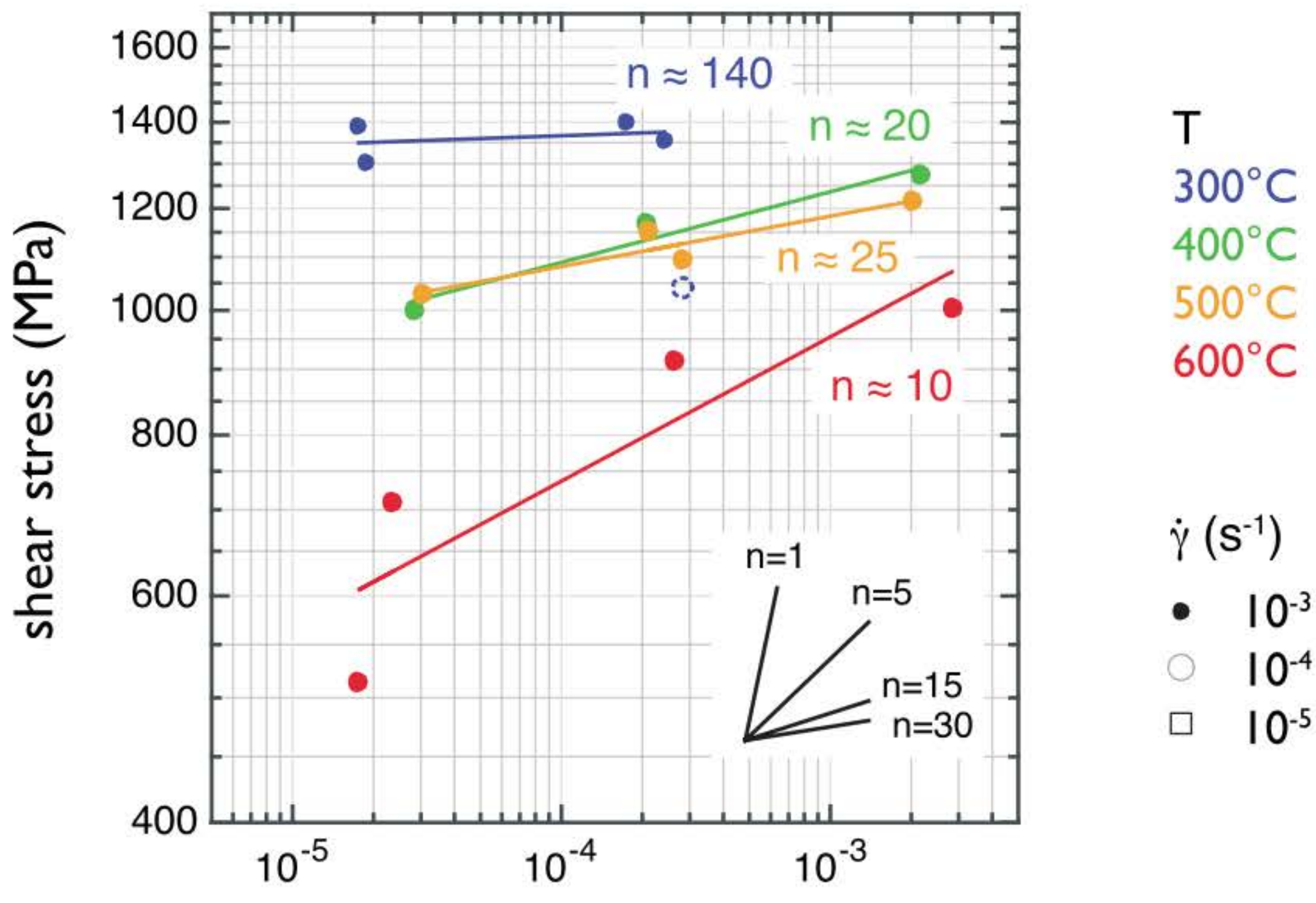
Mechanical Data



(modified after *Pec et al., JGR, 2016*
& Ortega - Arroyo et al., AGU Advances 2025)

- Transition from **stick-slip** to **slow slip** with **increasing T** and **decreasing rate**
- **Weak temperature & rate** dependence

Mechanical Data



(a)

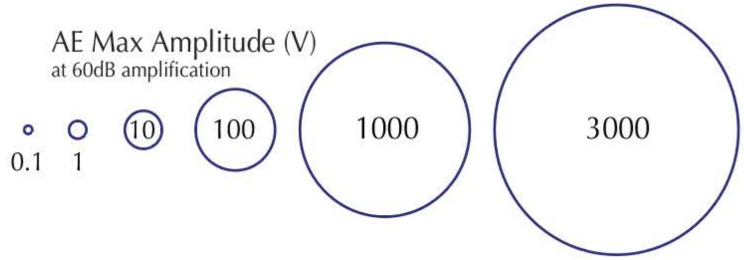
$$\dot{\varepsilon} = A\,\sigma^{n} exp\left(\frac{-Q}{RT}\right)$$

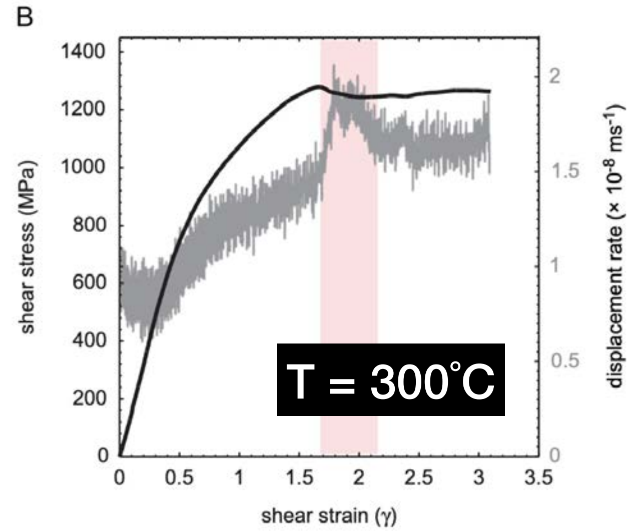
(Pec et al., JGR, 2016)

- Stress exponent **decreases** with **increasing T**

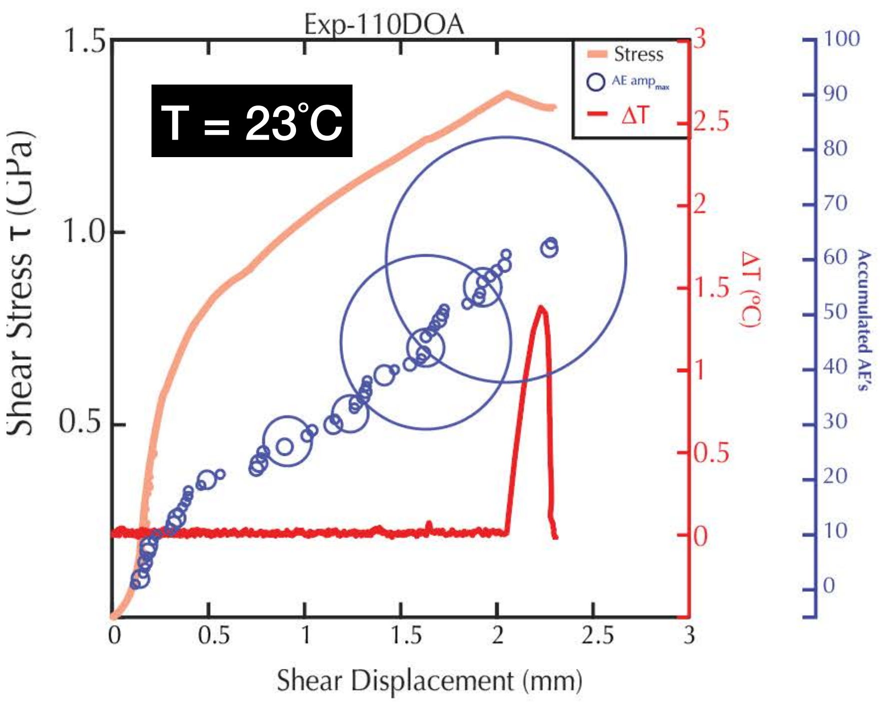
Labquakes & slow slip

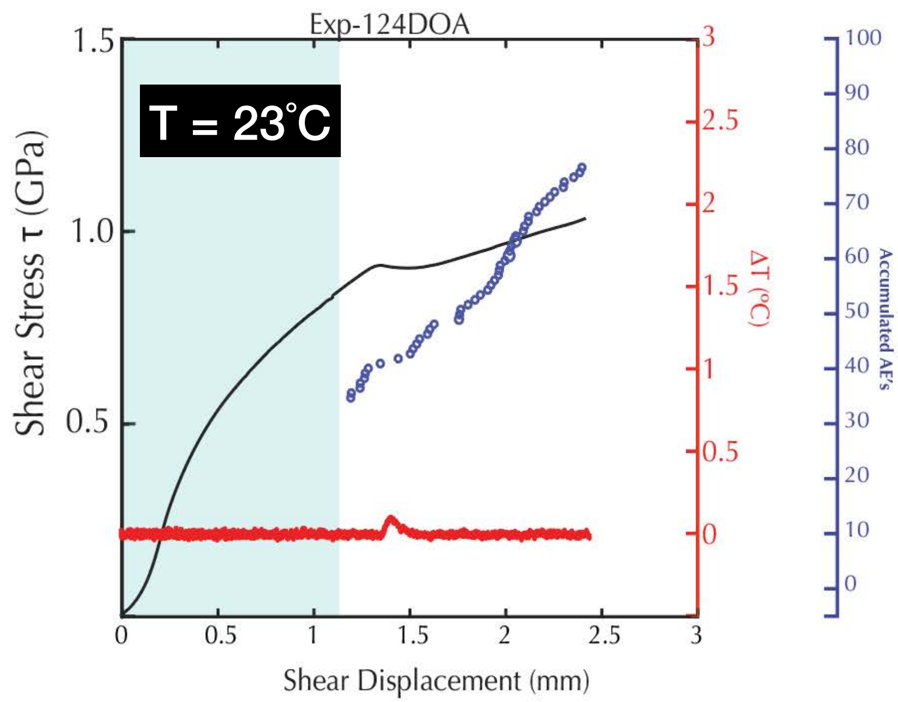
- **Abrupt failure** is accompanied by **rapid acceleration**, **T spikes** & **audible AE**
- **Slow weakening** is accompanied by **modest acceleration**, **smaller** and **longer duration T** transients





Pec et al. 2012, EPSL

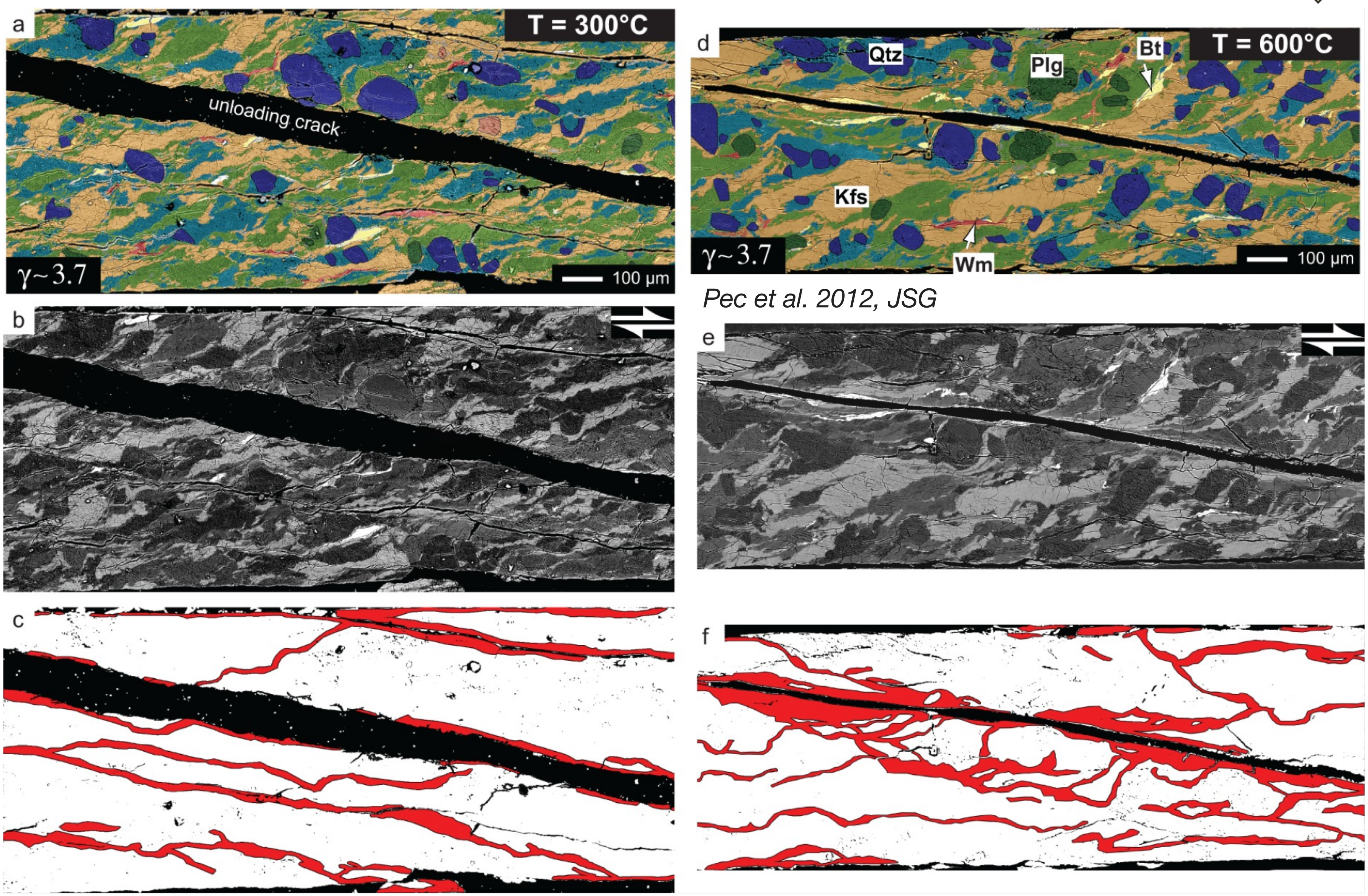




Ortega-Arroyo et al., 2025, AGU Advances & in prep.

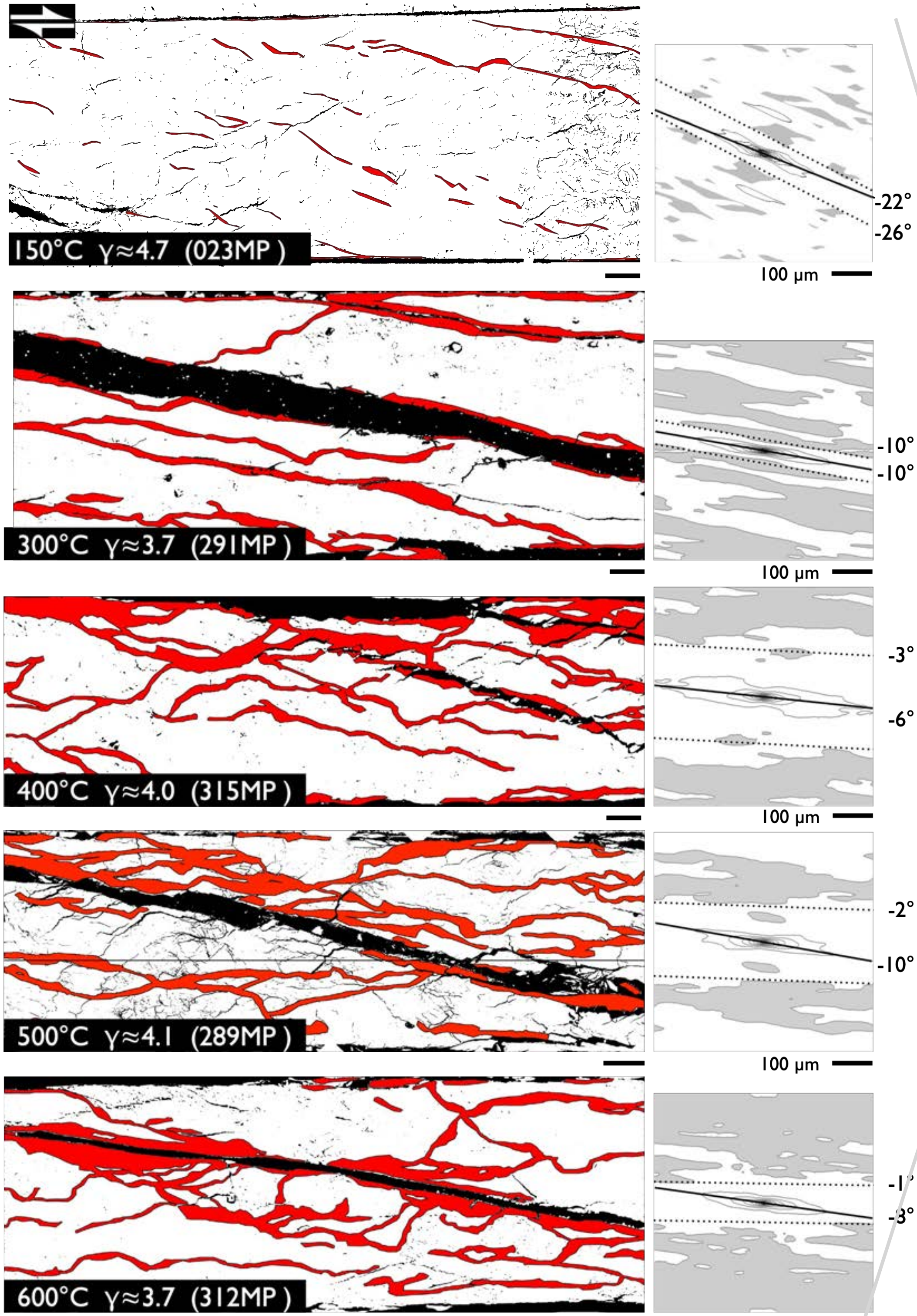
Microstructures

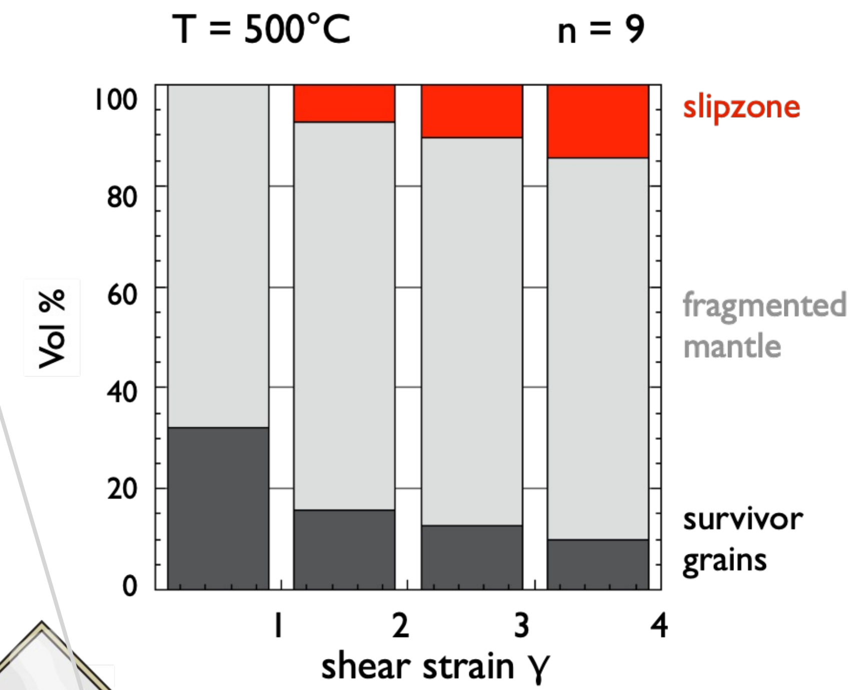
- Localization into **S-C-C'** structures

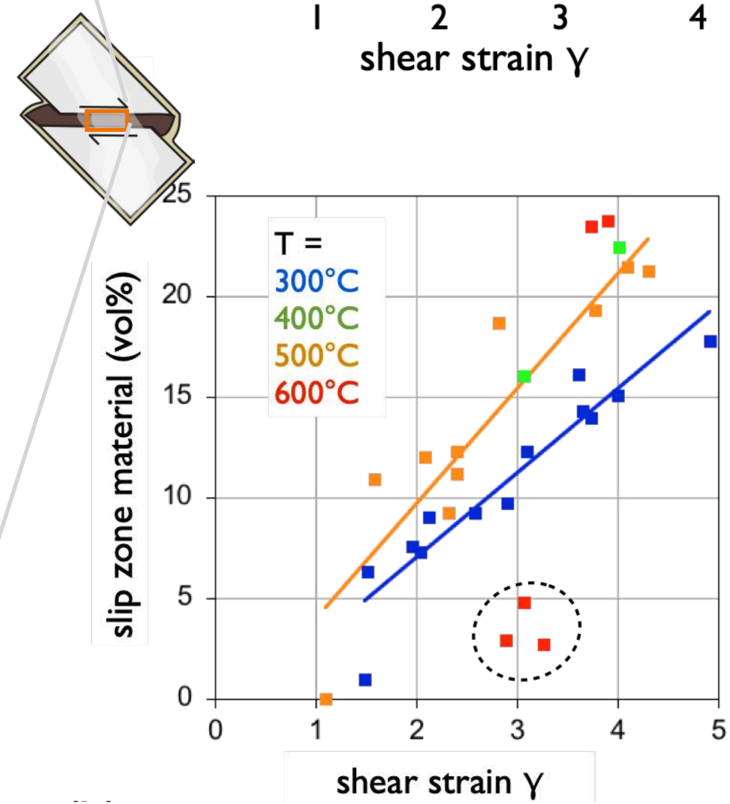


Pec et al. 2012, JSG

- Pc ~500 MPa, γ ~ 3.7, $\dot{\gamma}$ ~10^{-4} s^{-1}



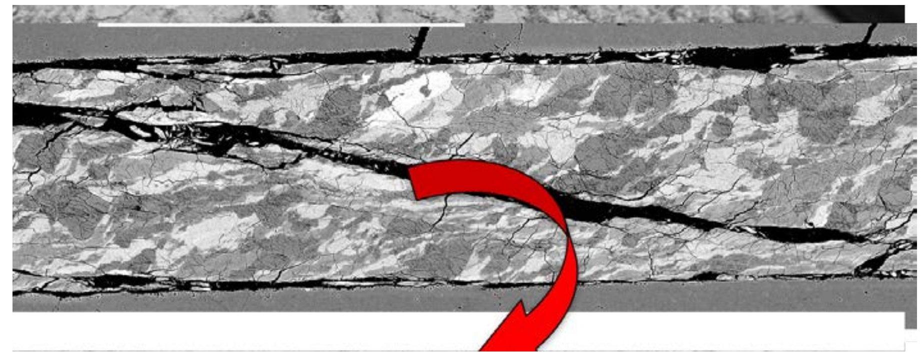


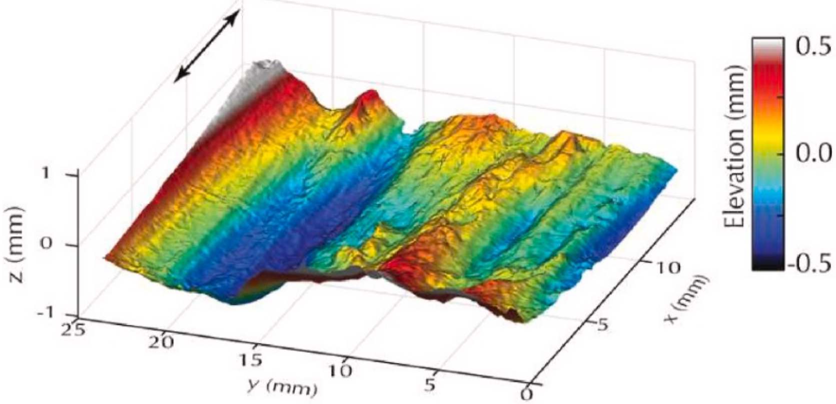


(Pec et al., JGR, 2016)

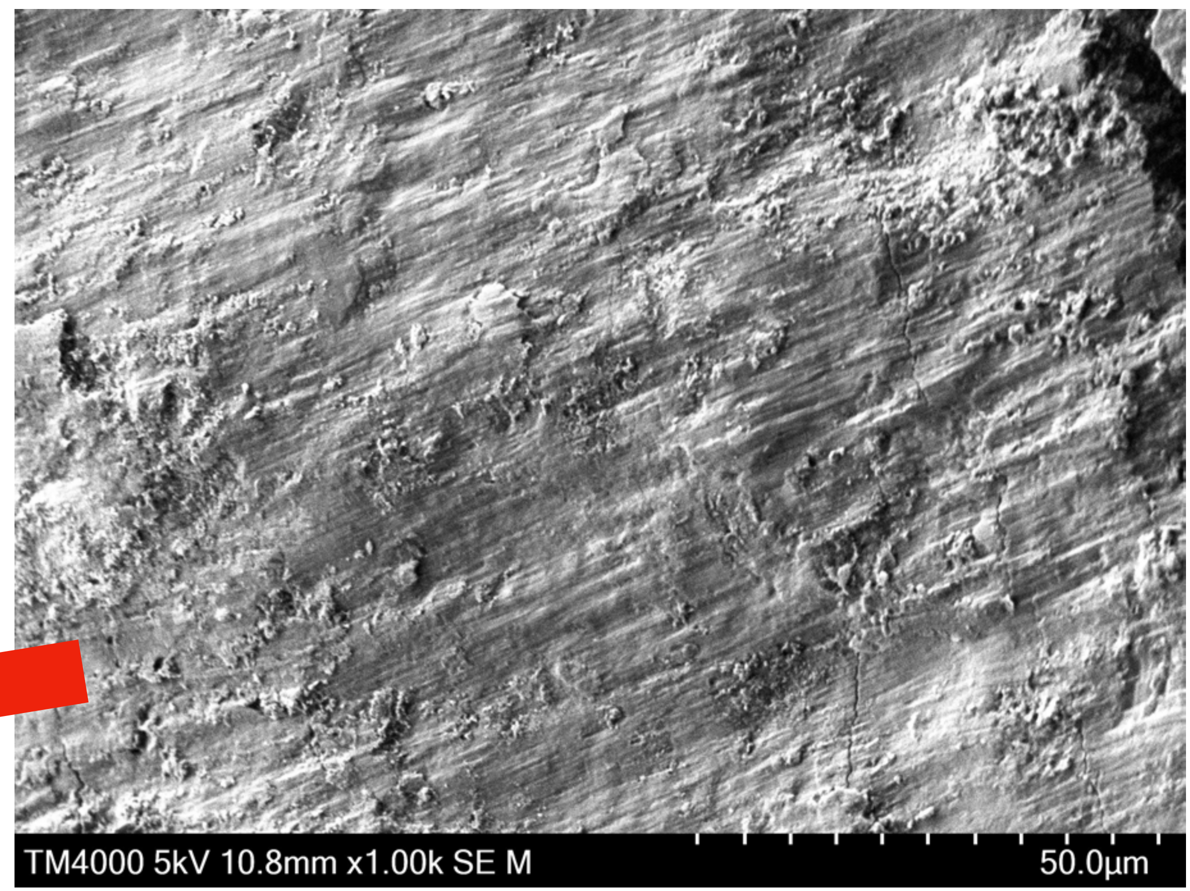
Microstructures

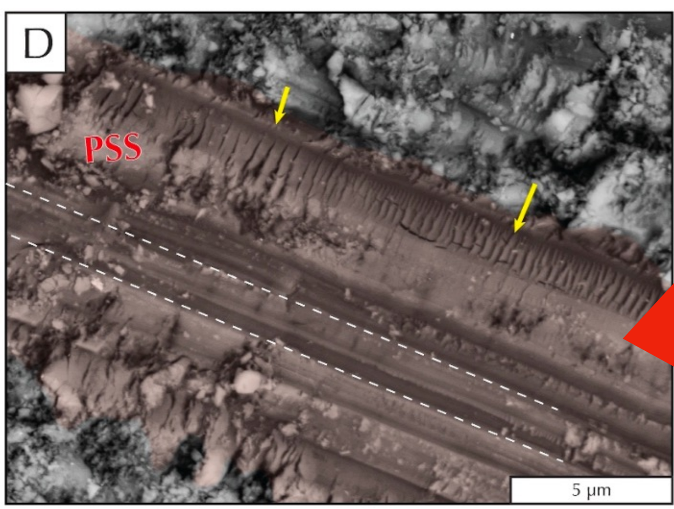
- Unloading cracks **exploit** the **slip zones** and expose a **“fault surface”**
- Qualitatively similar to **slickensides** observed in nature





Ortega-Arroyo & Peč 2023, JSG

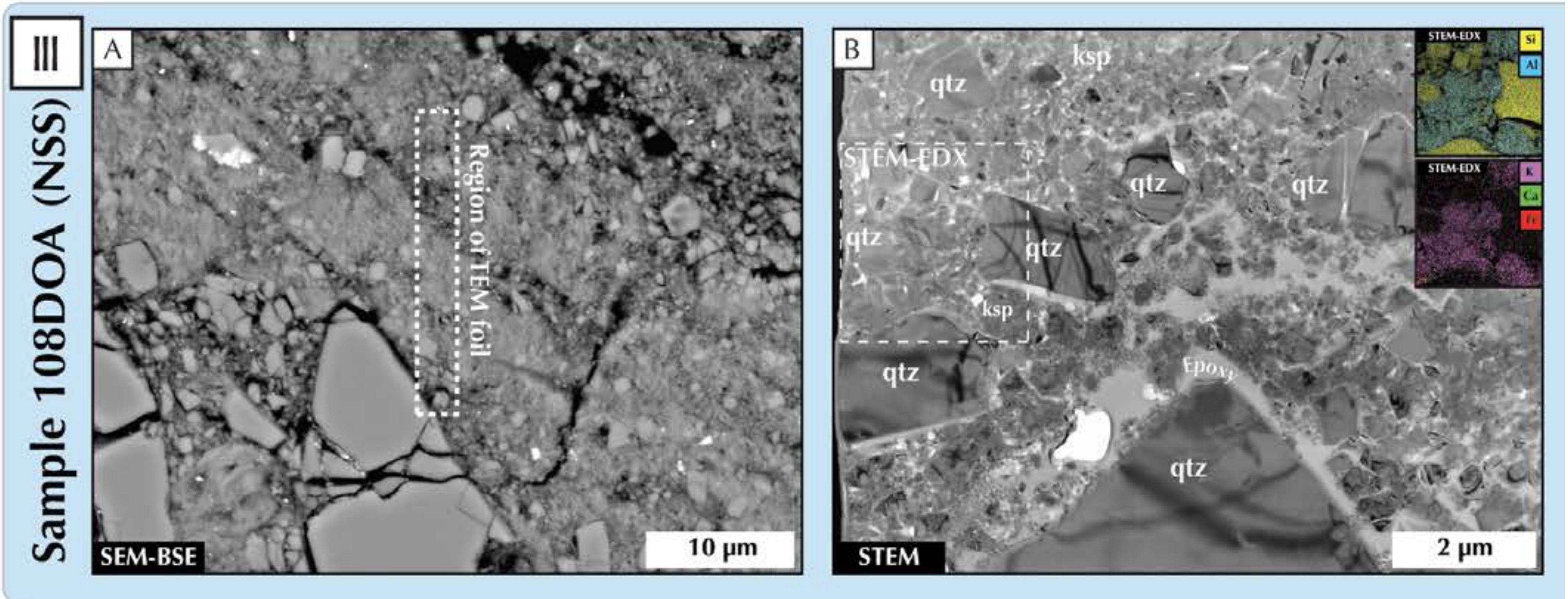




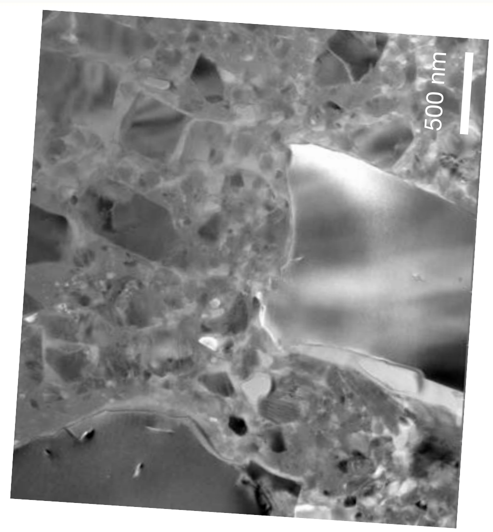
Ortega-Arroyo et al. 2025, AGU Advances

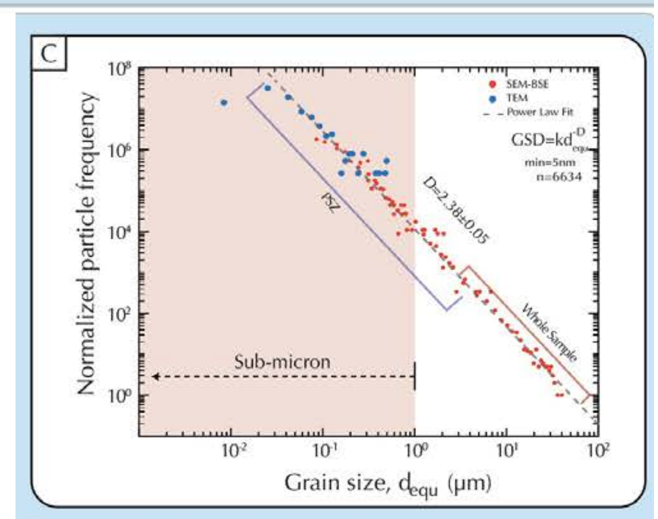
Slip zone origin: Comminution

Ortega-Arroyo et al. 2025, AGU Advances

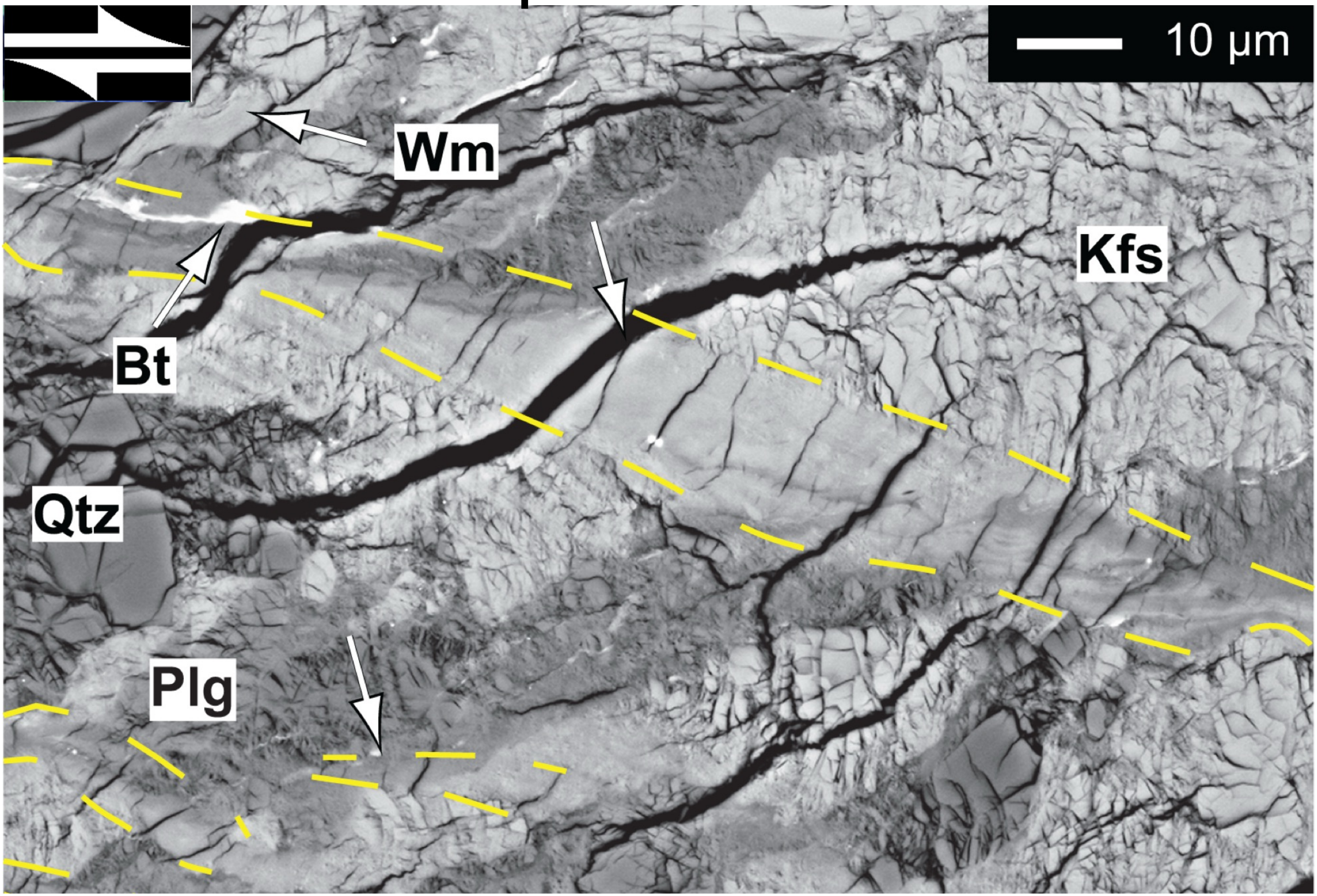


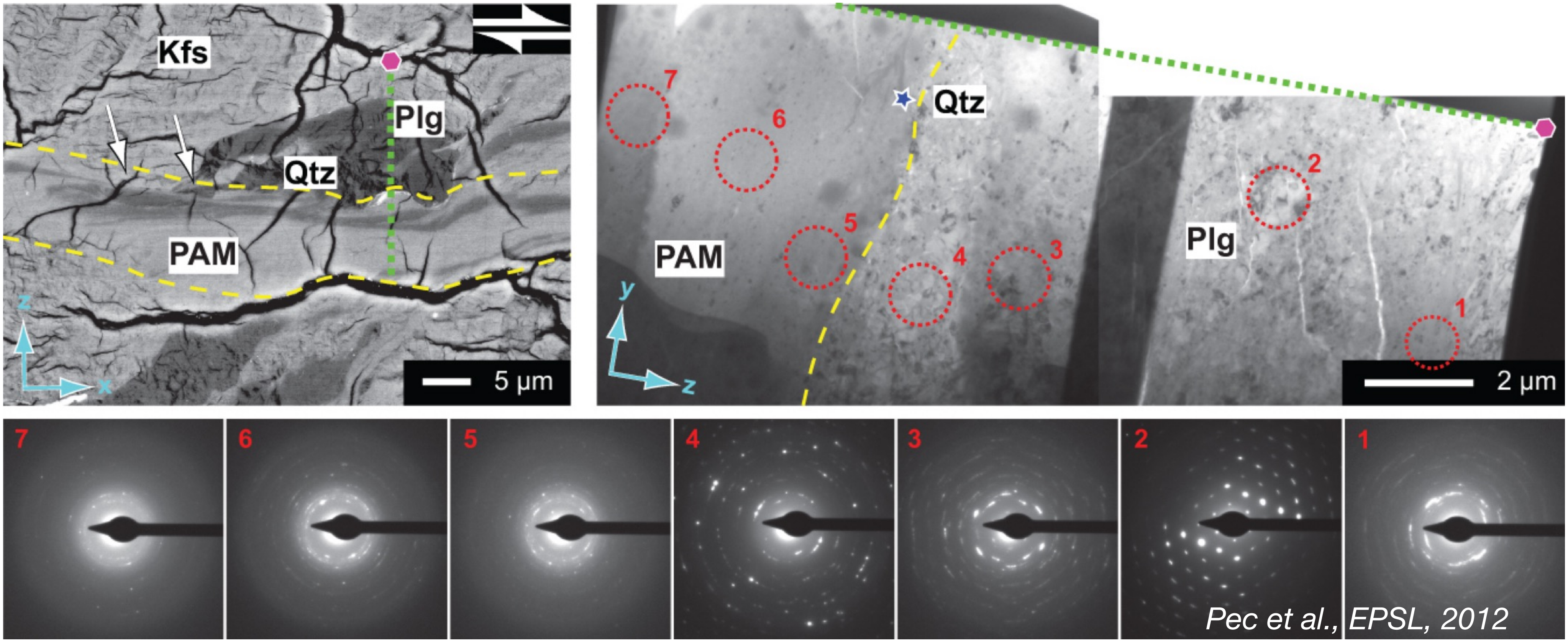
- Wide spread **comminution** to **nm sizes**
  - Smallest grains **~ 5 nm**
- **Qtz** - strong, **Fsp** - weak
- **No** evidence of **“grinding limit"**

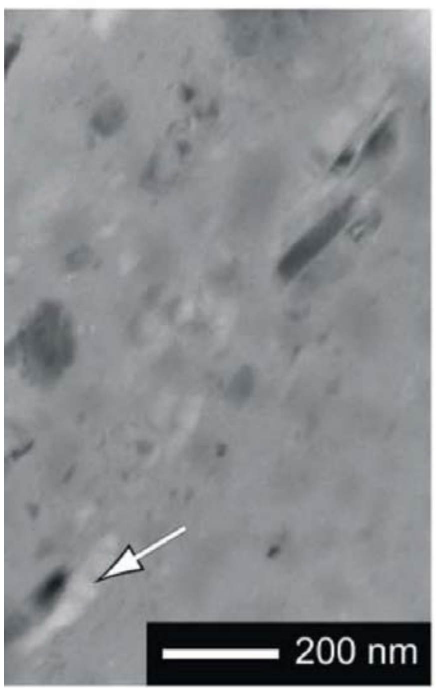


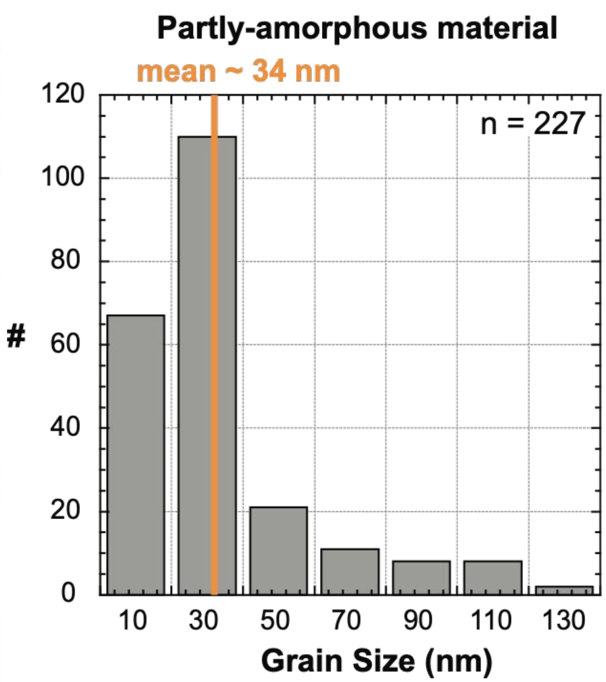


Slip zone origin: Transformation to partly amorphous material







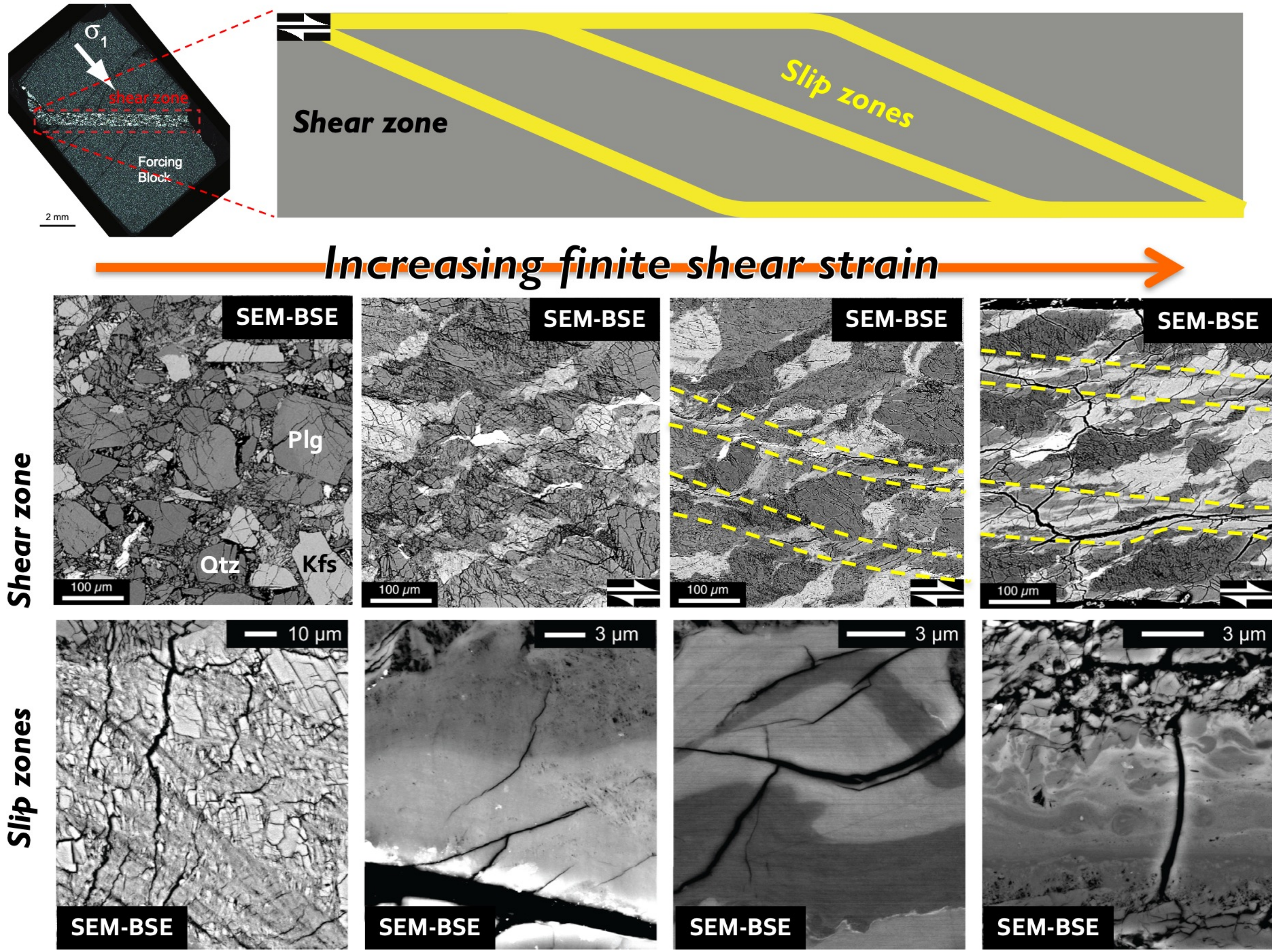


- Up to ~ 90% of PAM is TEM-amorphous

- smallest detectable grains, d ≈ 8 nm (volume ~ 370 unit cells, out of which ~200 unit cells form the surface)

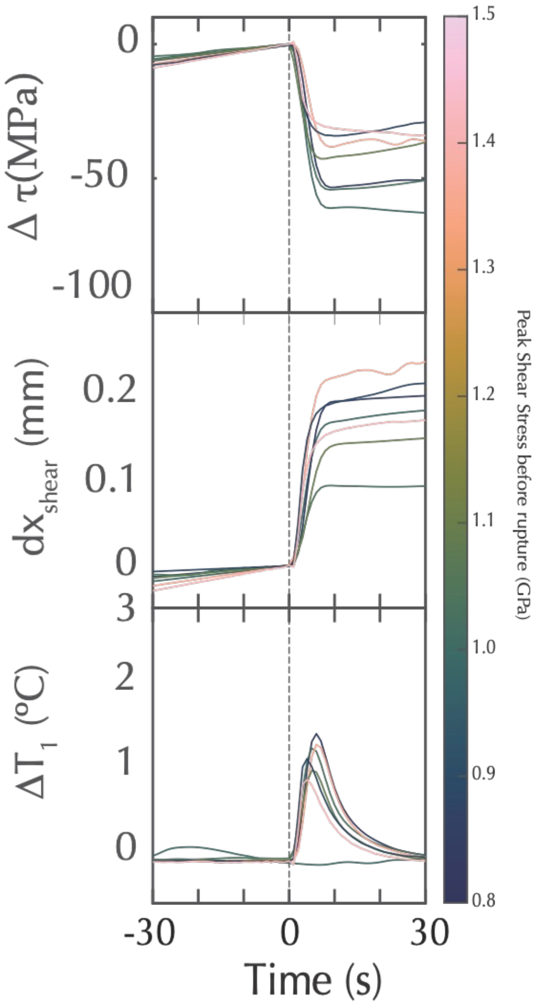
- $\gamma_{slip\ zone} > \gamma_{bulk}$

Slip zone evolution

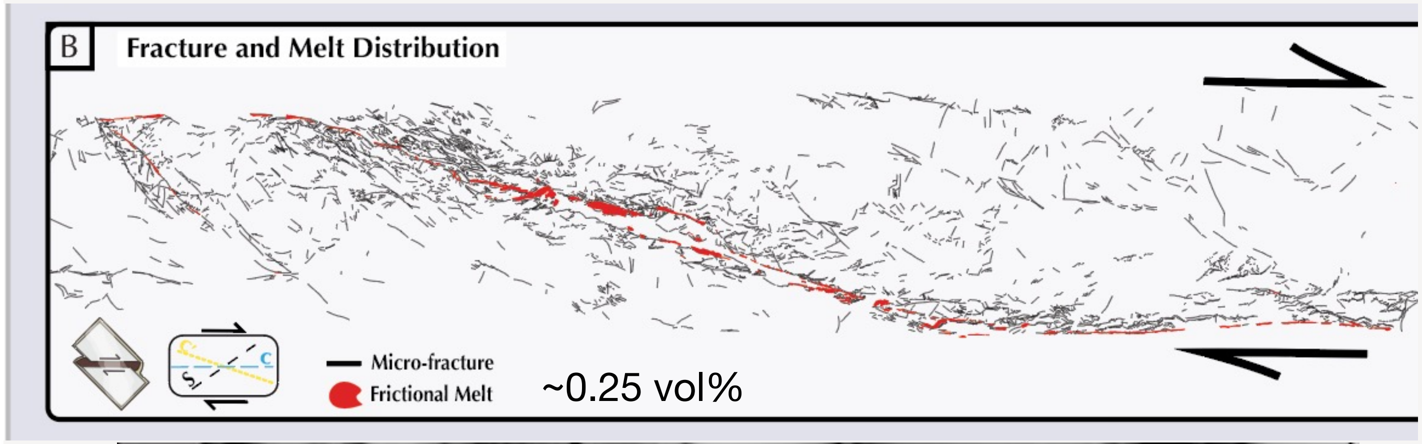


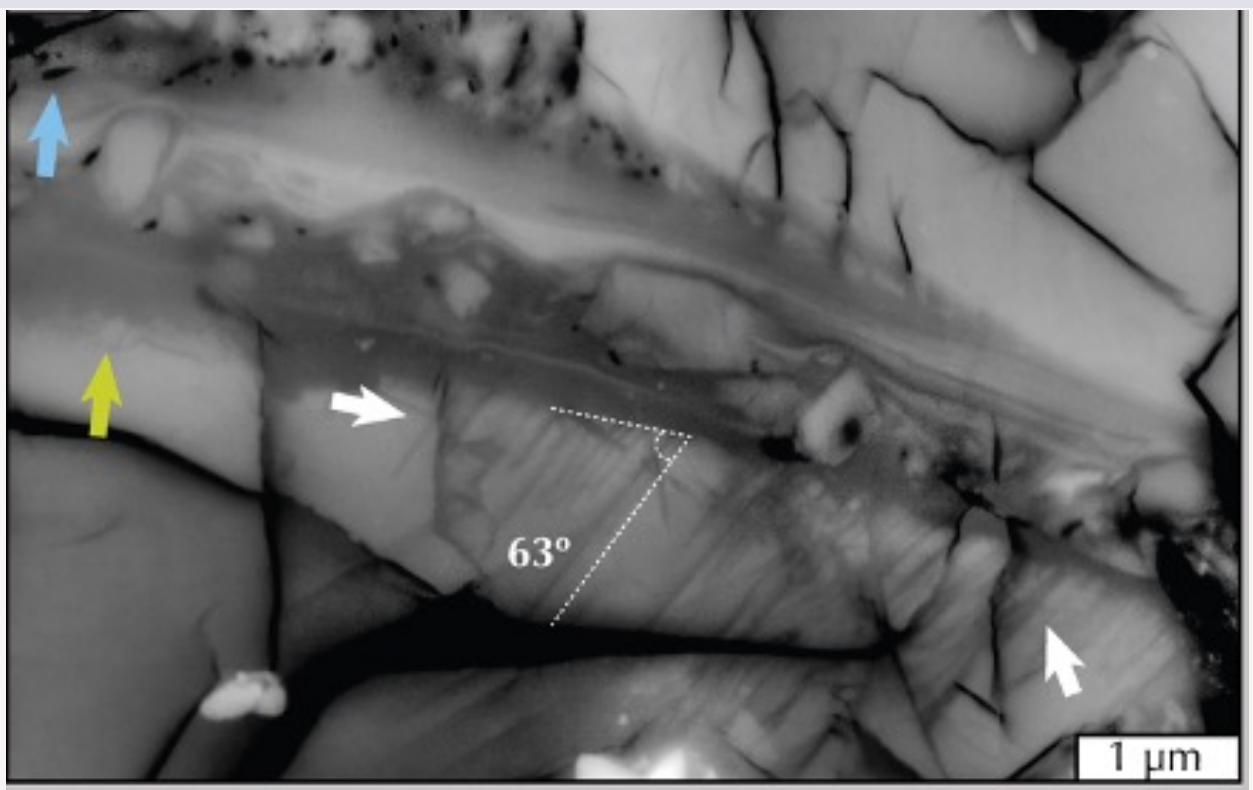
Slip zone evolution: Abrupt Failure

Far-Field at 1Hz



Microstructural Evidence for Heating





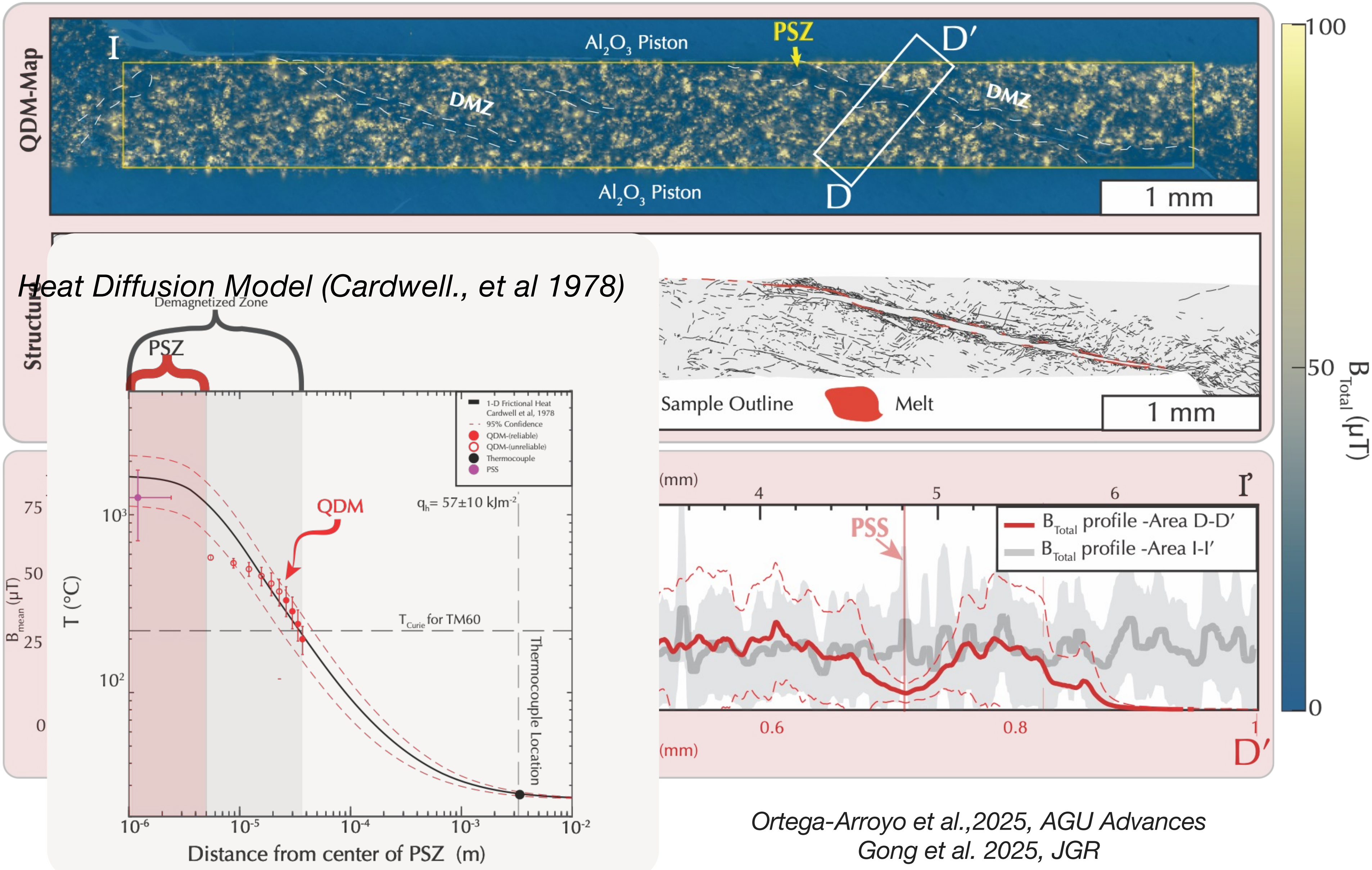
Ortega-Arroyo et al. 2025, AGU Advances

Quantum Diamond Microscopy

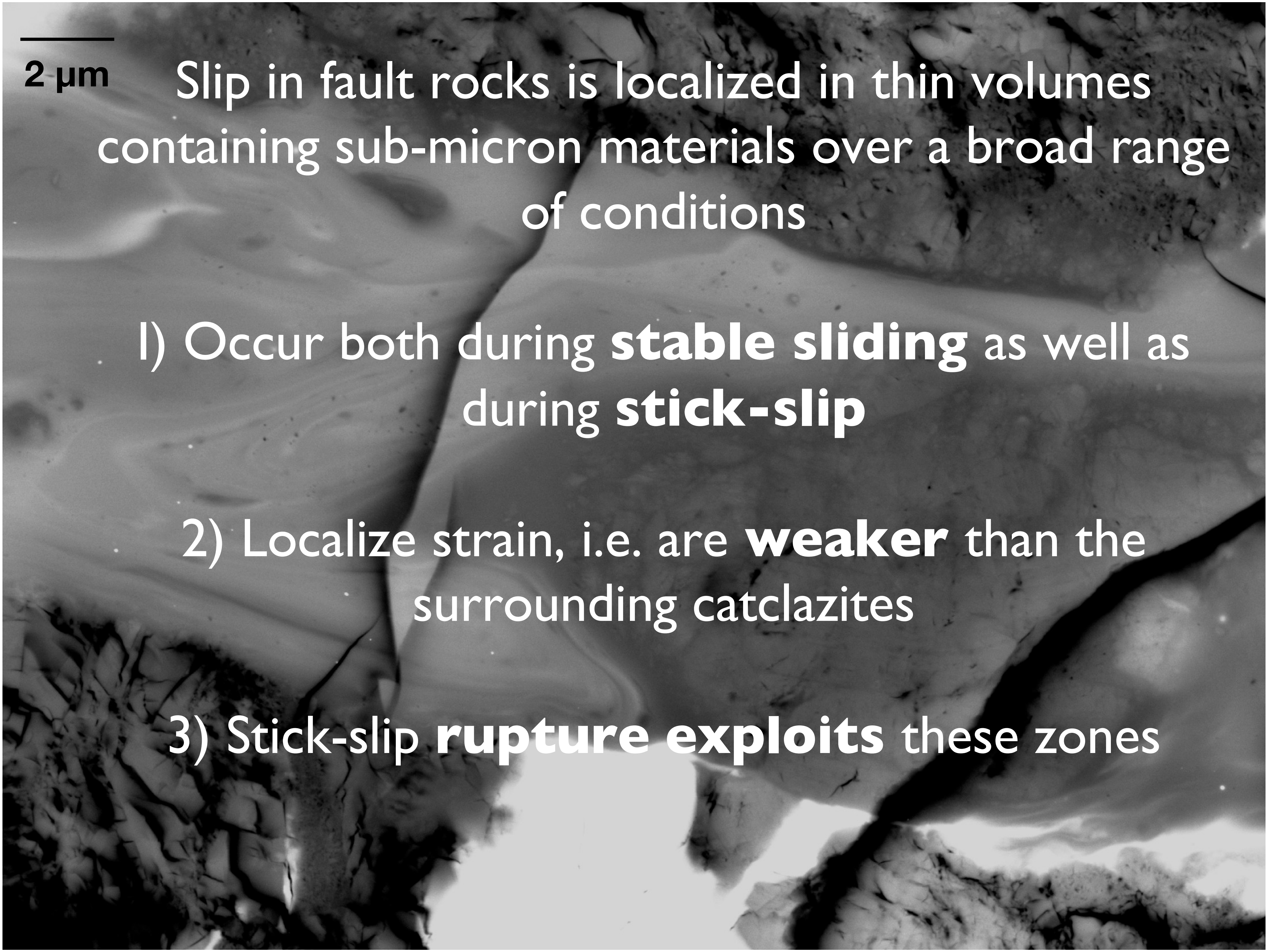
Frictional Heating

Demagnetized Zones (DMZ) around PSZ with melt

Heat Diffusion Model (Cardwell., et al 1978)



Ortega-Arroyo et al.,2025, AGU Advances
Gong et al. 2025, JGR



Slip in fault rocks is localized in thin volumes containing sub-micron materials over a broad range of conditions

1) Occur both during **stable sliding** as well as during **stick-slip**

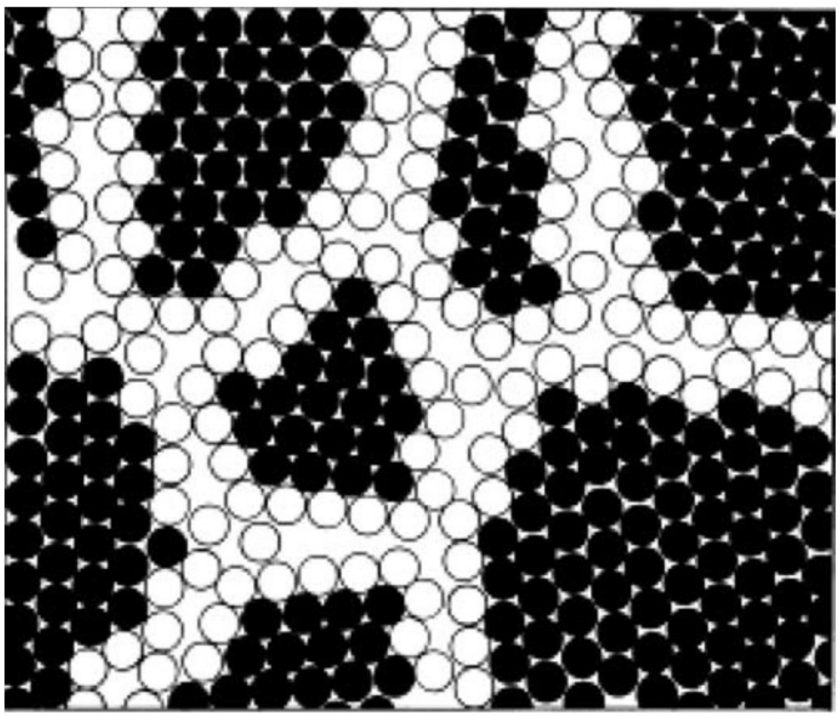
2) Localize strain, i.e. are **weaker** than the surrounding catclazites

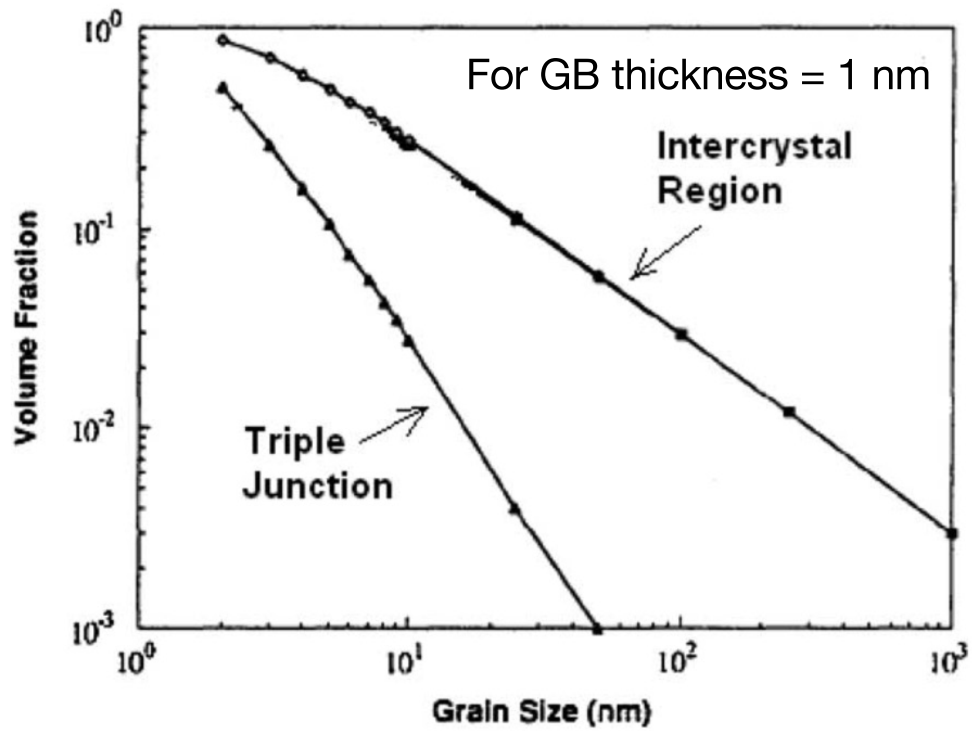
3) Stick-slip **rupture exploits** these zones

1 μm

What makes nano-crystalline materials “different”?

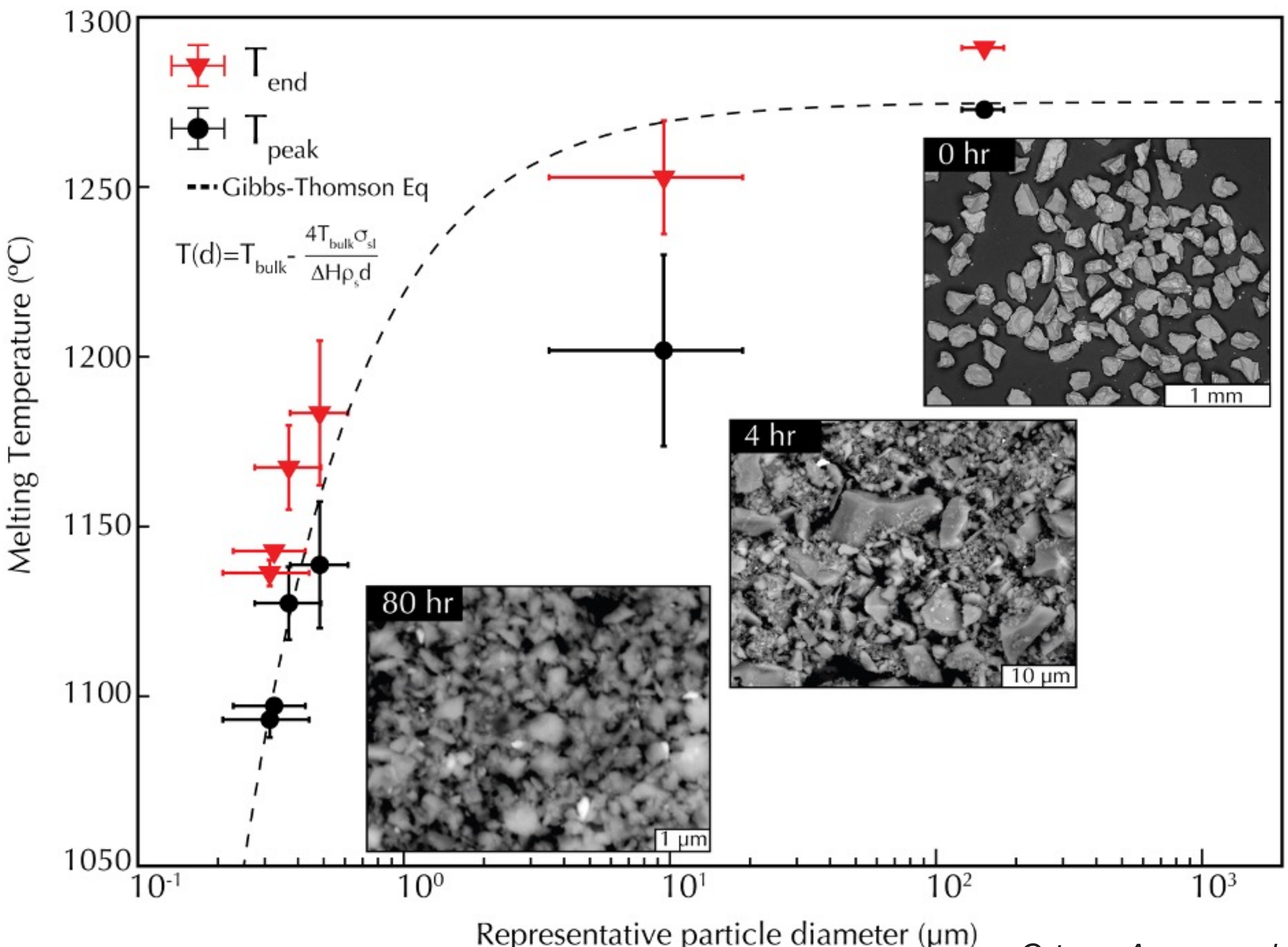
- Surface dominated materials
- Physical properties? Rheology?





Meyers et al. 2006

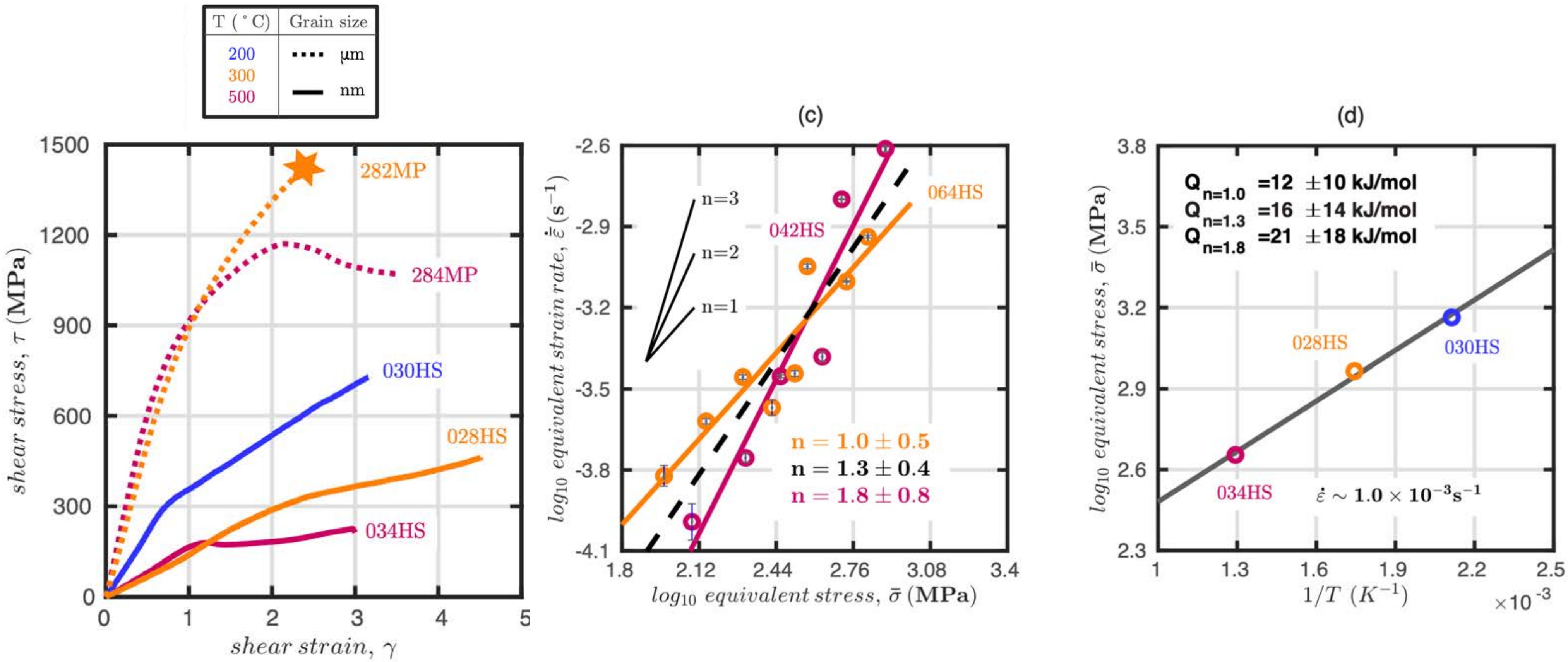
Melting of nano-crystalline fault rocks



Ortega-Arroyo and Peč, under review, GRL.

- Nanocrystalline materials **exhibit a profound melting point depression**
- Vulnerable to **T-induced weakening**

Rheology of nano-crystalline fault rocks



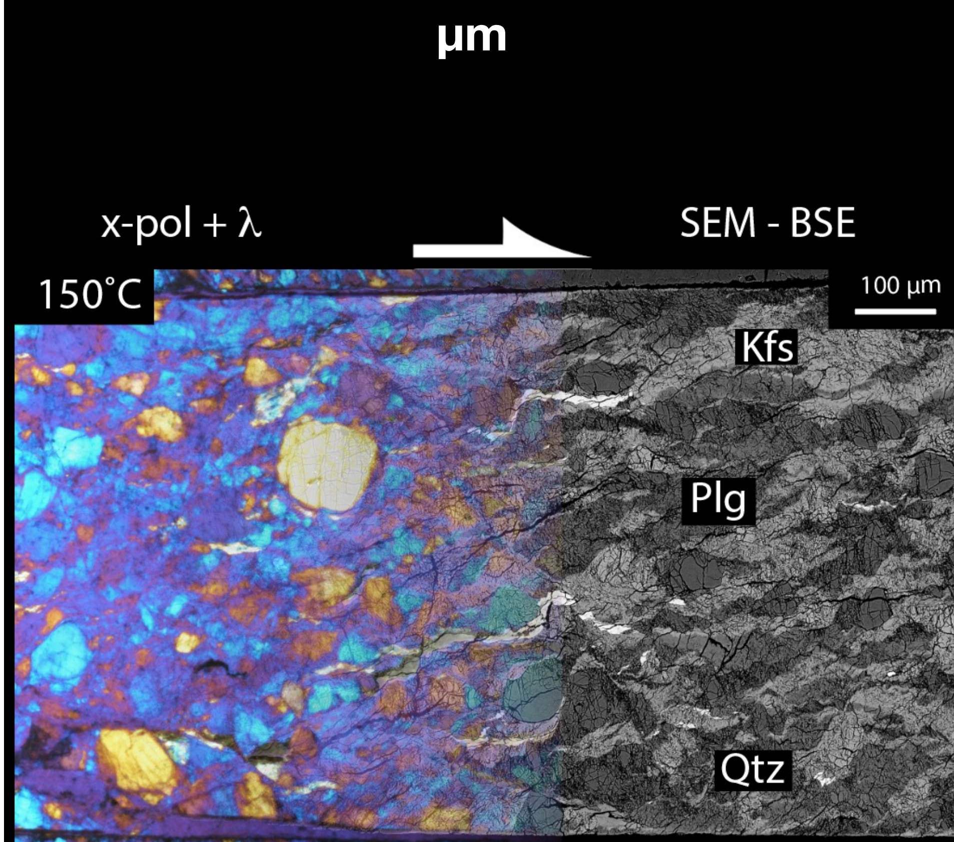
Sun and Peč 2021, Nat. Comm.

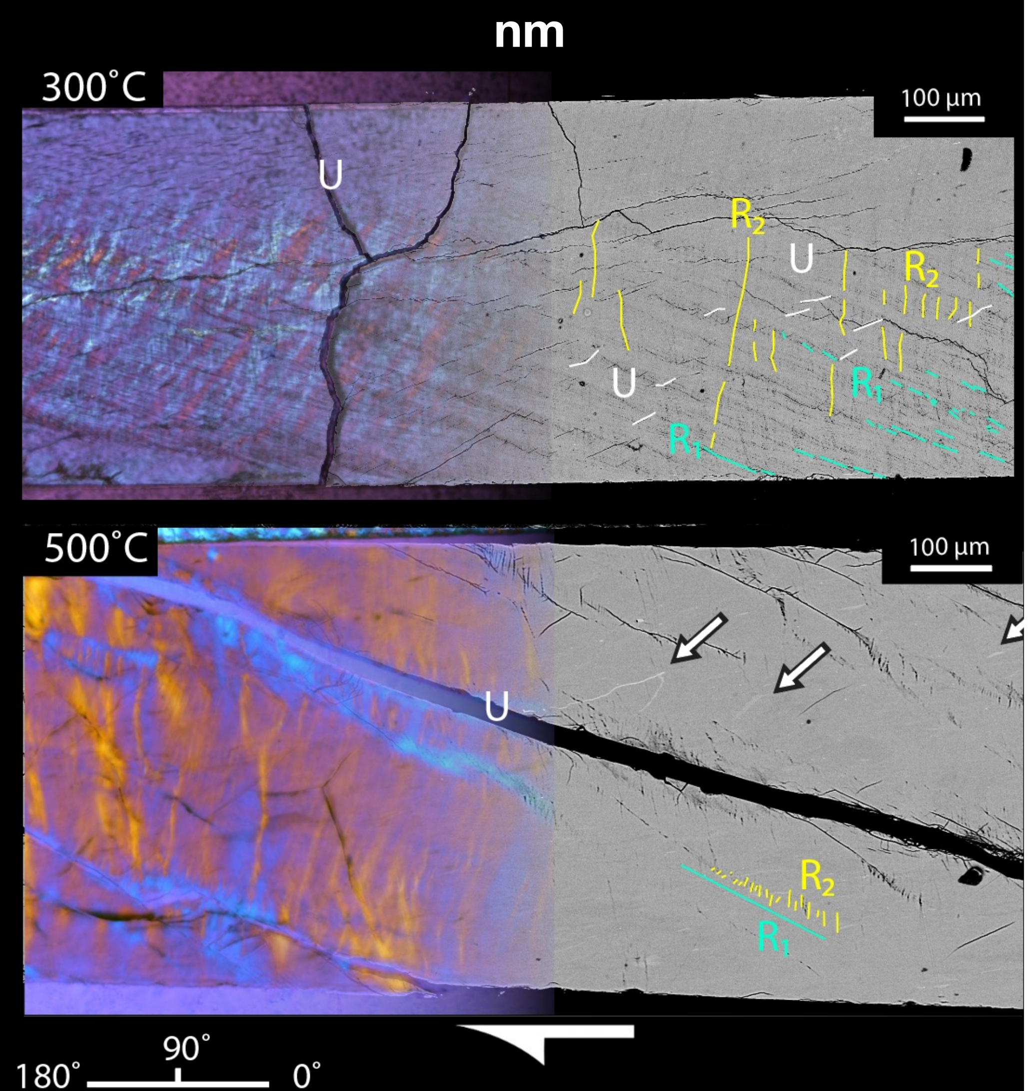
$$\dot{\varepsilon} = A\,\sigma^{n} exp\left(\frac{-Q}{RT}\right)$$

- Nanocrystalline (d ≈ 100 nm) materials **produced** by planetary ball milling **in bulk**
- ~**order of magnitude weaker** than µm cataclasites under identical conditions
- **Strongly rate strengthening** (n = 1-2), low T sensitivity (Q ≈ 10 - 20 kJ/mol)

Microstructures

- nm-fault rocks are optically and mechanically anisotropic (?!?)
- Sub-wavelength grating effects?



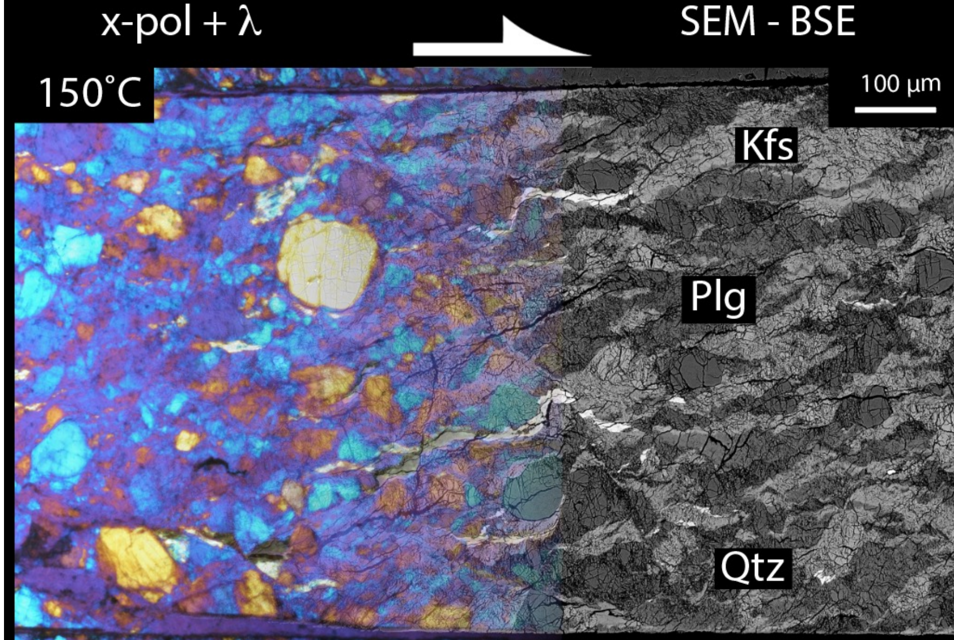


Sun & Pec, 2021, Nat. Commun.

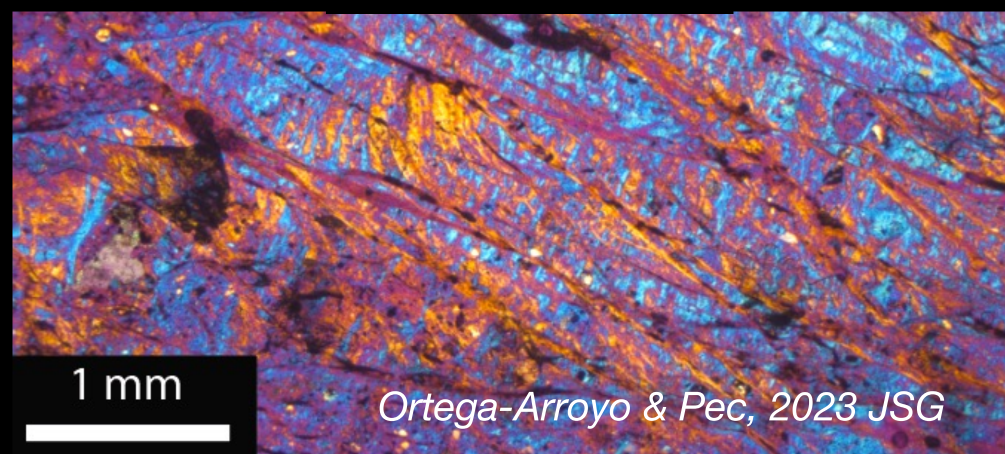
Microstructures

- nm-fault rocks are optically and mechanically anisotropic (?!?)
- Sub-wavelength grating effects?

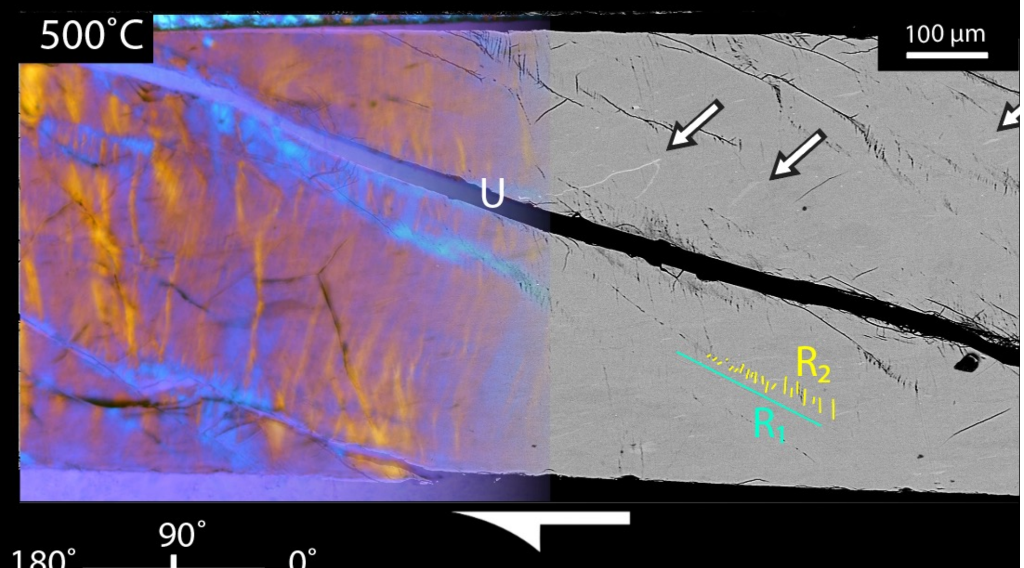
µm



Natural Slickenside

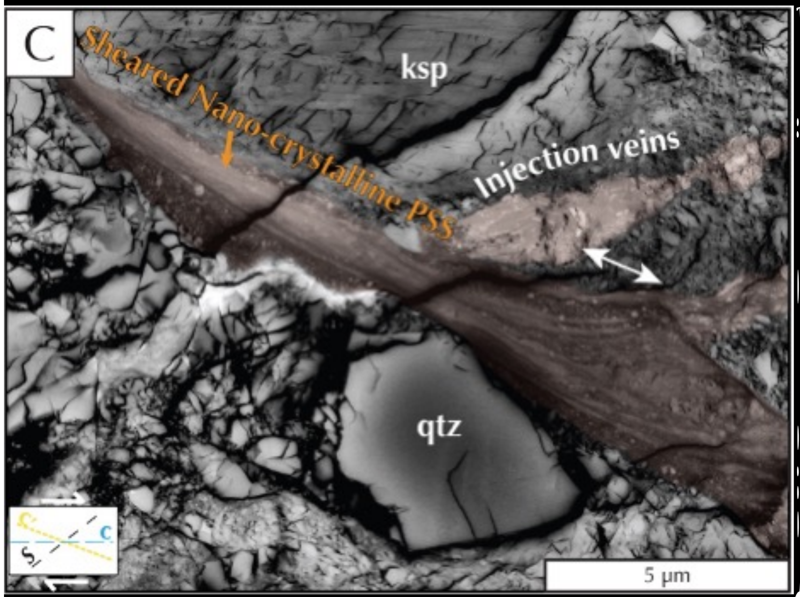


Ortega-Arroyo & Pec, 2023 JSG

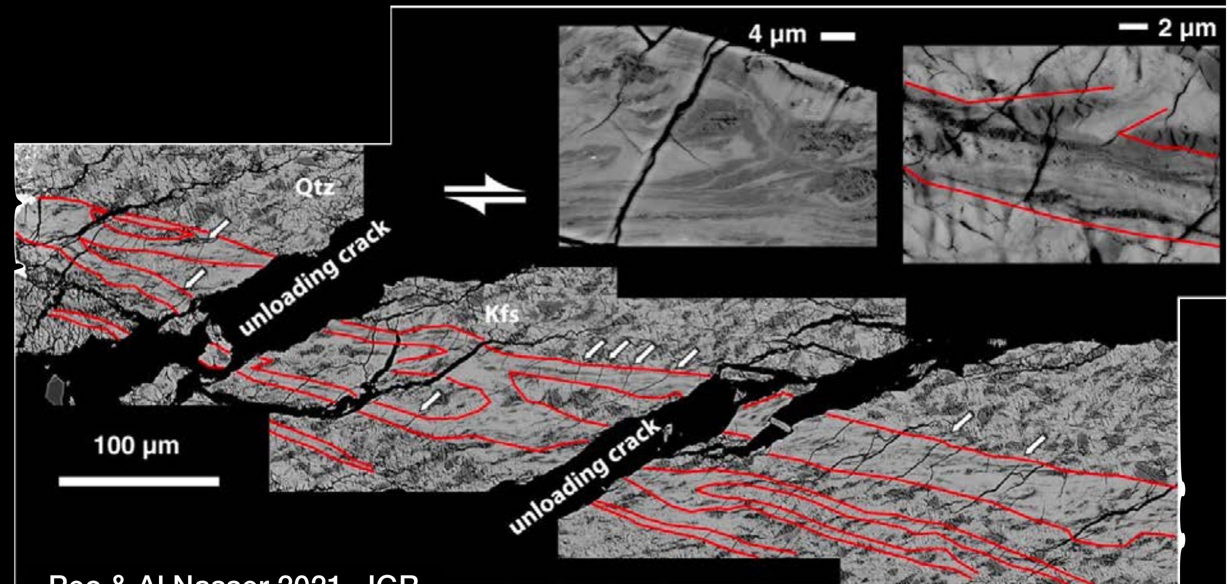


Sun & Pec, 2021, Nat. Commun.

How do Rocks Fail?

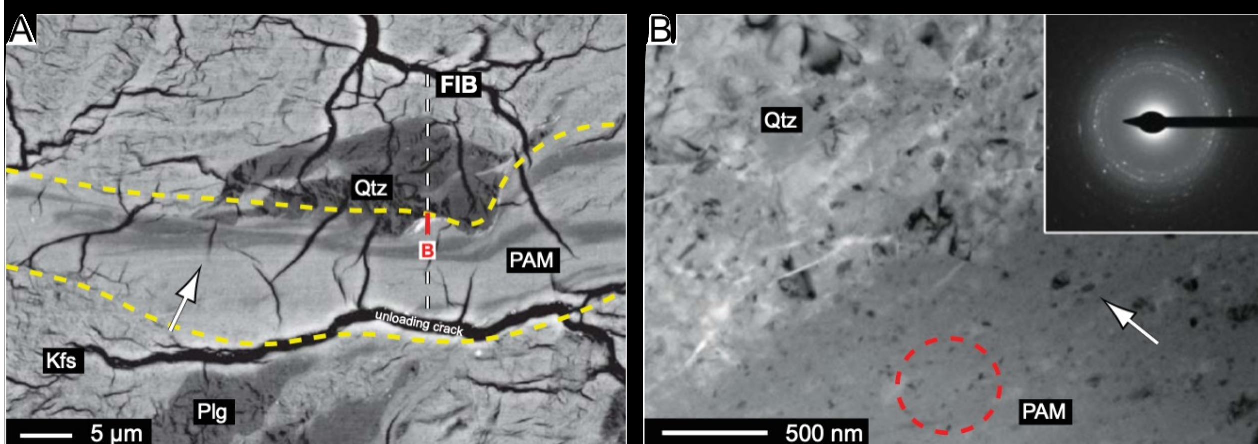


Ortega-Arroyo et al., 2025, AGU Advances

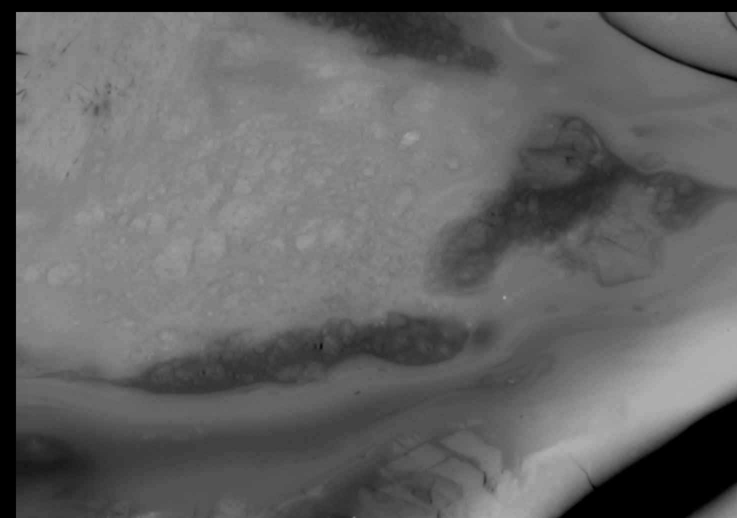


Pec & Al Nasser 2021, JGR

Pc = 300 - 1500 MPa, T = 21 - 750°C



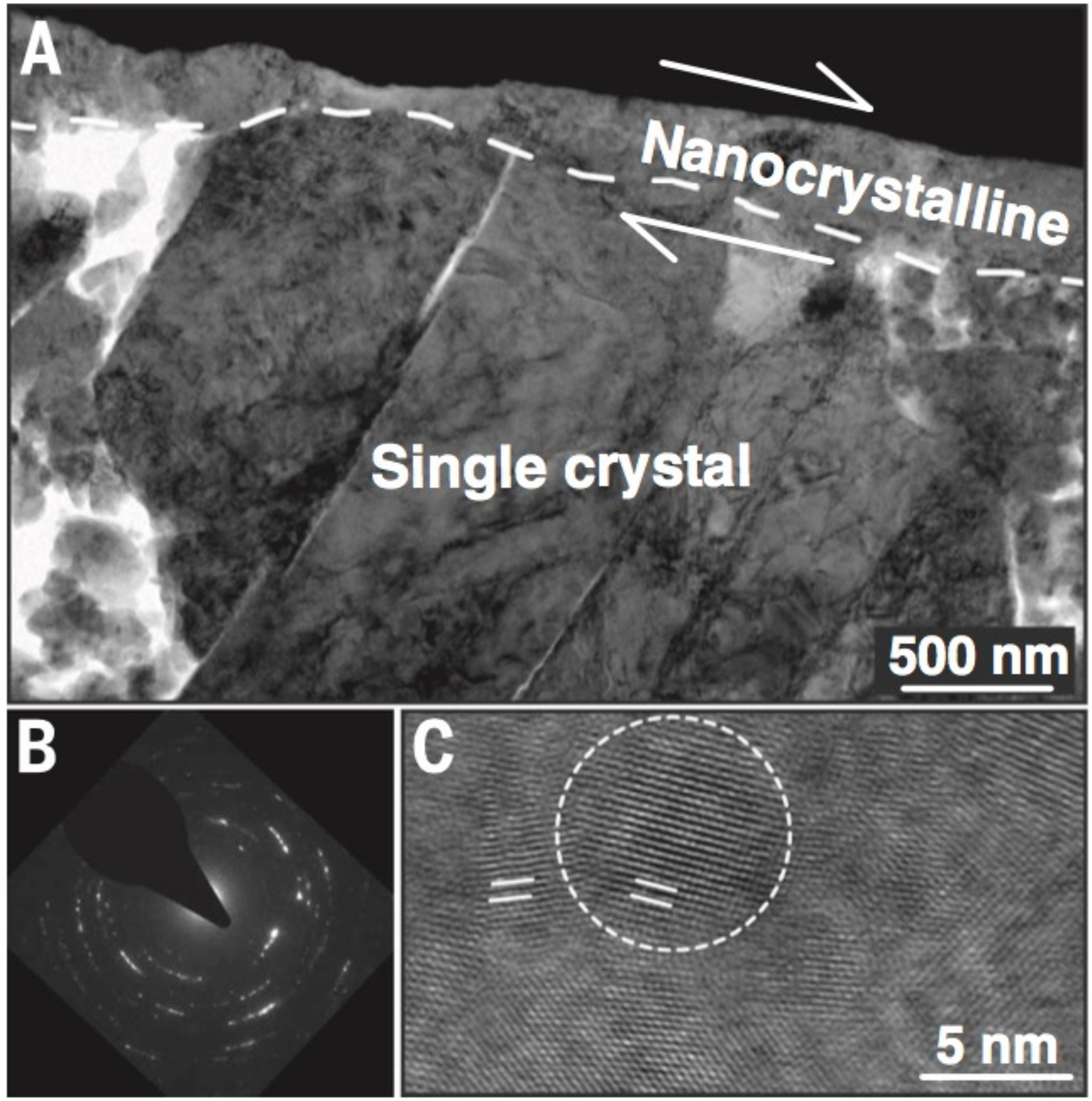
Pec et al. 2012, EPSL



1 µm Pec et al. 2016, JGR

Low P-T experiments

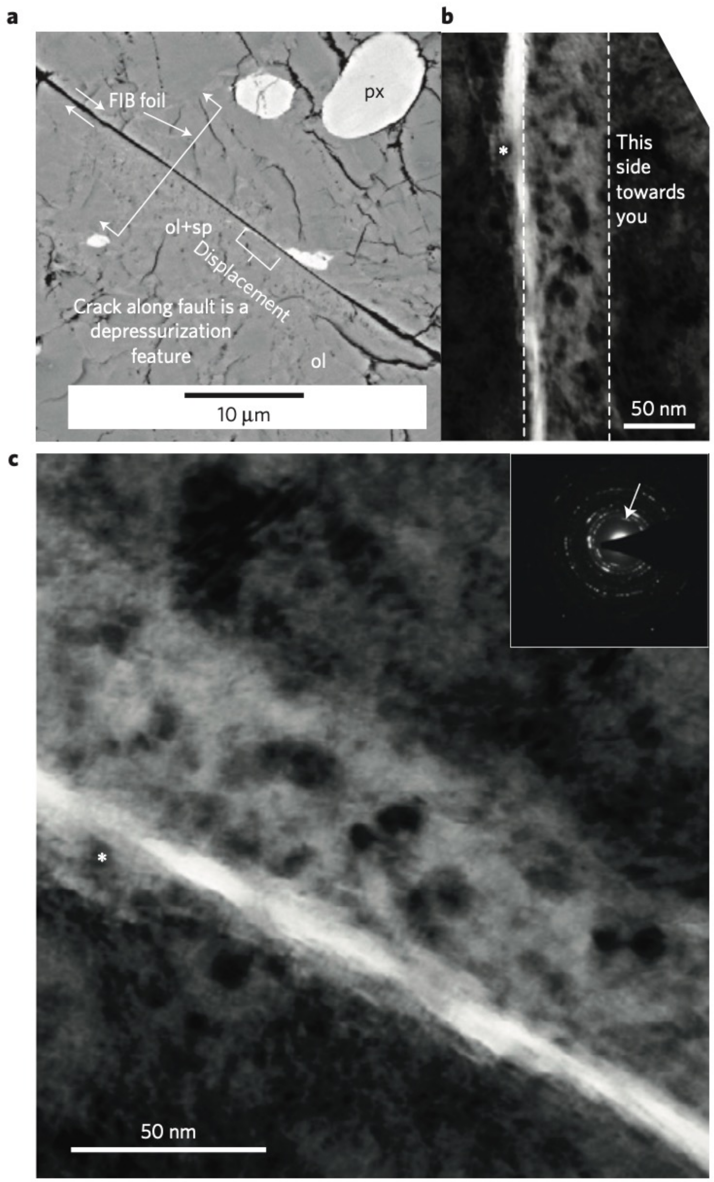
Pc = 50 MPa, T = 18 - 140°C



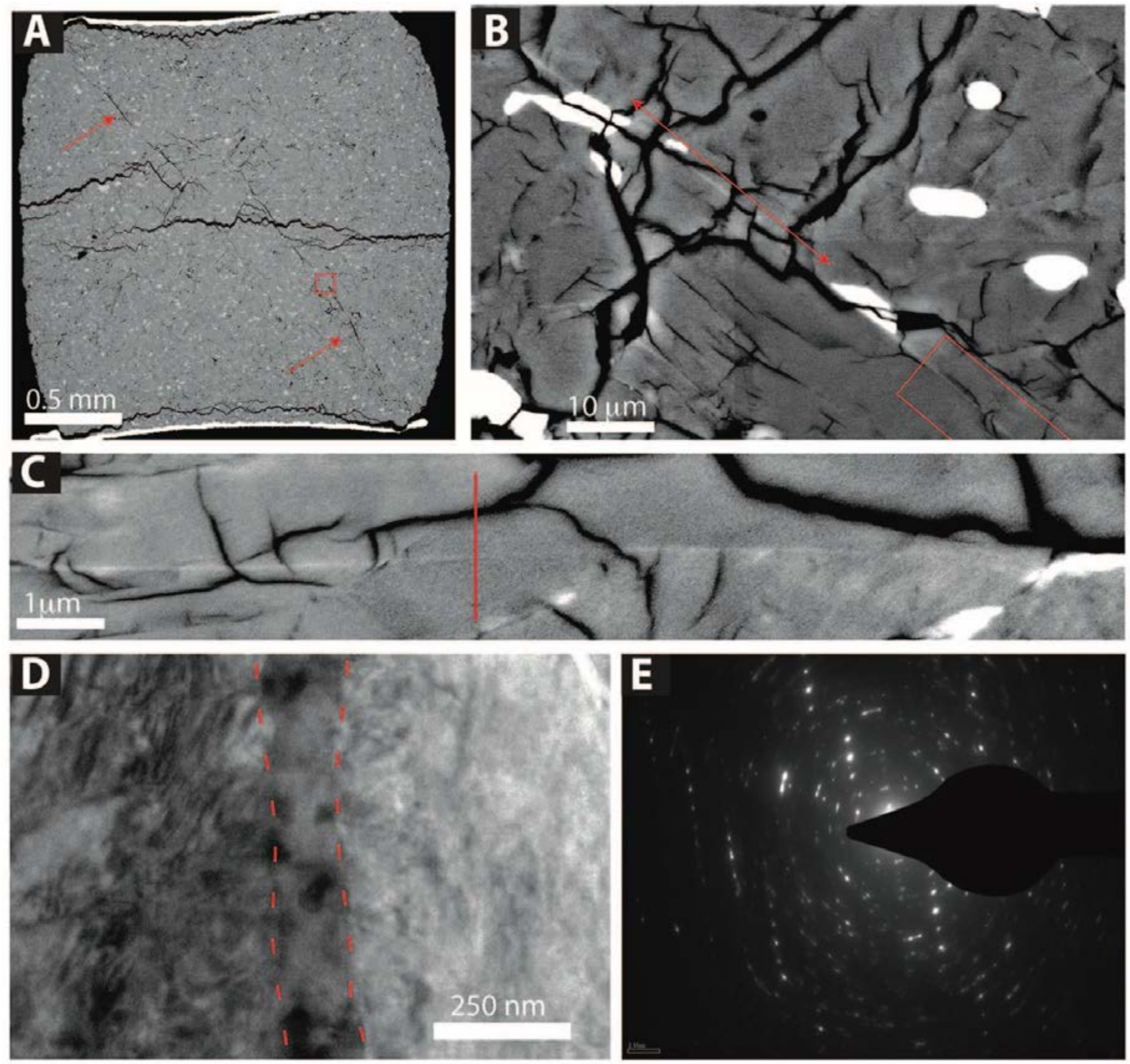
Verberne et al. 2014

Ultra-high P-T experiments

Pc = 1.3 - 5 GPa, T ≈ 750 - 950°C

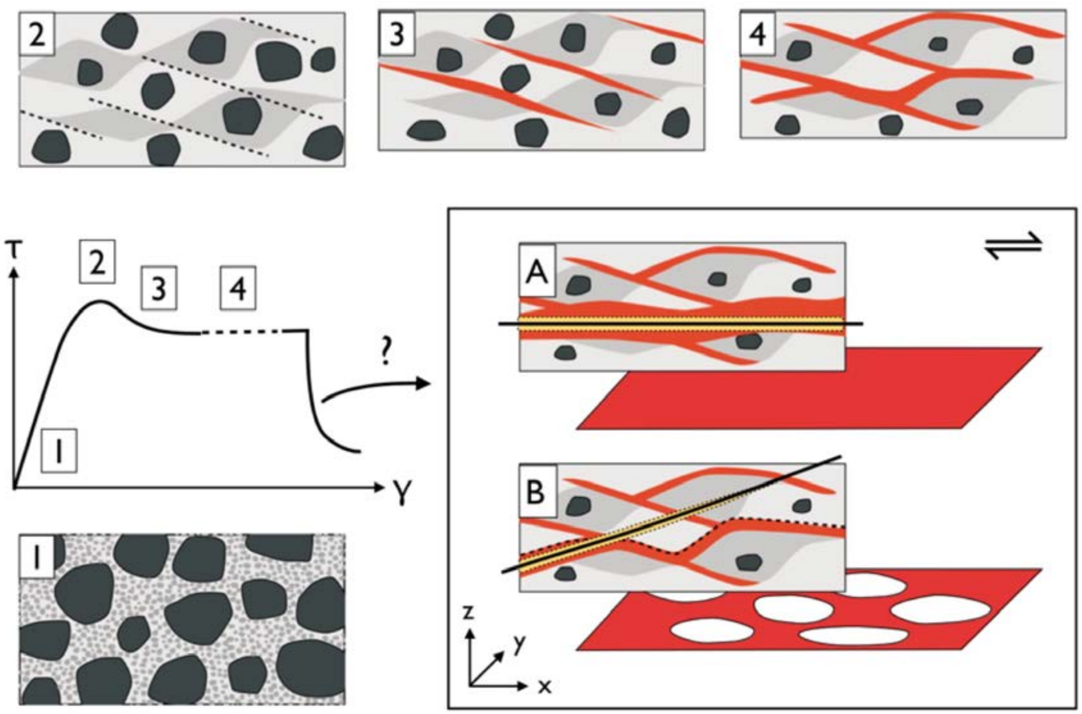


Green et al. 2015



Schubnel et al. 2013

How do Rocks Fail?

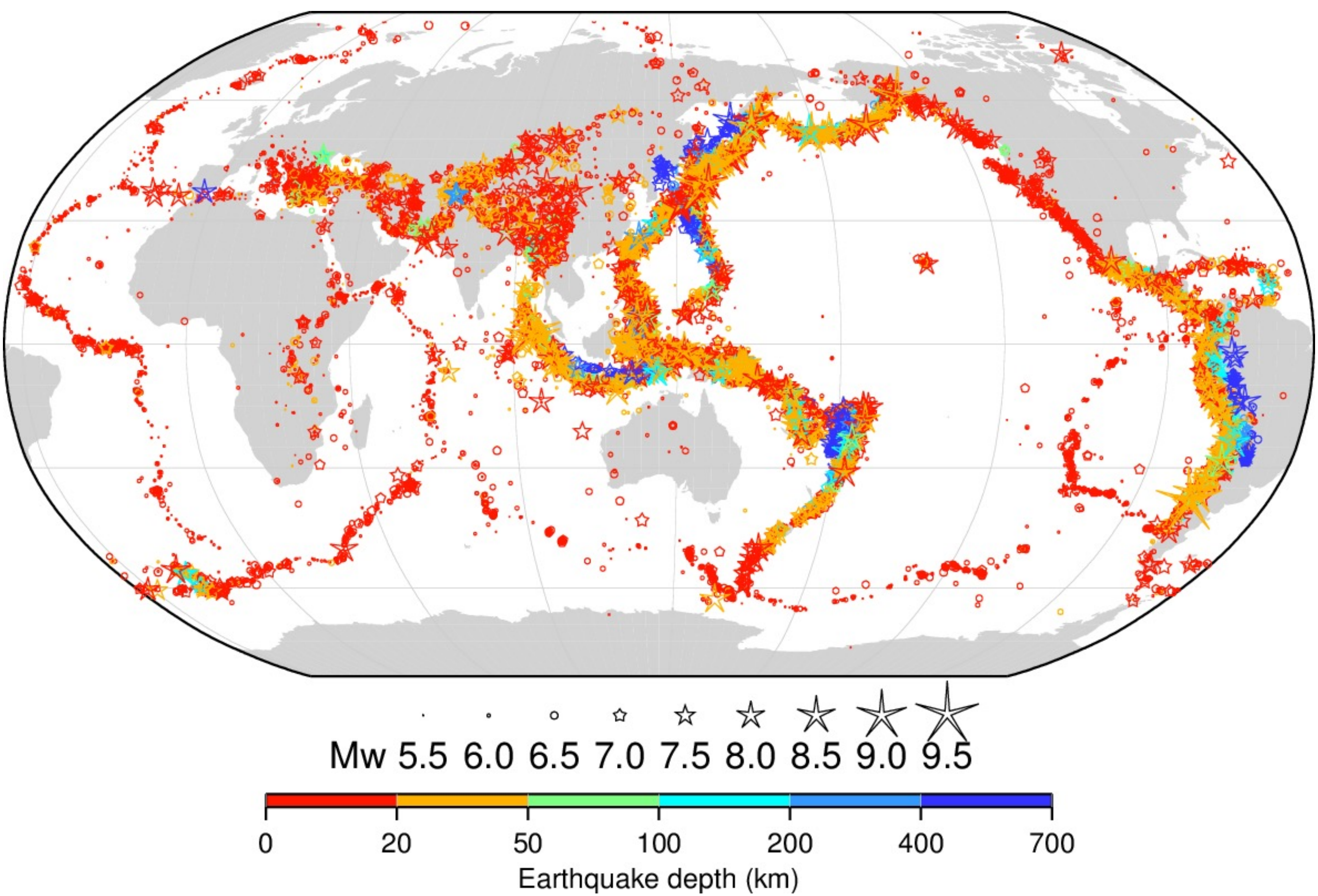


Pec et al. 2016

Takeaways

- Sub-micron fault rocks **are ubiquitous in zones of extreme localization**
- nm- **surface-dominated** materials have **distinct properties** from μm-v**olume-dominated** materials
- nm-fault rocks are **rate-strengthening,** with **low temperature sensitivity** and display a **melting point depression** of hundreds °C
- While nm-fault rocks are rate-strengthening, they are also **intrinsically very weak** (**≈ order** of mag. lower viscosity) and **vulnerable to melting**
- **Percolation of weak material** – accelerating slip at constant T and stress, **positive feedback** with T increase.
- Analogous to **deep-focus EQ?**

Thank you!



ISC-GEM catalogue 1904-2015