Fault pseudotachylytes: recent advances and open questions

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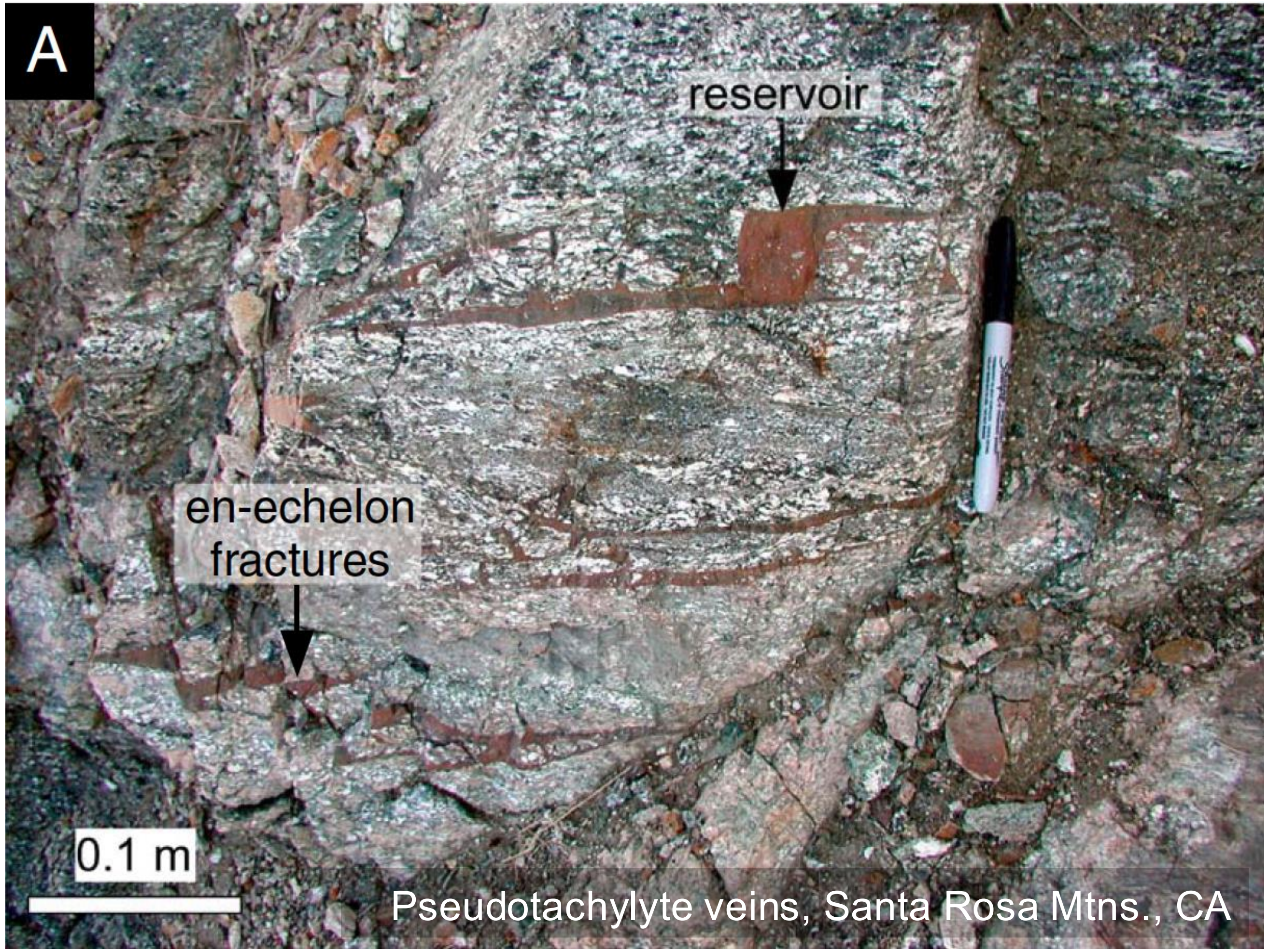
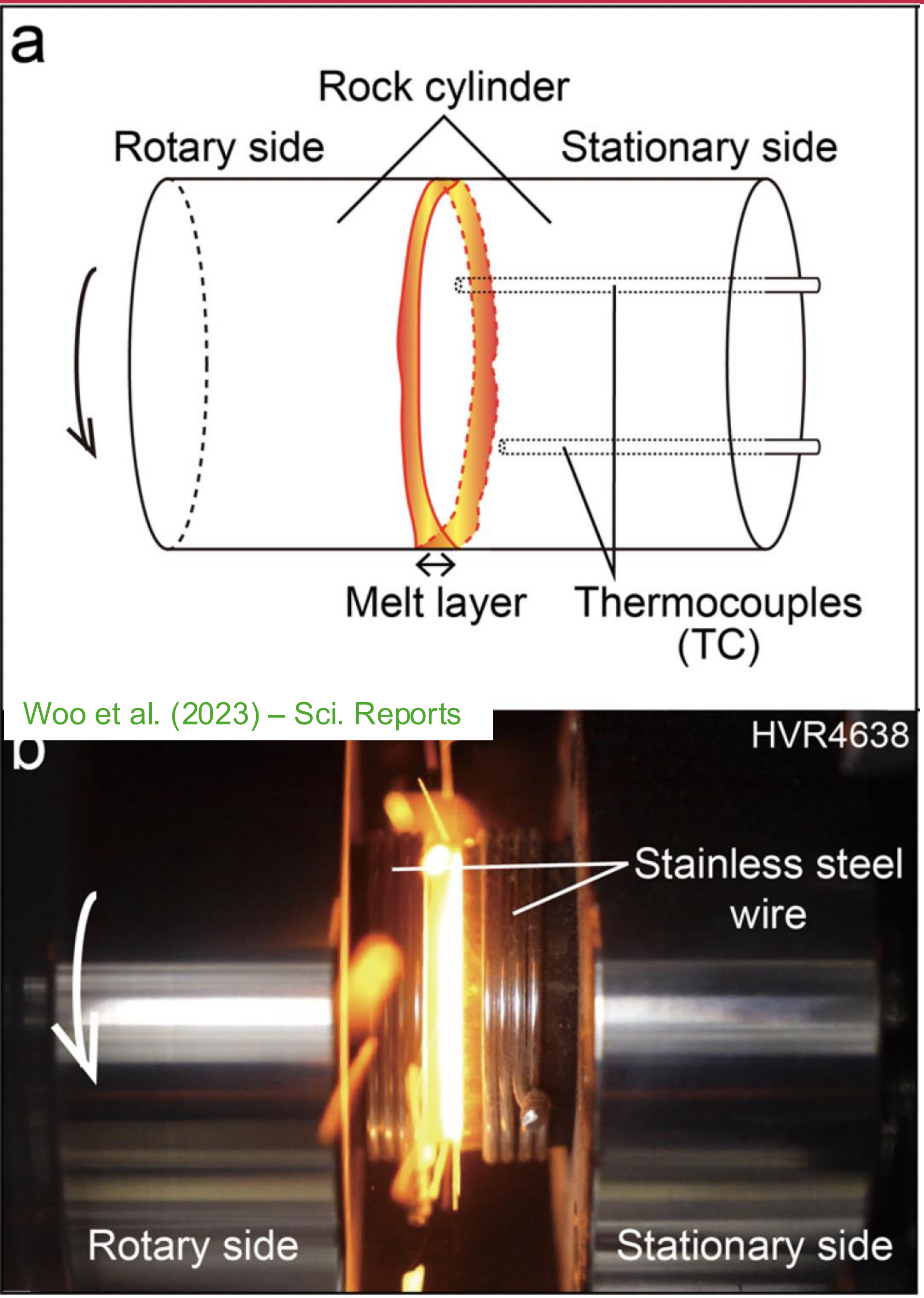
"What do we learn from pseudotachylytes about fault friction?"



Pseudotachylyte veins, Santa Rosa Mtns., CA

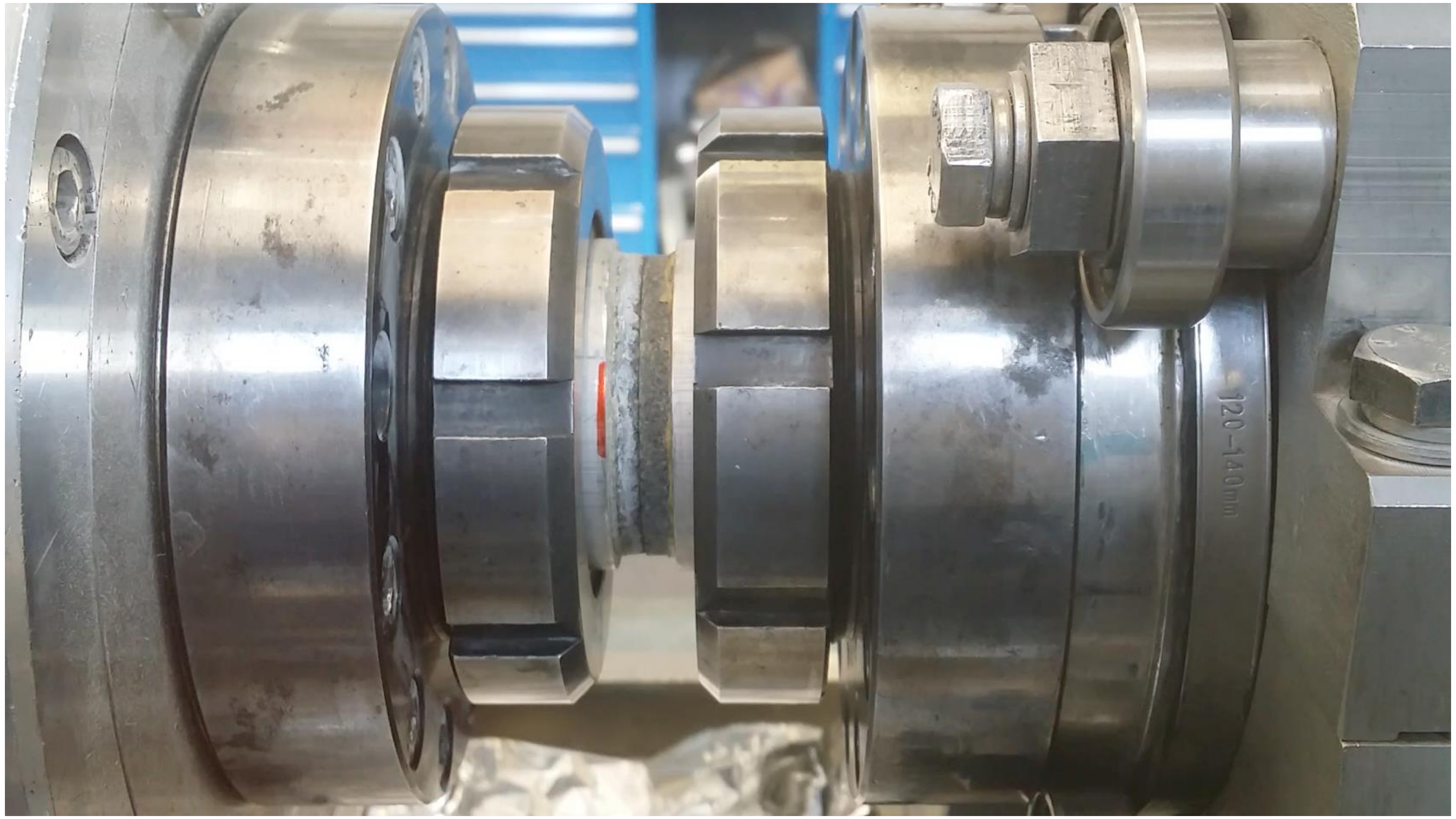
1. Pseudotachylytes: definition, basic concepts



Woo et al. (2023) – Sci. Reports

- Earlier views (<2000's) held that pseudotachylytes could form through *ultracomminution* (e.g., Wenk, 1978; Lin, 1996)

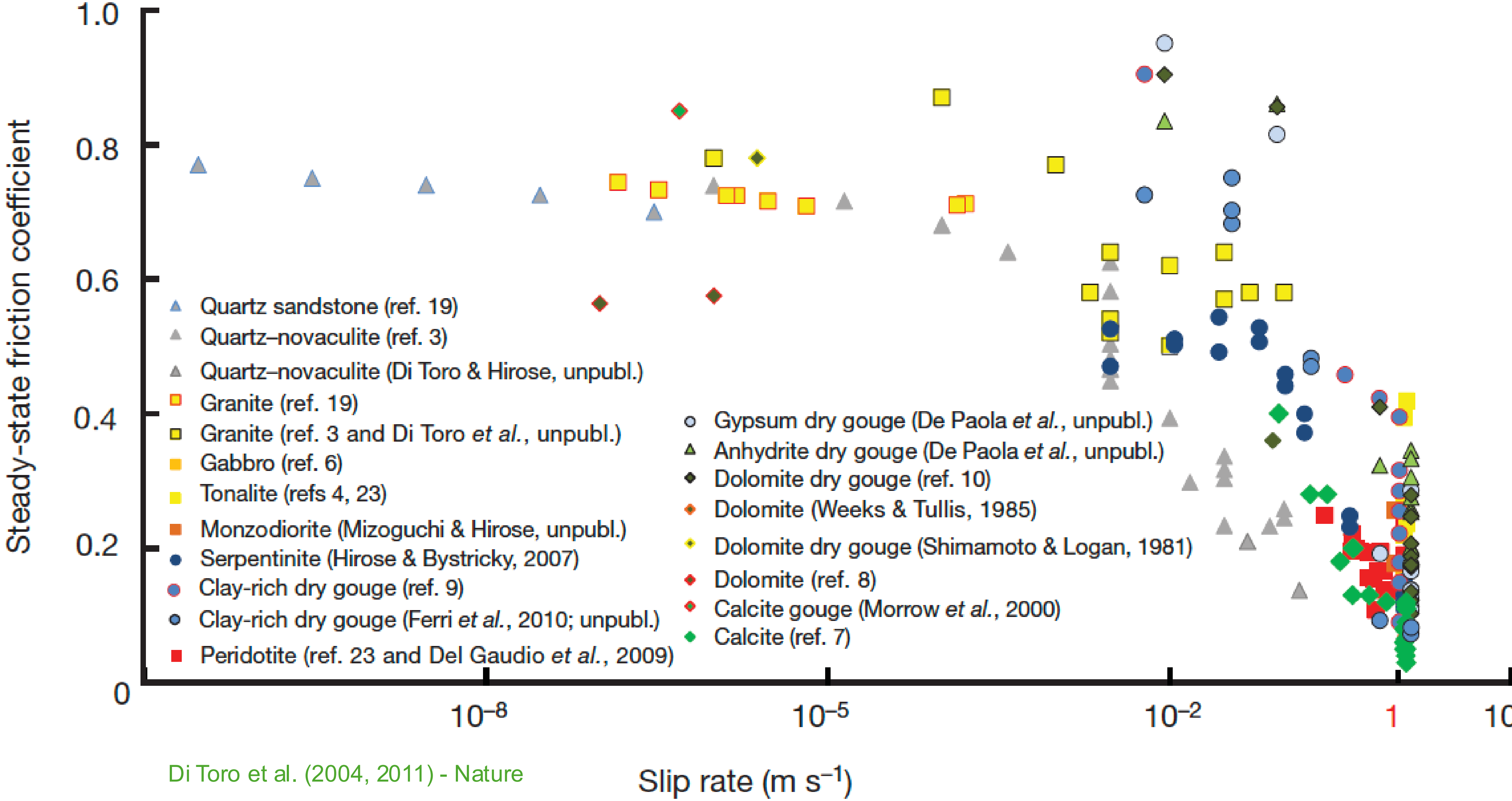
- However, modern *high-velocity rotary (HVR) shear experiments* prove that pseudotachylytes form through frictional melting



Gabbro, experiment on SHIVA (Di Toro) – 01.26.2016 – HVR110905

2. Pseudotachylytes as fault lubricant

- Experiments show that **friction systematically falls towards zero** as slip velocity approaches seismic rates in all types of materials



Di Toro et al. (2004, 2011) - Nature

3. Pseudotachylytes: indicators of slip at slip velocities > 0.1 m s^{-1}

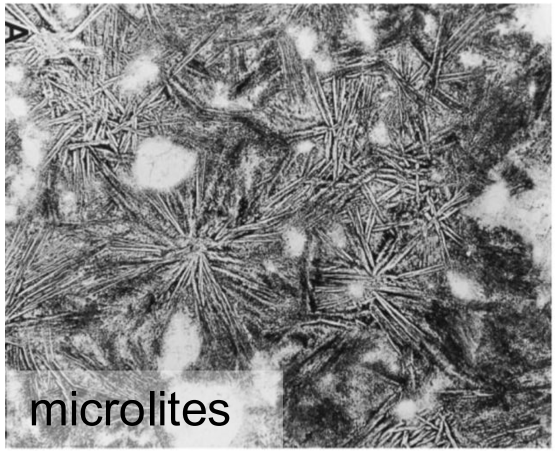
- The melt origin of pseudotachylyte is attested by melt ***microstructures***: glass, microlites, spherulites, vesicules, dendritic crystals, injection veins, thermally corroded clasts, and chilled margins

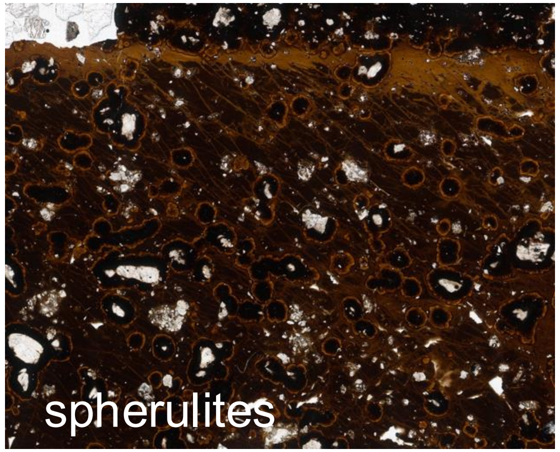
- Friction drops because melt acts as a **lubricant**: η ~10^7 Pa.s vs 10^{26} Pa.s for a granite)

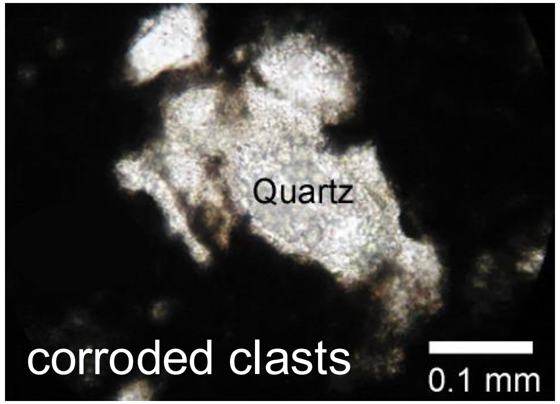
- As pseudotachylytes occur along many faults known to have slipped seismically, they indicate ***slip at velocities >0.1 m.s^{-1}***

- Yet, pseudotachylytes are not reported along all seismogenic faults, possibly due to a petrological **thresholds** in frictional melting, or geometrical **barriers** that prevent smooth slip like in experiments

- The longuest exposures of pseudotachylyte are **kilometers in length** (Ikertôq shear zone in Greenland ~55 km; Homestake shear zone in Colorado ~21 km; Jones Corner fault zone in Maine >3 km)



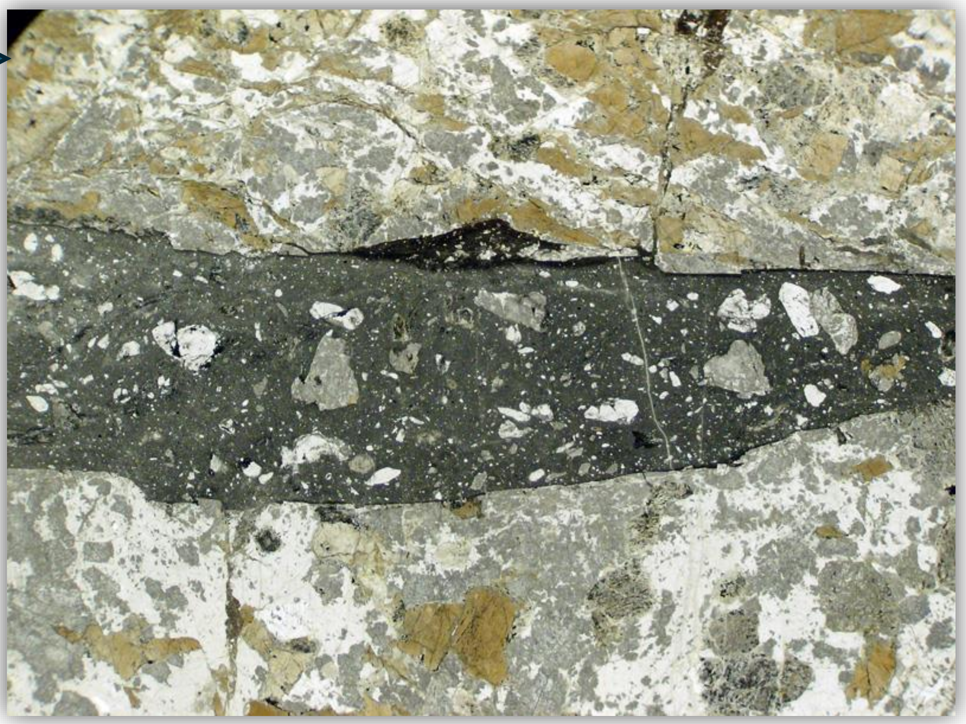




4. Frictional melting and fluids

Frictional melting is **more likely in the absence of fluids**:

- aqueous fluids drastically enhance heat dissipation due to their higher heat conductivity, compared to dry rock
- fluids circulate along microfractures and distribute heat
- fluids promote grain-boundary sliding, pressure-solution and hydrothermal alteration
- fluids trigger hydrous mineral breakdown, hydrothermal veining, precipitation of quartz, calcite – **all endothermic processes**
- fluids reduce rock strength hence preventing high-energy rupture



Pseudotachylyte in dry gabbro, Ivrea Zone, Balmuccia, Italy

Yet, if earthquake energy is sufficient, frictional heating still occurs **in the presence of fluids** (*e.g.*, in the phyllosilicate-rich turbidites of the Kodiak Island)

Also, in rare cases, vesiculated pseudotachylyte can form in hydrothermal systems (*e.g.*, Gomila et al., 2021)

Pseudotachylyte in wet chlorite-rich ultracataclasite, Bolfin Fault, Atacama, Chile

5. Pseudotachylytes and extreme strain localization

Pseudotachylytes typically form thin (mm to cm) zones where frictional melting occurred

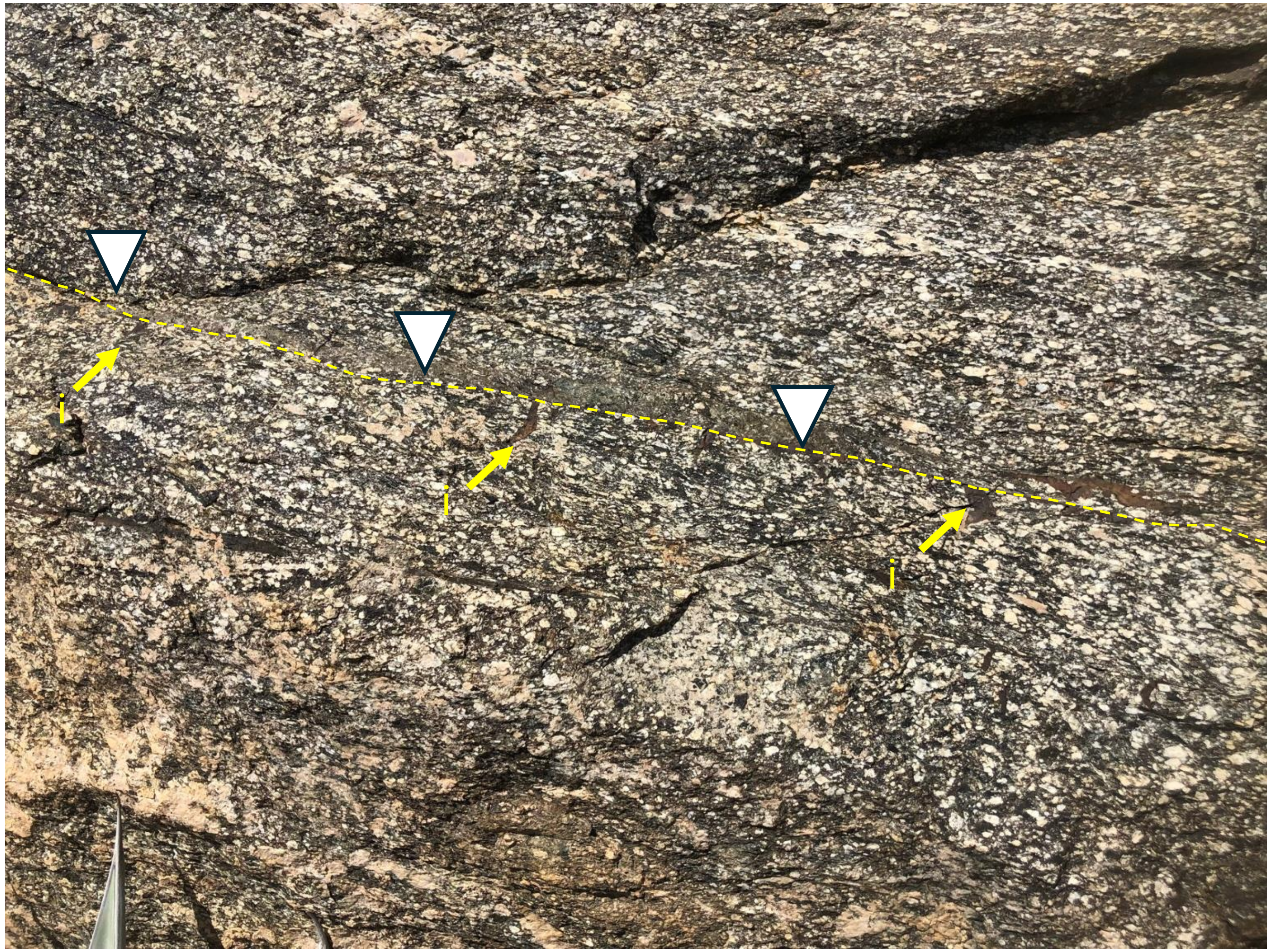
Pseudotachylytes form in **ultra-localized** and **self-accelerating** slip zones

In order to melt rocks, high temperatures are needed (~1,200 to 2,000ºC) and thus frictional heat needs to be concentrated along a very thin zone

Pseudotachylytes also require **high slip rates** (>1 m s^{-1}) / **high strain rates** to form (10^1 to 10^4 s^{-1})

Survivor clasts tend to be angular and small

Clogging by angular clasts in an injection vein, Santa Rosa Mtns., CA



Thin pseudotachylyte generation vein with injection veins, Santa Rosa Mtns., CA

6. Pseudotachylytes and stress drop

To melt rocks by friction, shear stress must be sufficiently high to produce

- High slip rates
- Rapid heat production from work
- Temperature >1,000ºC within ms to s

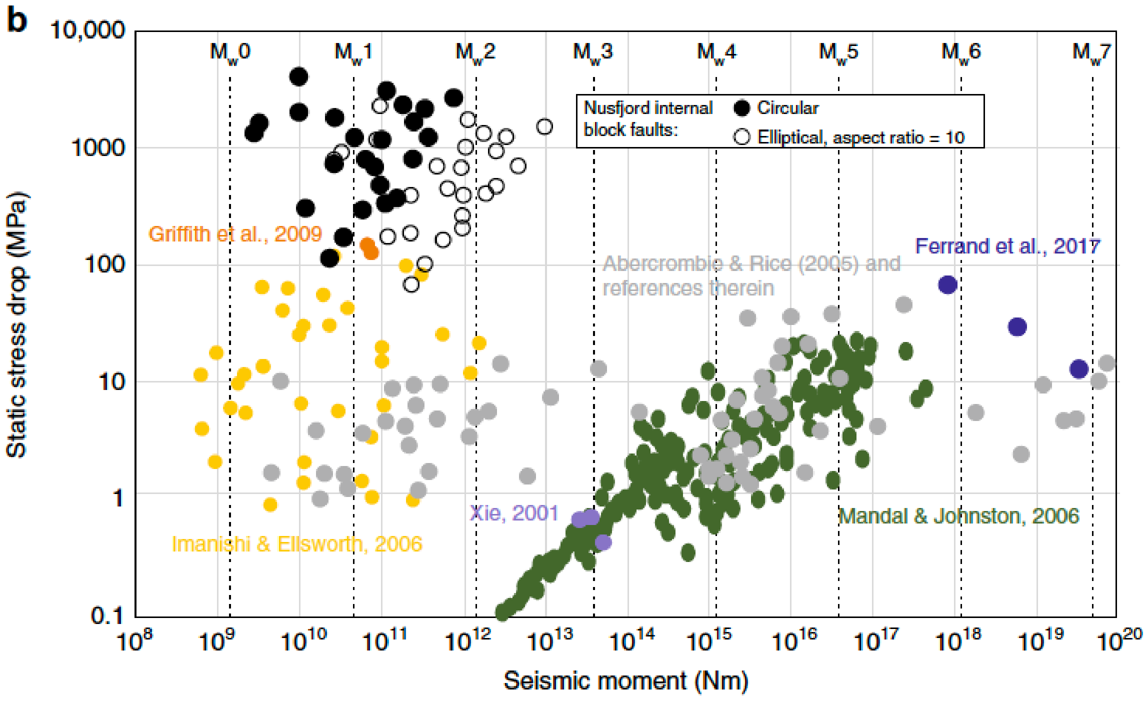
Pseudotachylyte veins show evidence of slip weakening

- Razor-sharp boundaries
- Melt injection into host-rock
- Microlithic quenching microstructures
- Rapid fault lubrication by melt

Laboratory experiments show large stress drops

- Shear resistance drops 80-95
- Steady-state friction falls to μ = 0.1 or lower
- Melt lubrication enables quasi-instantaneous stress reduction

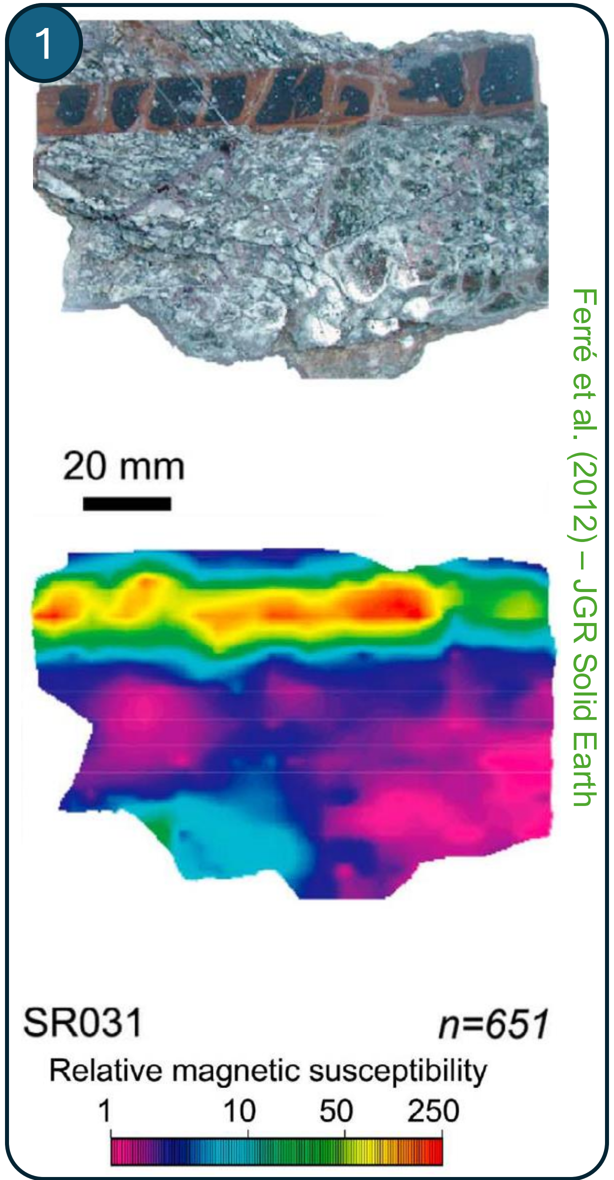
Numerical modelling suggest that most work is converted to heat



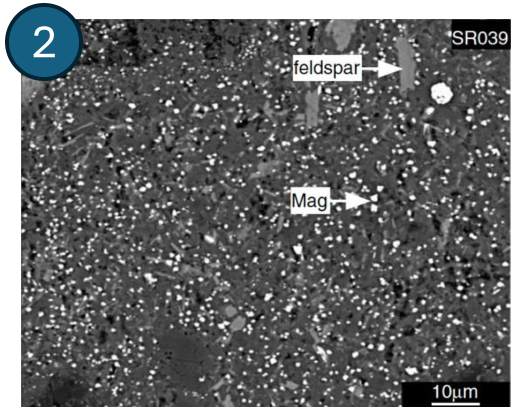
Campbell et al. (2020) – Nature Communications

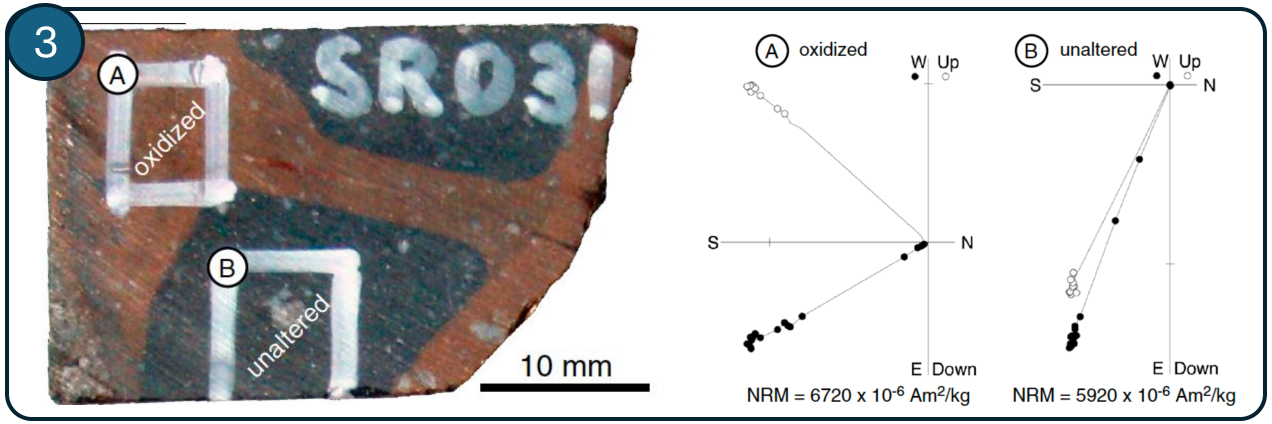
7.1. Recent advances

- Insights into frictional melting from pseudotachylyte magnetic properties



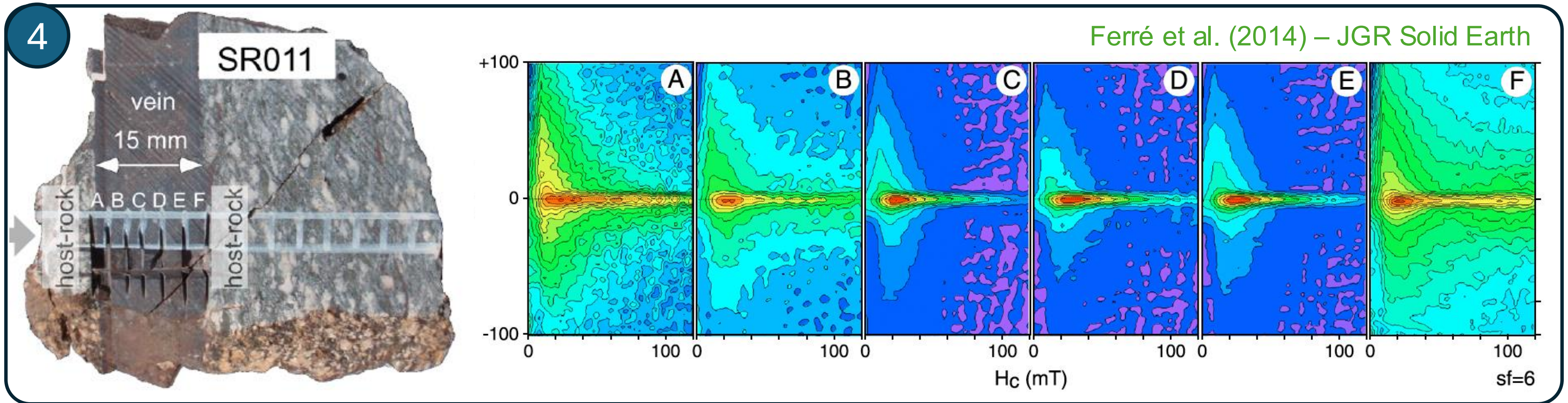
Ferré et al. (2012) – JGR Solid Earth





Ferré et al. (2014) – JGR Solid Earth

1. Pseudotachylytes are ~30x more magnetic than their host
2. Magnetite is the main magnetic mineral and it forms through breakdown of Fe-bearing minerals
3. Paleomagnetic data shows that alteration occurred long after seismic slip
4. Magnetite grain size decreases towards vein margins (chilled margins)

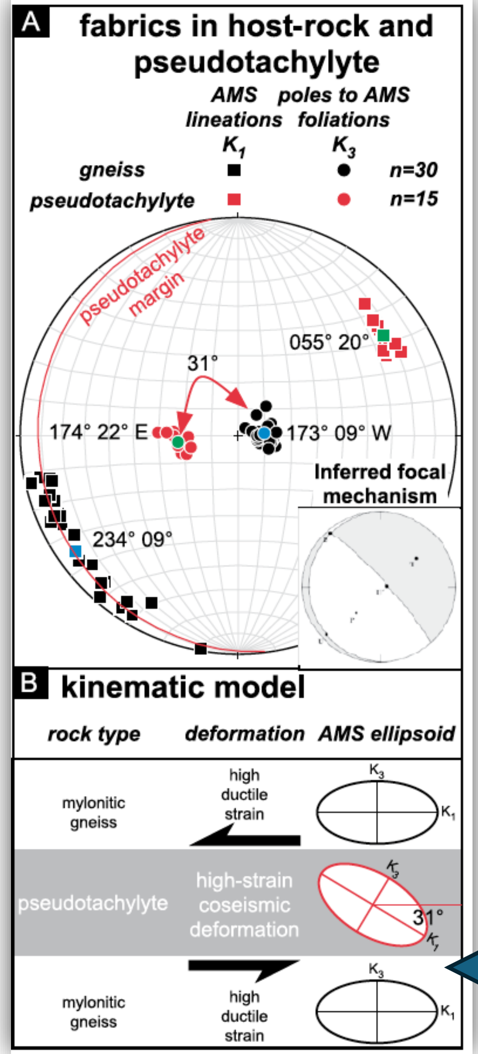


Ferré et al. (2014) – JGR Solid Earth

7.2. Recent advances

- Do fault pseudotachylytes record focal mechanism?
- Absolutely, YES!

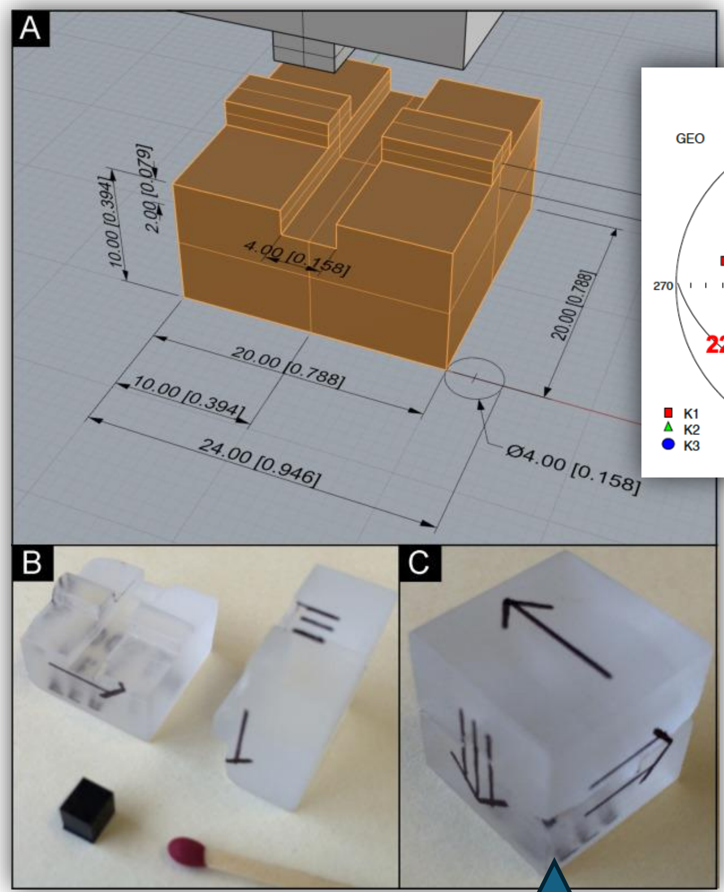
Dora Maira UHP massif, Italy

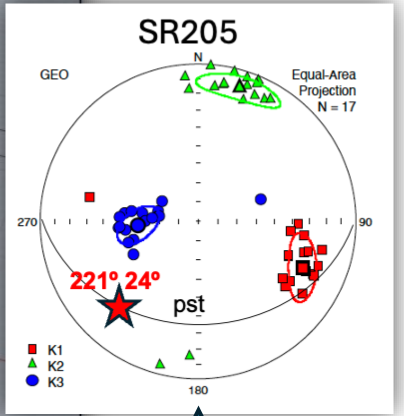


The obliquity of the AMS reflects the seismic slip sense

Ferré et al. (2015) - Geology

Scotland, California, Taiwan Qtz-feldspathic rocks



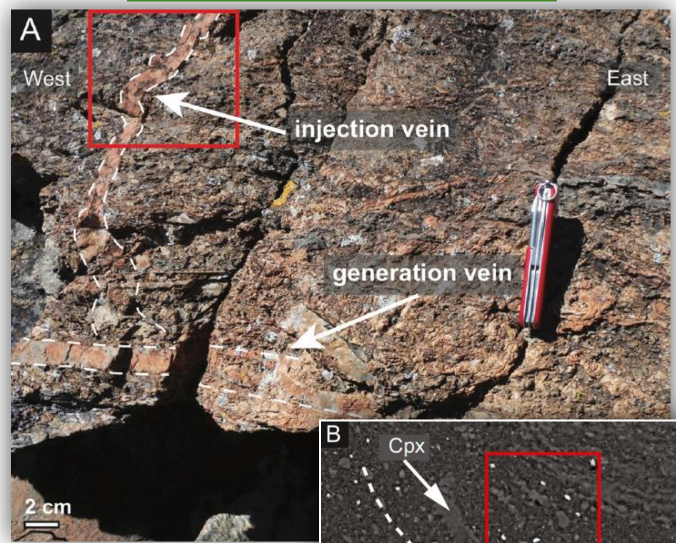


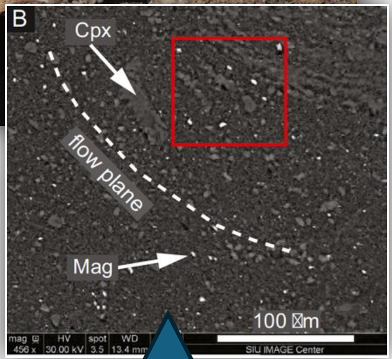
Very consistent AMS fabric

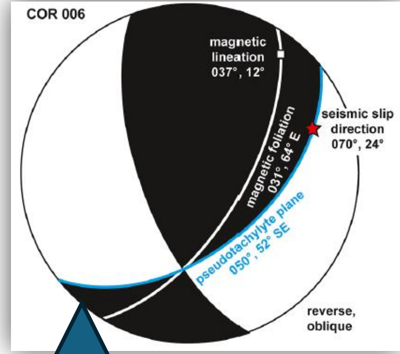
Custom-designed sample holders allow to measure at a resolution of 3.5 mm

Ferré et al. (2016) – J. Structural Geology

Corsica ophiolitic peridotite





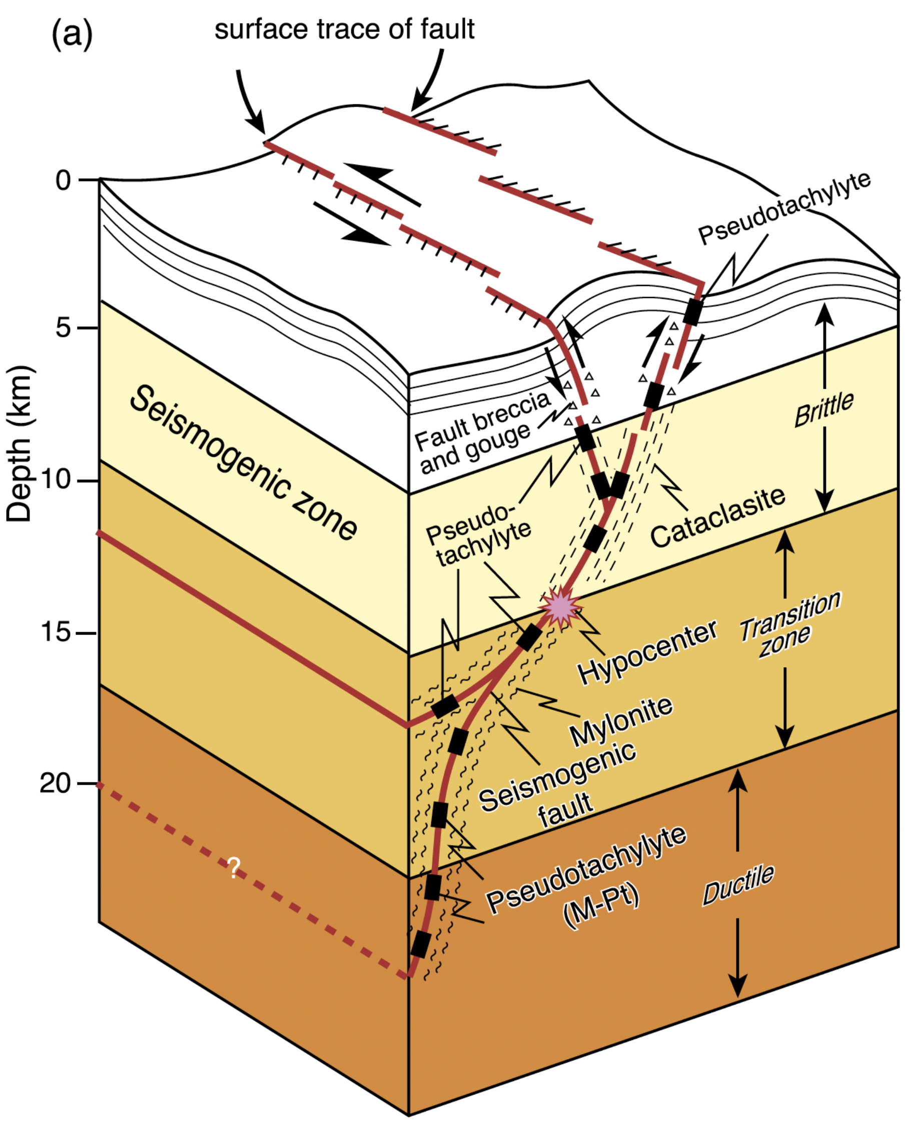


The AMS records viscous flow of magnetite grains

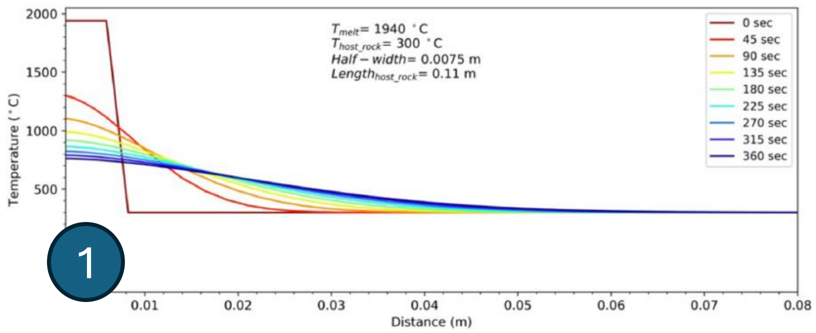
Earthquake focal mechanisms determined from obliquity of AMS with vein

Hosseinzadehsabeti et al. (2021) – JGR Solid Earth

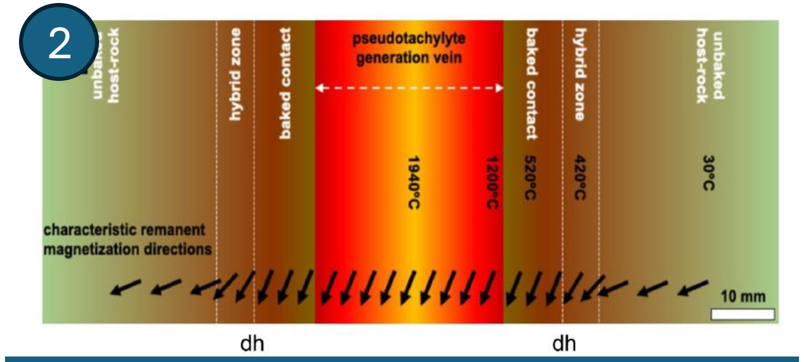
- At what depth do pseudotachylytes form?



Yang et al. (2020) – Reviews in Geophysics

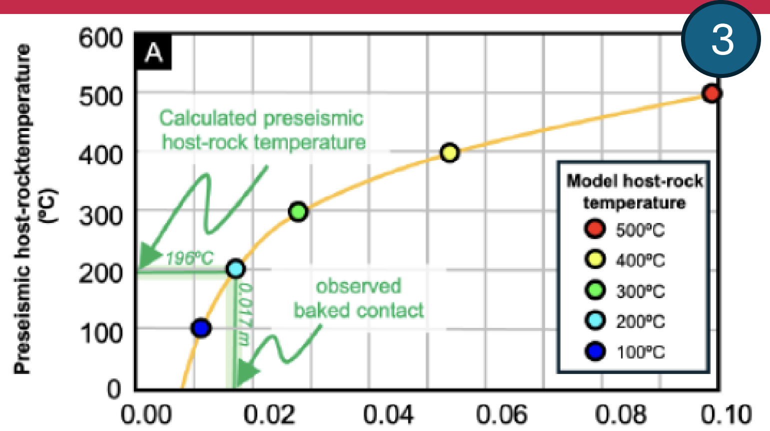


1-D numerical model of conductive cooling for a **15 mm-thick vein**

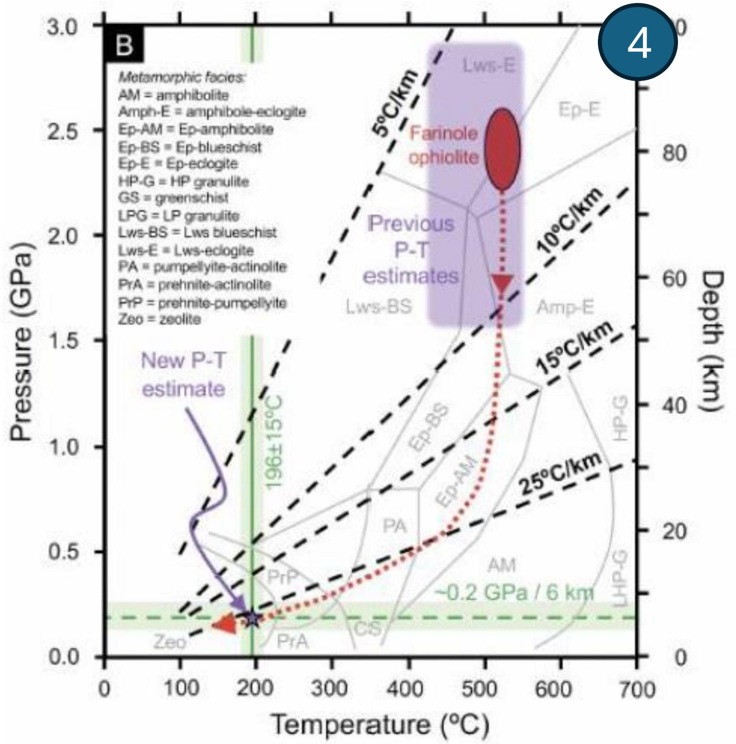


Paleomagnetic baked contact test on the same vein ⇒ 17 mm baked zone

Honarbakhsh et al. (2025) - EPSL

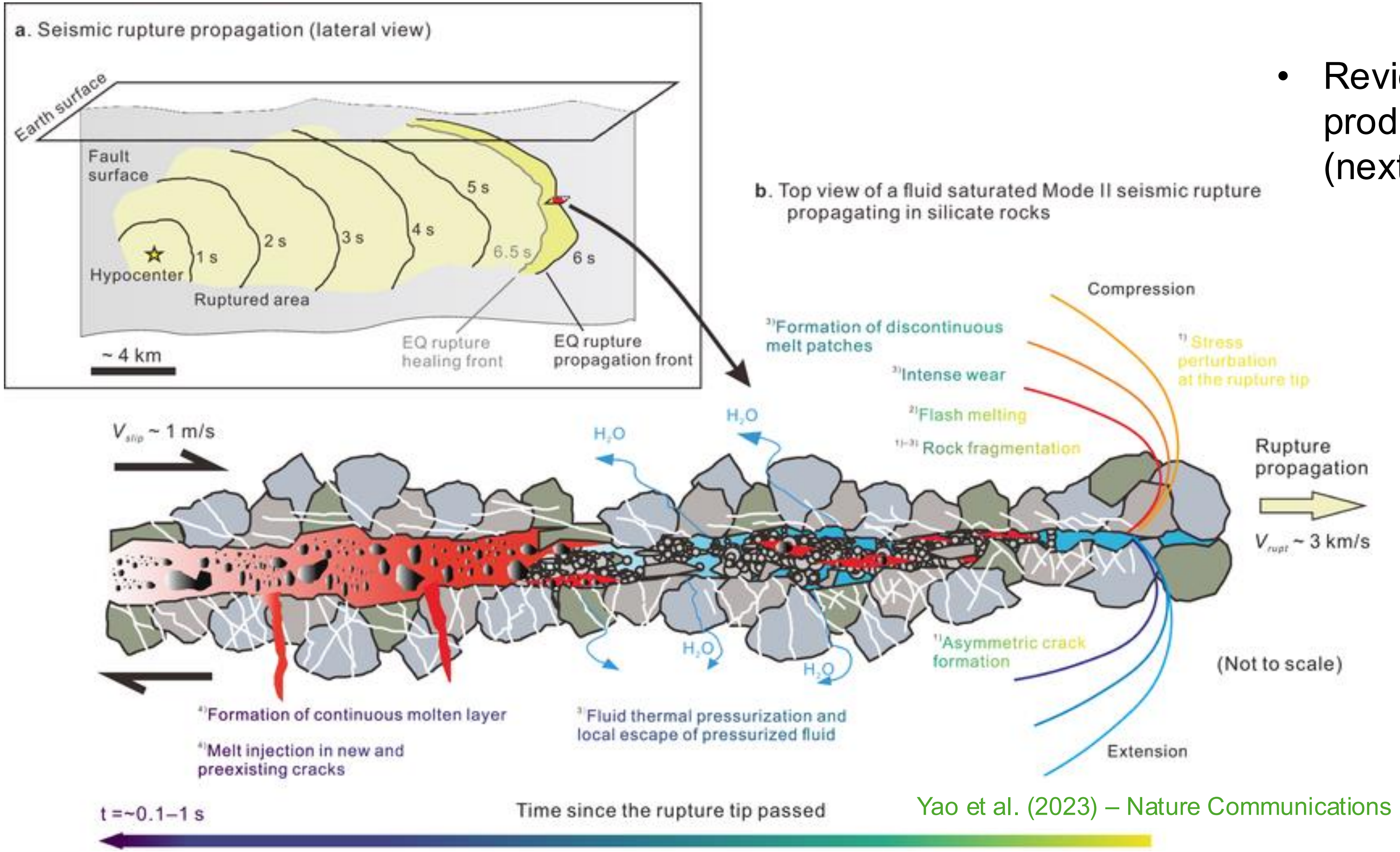


Predicted baked zone width vs host T°C



Coseismic host-rock ~196ºC
⇒ ~6 km depth (not 80 km as previously tought) …

- Do fault pseudotachylytes record coseismic rupture direction?



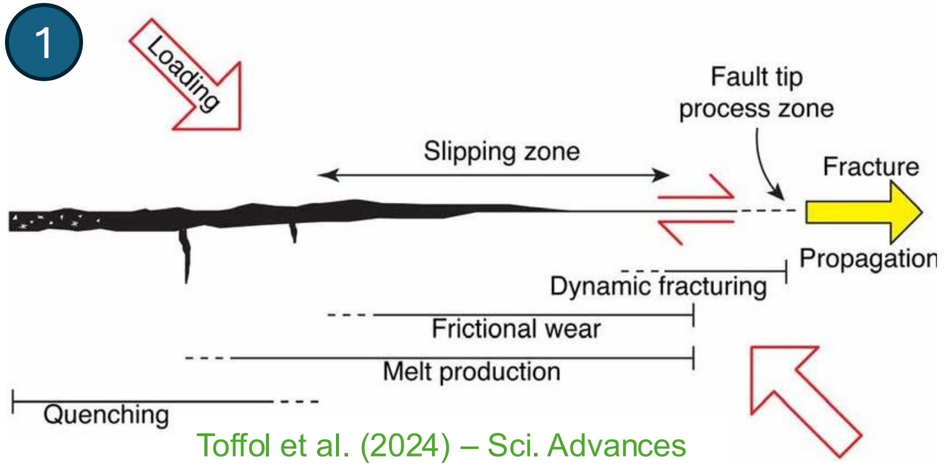
Yao et al. (2023) – Nature Communications

- Illustration of **crack tip** processes
- Review of macroscopic structures produced by **crack tip** propagation (next slide)

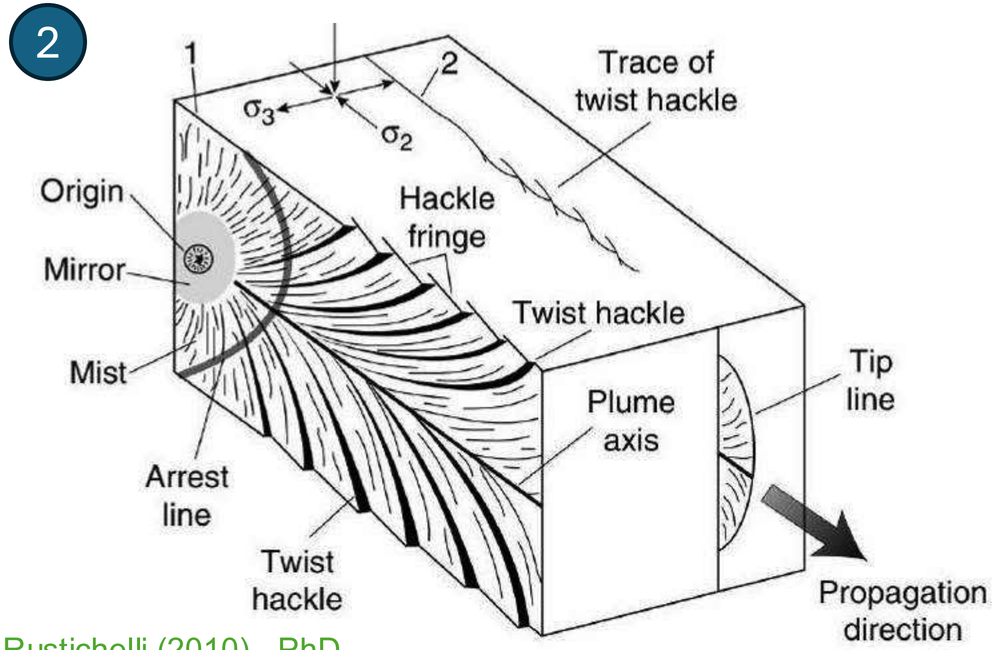
- Probably, YES!

8. Open questions

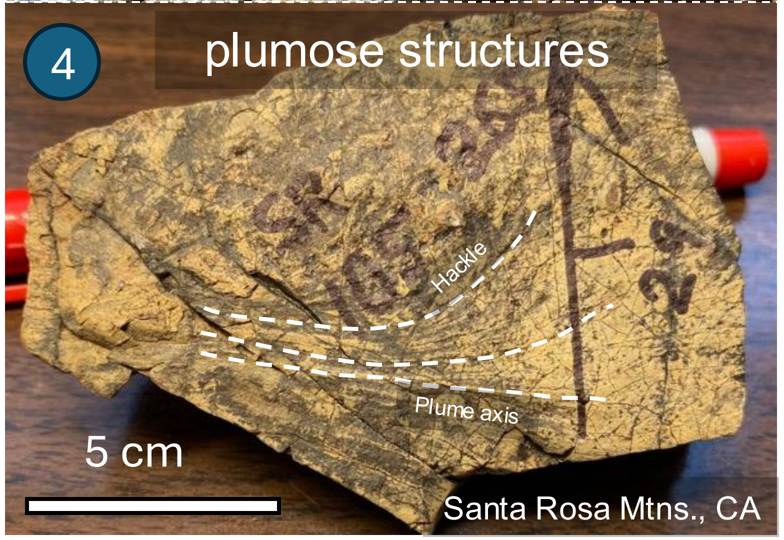
- Do fault pseudotachylytes record coseismic rupture direction?



Toffol et al. (2024) – Sci. Advances



Rustichelli (2010) - PhD



- In the Santa Rosa Mtns. pseudotachylytes, **slickenside steps** and **plumose structures** are observed, indicating coseismic rupture direction (work in progress)

- Probably, YES!

Conclusions

1. **Pseudotachylytes are definitive indicators of seismic slip**, formed through frictional melting at high slip rates (>0.1–1 m/s), providing clear evidence of extreme strain localization, rapid stress drop, and melt-driven fault lubrication during earthquakes

2. **Recent advances show that pseudotachylytes preserve rich information about earthquake processes**, including focal mechanisms, slip direction, rupture propagation, formation depth, and post-seismic magnetic and thermal histories

3. **Key open questions remain about rupture dynamics and conditions of melt formation**, especially the influence of fluids, geometric barriers, and crack-tip processes, highlighting pseudotachylytes as crucial natural recorders for advancing our understanding of fault mechanics and seismic hazards.

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