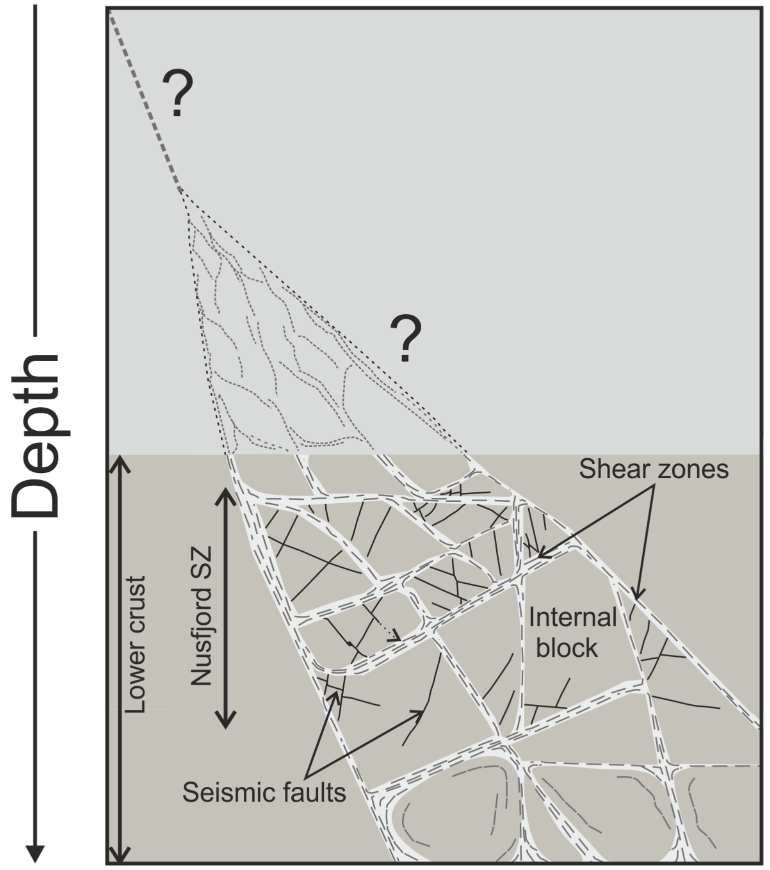
Pyroxene low-temperature plasticity and fragmentation as a record of seismic stress evolution in the lower crust



- Lower crustal pseudotachylytes associated with shear zones are proposed to represent a mechanism of deep earthquake nucleation where **localised stress amplifications are generated within active shear zone networks** [1]
- Dynamic rupture also generates transient stresses around the rupture front

What is the microstructural evidence for such stress oscillations?

-> Progressive twinning, low-temperature plasticity, fracturing and fragmentation in pyroxenes associated with pseudotachylyte faults represent a damage response to transient high stresses

Structural context
Lower crustal ruptures
Microstructure
Implications

UNIVERSITY OF PLYMOUTH
School of Geography, Earth and Environmental Sciences

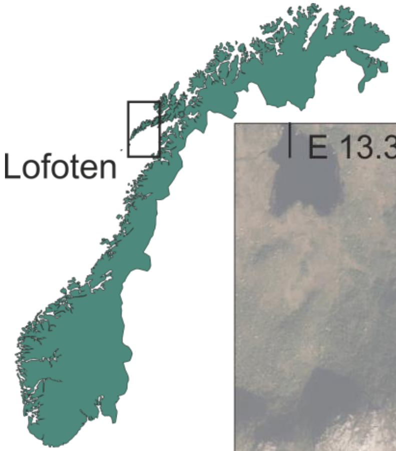
Lucy Campbell[a] and Luca Menegon[a,b]

[a] School of Geography, Earth and Environmental Sciences, University of Plymouth, UK (lucy.campbell@plymouth.ac.uk)

[b] The Njord Centre, Department of Geoscience, University of Oslo, Norway

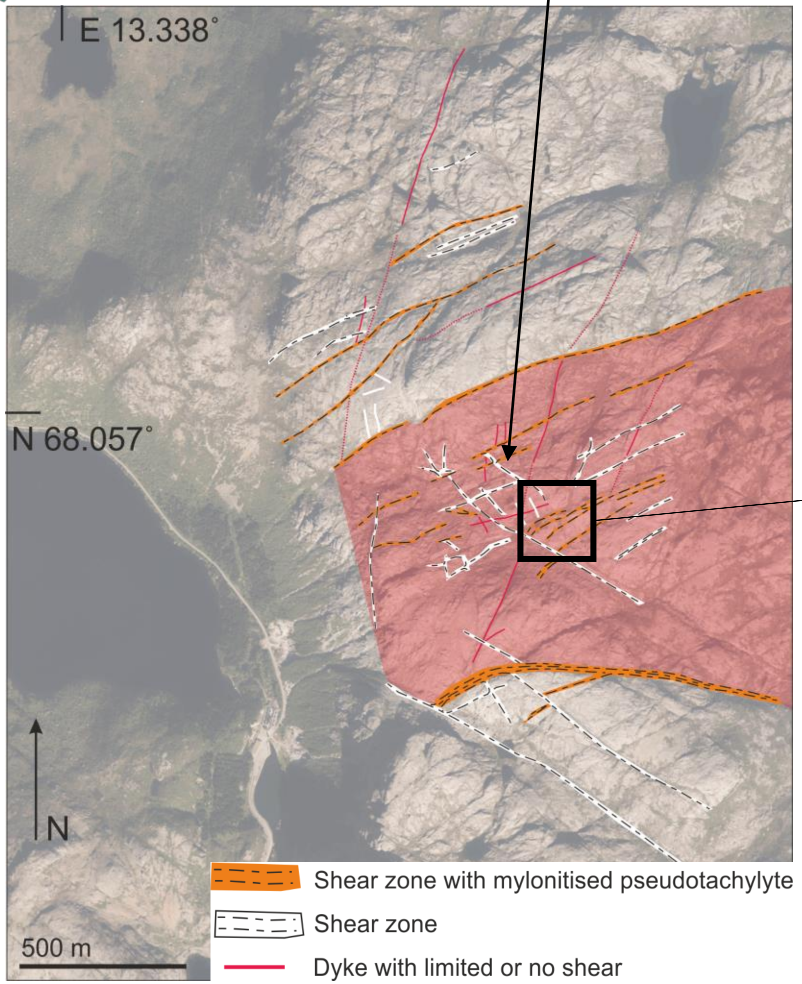
Structural context

HOME

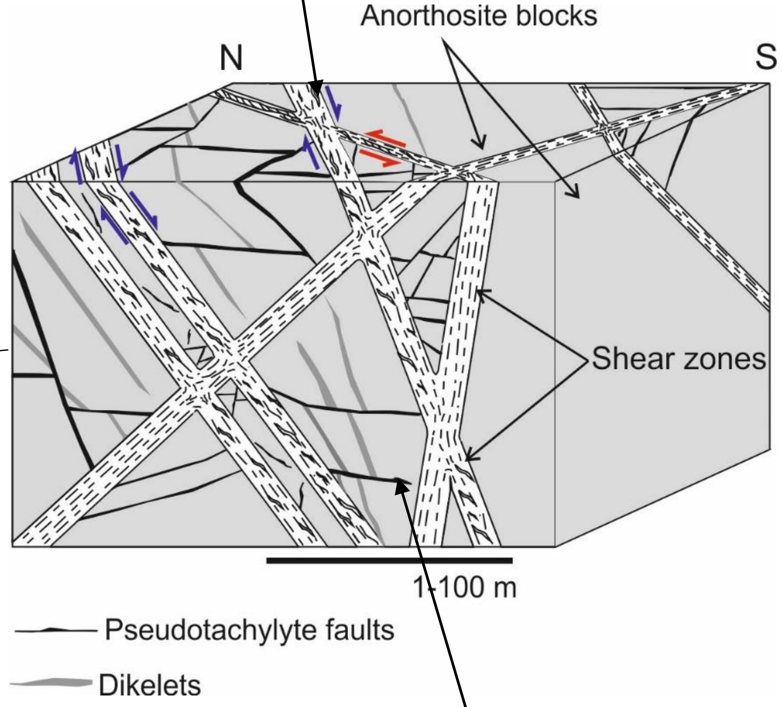


Case study: Nusfjord east shear zones

Multiple coeval shear zone orientations



Shear zones highly localised, preserving low strain blocks of strong anorthosite between them



Pseudotachylyte-bearing faults dissect these strong blocks and are demonstrably coeval with (and form in response to) viscous creep along shear zones [1]

Exhumed shear zones in anhydrous anorthosite preserve deformation of lower continental crust [2]

HOME

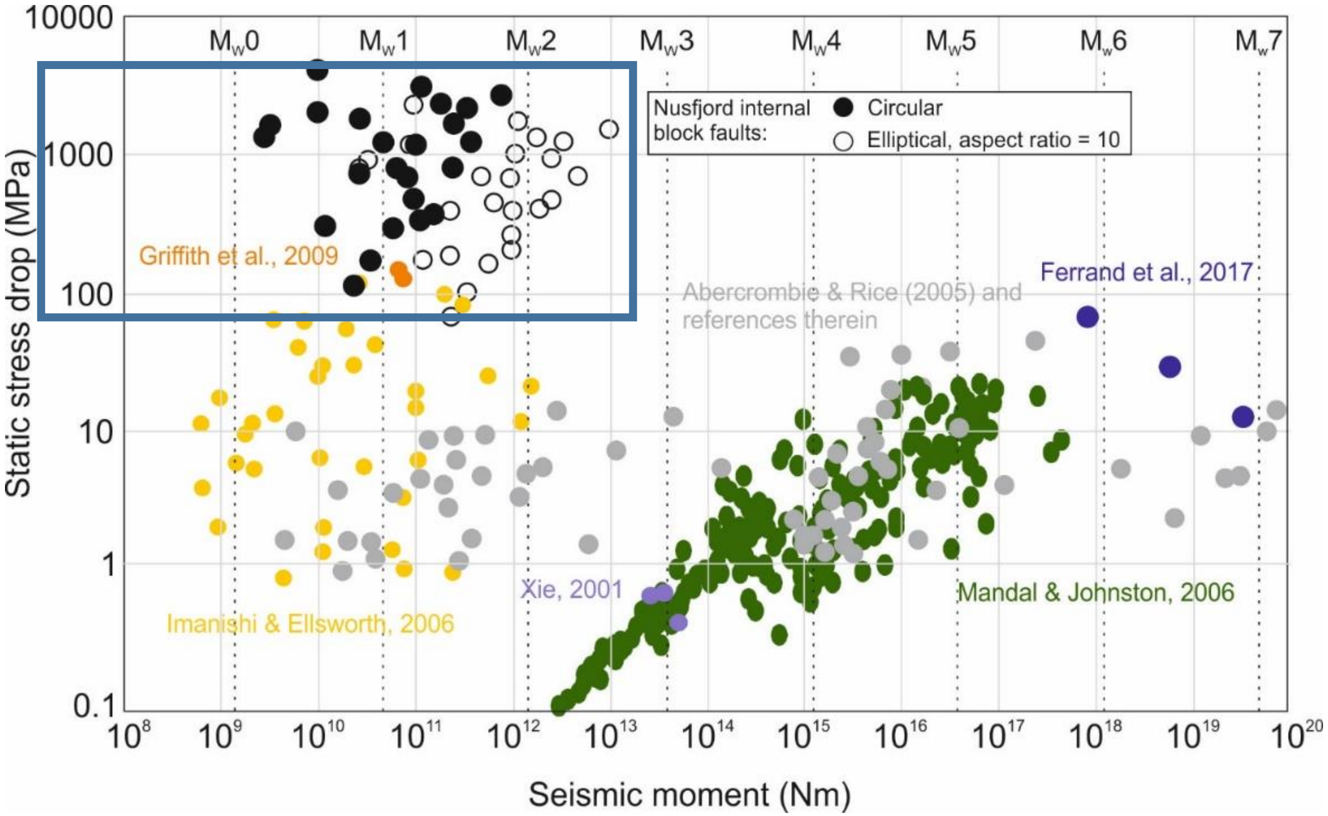
Pseudotachylyte faults as evidence of transient stress amplification?

High stress drops calculated for ancient seismic ruptures preserved in exhumed shear zones (pseudotachylytes) indicate high failure stresses.

Is there evidence for transiently high stresses within lower crustal shear zone networks?

Approach:

- Investigate microstructural record of **rupture-related deformation mechanisms**
- Pyroxenes: clear record of overprinting and evolving deformation microstructures

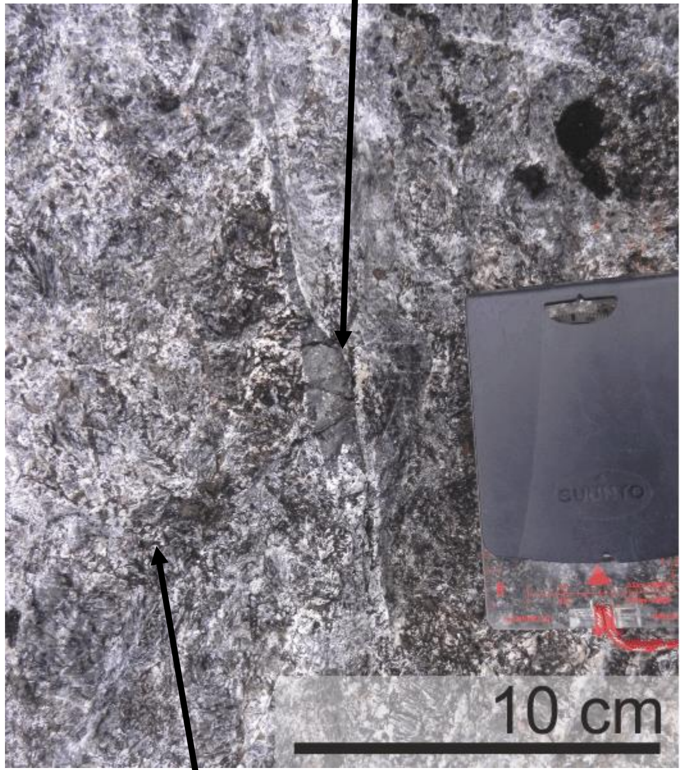


Campbell et al., 2020

Context **Pseudotachylytes** High stress microstructures: host rock High stress microstructures: clasts Implications

Pseudotachylyte faults: evidence for seismic slip in the lower crust

Fault stepover with pseudotachylyte

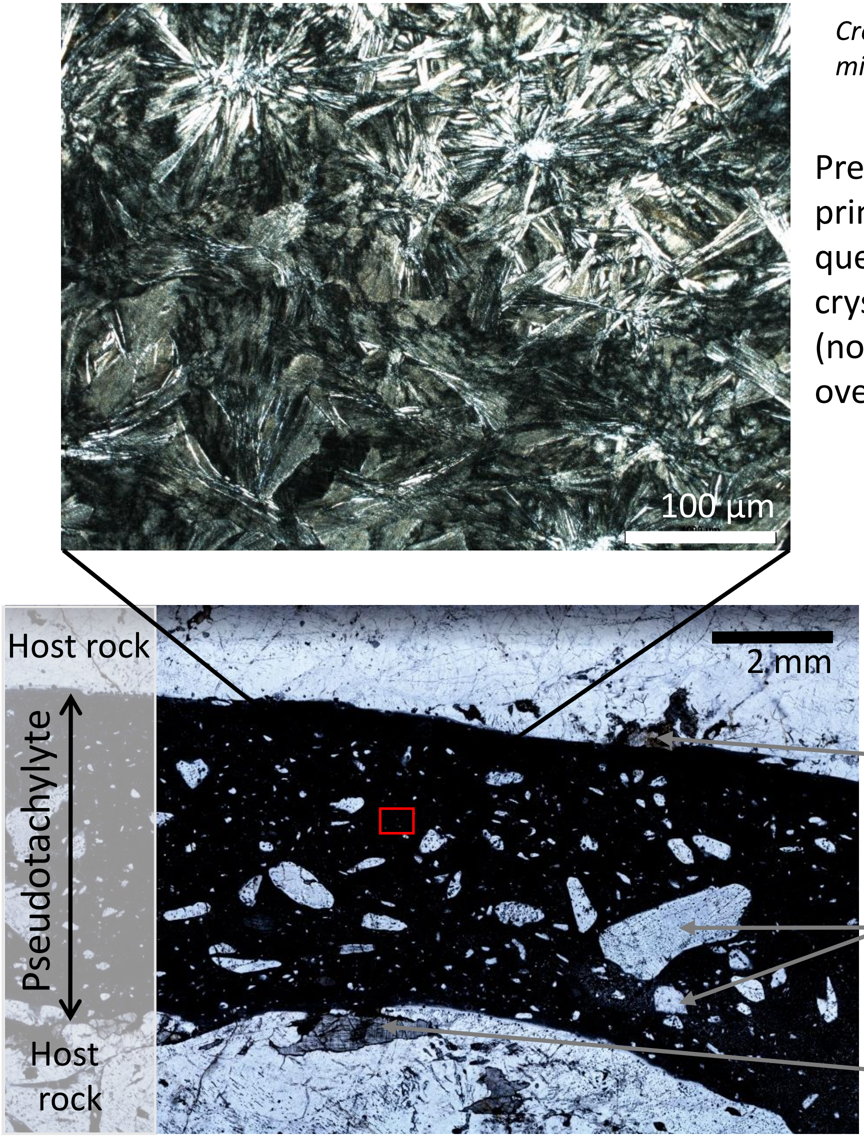


Campbell et al., 2020

Microfractured anorthosite

Cross-polarised micrograph

Preservation of primary quench crystallisation (no viscous overprint)

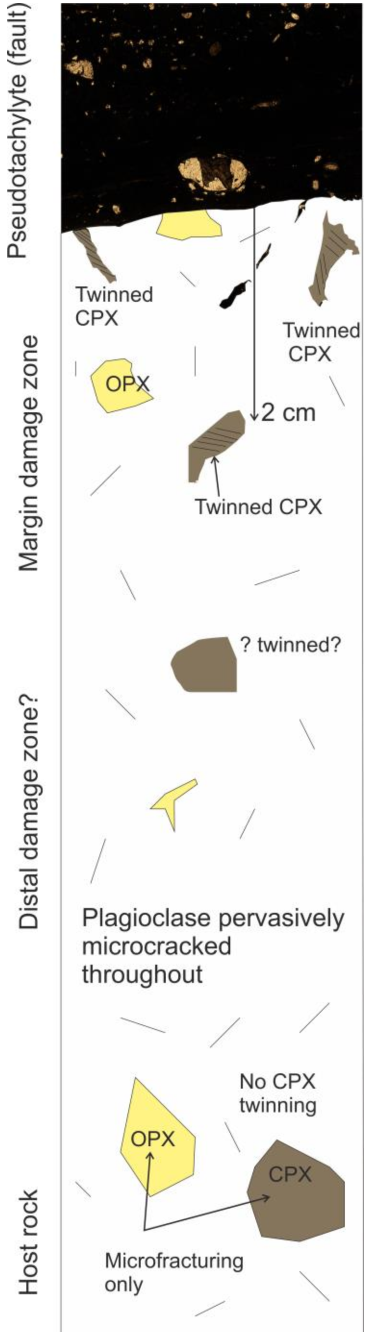


Plane-polarised micrograph

Orthopyroxene

Clasts

Clinopyroxene

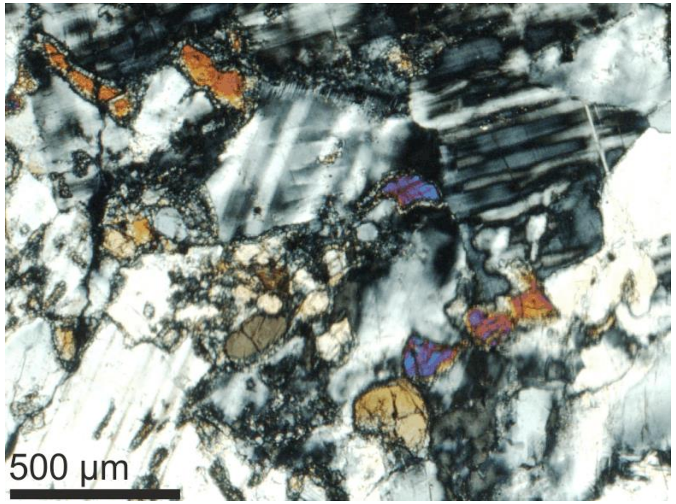


HOME

Microstructural evidence for high stress oscillations: host rock

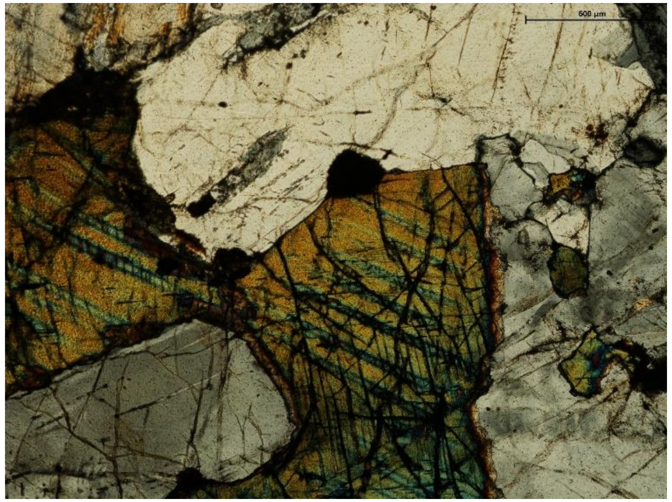
Clinopyroxene

A



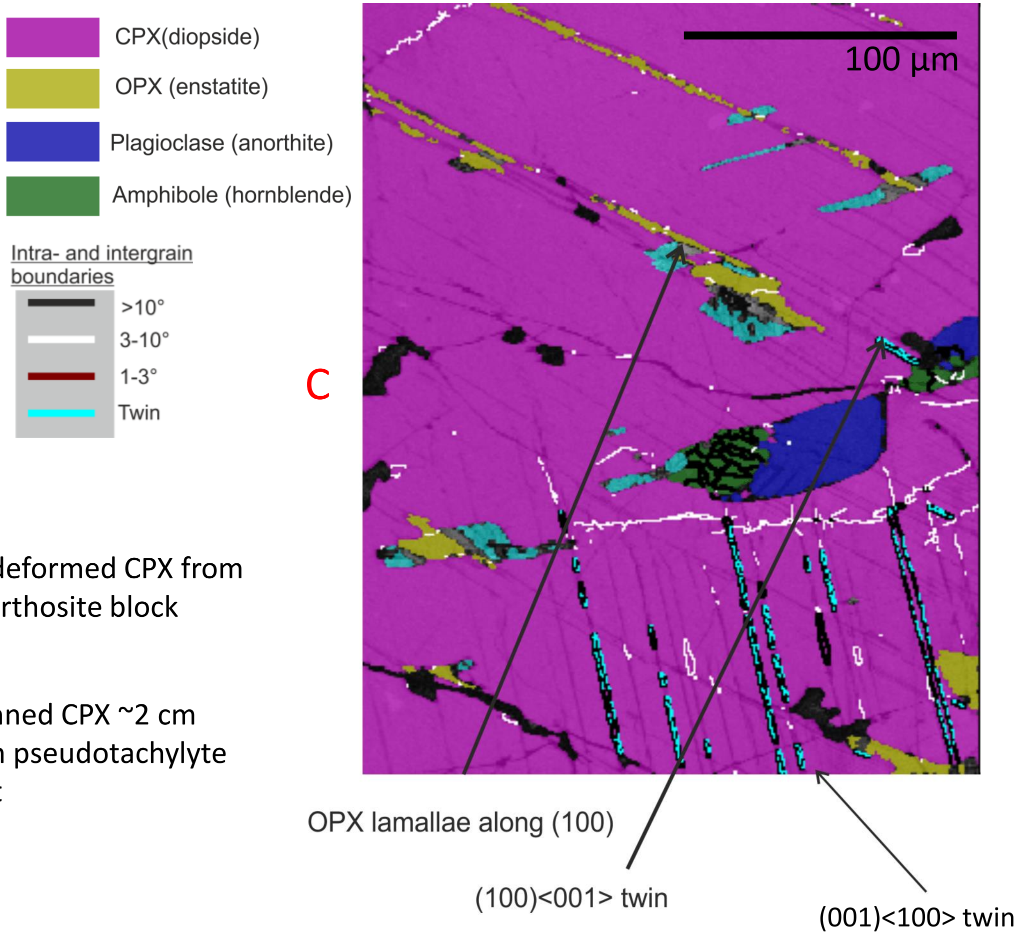
Undeformed CPX from anorthosite block

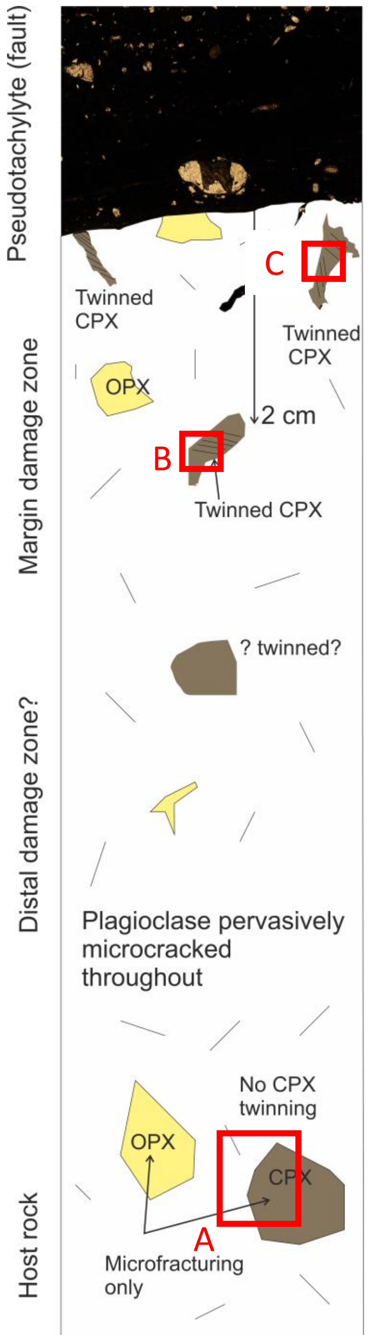
B



Twinned CPX ~2 cm from pseudotachylyte fault

C





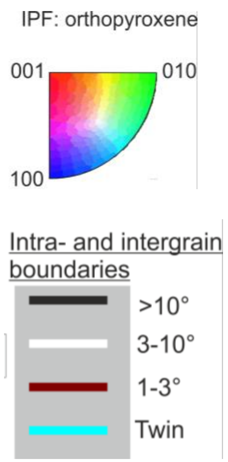
- Deformation twinning spatially associated with fault?
- Earliest deformation microstructure
- Indicates $\tau_{resolved}$ > 160 MPa [3]

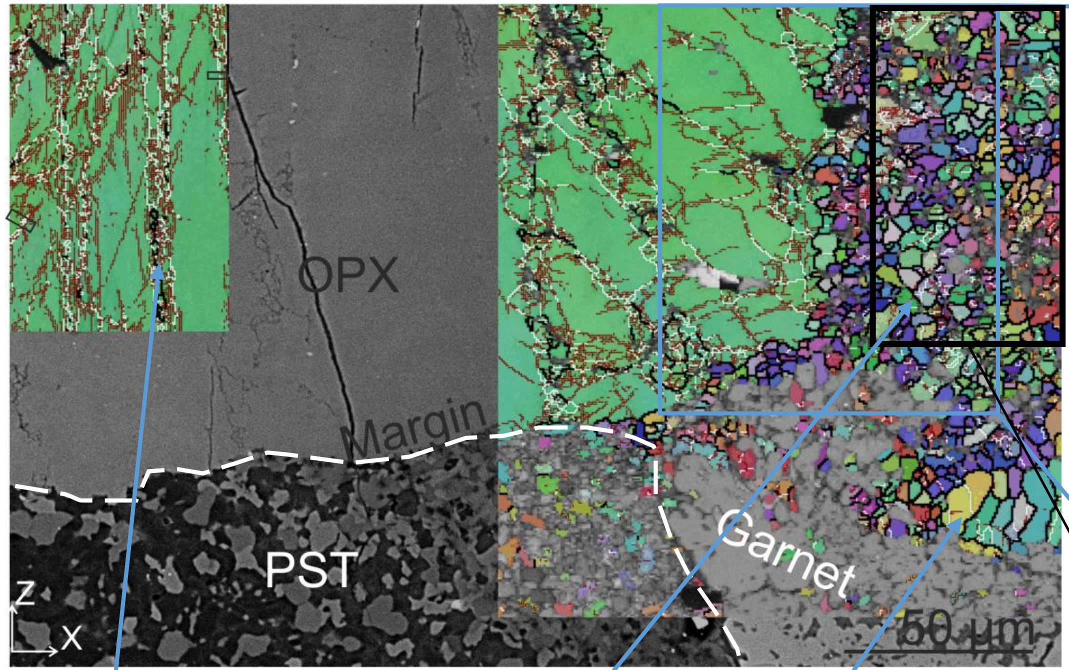
Context | Pseudotachylytes | **High stress microstructures: host rock** | High stress microstructures: clasts | Implications

Microstructural evidence for high stress oscillations: host rock

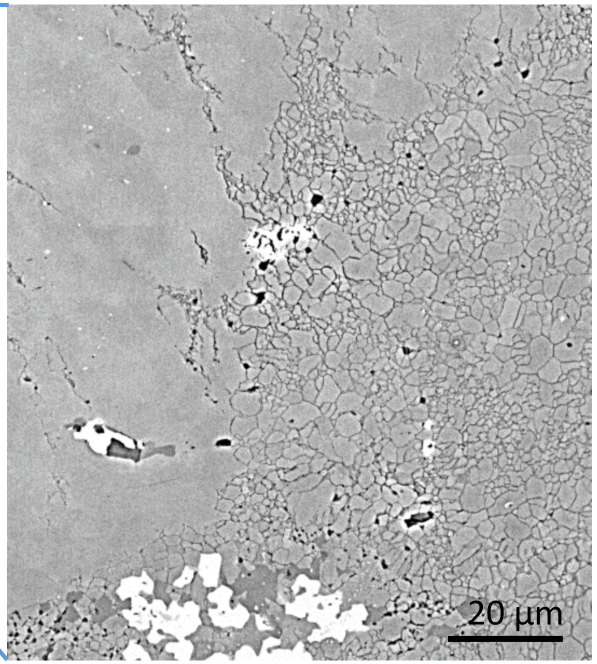
Orthopyroxene

HOME





Deformed OPX in fault wall
IPF X (orientation) EBSD map

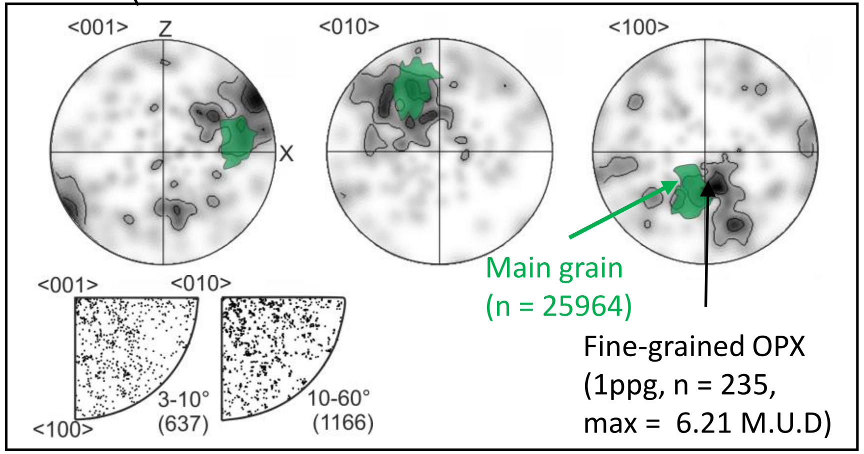


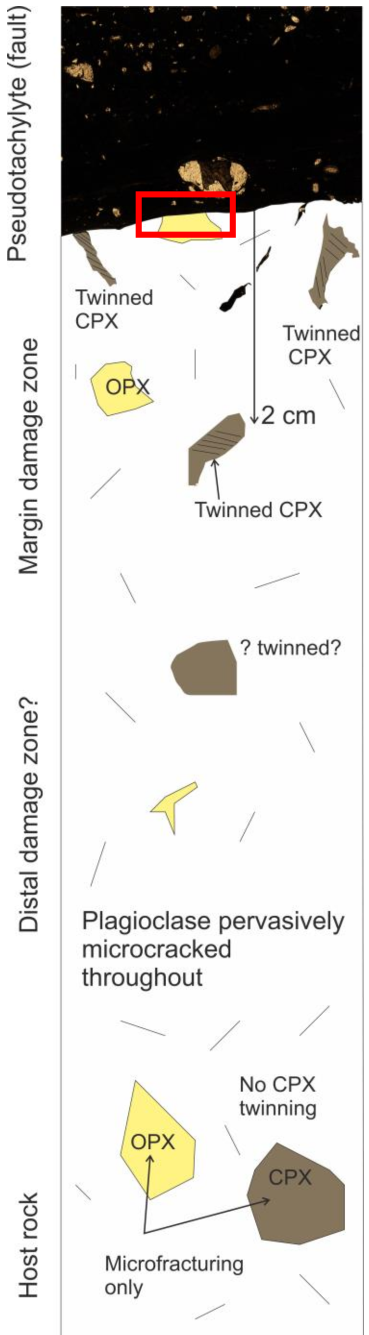
Fragmented OPX
Backscattered electron image

Grain growth

Large regions of pulverisation-style shattered OPX (no shear between fragments)

Earlier fracturing preserved away from fragmented region



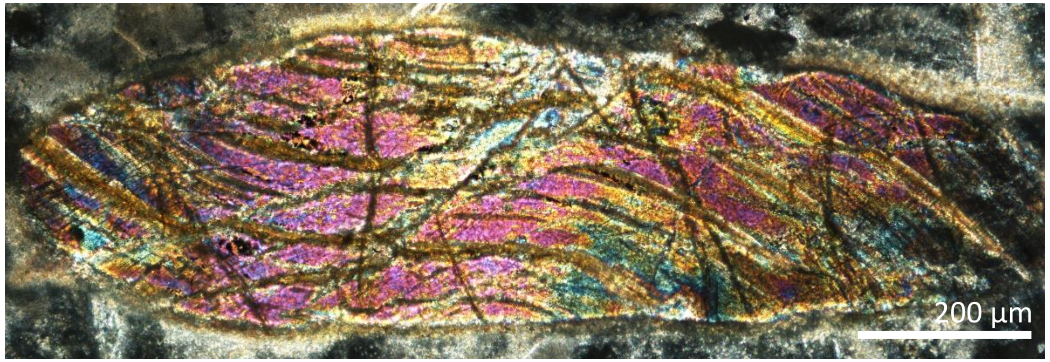


Context | Pseudotachylytes | **High stress microstructures: host rock** | High stress microstructures: clasts | Implications

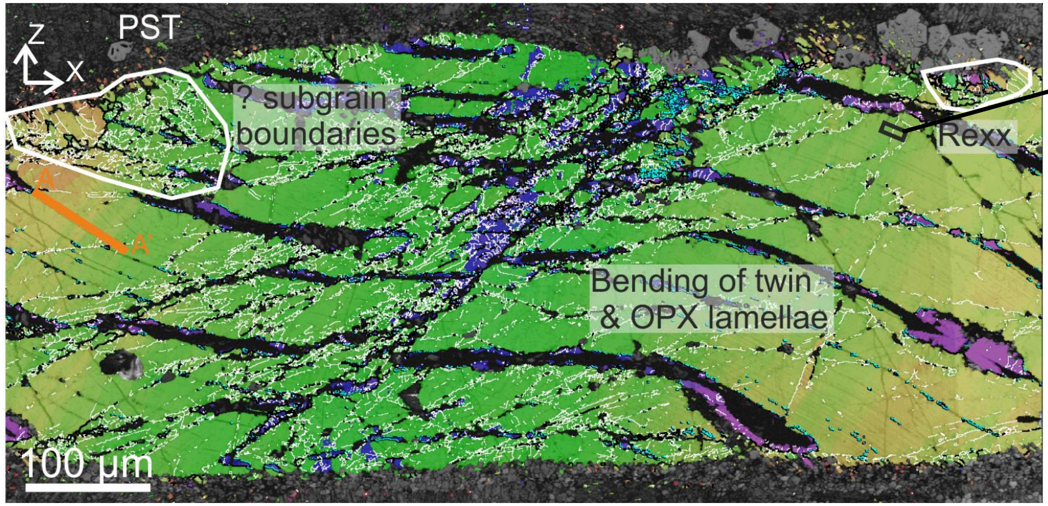
HOME

Microstructural evidence for high stress oscillations: fault clasts

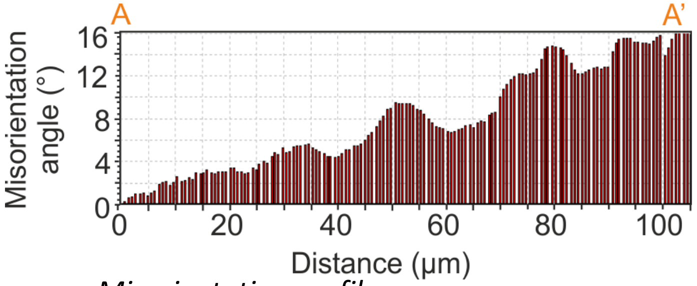
Clinopyroxene



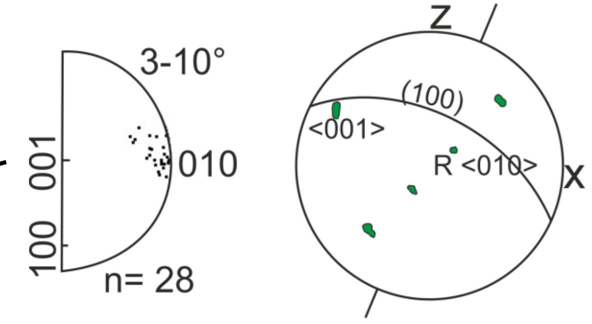
Deformed CPX clast, cross-polarised image



Deformed CPX clast IPF X (Orientation) EBSD map

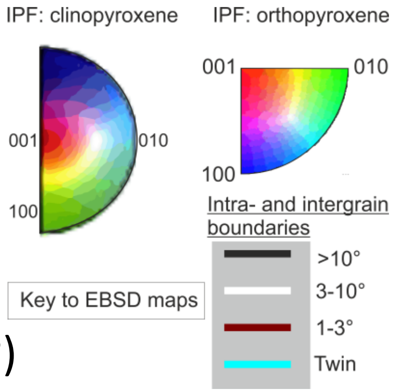


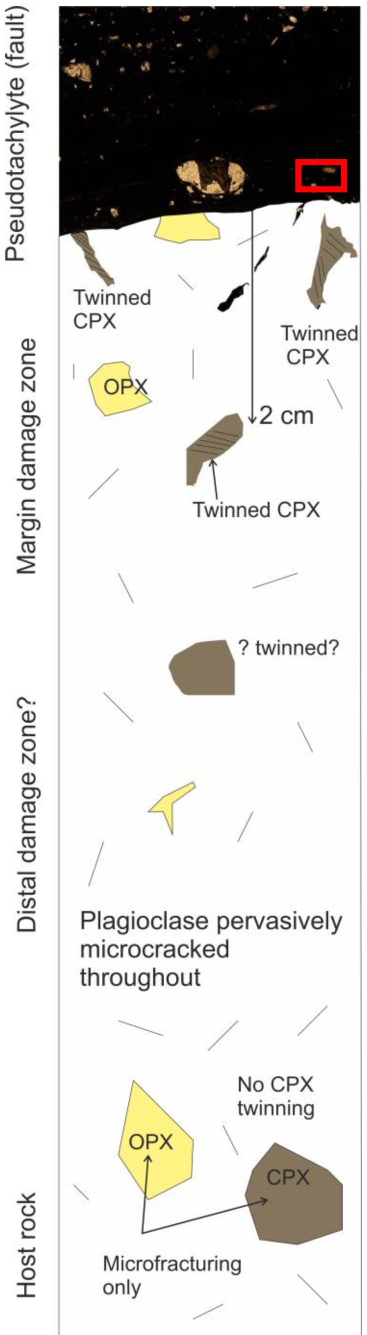
Misorientation profile



Boundary trace analysis

Regular low-angle undulations (<3°) suggest glide on (100)<001> - <u>high stress response</u> [4]





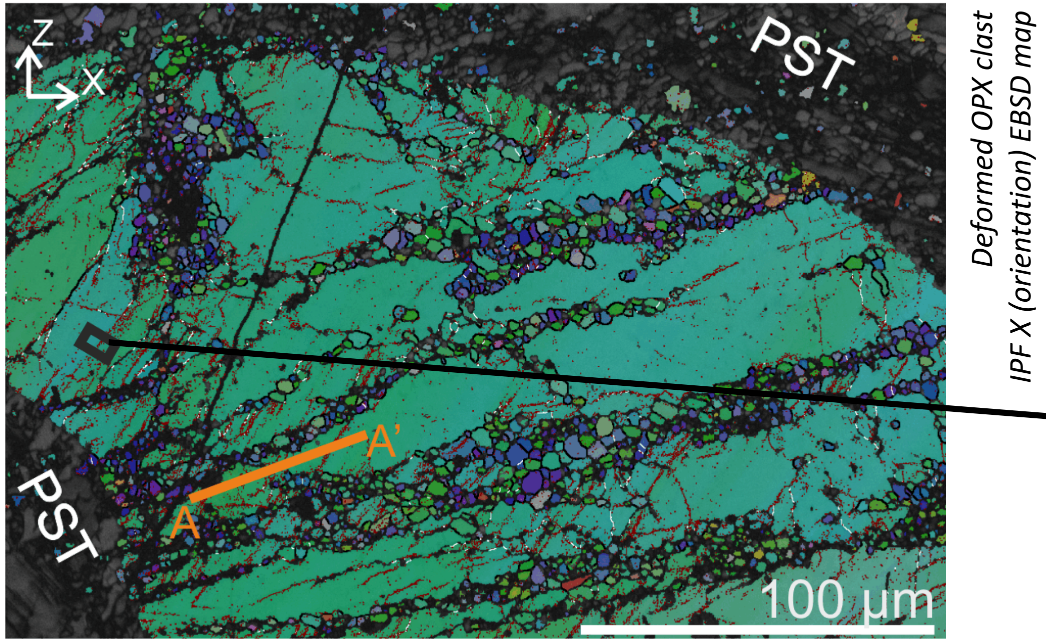
- Twins deformed and cut by low-angle boundaries and cracks
- Network of low-angle boundaries develops
- Clustered low-angle & high-angle boundaries at clast edge (temperature effect?)

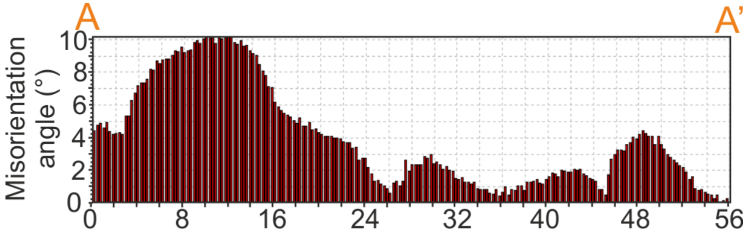
Context Pseudotachylytes High stress microstructures: host rock **High stress microstructures: clasts** Implications

Microstructural evidence for high stress oscillations: fault clasts

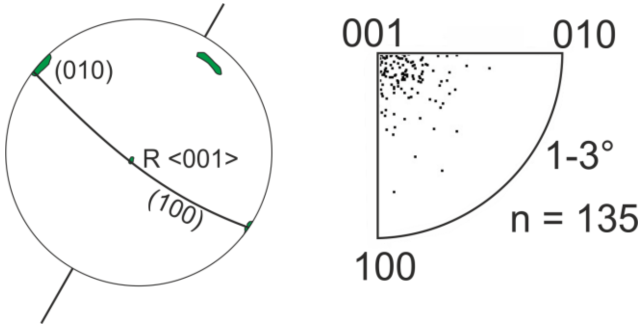
Orthopyroxene

HOME

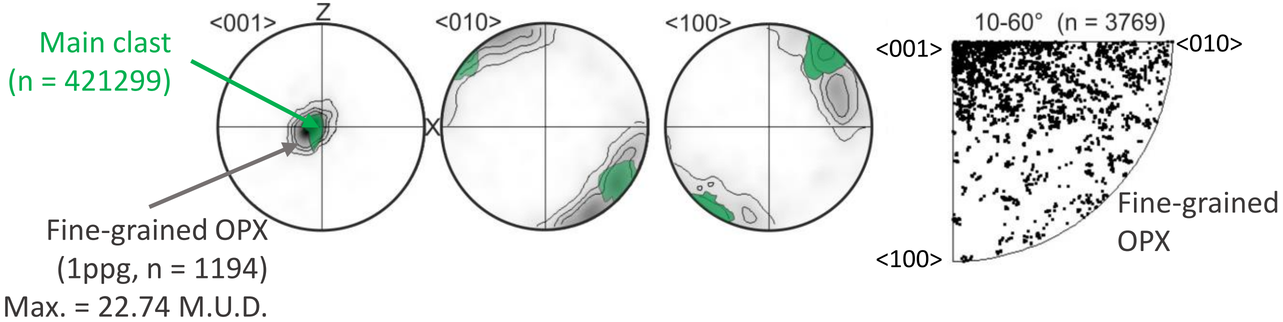


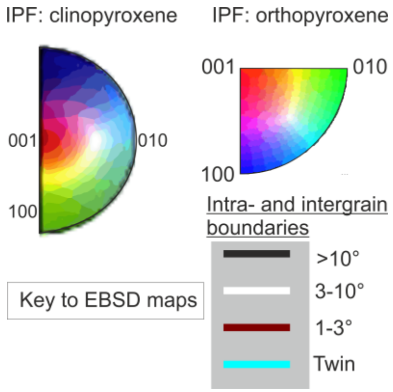


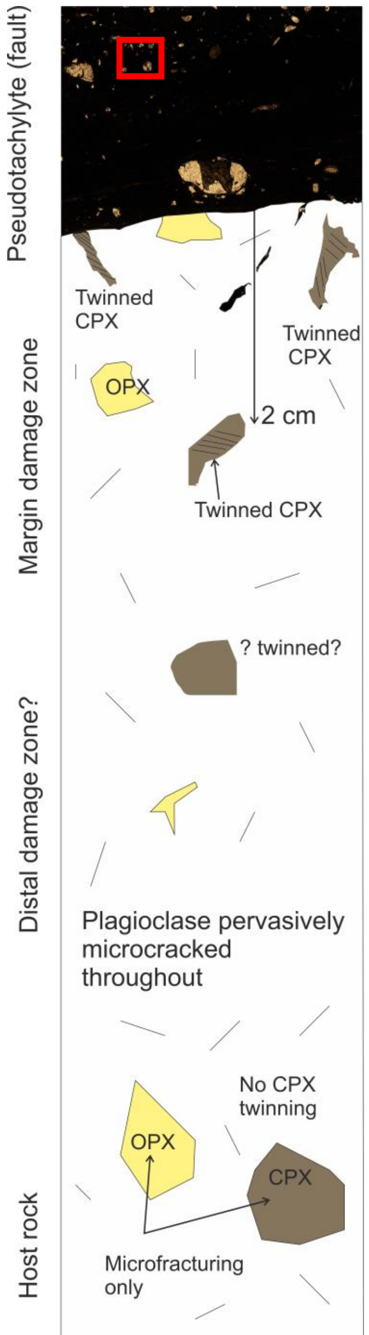
Misorientation profile (oblique to undulation trend)



Boundary trace analysis







- Regular low angle undulations suggest glide on (100)<010> - high stress response [4]
- Cross-cutting fractures contain linear arrays of fine-grained OPX

Context Pseudotachylytes High stress microstructures: host rock **High stress microstructures: clasts** Implications

Evolution of high stresses and association with rupture

Clinopyroxene deformation

Low-T plasticity

Twinning (moderate stress)

↓

Undulose extinction
(high stress)

↓

Low angle boundaries
(high stress)

In fault clasts only

Orthopyroxene deformation

Low-temperature plasticity?

↓

Undulose extinction (in clast only,
high stress)

↓

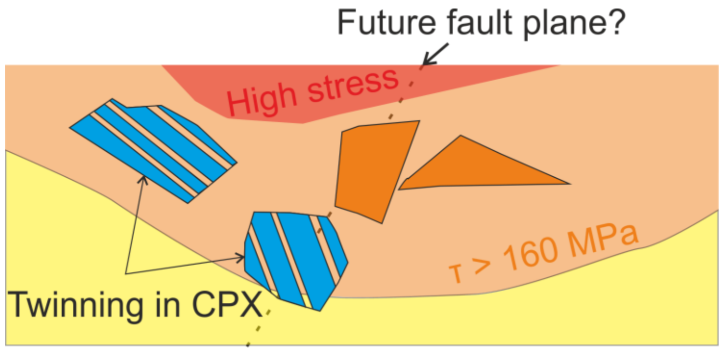
Fracturing

↓

Fragmentation (fault wall only, high
stress)

Rupture
tip

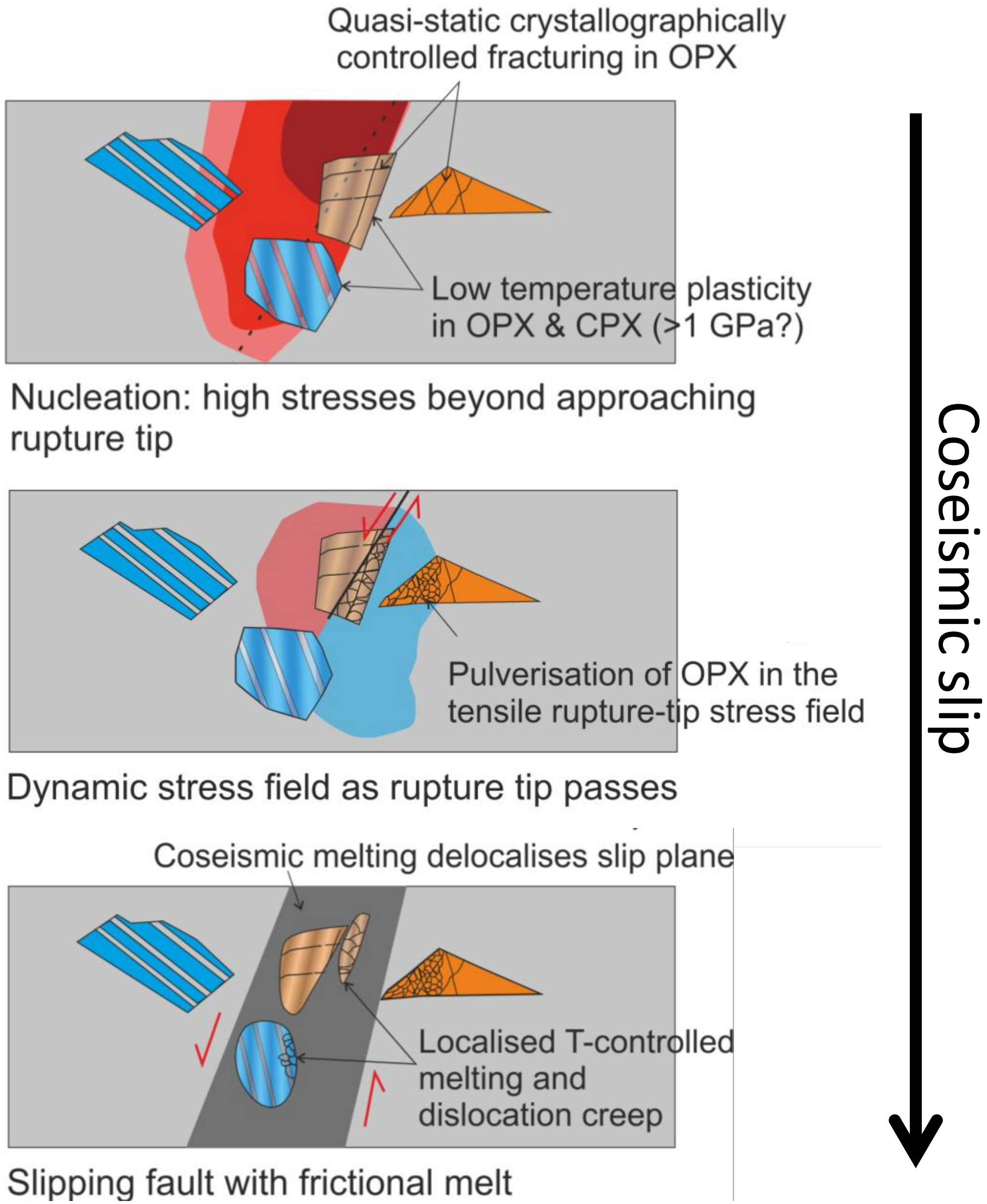
Evolution of high stresses and association with rupture



Stress amplification in anorthosite block during viscous shear zone creep

Twinning in CPX:

- Moderate stress response, diffuse spatial distribution – may be local stress amplifications
- Earliest deformation in every case



Pyroxene deformation adjacent to and within fault planes:

- dominated by low-temperature plasticity and fracturing;
- 2. exhibits several high stress deformation mechanisms (twinning [3], short-wavelength undulose extinction [4], and pulverisation-style fragmentation [5])
- 3. displays progressive strain hardening

References

[1] Campbell, L.R., Menegon, L., Fagereng & Pennacchioni, G. 2020. Earthquake nucleation in the lower crust by local stress amplification. *Nature Communications*, **11**, 1322, https://doi.org/10.1038/s41467-020-15150-x.

[2] Menegon, L., Pennacchioni, G., Malaspina, N., Harris, K., & Wood, E. (2017). Earthquakes as Precursors of Ductile Shear Zones in the Dry and Strong Lower Crust. *Geochemistry, Geophysics, Geosystems*, *18*(12), 4356–4374. https://doi.org/10.1002/2017GC007189

[3] Kollé, J. J., & Blacic, J. D. (1982). Deformation of single-crystal clinopyroxenes: 1. Mechanical twinning in diopside and hedenbergite. *Journal of Geophysical Research: Solid Earth*, *87*(B5), 4019–4034. https://doi.org/10.1029/JB087iB05p04019

[4] Trepmann, C. A., & Stöckhert, B. (2013). Short-wavelength undulatory extinction in quartz recording coseismic deformation in the middle crust – an experimental study. *Solid Earth*, *4*(2), 263–276. https://doi.org/10.5194/se-4-263-2013

[5] Sullivan, W. A., & Peterman, E. M. (2017). Pulverized granite at the brittle-ductile transition: An example from the Kellyland fault zone, eastern Maine, U.S.A. *Journal of Structural Geology*, *101*, 109–123. https://doi.org/10.1016/j.jsg.2017.07.002

See also:

Campbell, L. R., & Menegon, L. (2019). Transient High Strain Rate During Localized Viscous Creep in the Dry Lower Continental Crust (Lofoten, Norway). *Journal of Geophysical Research: Solid Earth*, *124*, 10240–10260. https://doi.org/10.1029/2019JB018052

Jamtveit, B., Petley-Ragan, A., Incel, S., Dunkel, K. G., Aupart, C., Austrheim, H., et al. (2019). The Effects of Earthquakes and Fluids on the Metamorphism of the Lower Continental Crust. *Journal of Geophysical Research: Solid Earth*, *0*(0). https://doi.org/10.1029/2018JB016461

Petley-Ragan, A., Ben-Zion, Y., Austrheim, H., Ildefonse, B., Renard, F., & Jamtveit, B. (2019). Dynamic earthquake rupture in the lower crust. *Science Advances*, *5*(7), eaaw0913. https://doi.org/10.1126/sciadv.aaw0913