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.

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Structural context

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

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]

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

[Image of a graph showing the relationship between seismic moment and static stress drop. The graph includes data points from various studies, such as Nusfjord internal block faults, Circular, Elliptical, and references from Ferrand et al., 2017, Abercornbrie & Rice, 2008, and others.]

**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

Microfractured anorthosite

Preservation of primary quench crystallisation (no viscous overprint)

Cross-polarised micrograph

Plane-polarised micrograph

Pseudotachylyte

Host rock

Orthopyroxene

Clasts

Clinopyroxene

Context  Pseudotachylytes  High stress microstructures: host rock  High stress microstructures: clasts  Implications
Microstructural evidence for high stress oscillations: host rock

Clinopyroxene

- Deformation twinning spatially associated with fault?
- Earliest deformation microstructure
- Indicates \( \tau_{\text{resolved}} > 160 \text{ MPa} \) \[^3\]
Microstructural evidence for high stress oscillations: host rock

Orthopyroxene

Fragmented OPX
Backscattered electron image

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

Main grain
(n = 25964)

Fine-grained OPX
(1ppg, n = 235, max = 6.21 M.U.D)

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

Earlier fracturing preserved away from fragmented region

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Pseudotachylytes
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Microstructural evidence for high stress oscillations: fault clasts

**Clinopyroxene**

- 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?)

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

**Context**

- Pseudotachylytes
- High stress microstructures: host rock
- High stress microstructures: clasts

**Implications**
Microstructural evidence for high stress oscillations: fault clasts

**Orthopyroxene**

- Regular low angle undulations suggest glide on (100)<010> - *high stress response*\(^4\)
- Cross-cutting fractures contain linear arrays of fine-grained OPX
Evolution of high stresses and association with rupture

**Clinopyroxene deformation**
- Twinning (moderate stress)
- Undulose extinction (high stress)
- Low angle boundaries (high stress)

**Orthopyroxene deformation**
- Low-temperature plasticity?
- Undulose extinction (in clast only, high stress)
- Fracturing
- Fragmentation (fault wall only, high stress)

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

**Implications**
- Rupture tip
Evolution of high stresses and association with rupture

**Pyroxene deformation adjacent to and within fault planes:**

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

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

**Stress amplification in anorthosite block during viscous shear zone creep**

**Coseismic slip**

**High stress microstructures: host rock**

**High stress microstructures: clasts**

**Implications**

**Context**

**Pseudotachylytes**
References


See also:
