

The Cora Lake Shear Zone:

A Natural Laboratory for Mixed Brittle and Ductile Deformation in the Continental Lower Crust

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What's a 'natural laboratory' for geology?

- Well-exposed
- Well-preserved
- Most importantly, preserves **complexity** of natural processes

A 'natural laboratory' in the lower crust allows the investigation of a broad range of hypotheses:

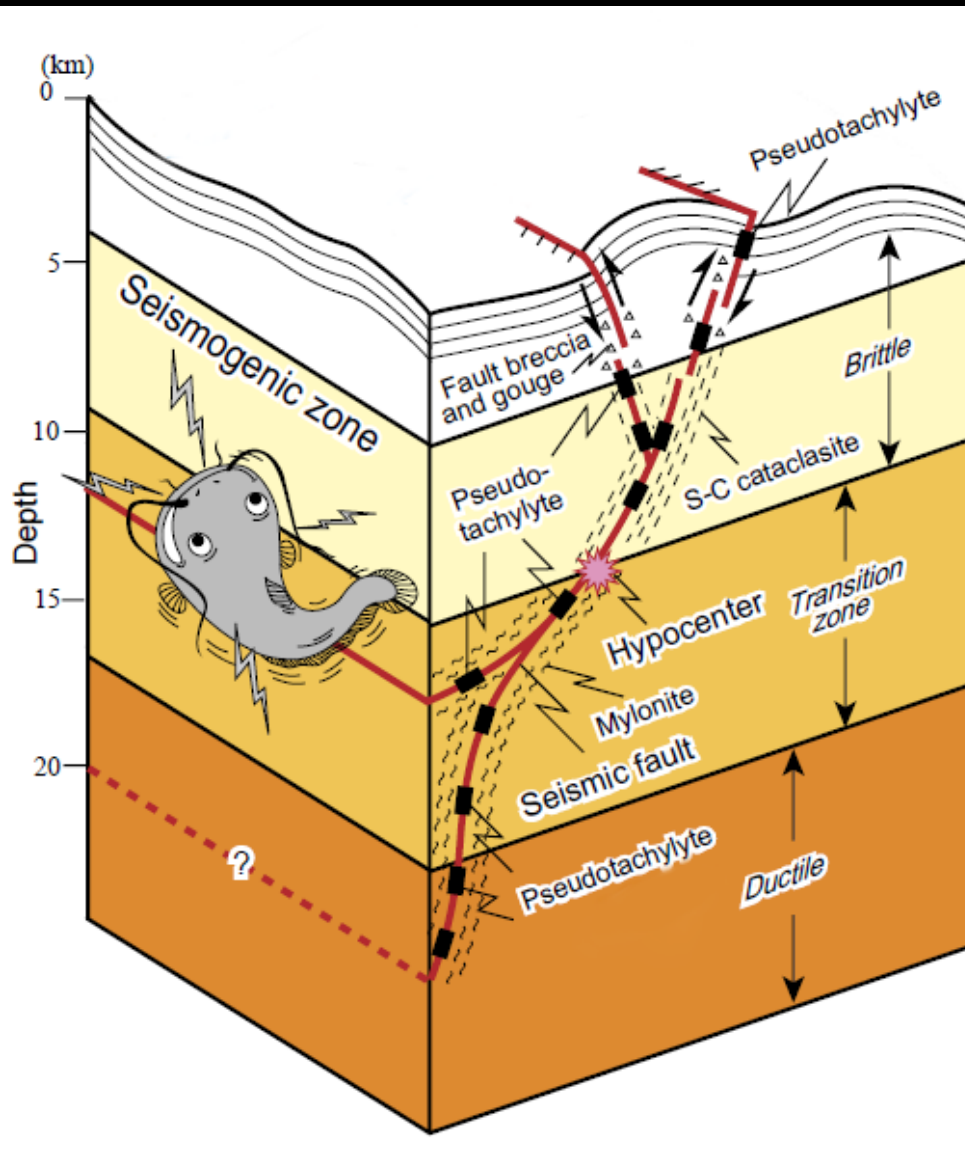
- Strength of the lithospheric crust
- Passive properties of ductile deformation visible from surface
- Patterns in the alignment of crystals in deformed rocks
- Metamorphic reactions between minerals, fluids, melts

A 'natural laboratory' in the lower crust allows the investigation of a broad range of hypotheses:

- **Strength of the lithospheric crust**
- Passive properties of ductile deformation visible from surface
- Patterns in the alignment of crystals in deformed rocks
- Metamorphic reactions between minerals, fluids, melts

Why do we need to study
the strength of the crust?

Typical crustal strength profile

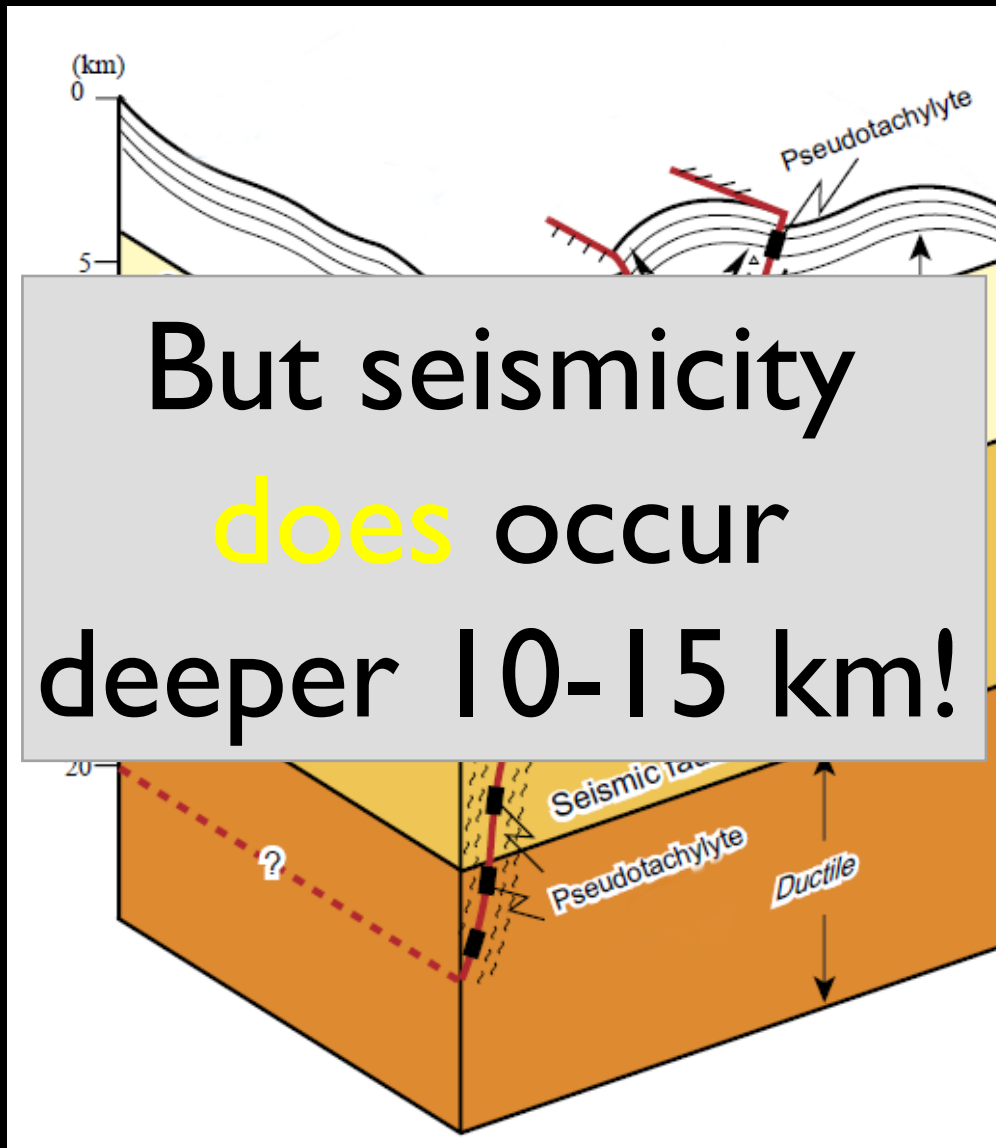


‘Strong’ upper crust
is seismic

‘Weak’ lower crust is
aseismic

Transition is based on
temperature and
predictable to **10-15
km depth**

Typical crustal strength profile

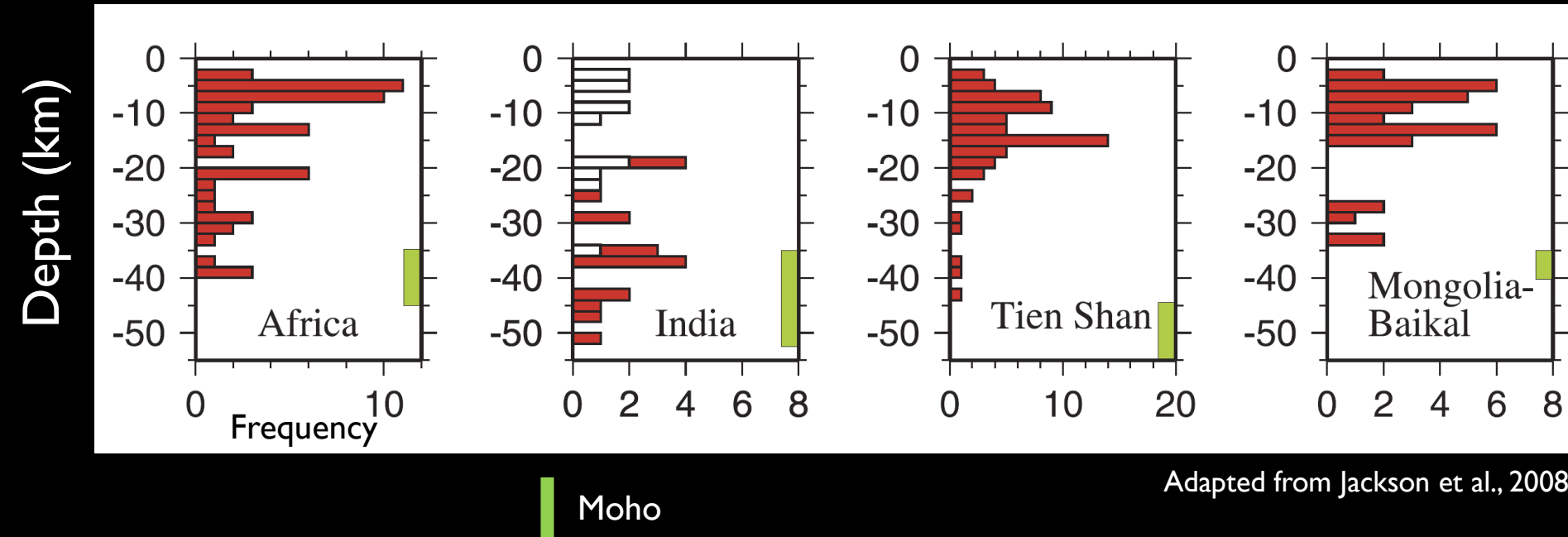


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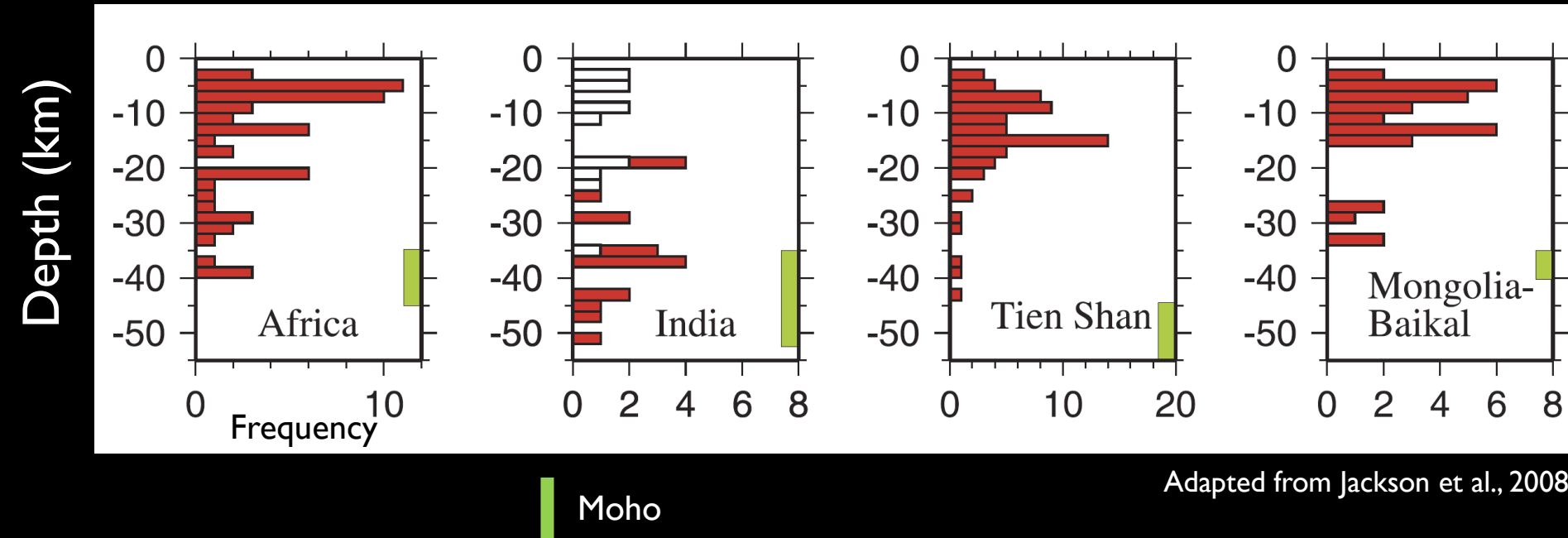
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Deep earthquakes throughout the crust in many settings ($>5.3 M_b$)



Adapted from Jackson et al., 2008

Deep earthquakes throughout the crust in many settings ($>5.3 M_b$)



Adapted from Jackson et al., 2008

What would those deep seismic events look like in the rock record, and why do they occur?

Roadmap:

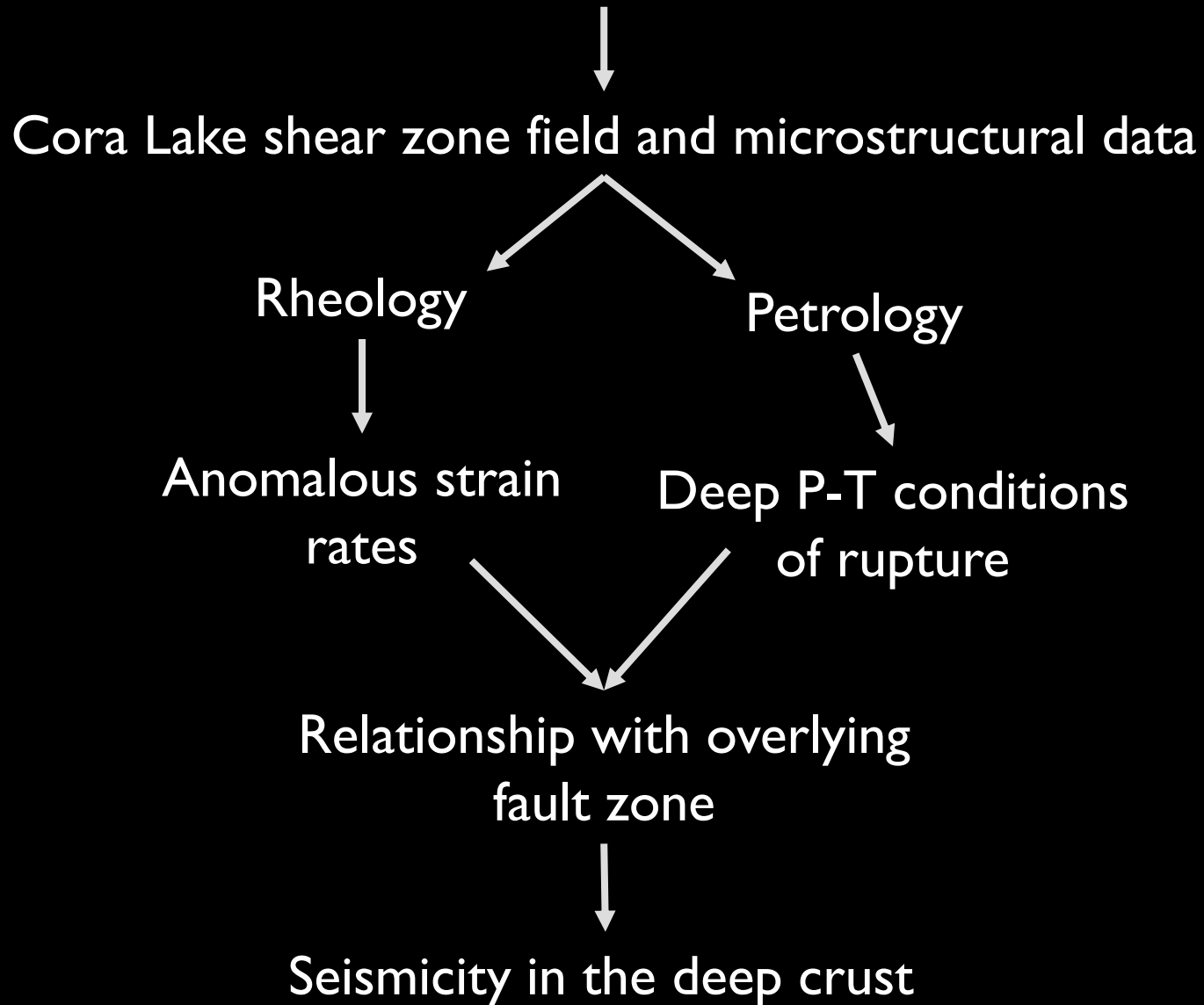
How do we even know we have an interesting problem? (Orlandini et al., 2018)

- Introduction to frictional melts
- Establishing the depth of rupture

Once we're sure we have deep rupture: (Orlandini et al., 2020)

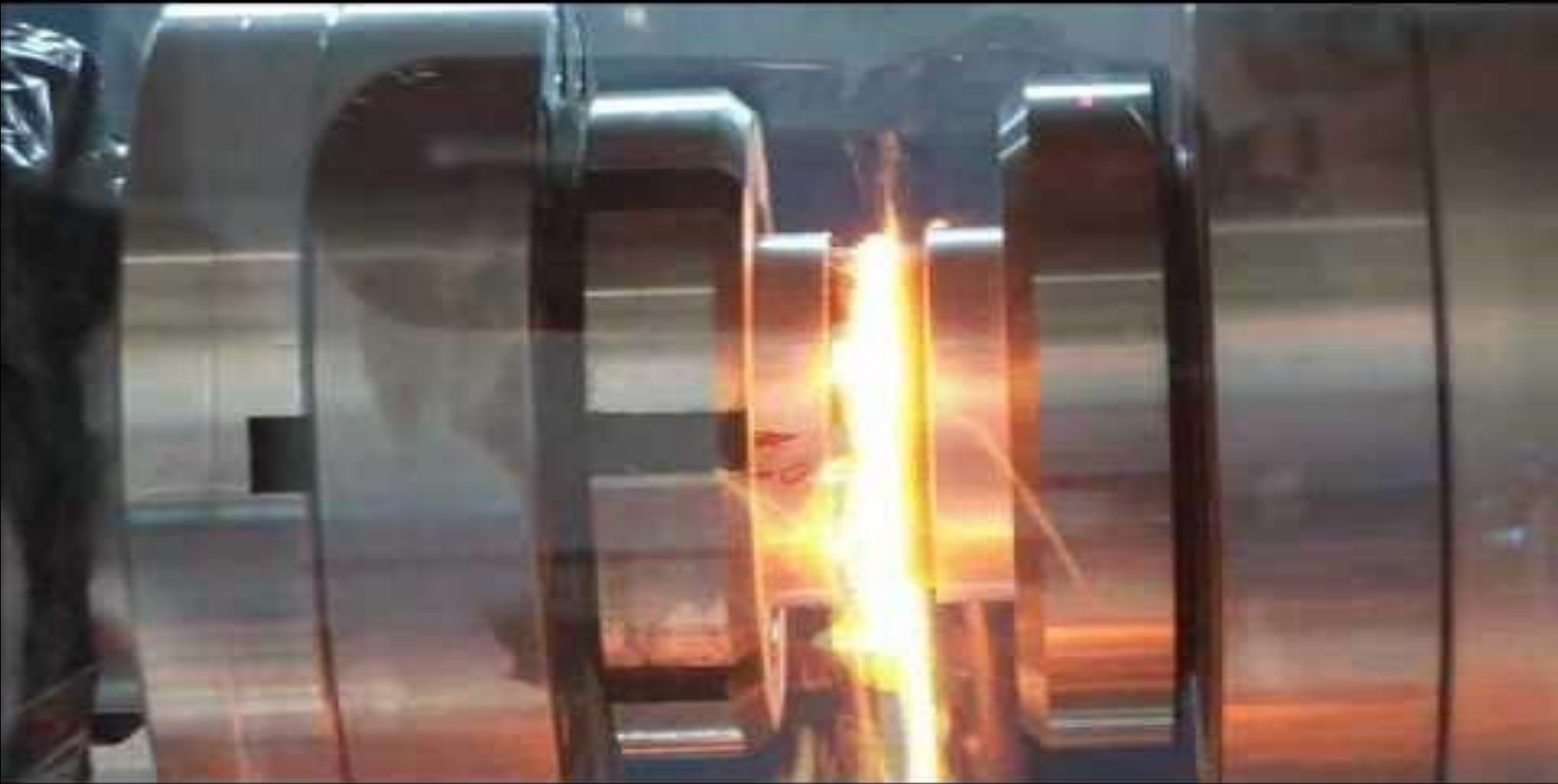
- How did this happen?
- How can we tell if it is happening today?

Geophysical observations of deep seismicity



Introduction:

What's a
pseudotachylyte?



SHIVA rotational friction device at INGV Rome
Basalt rings, 5 meters per second (seismic slip rate)

Natural occurrence of pseudotachylyte

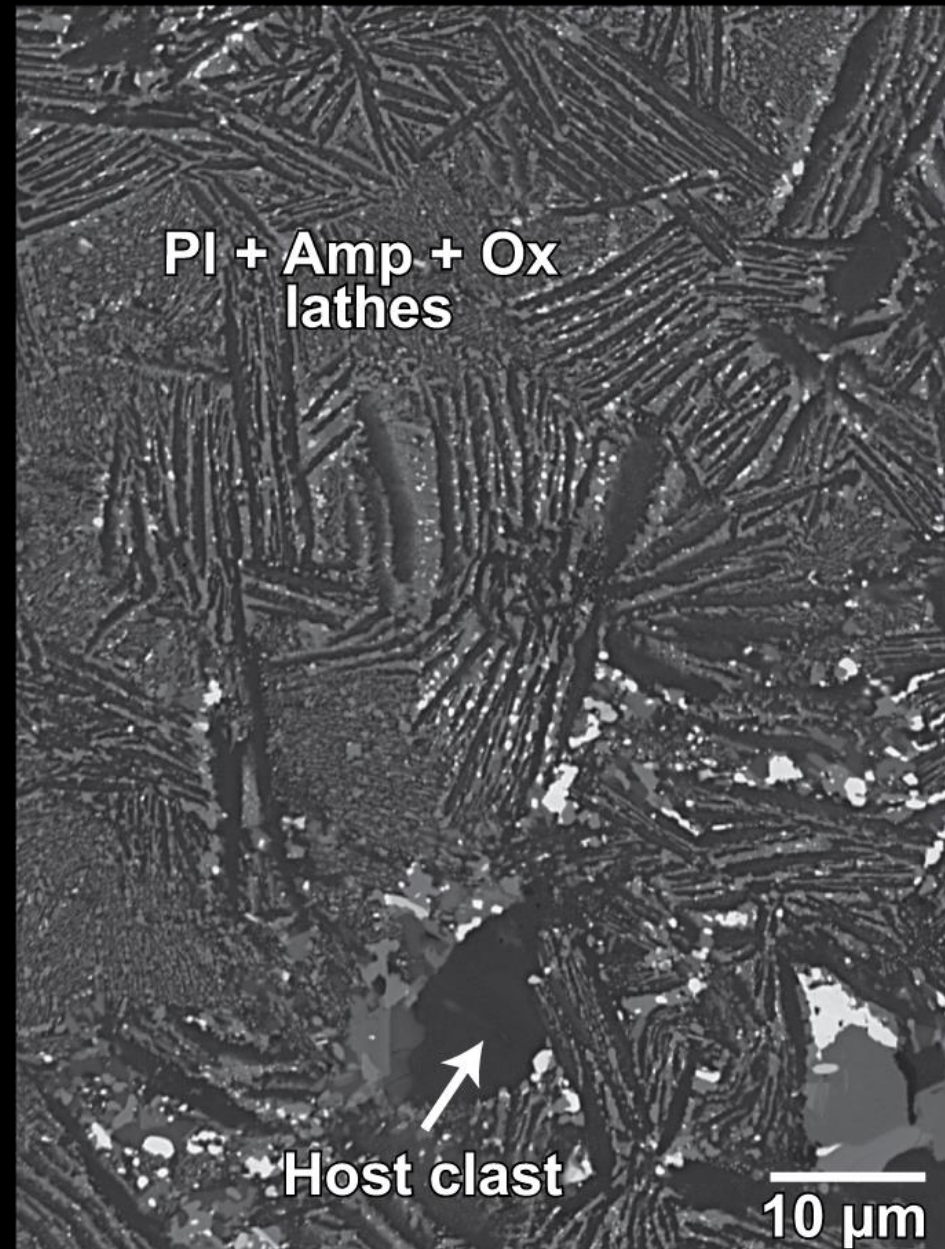
Injection vein from melt expansion

Host rock clasts

Quenched melt

Natural occurrences of pseudotachylyte

- Vein temperatures $>1800\text{ }^{\circ}\text{C}$
- Form as cm-thick sheets with huge surface areas
- Cool to ambient T very quickly, leading to quench textures and glass
- **Reliable indicator of seismic slip rates**

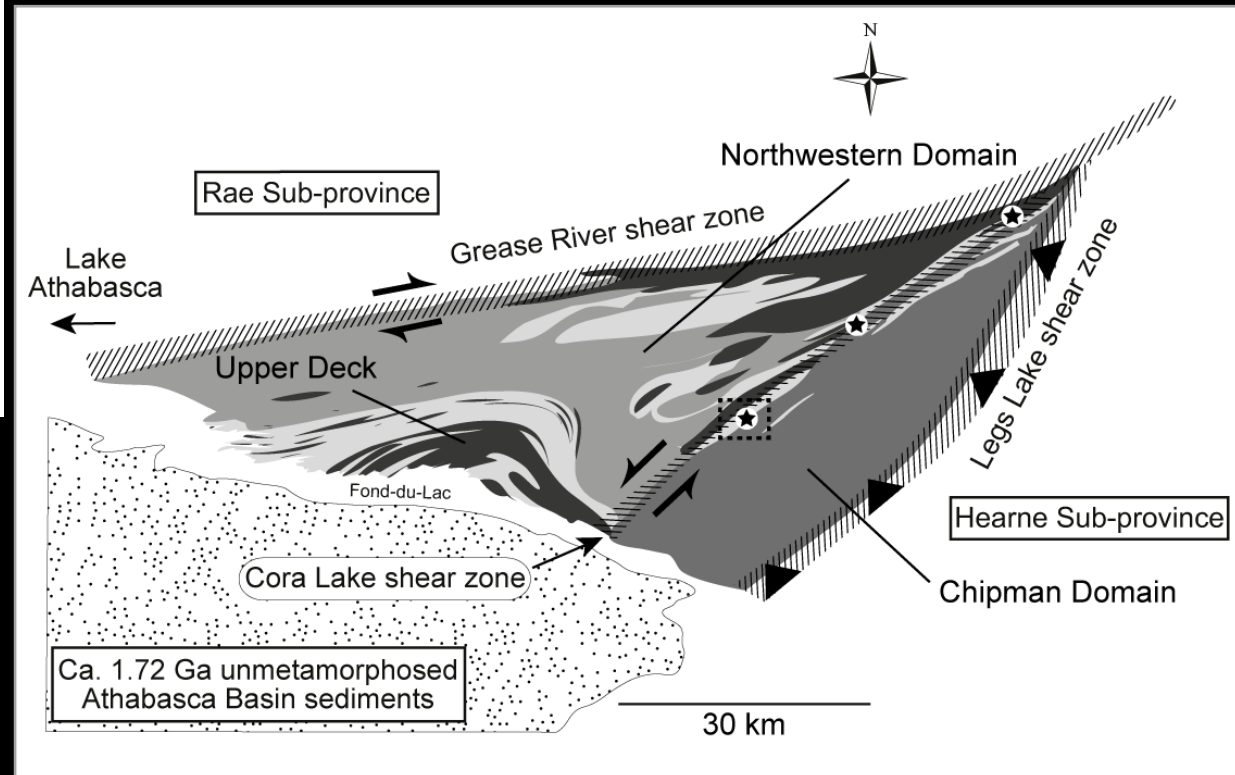


BSE image from Orlandini et al., 2018

Location:

The Cora Lake shear zone

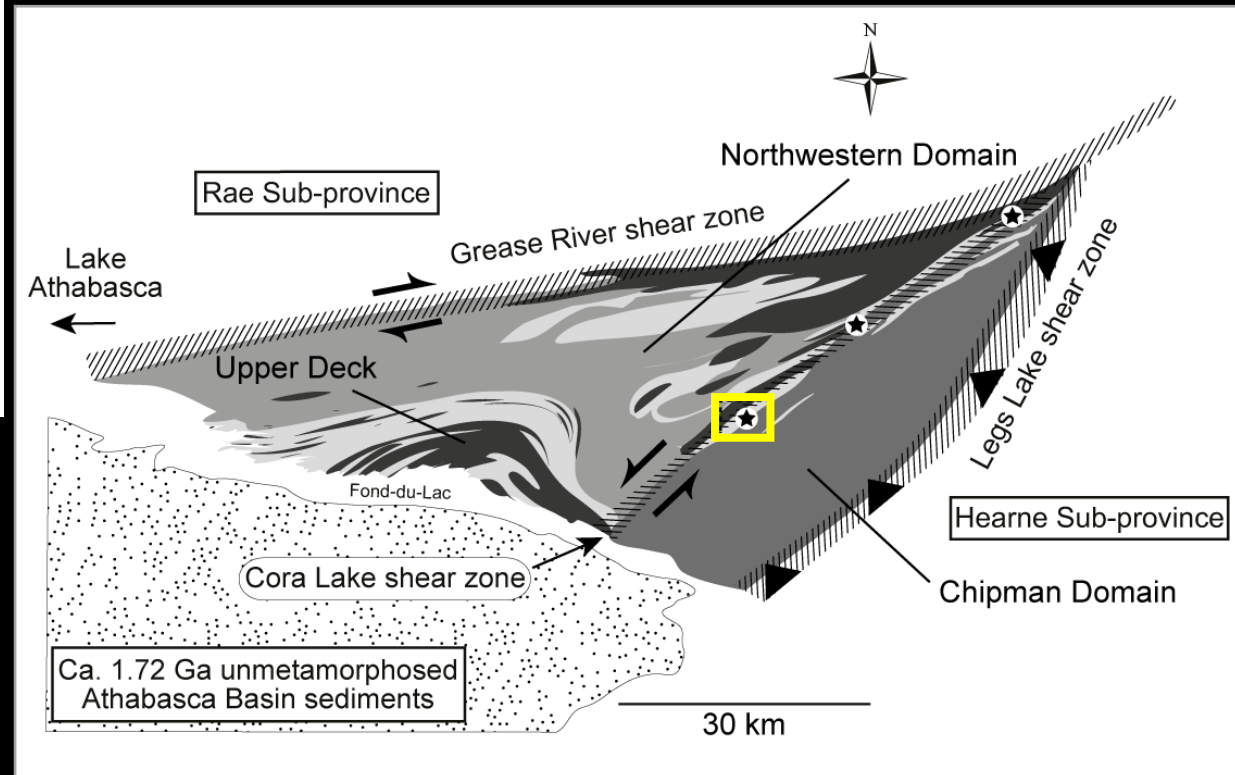
East Athabasca mylonite triangle



Map view

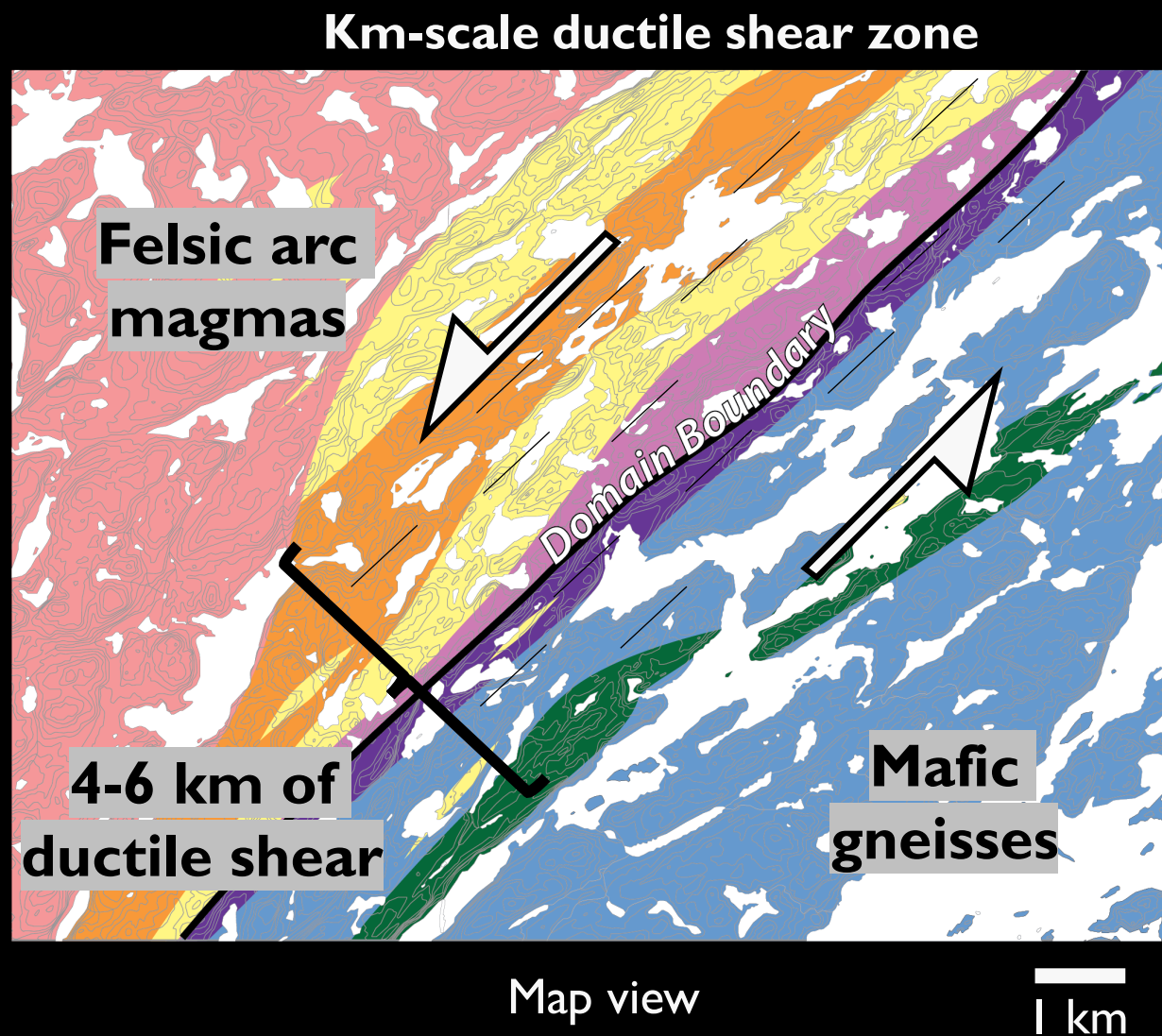
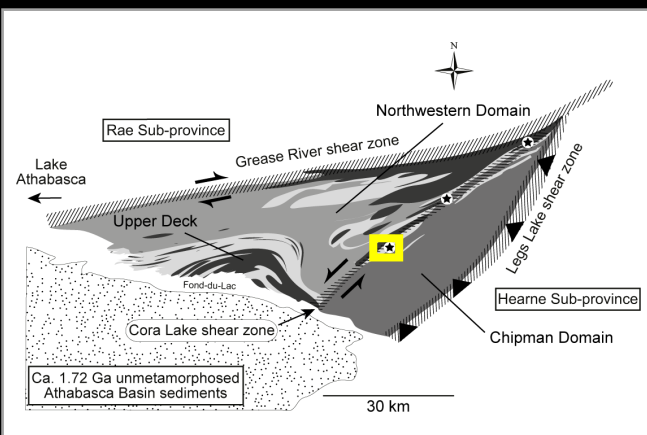
- Western Canadian Shield, Saskatchewan
- Huge exposure of continental lower crust
- Three terranes juxtaposed by major ductile structures

East Athabasca mylonite triangle



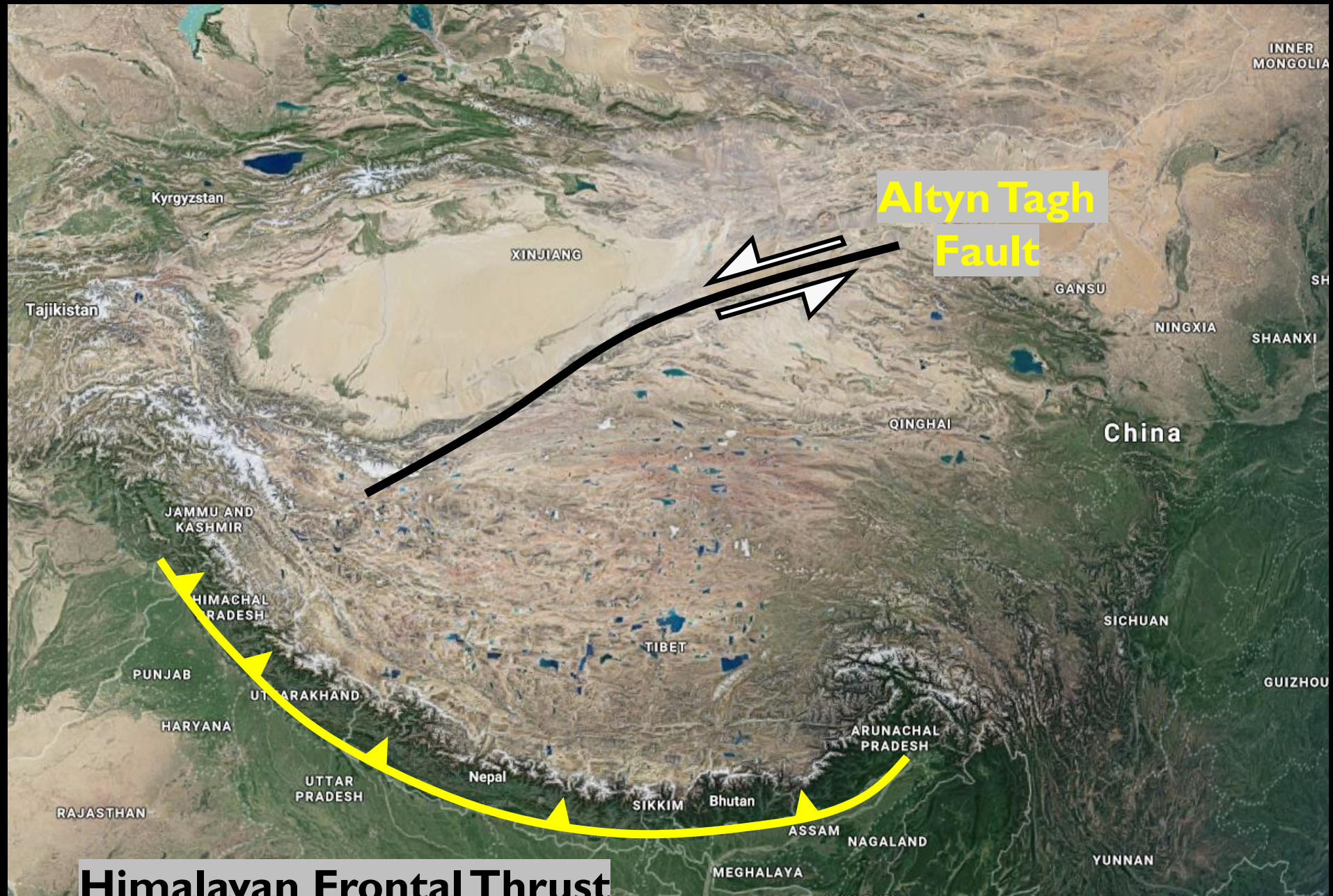
Map view

- Western Canadian Shield, Saskatchewan
- Huge exposure of continental lower crust
- Three terranes juxtaposed by major ductile structures



- ~1.8 Ga primarily strike-slip deformation
- Lower crust: 26 – 36 kilometers depth, 700 – 800 °C
- 4 – 6 km wide, ≥ 70 km long

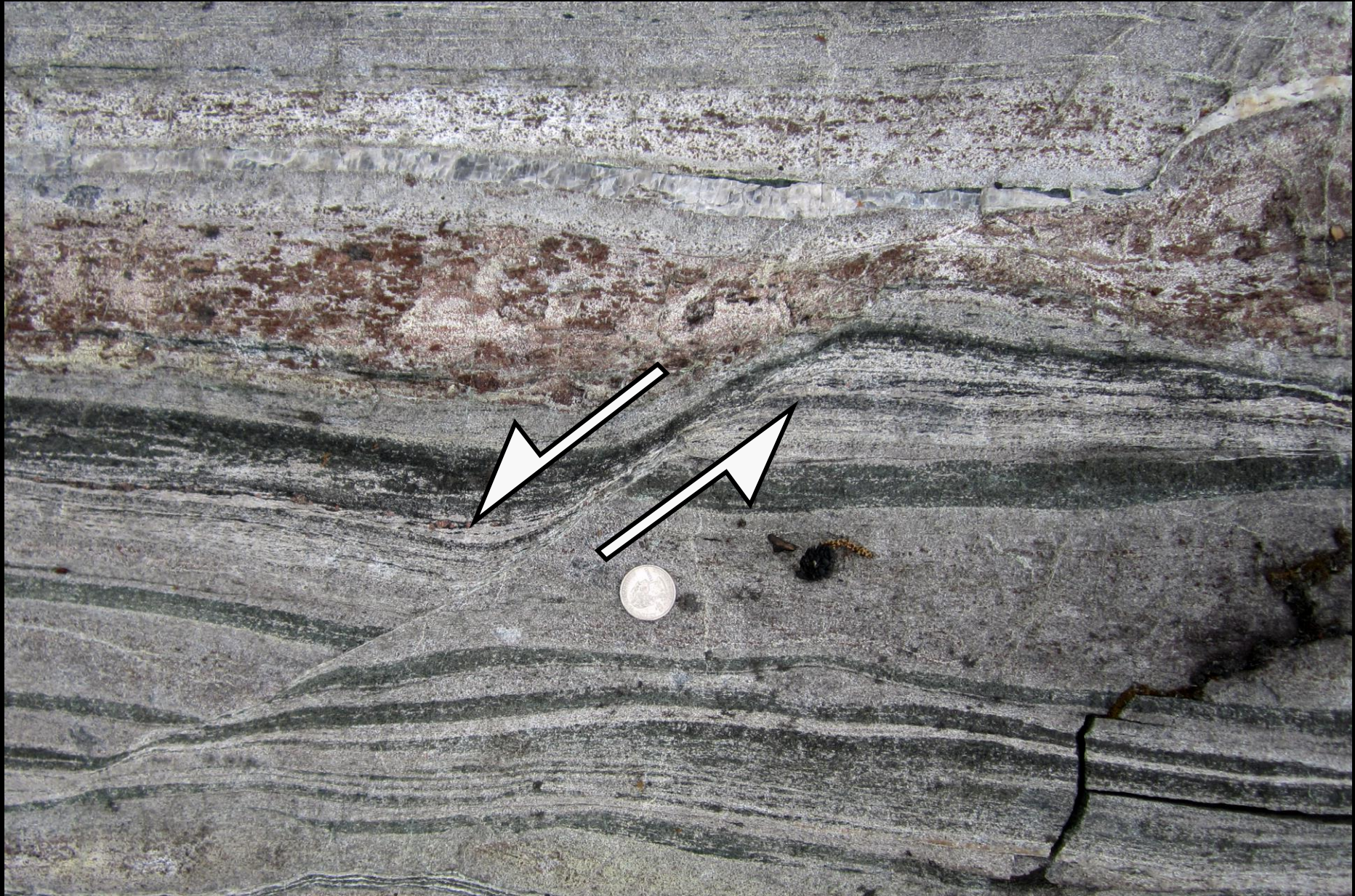
Modern day equivalent to Cora Lake shear zone



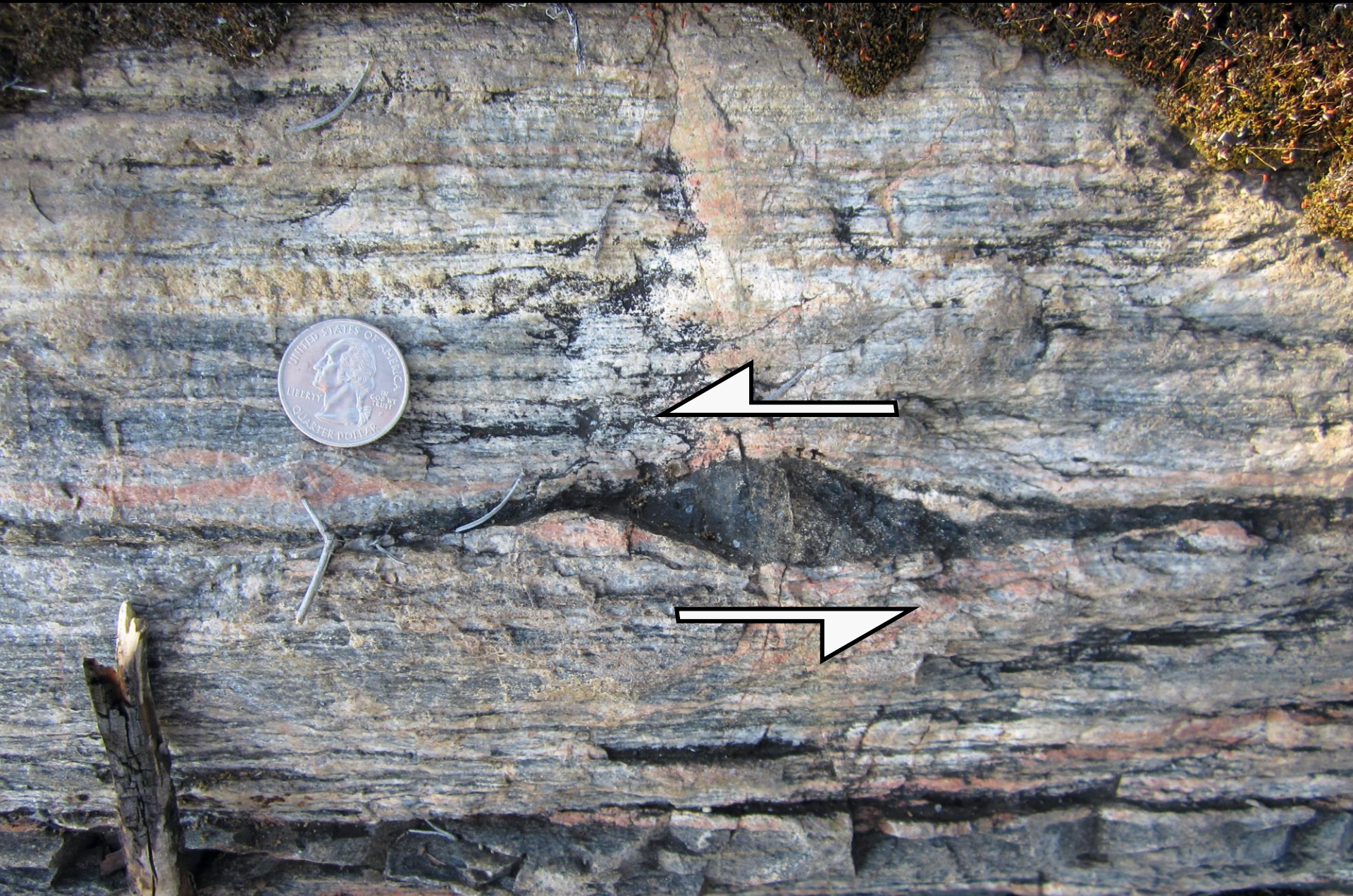
Aside:

What's a ductile shear zone?

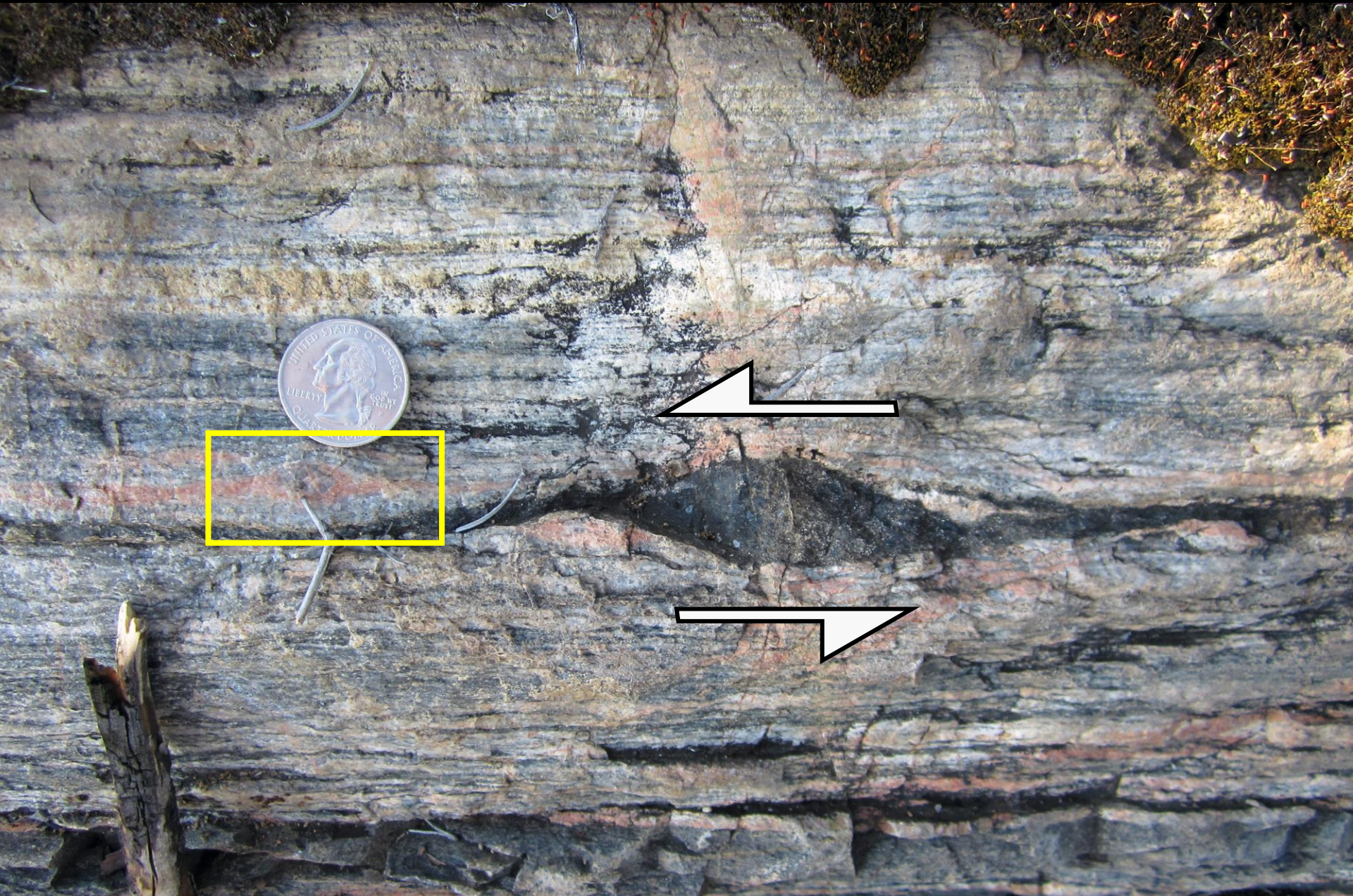
Meter-scale ductile shear zone



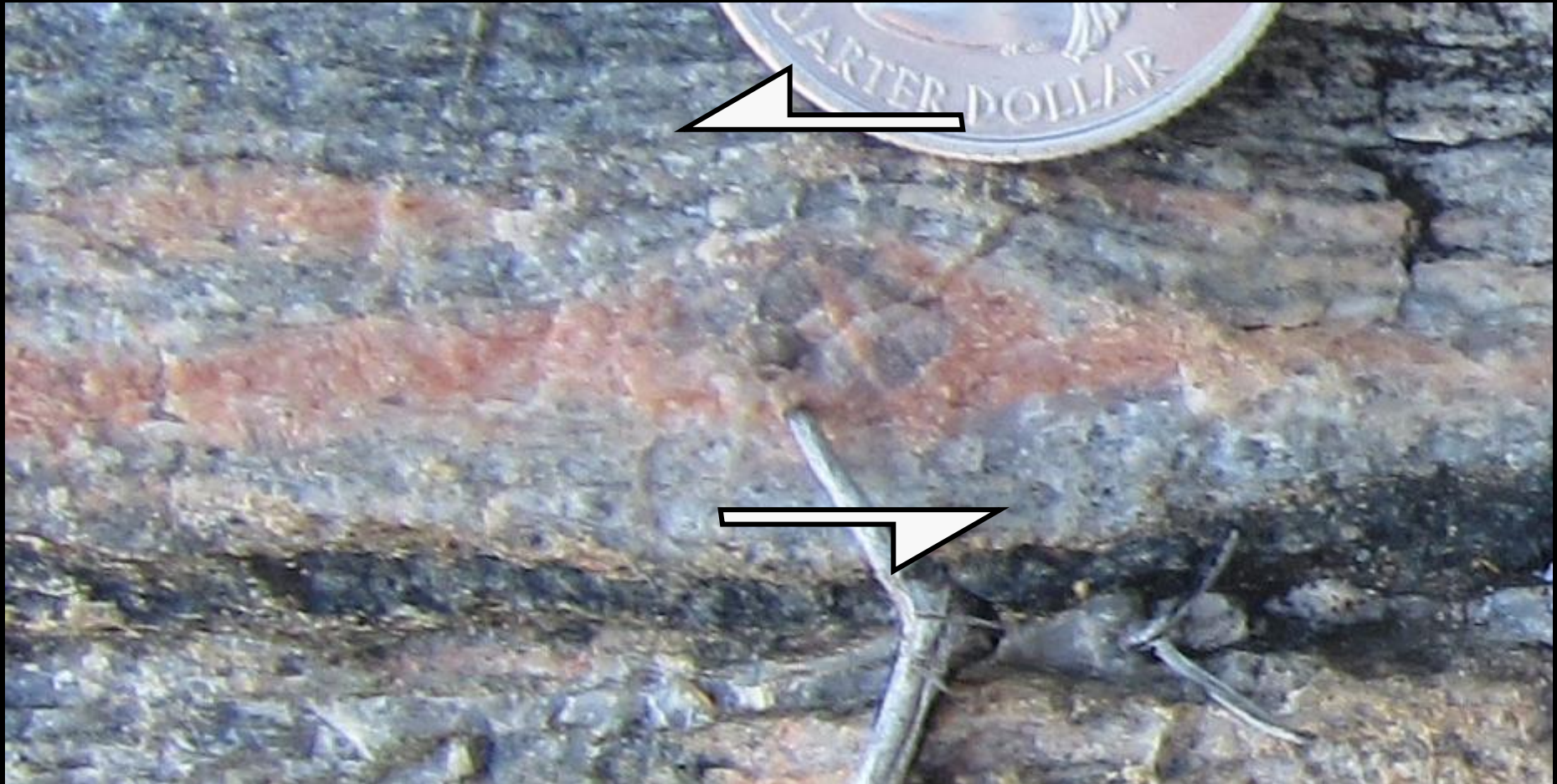
Outcrop photo of CLsz ductile deformation



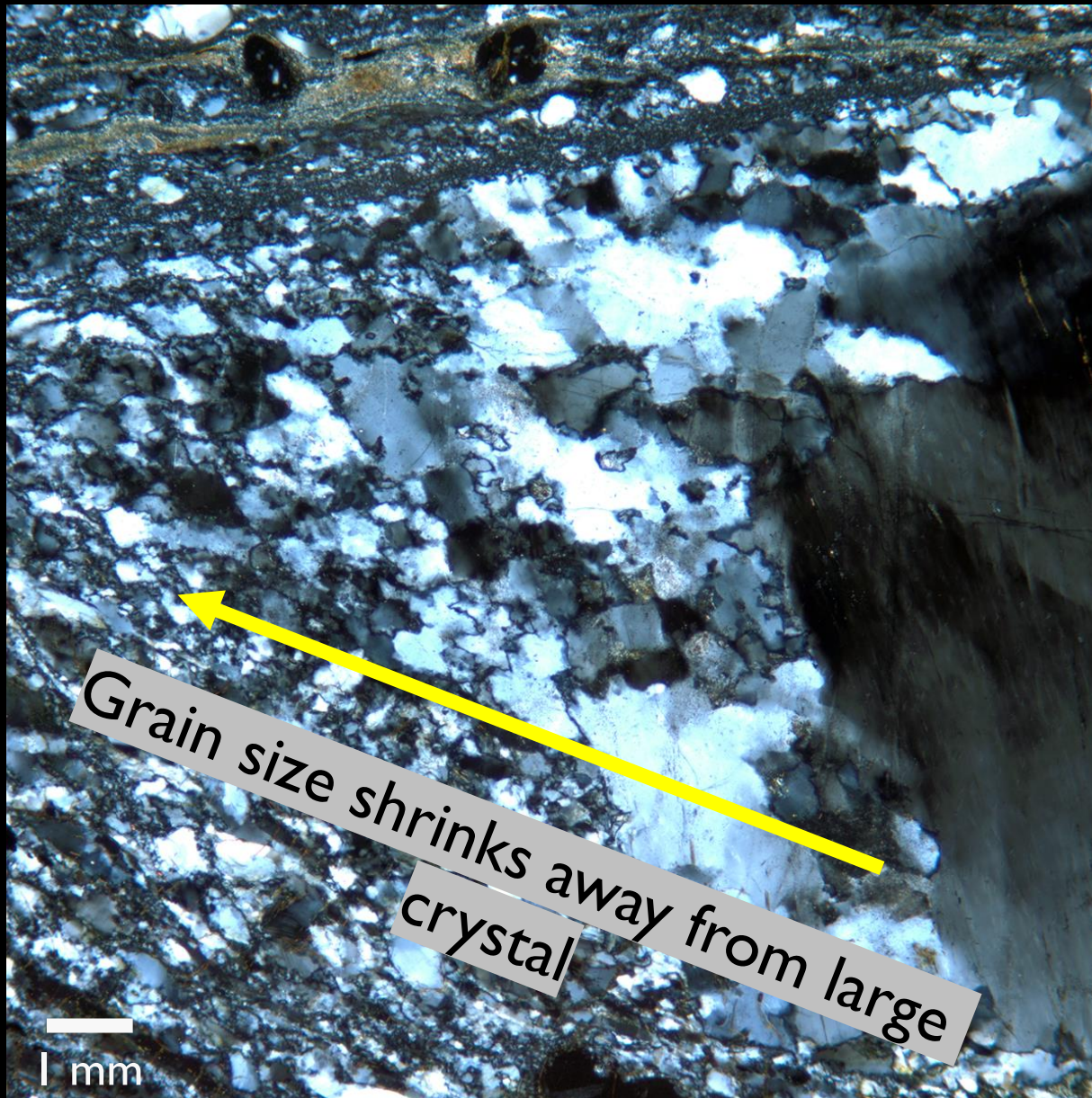
Outcrop photo of CLsz ductile deformation



Outcrop photo of CLsz ductile deformation

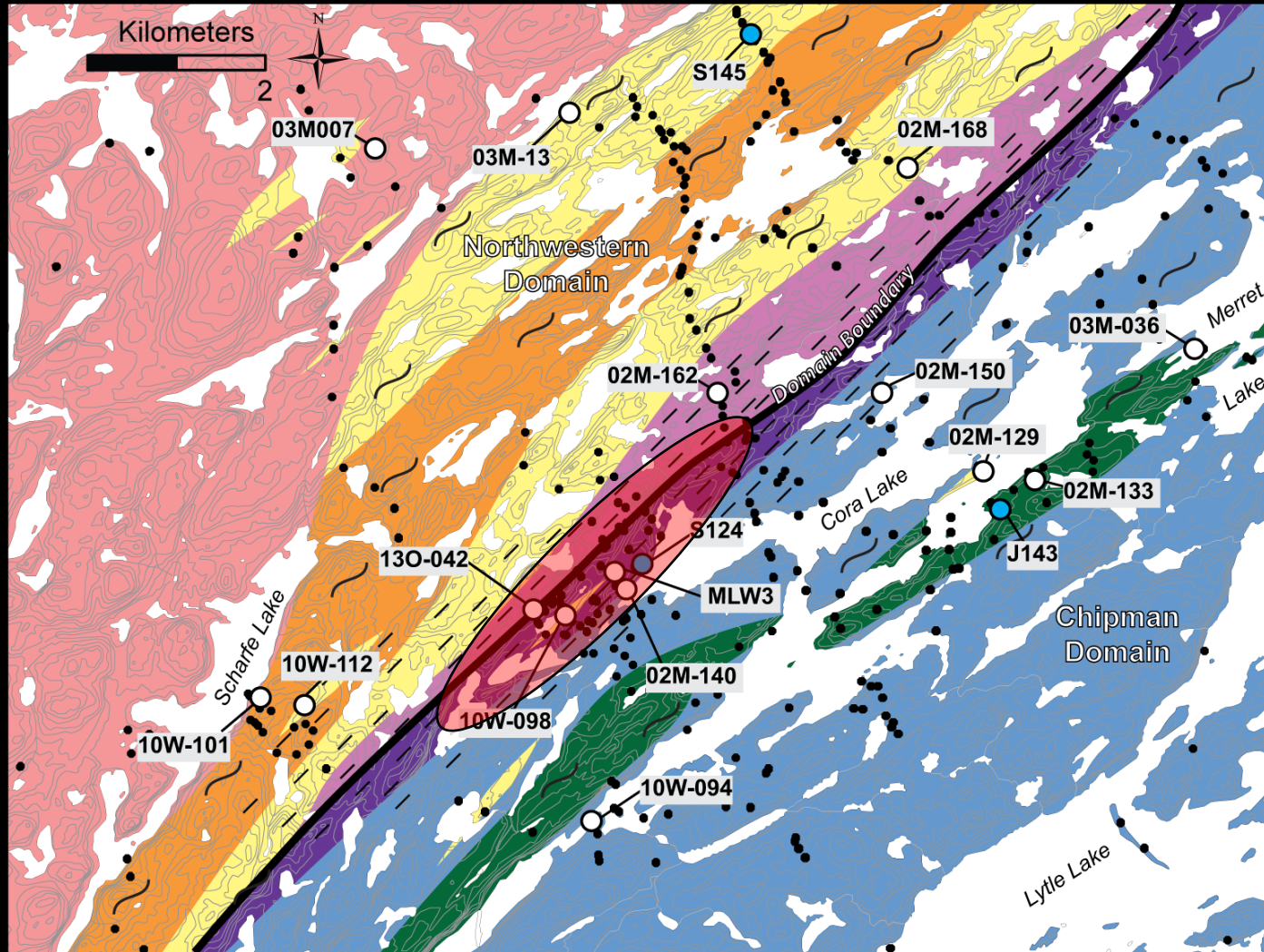


Mylonite: grain size reduction through ductile deformation



Cross-polarized light image from Orlandini et al, 2020

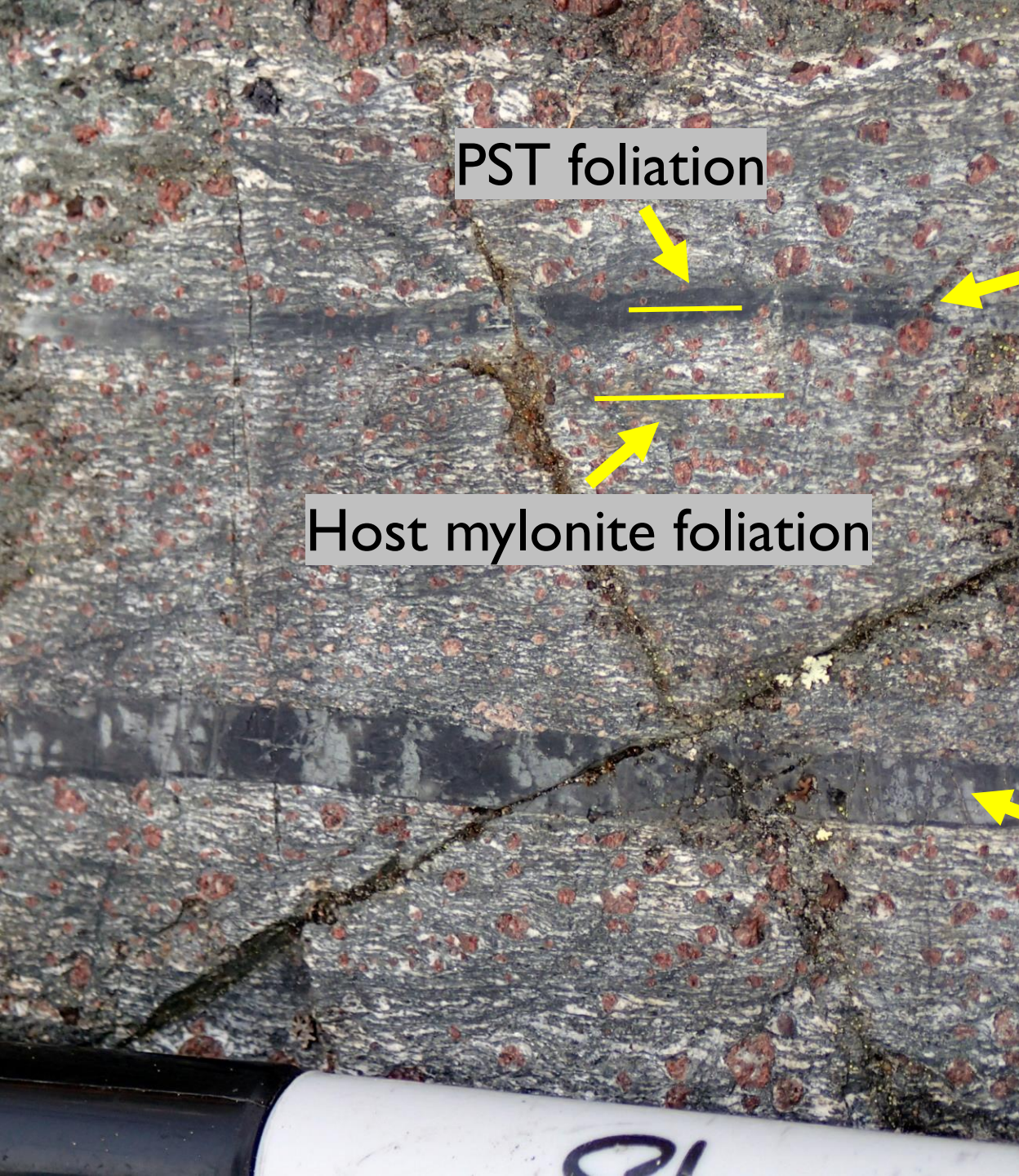
Investigating the Cora Lake shear zone



- Previous work provided dozens of field observations and samples over >20 years
- 2 field seasons focused on pseudotachylite at domain contact

Cora Lake shear zone pseudotachylyte (PST)

- Primarily hosted by quartz-poor, plagioclase-rich mafic lithologies
- Many individual veins of PST have been recrystallized and deformed



PST foliation

Strongly
deformed PST

Host mylonite foliation

Slightly
deformed PST

Ductile PST injection vein



Host mylonite
foliation



Ductile PST foliation



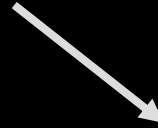
Question 1:

Did the pseudotachylyte form
at the same time as the
ductile shear zone?

Geophysical observations of deep seismicity

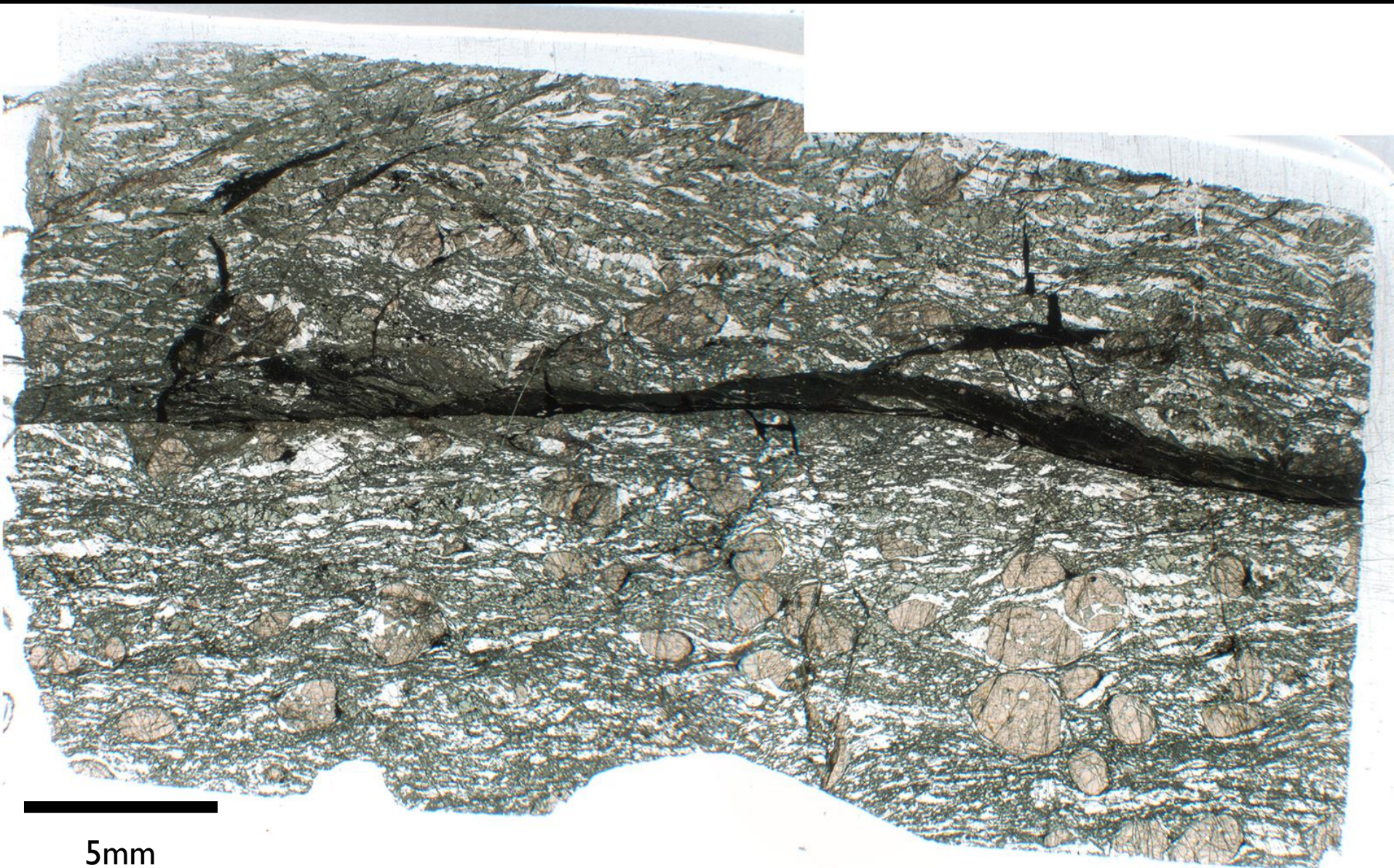


Cora Lake shear zone field and microstructural data



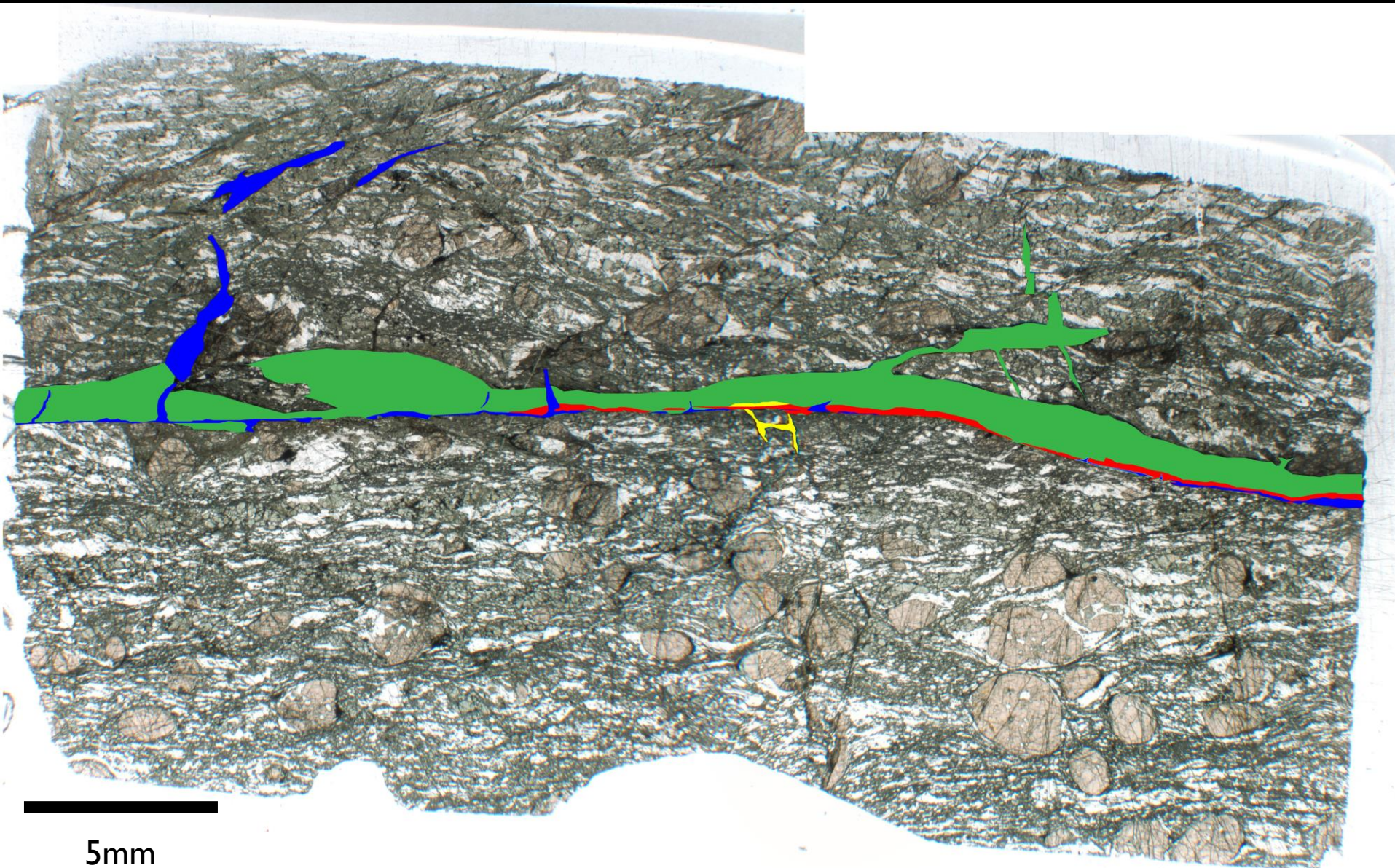
Petrology

PST microstructures

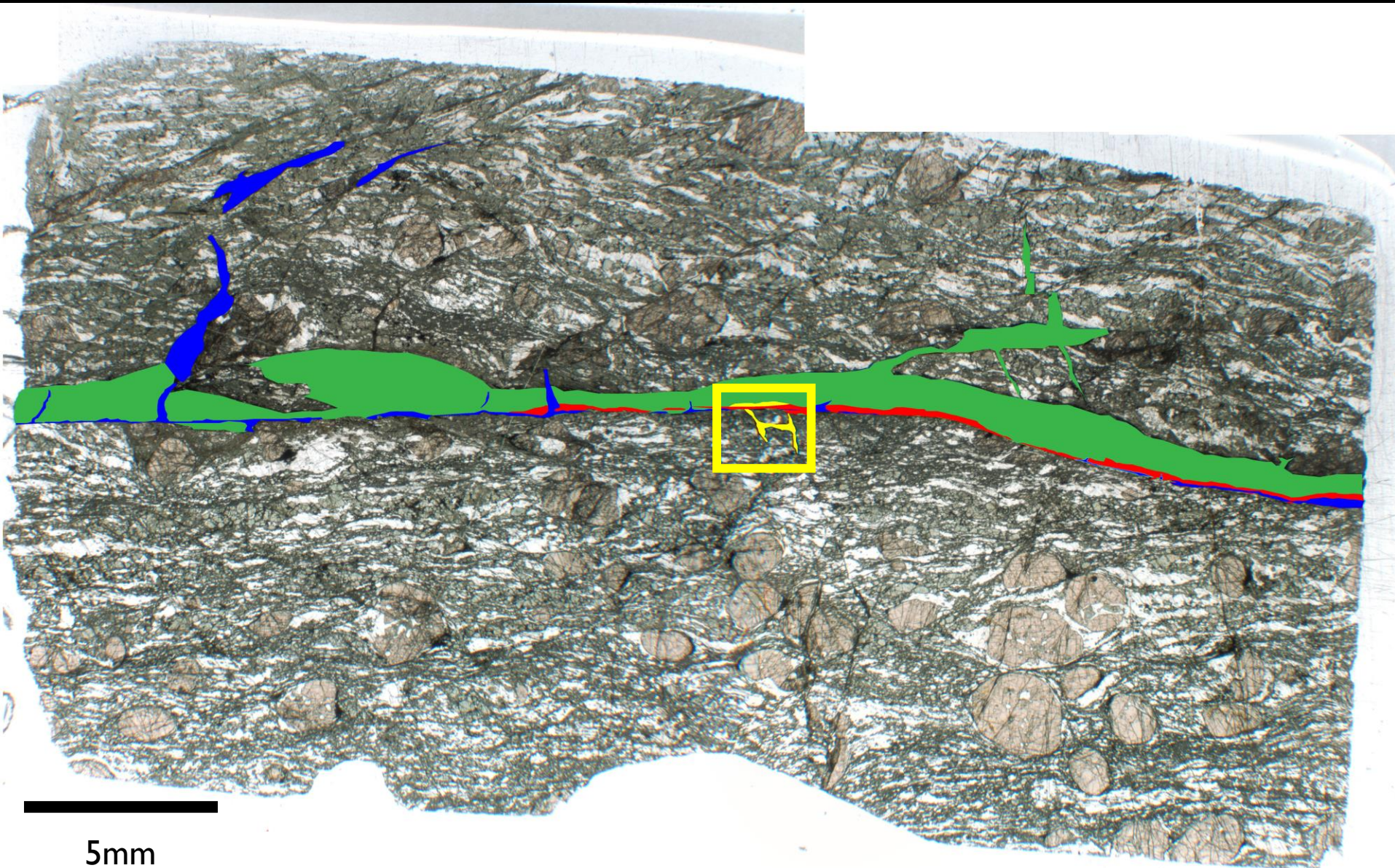


Plane polarized light thin section of multiple pseudotachylyte generations

PST microstructures



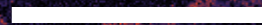
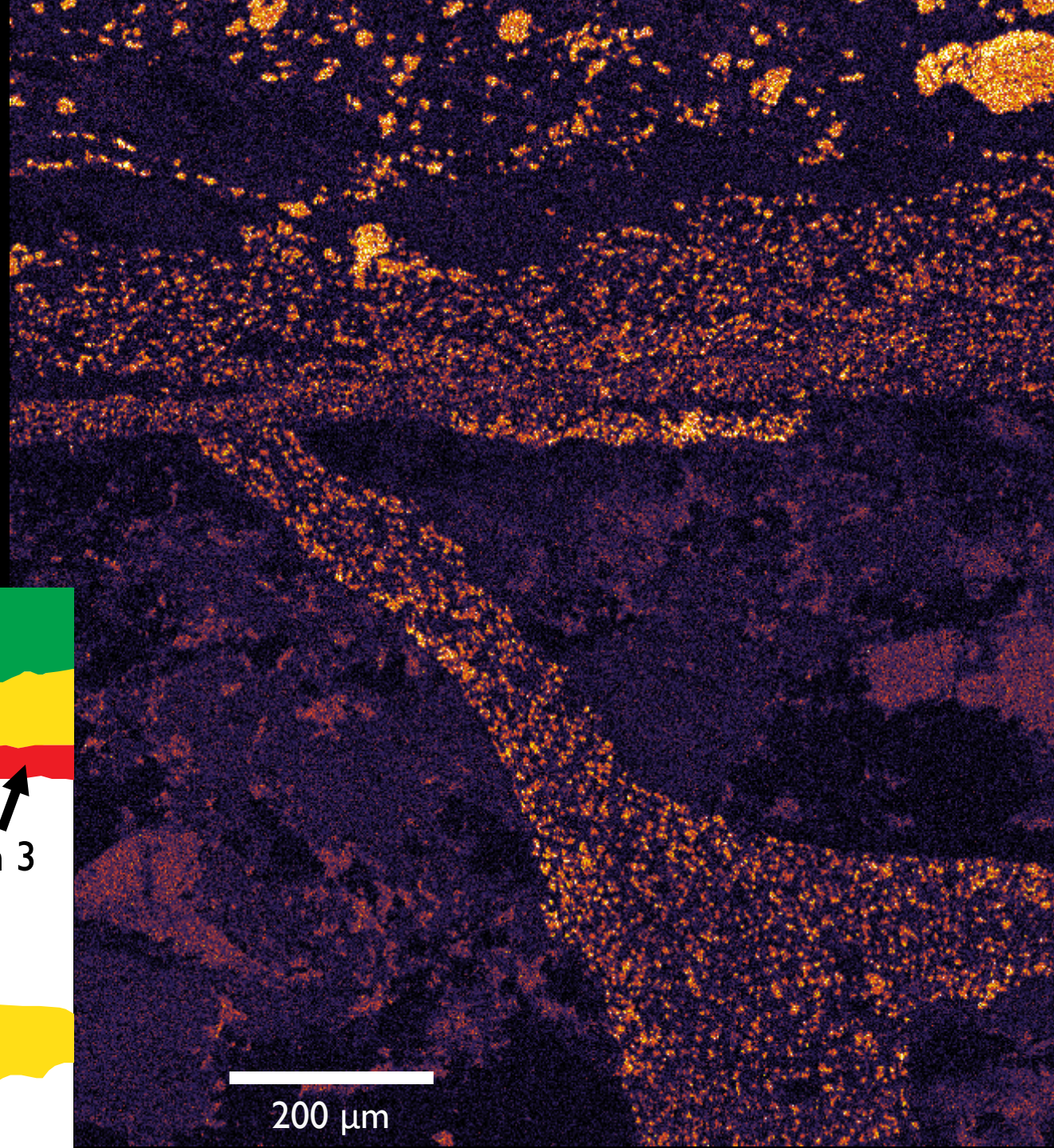
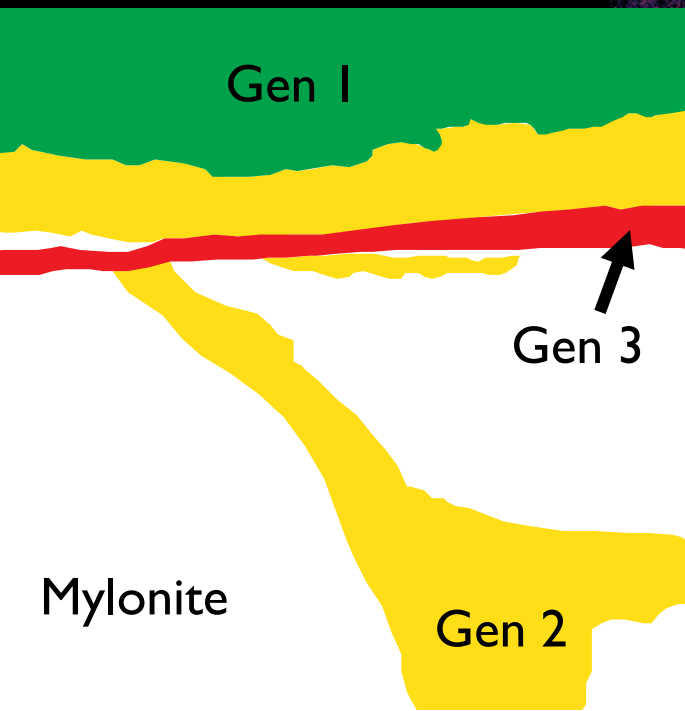
PST microstructures



5mm

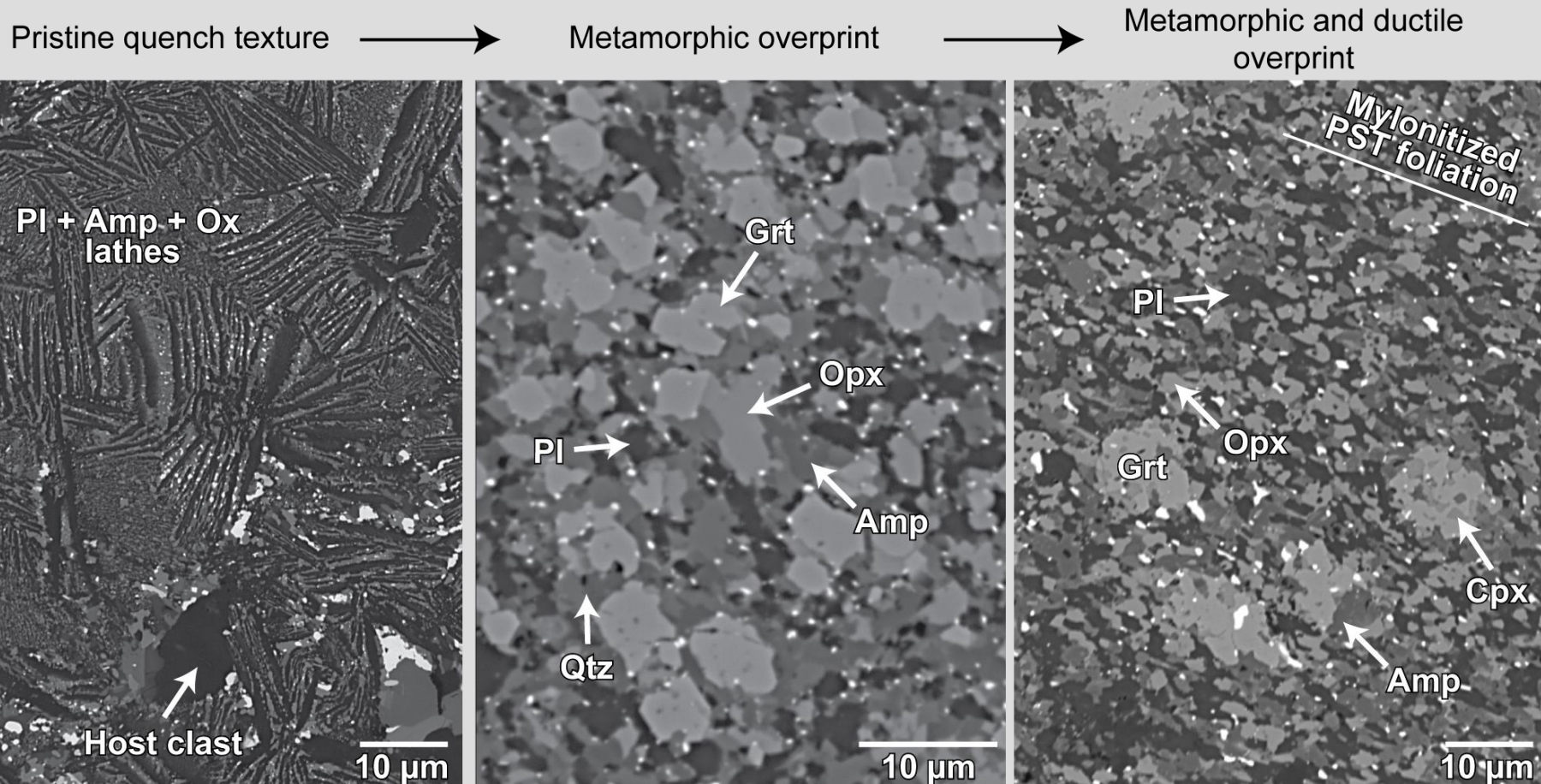
Mn K α

Garnet size
populations
highlight multiple
PST generations

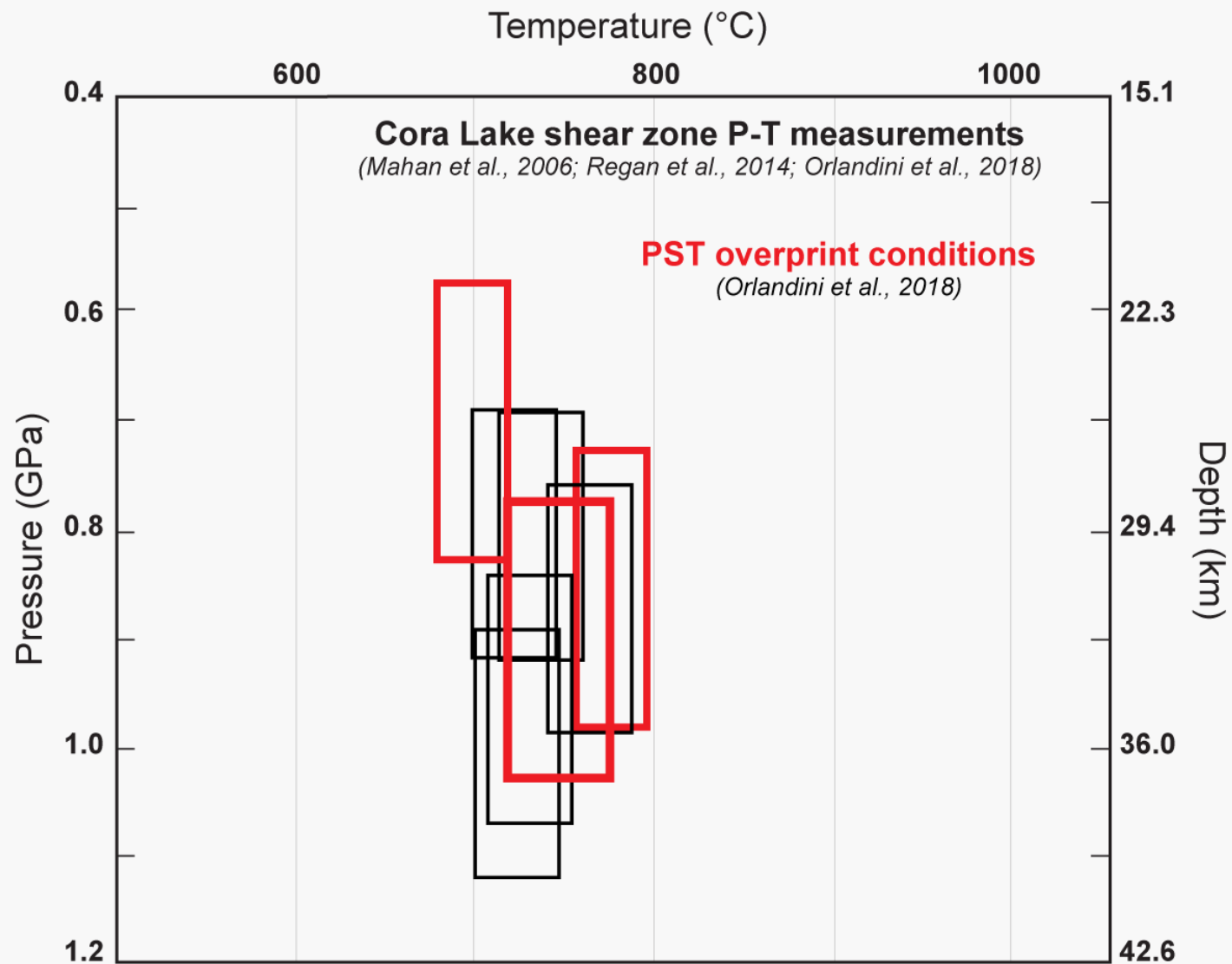


200 μm

Evolution of PST overprinting



Many generations of PST with many stages
of overprint



PST generations record pressure-temperature conditions **identical** to km-scale shear zone host

Question 1:

Did the pseudotachylyte form synkinematically with the ductile shear zone?

- Some PST veins have the same foliation as the ductile mylonites
- Recrystallized and foliated PST records the same PT conditions as the shear zone

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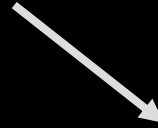
Did the pseudotachylyte form synkinematically with the ductile shear zone?

- Some PST veins have the same foliation as the ductile mylonites
- Recrystallized and foliated PST records the same PT conditions as the shear zone
- **Generation of PST during active lower crustal ductile deformation was cyclic and long-lived**

Geophysical observations of deep seismicity



Cora Lake shear zone field and microstructural data



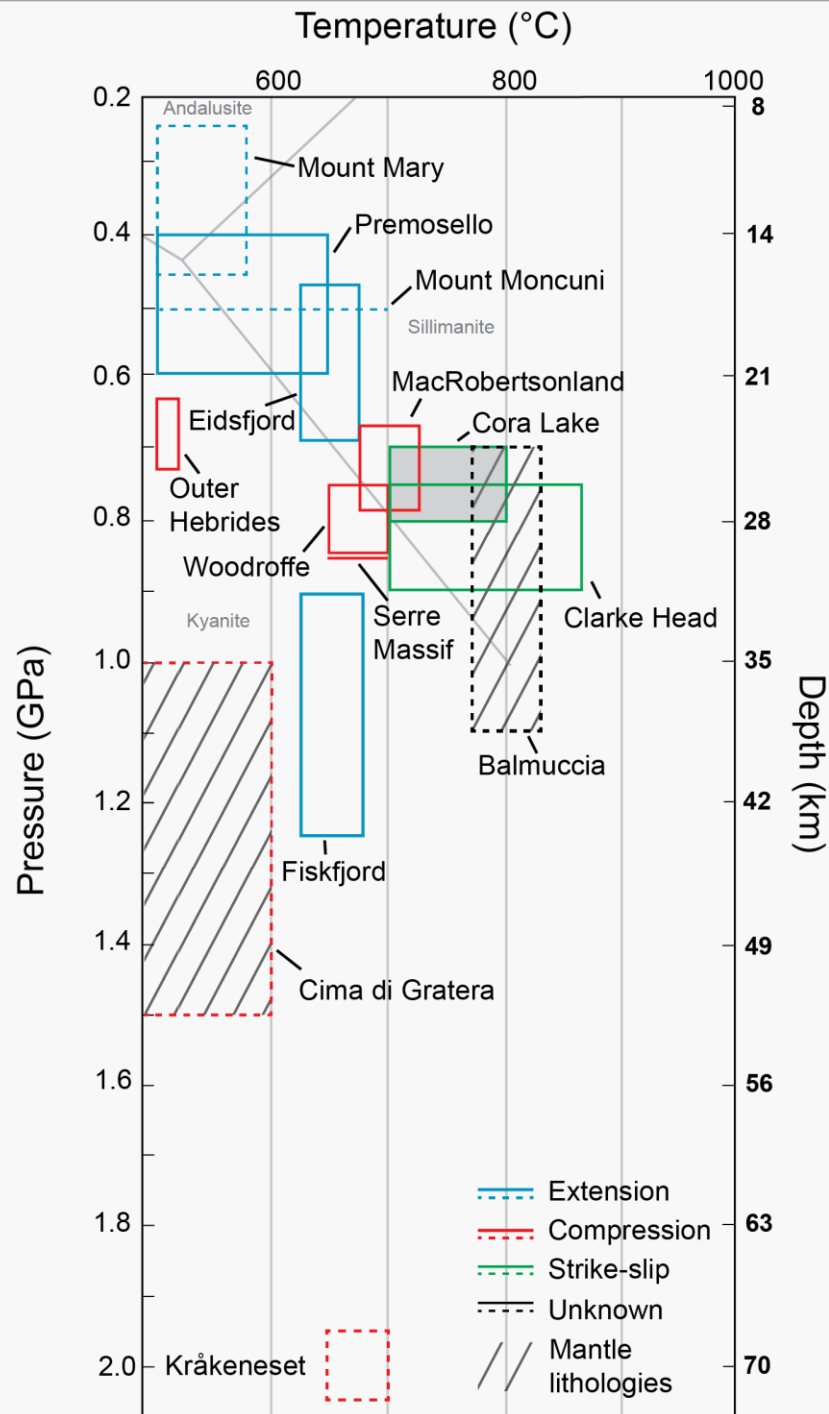
Petrology



Deep P-T conditions
of rupture

Question 2:

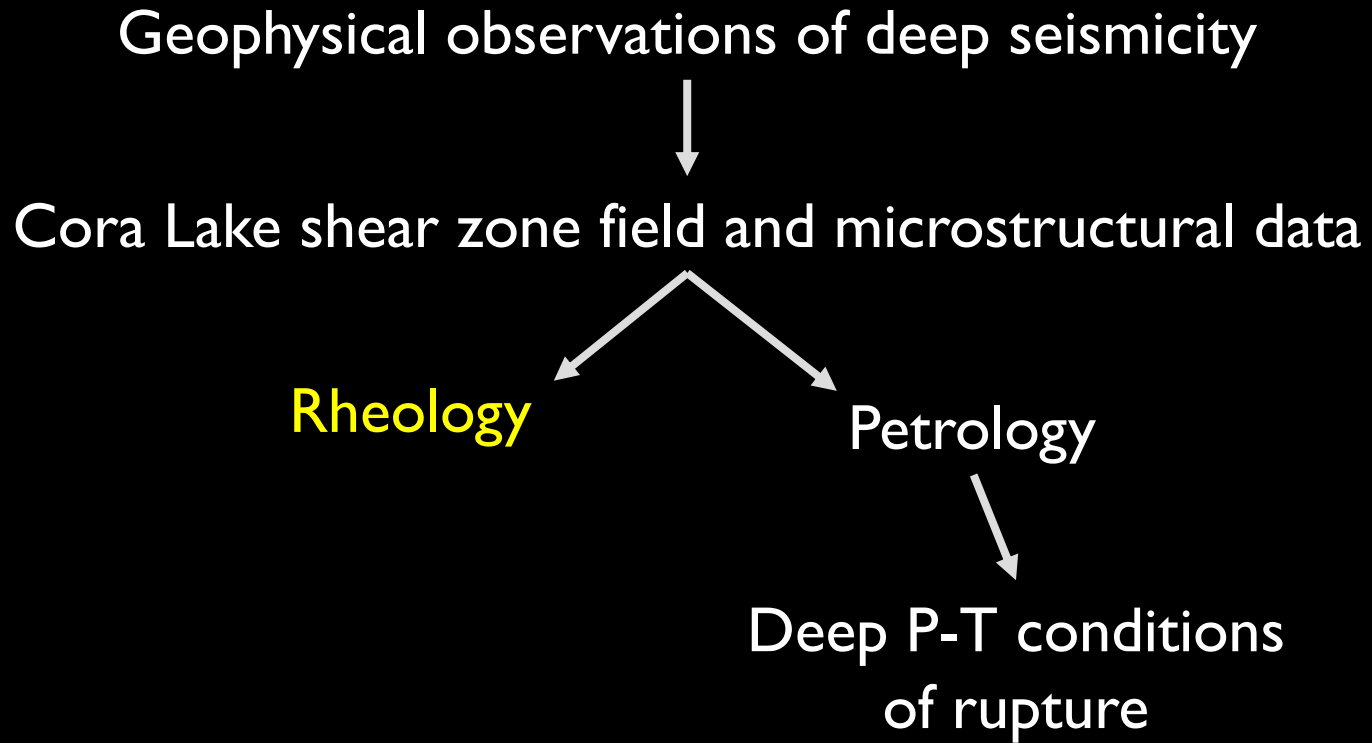
What is the mechanical relationship between the pseudotachylyte and the hosting shear zone?



The Cora Lake shear zone is far from the only occurrence of deep PST!

At least a dozen other documented cases of PST well below the brittle-ductile transition

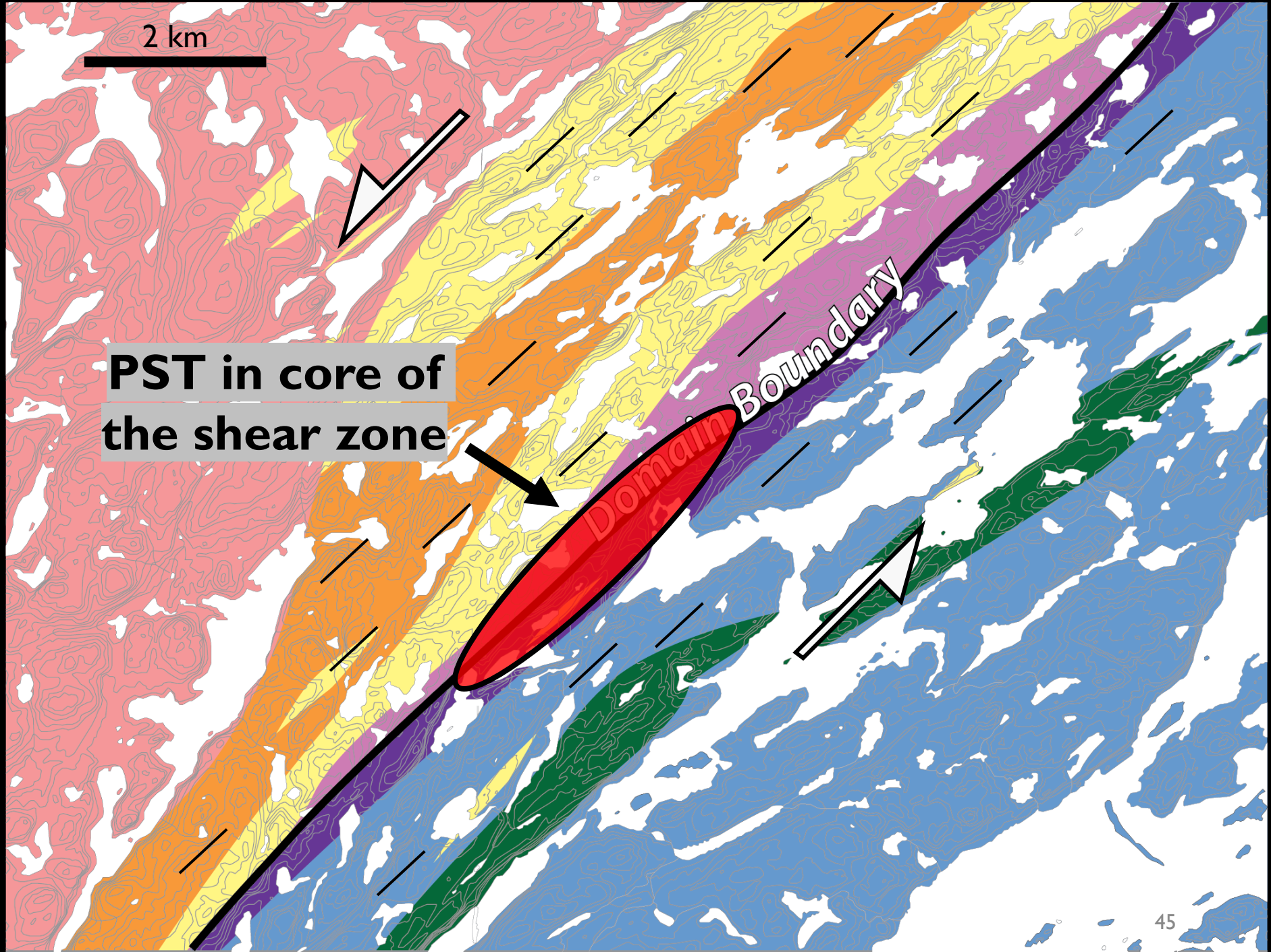
But there is **no clear consensus on how** this can occur



2 km

**PST in core of
the shear zone**

Domain Boundary

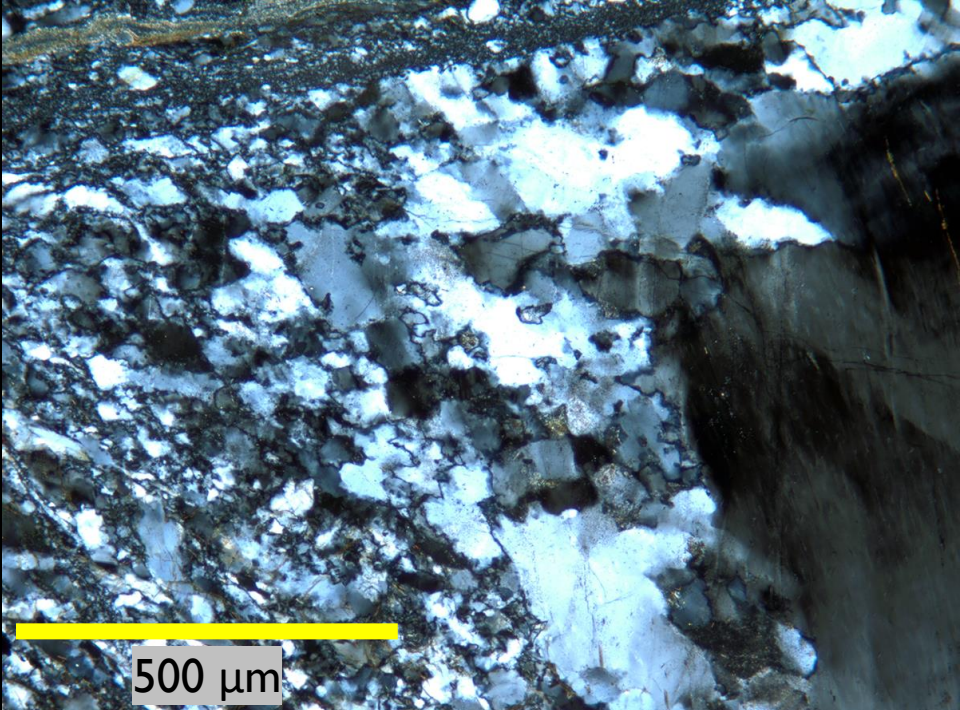


Understanding ductile deformation

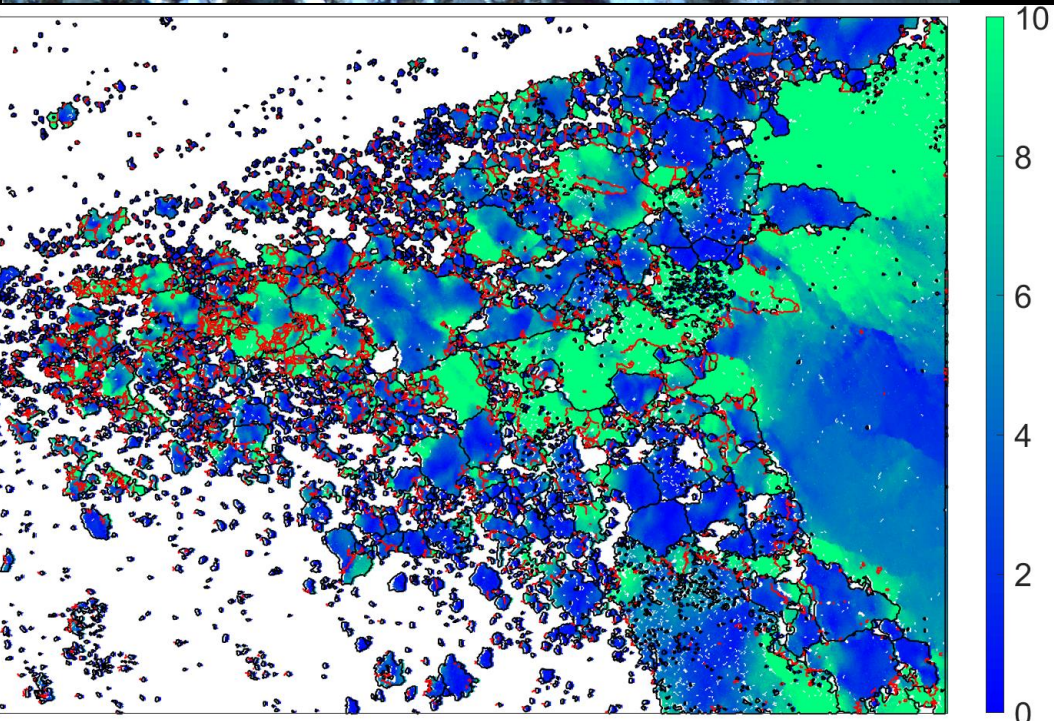
- Ductile deformation occurs at the scale of the crystal lattice, spread out over kilometers
- To understand the map-scale patterns, we need to be able to understand the shear zone at 1/1000 of a millimeter!

Understanding ductile deformation

- Ductile deformation occurs at the scale of the crystal lattice, spread out over kilometers
- To understand the map-scale patterns, we need to be able to understand the shear zone at 1/1000 of a millimeter!
- **Electron backscatter-diffraction is the answer**



Cross-polarized light image
of deforming feldspar

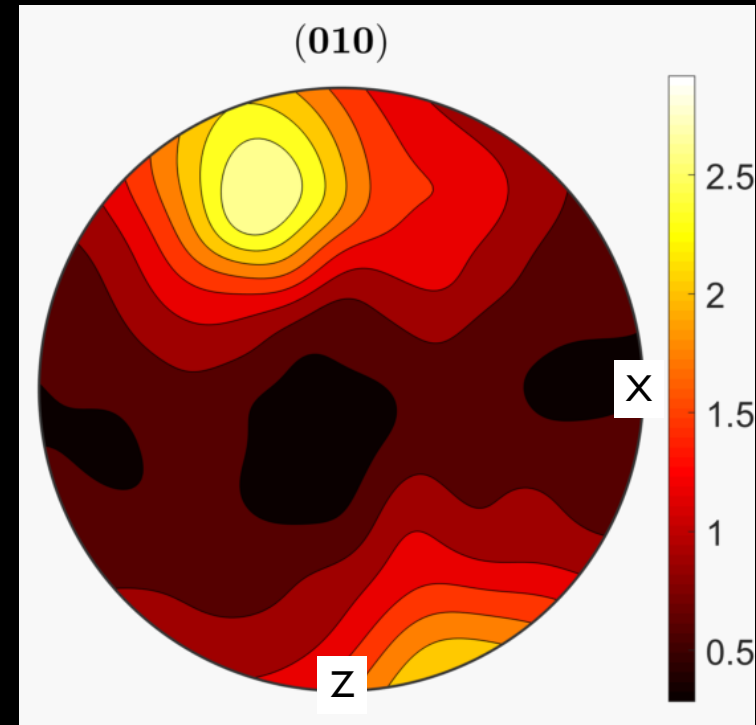
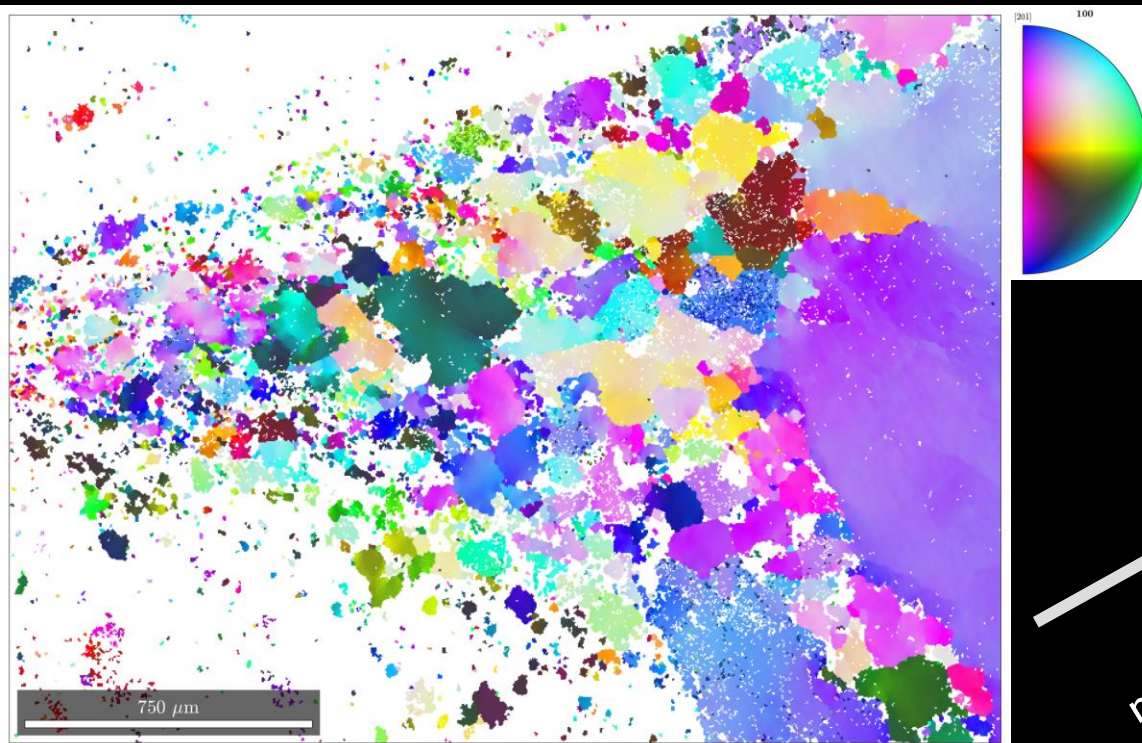


EBSD map showing warping
of the crystal lattice

3 μm pixels
555,000 measurements
~5 hours

Orientation data as pole figures

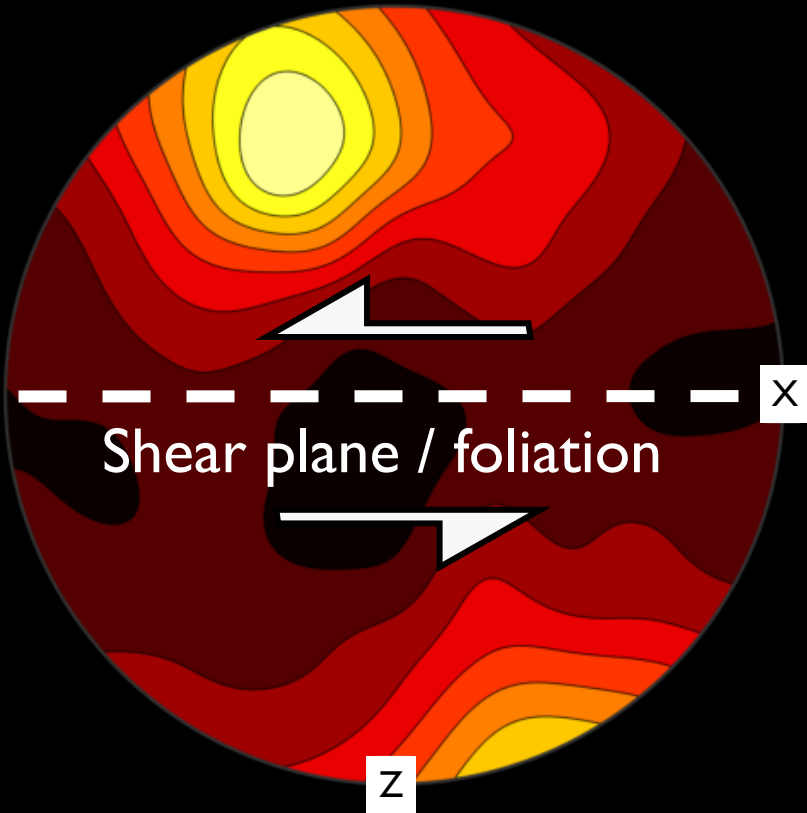
- Pole figure: hemispherical projection of lines and planes
- Contours are Multiples of Uniform Distribution (MUD) and indicate intensity



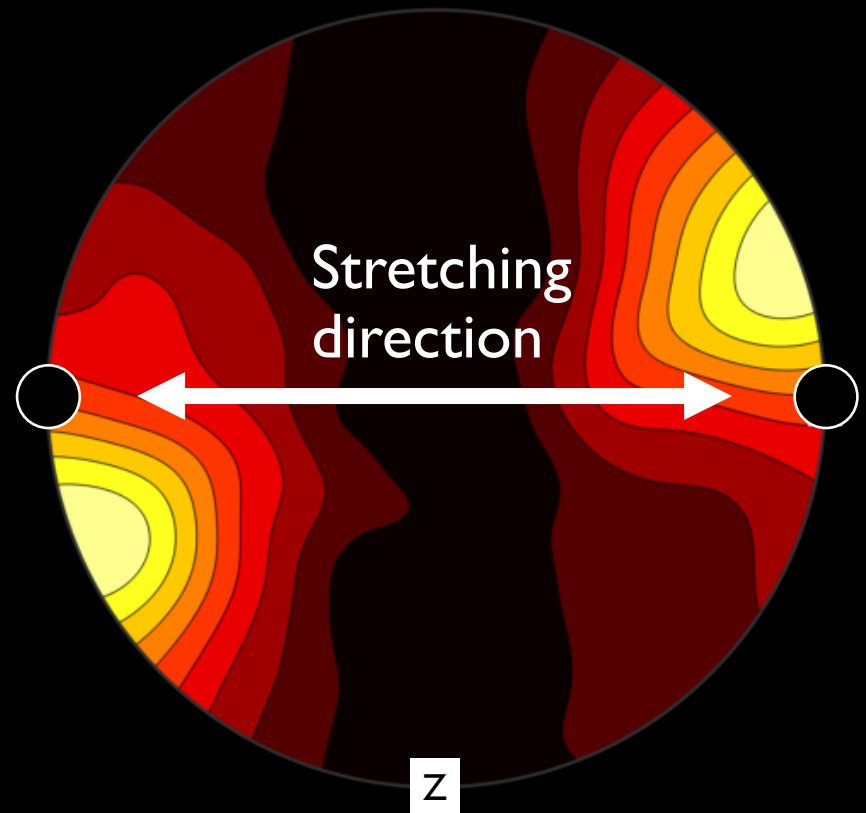
555,000
measurements

All pole figures and microstructural images are in the same reference frame

Slip plane (010)



Primary slip direction [001]



Example of a well-developed CPO suggesting the (010)[001] slip system

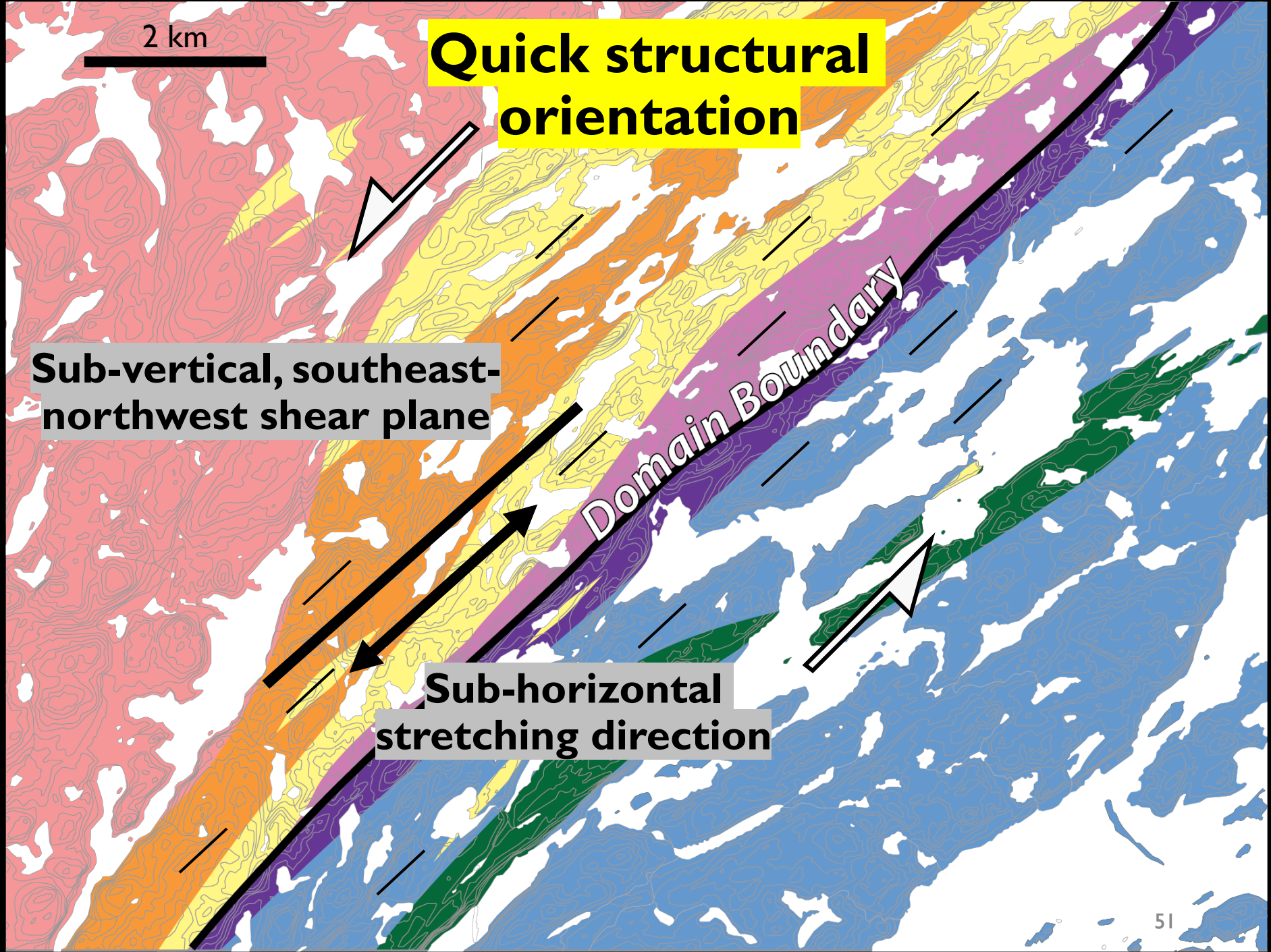
2 km

Quick structural orientation

Sub-vertical, southeast-northwest shear plane

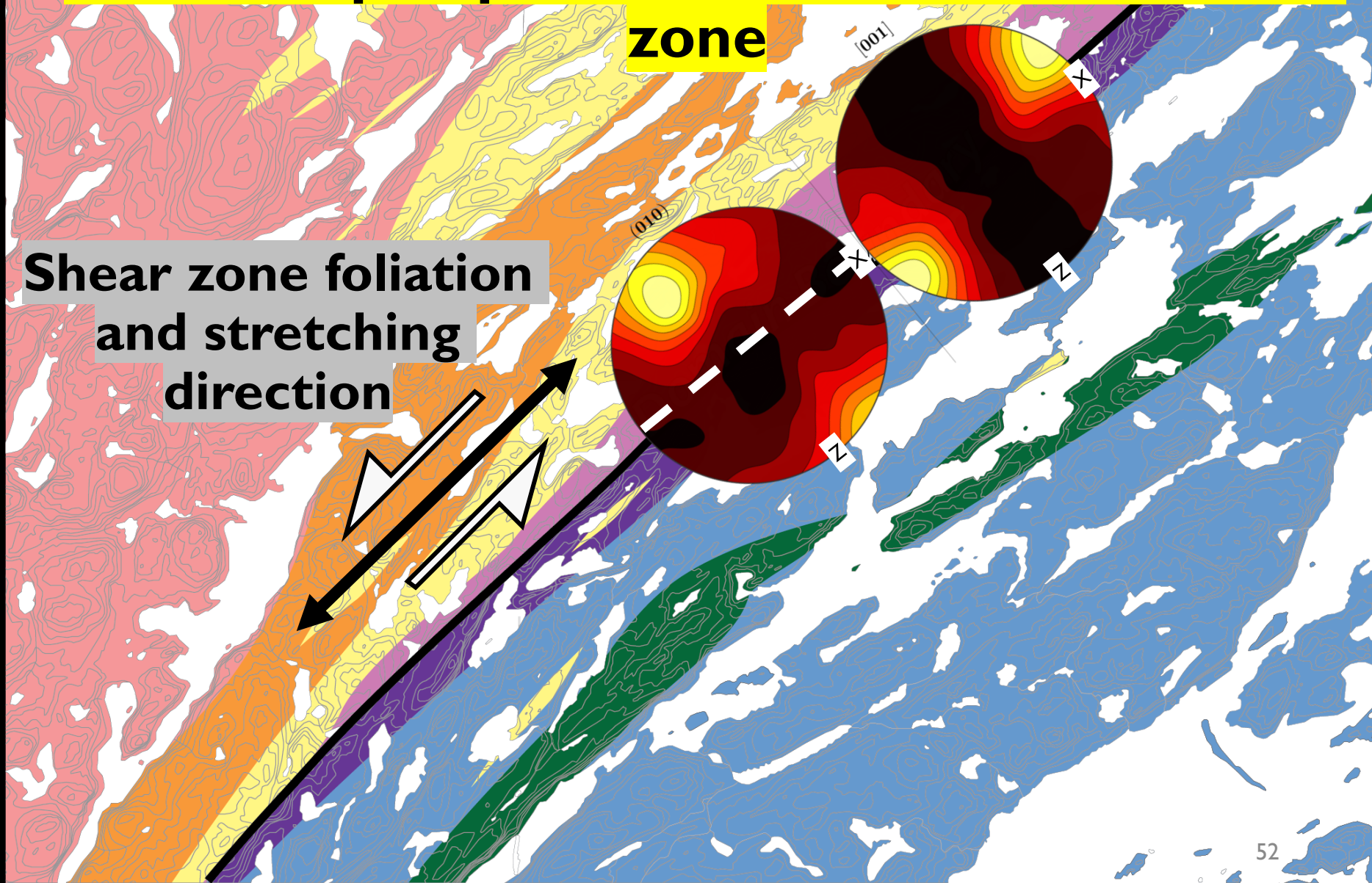
Domain Boundary

Sub-horizontal stretching direction

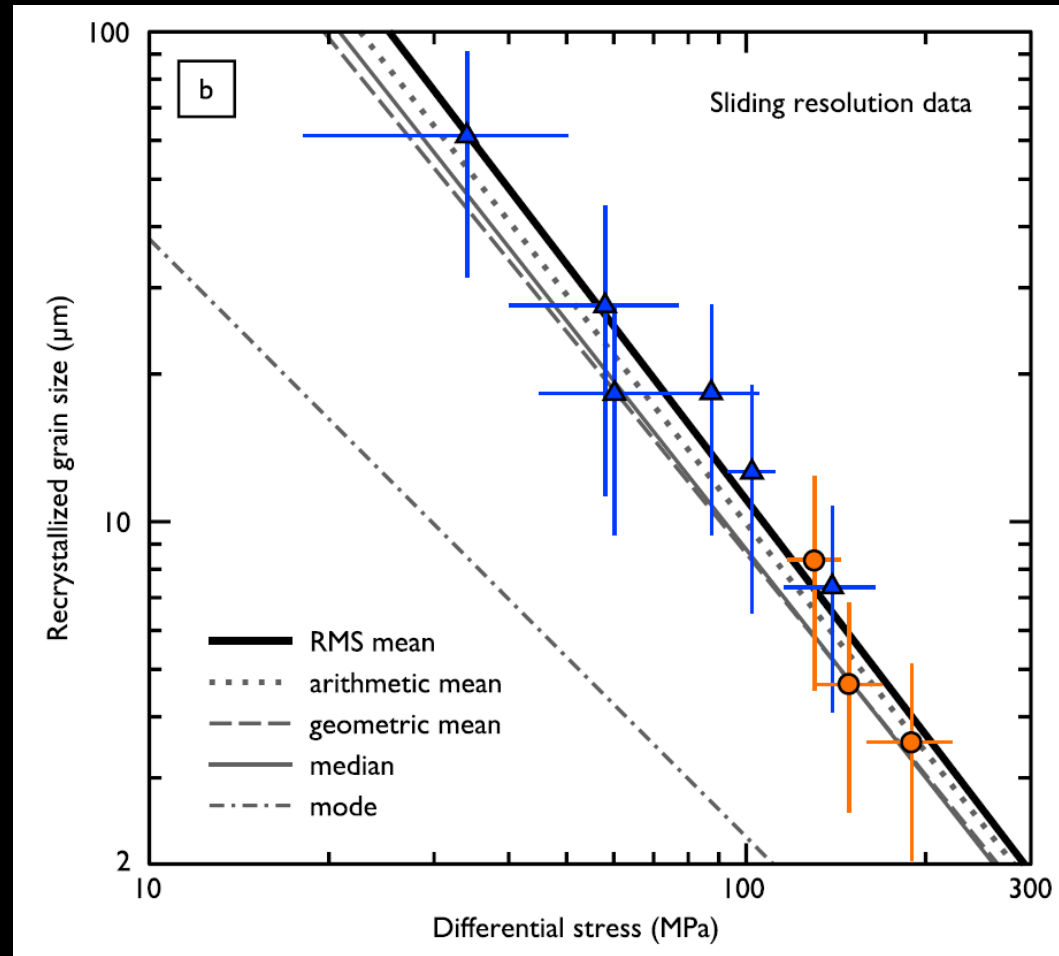


Crystal orientations can be viewed from the same perspective as the km-scale shear zone

Shear zone foliation and stretching direction



Flow stresses



Cross et al., 2017

- Smaller grains = higher flow stresses
- High stresses in the shear zone may relate to PST formation

2 km

Field observations

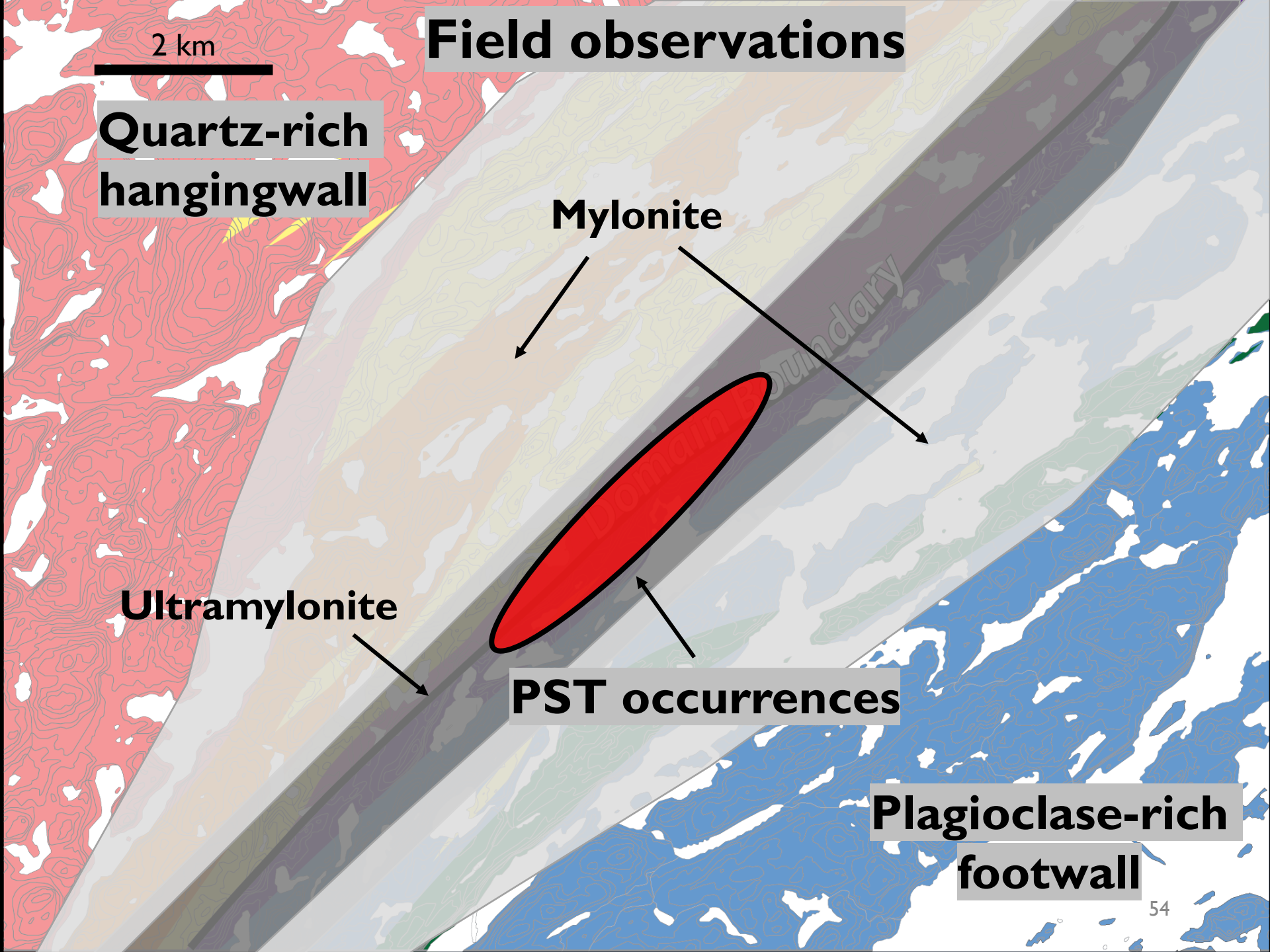
**Quartz-rich
hangingwall**

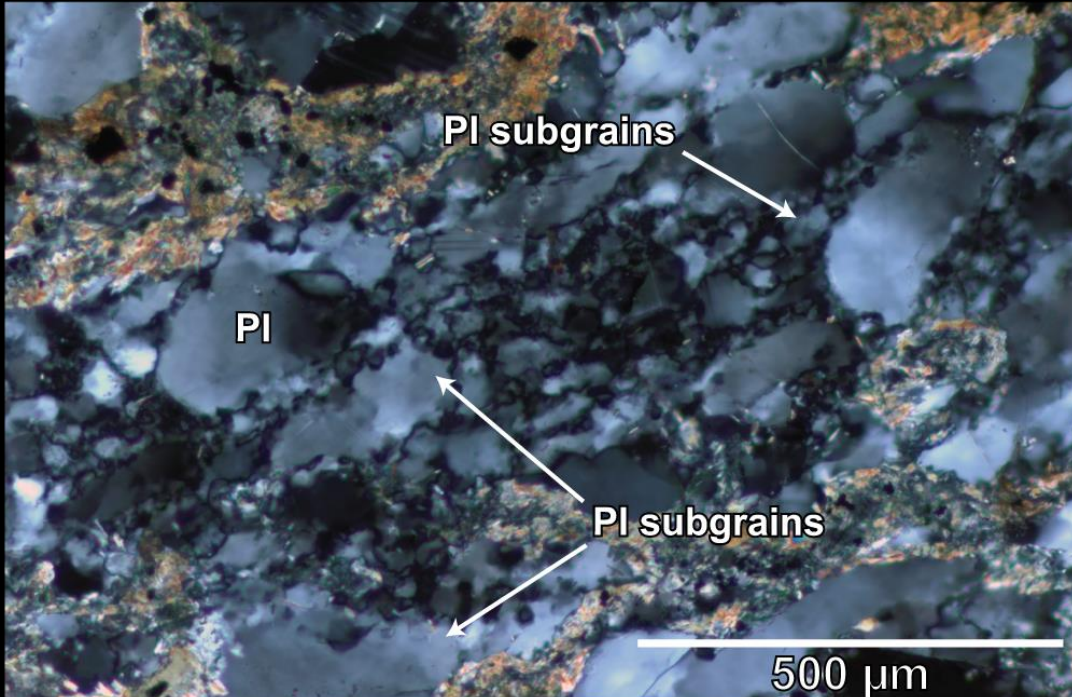
Mylonite

Ultramylonite

PST occurrences

**Plagioclase-rich
footwall**

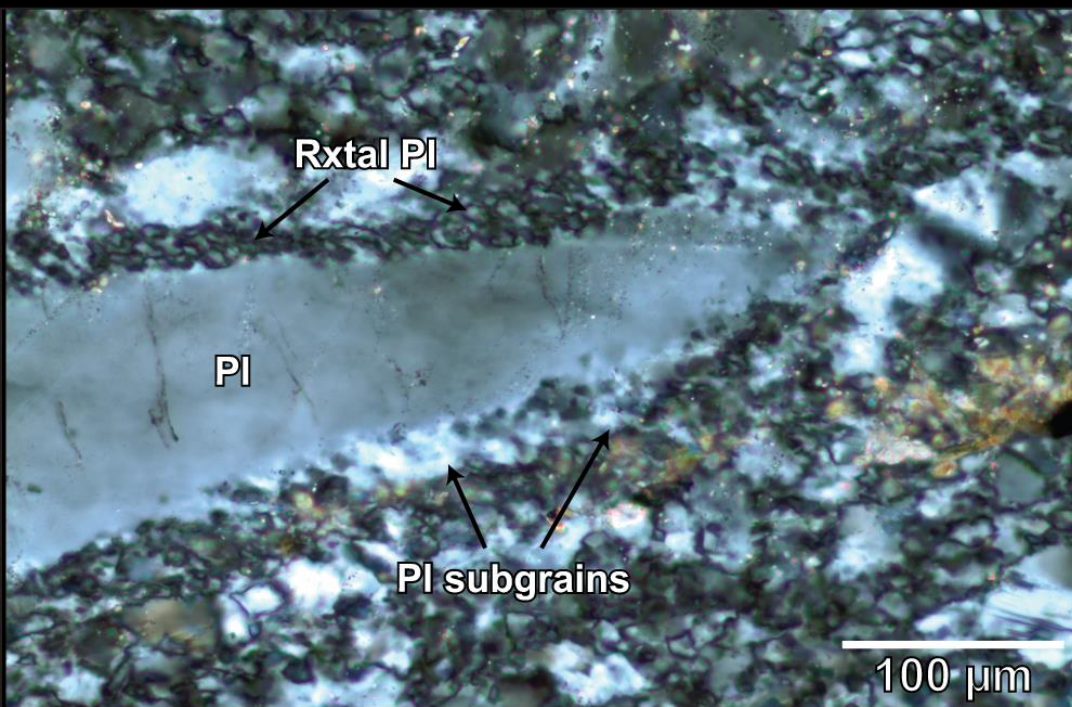
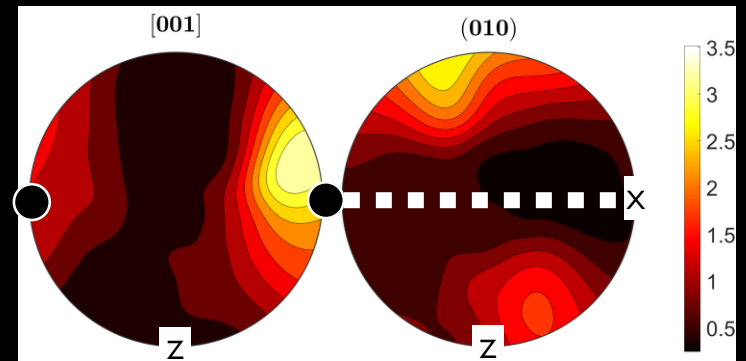




Mylonitic plagioclase

Mean grain size = $36 \pm 31 \mu\text{m}$

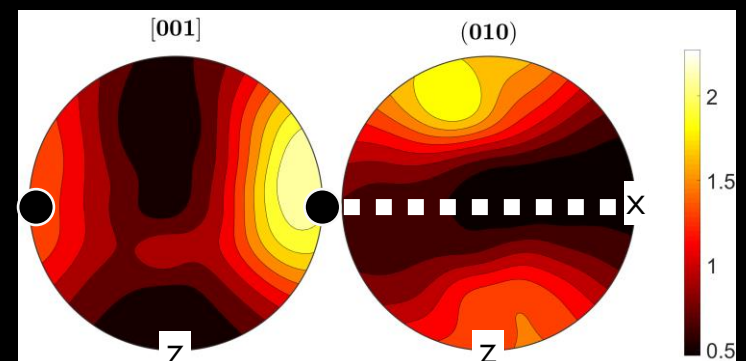
Flow stress = 70-80 MPa

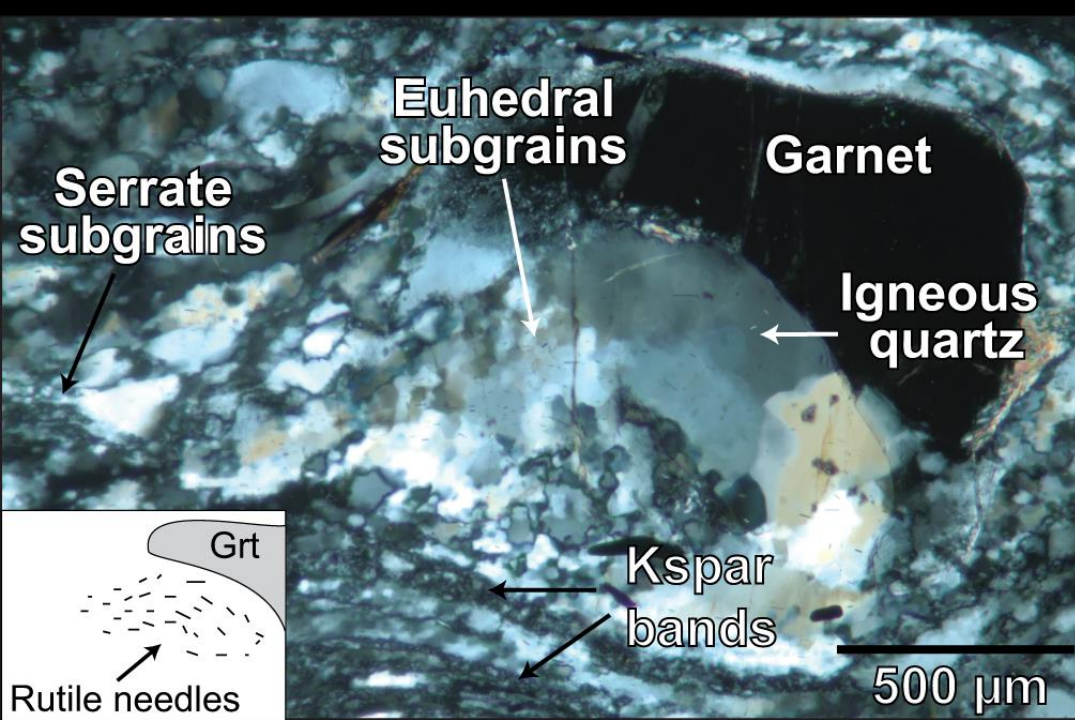


Ultramylonitic plagioclase

Mean grain size = $11 \pm 8 \mu\text{m}$

Flow stresses = **> 170 MPa**

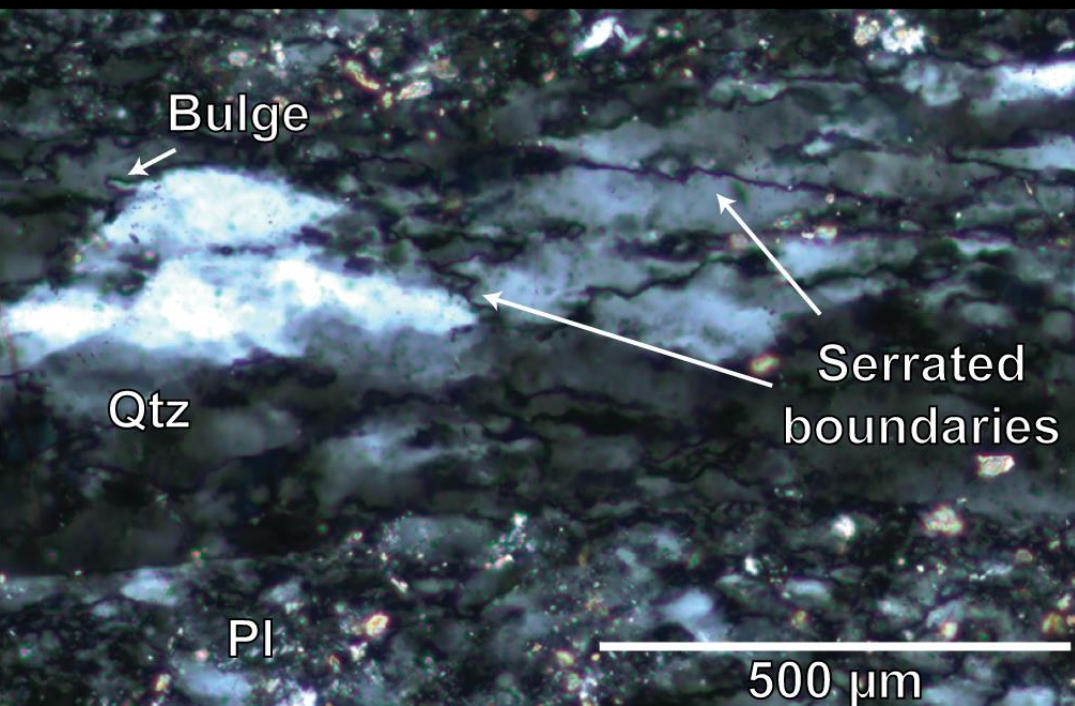
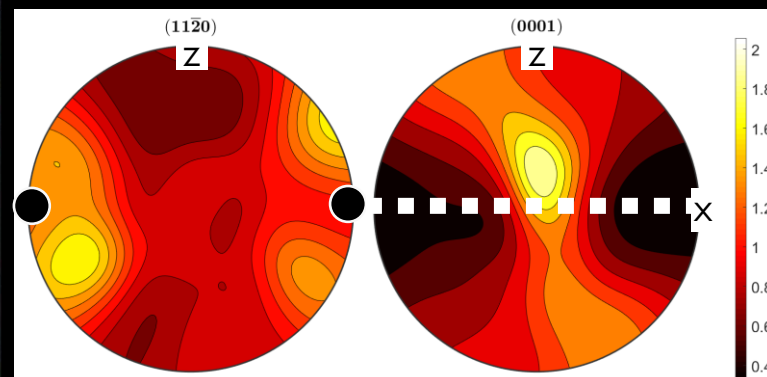




Mylonitic quartz

Mean grain size = $21 \pm 20 \mu\text{m}$

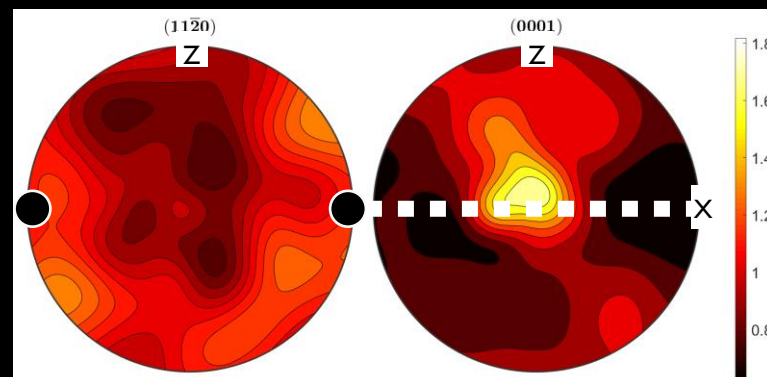
Flow stresses = 60-70 MPa



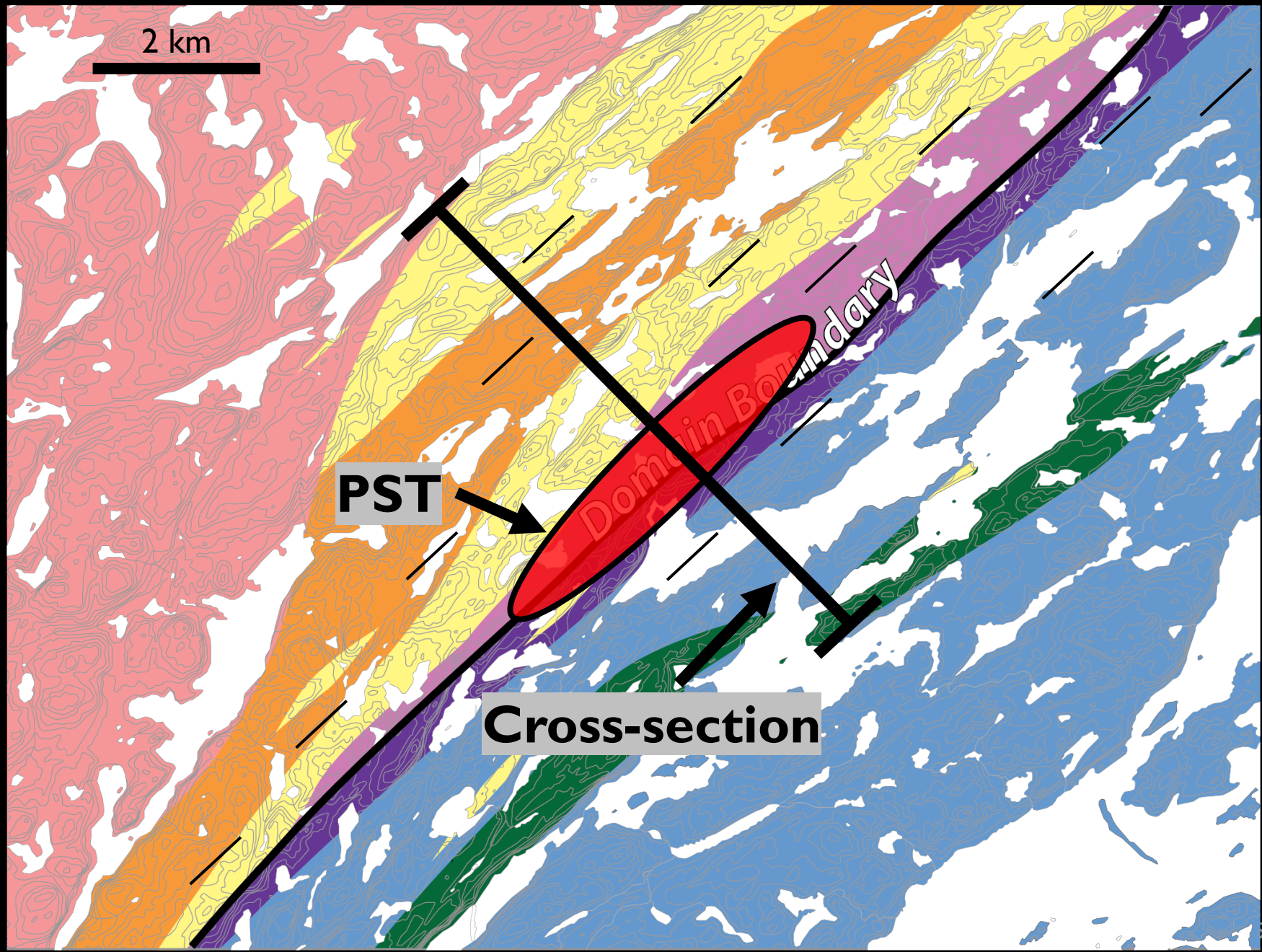
Ultramylonitic quartz

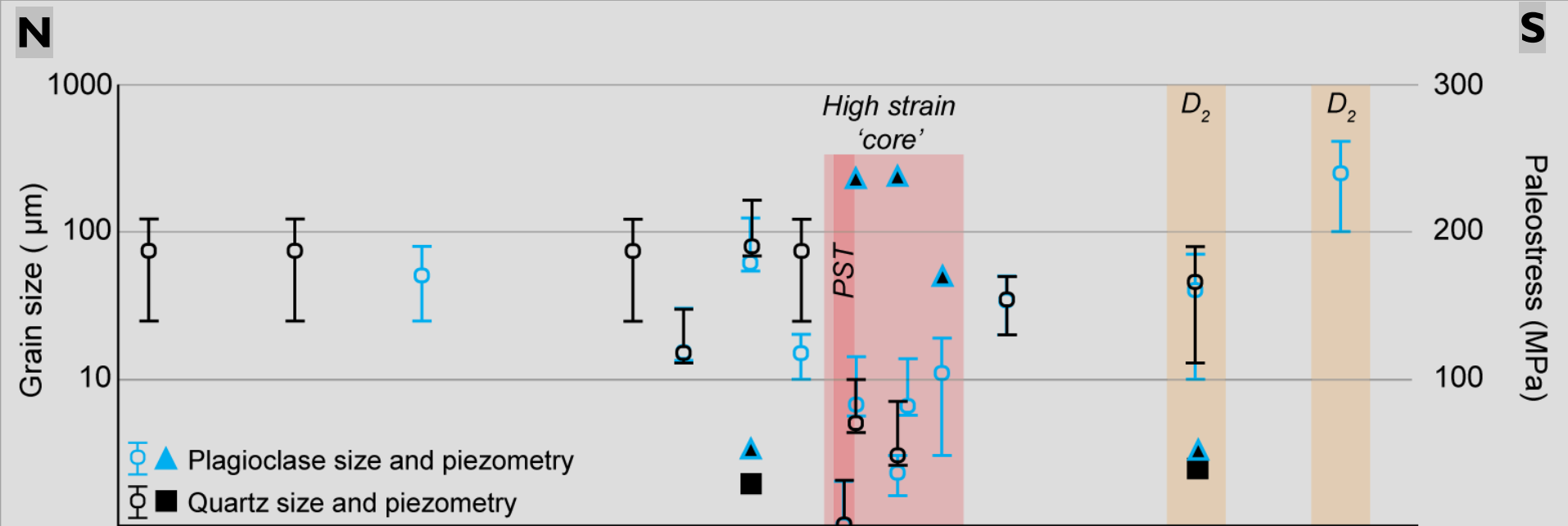
Mean grain size = $10 \pm 8 \mu\text{m}$

Flow stresses = > **160 MPa**



Trends across the shear zone core



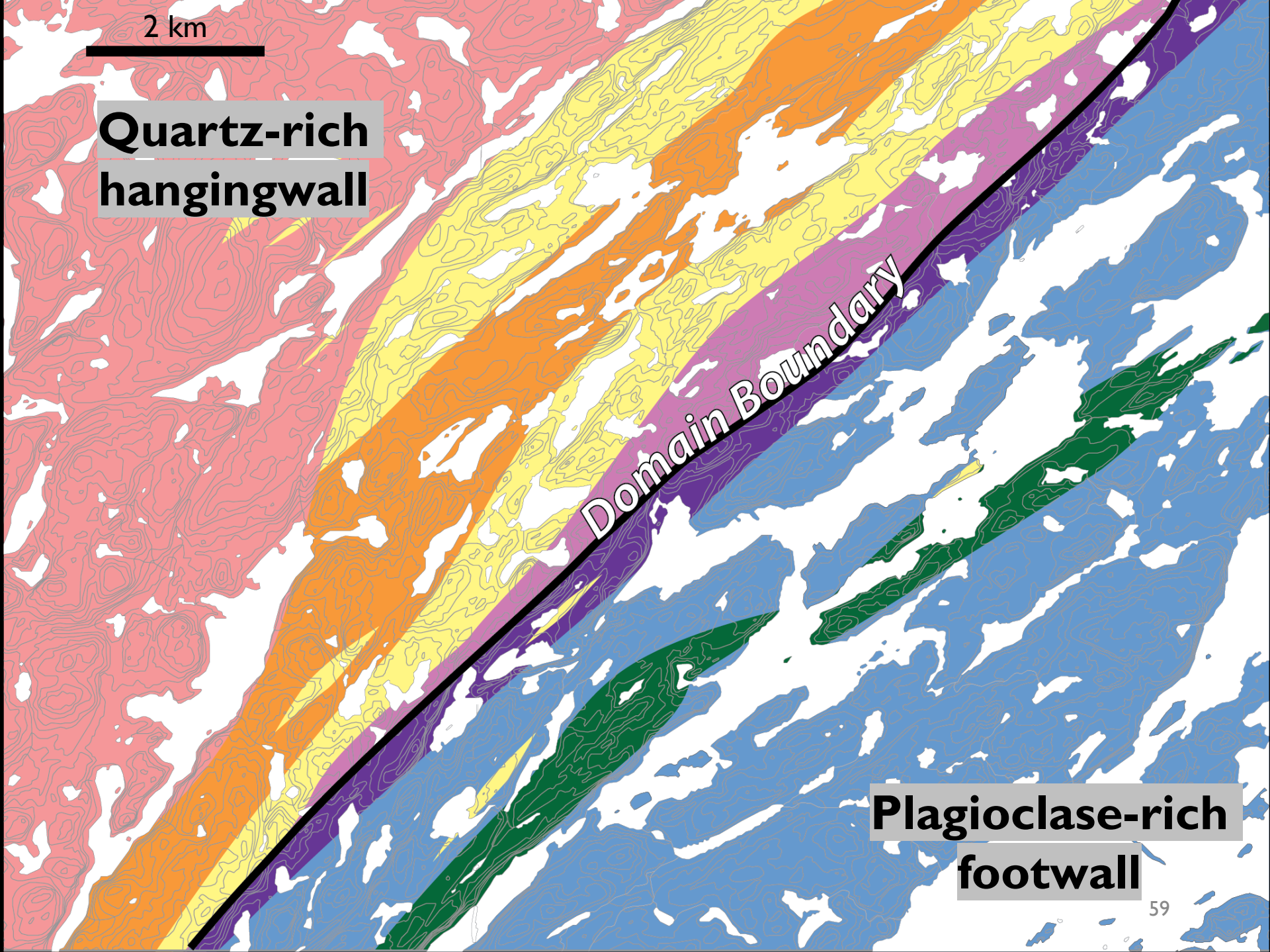


2 km

**Quartz-rich
hangingwall**

Domain Boundary

**Plagioclase-rich
footwall**



2 km

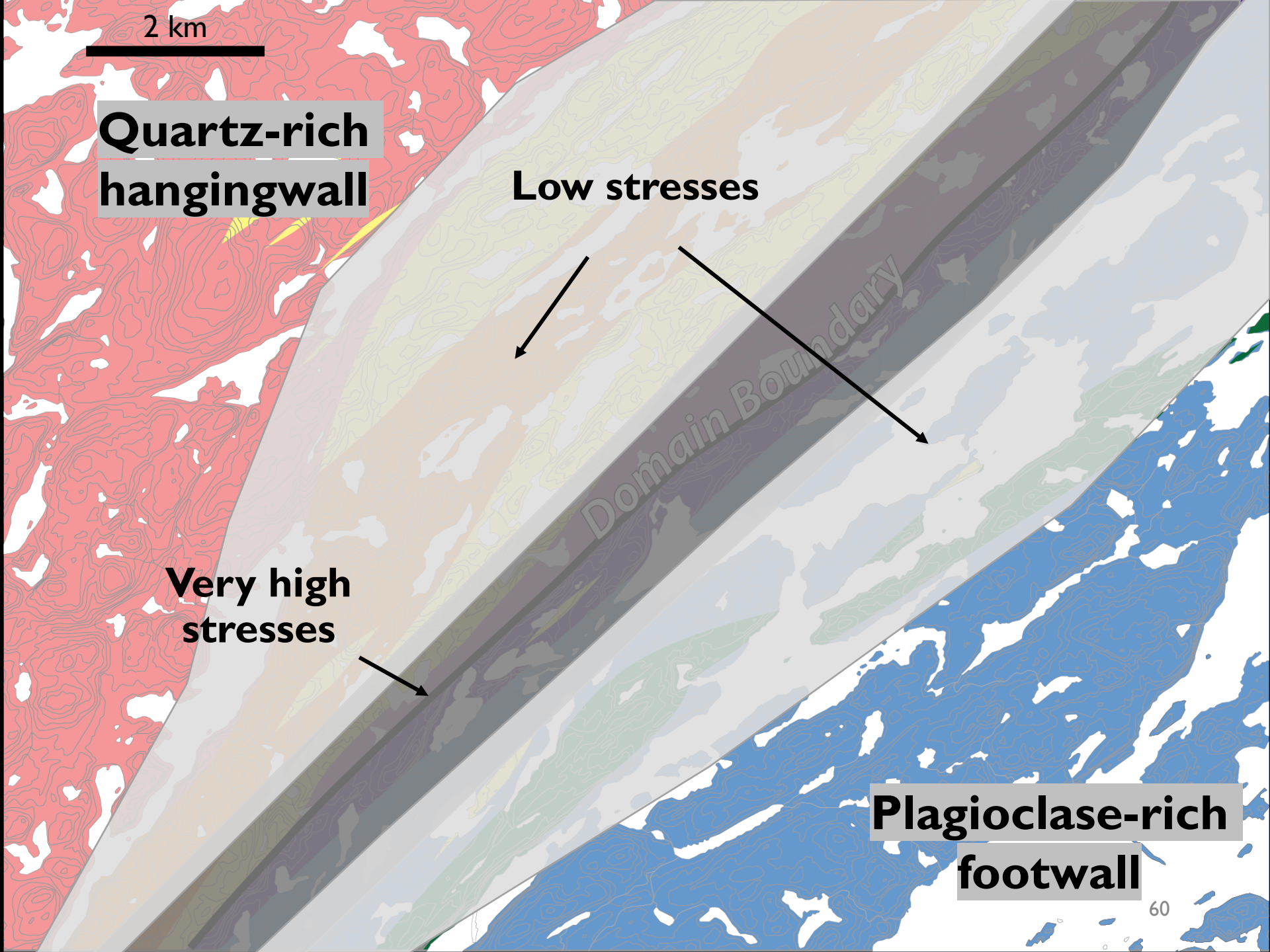
**Quartz-rich
hangingwall**

Low stresses

**Very high
stresses**

Domain Boundary

**Plagioclase-rich
footwall**



2 km

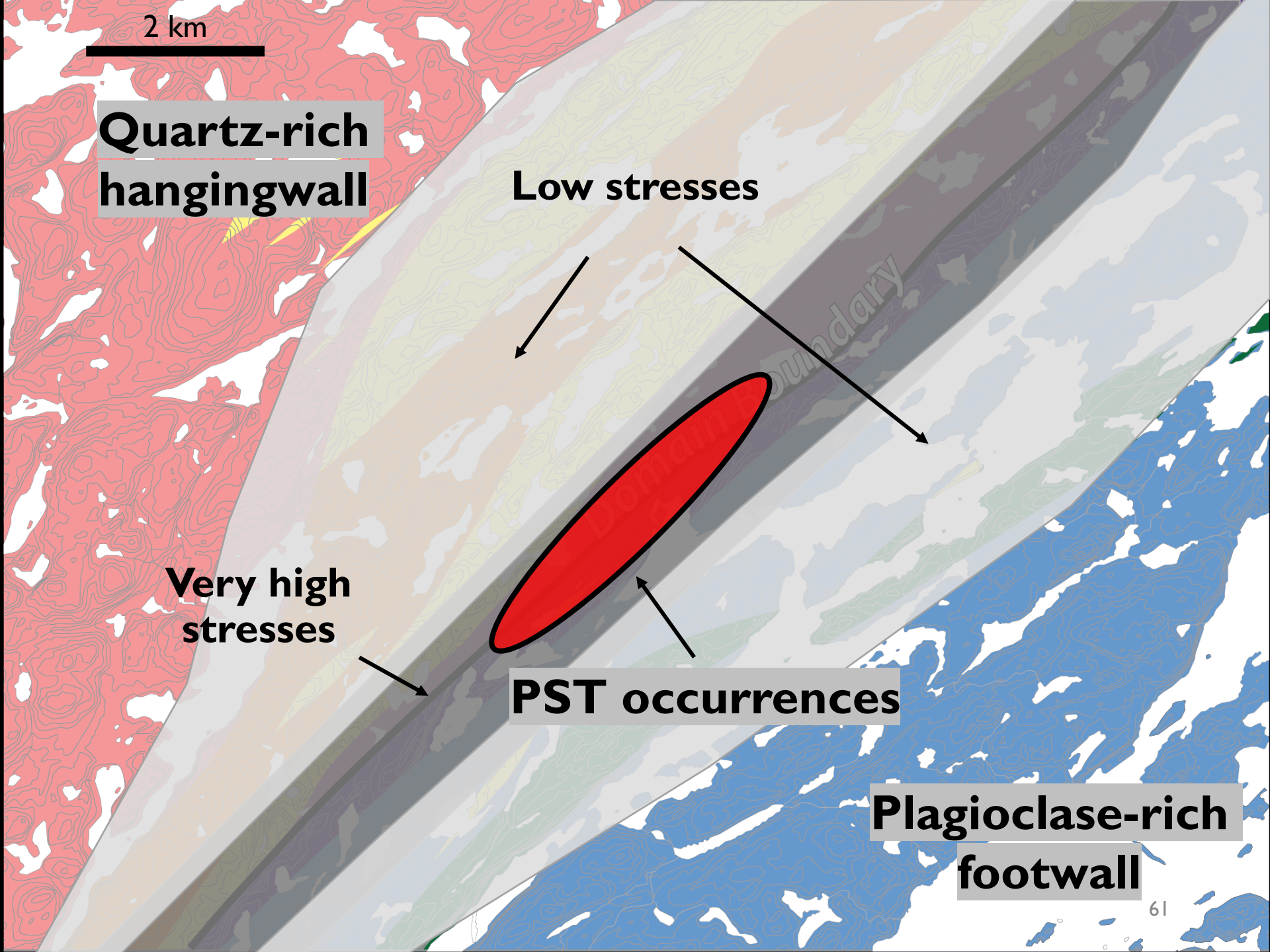
**Quartz-rich
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PST occurrences

**Plagioclase-rich
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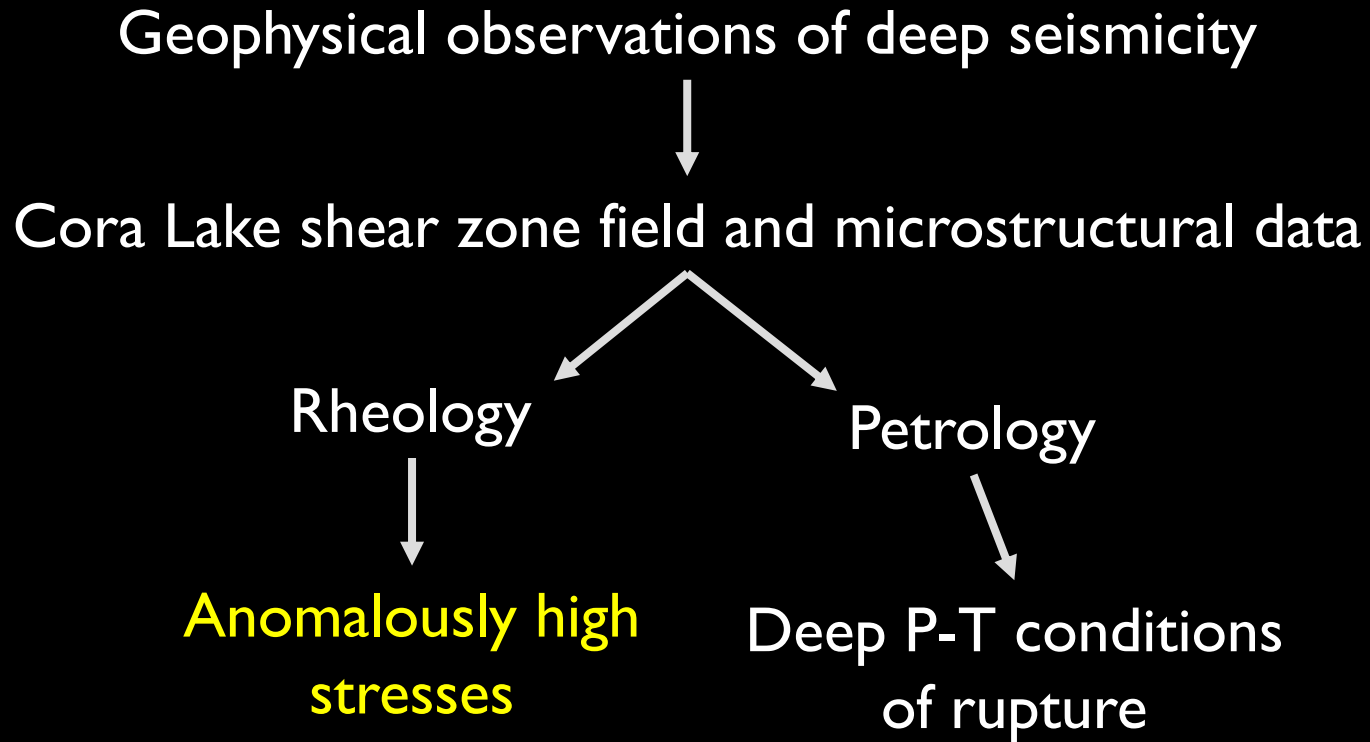


Ductile deformation in the Cora Lake shear zone

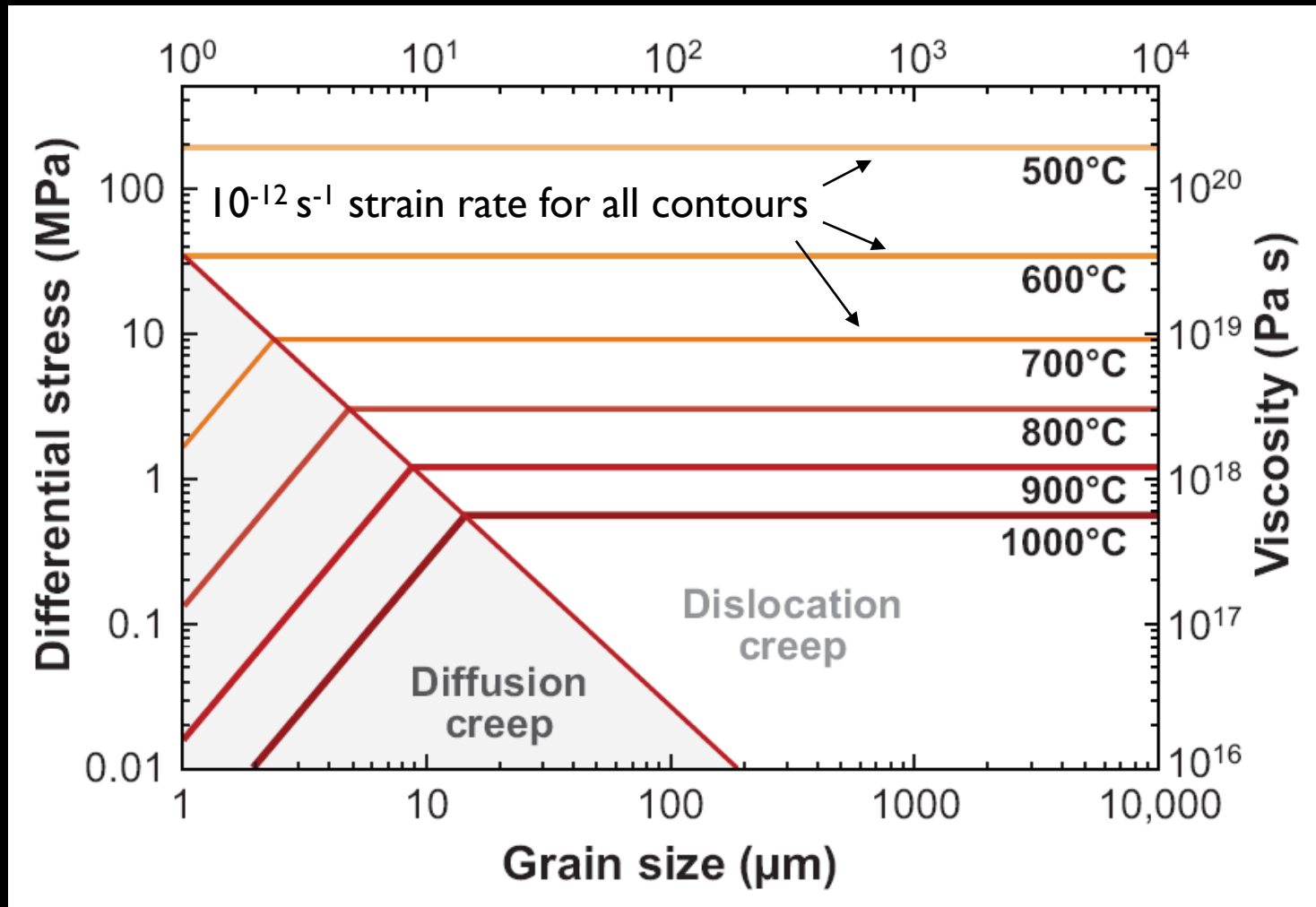
- The mylonite records mid- to low-stresses
 - Fits the general idea of a hot, weak shear zone
- The ultramylonite records **very high stresses**
 - Does NOT fit the idea of hot, weak rocks – these are strong rocks!
- Crystal orientations the same for mylonite and ultramylonite
 - Since they deformed the same way, we can apply **experimental laws to understand ductile flow**

Question 2a.

Why does stress vary within the shear zone?

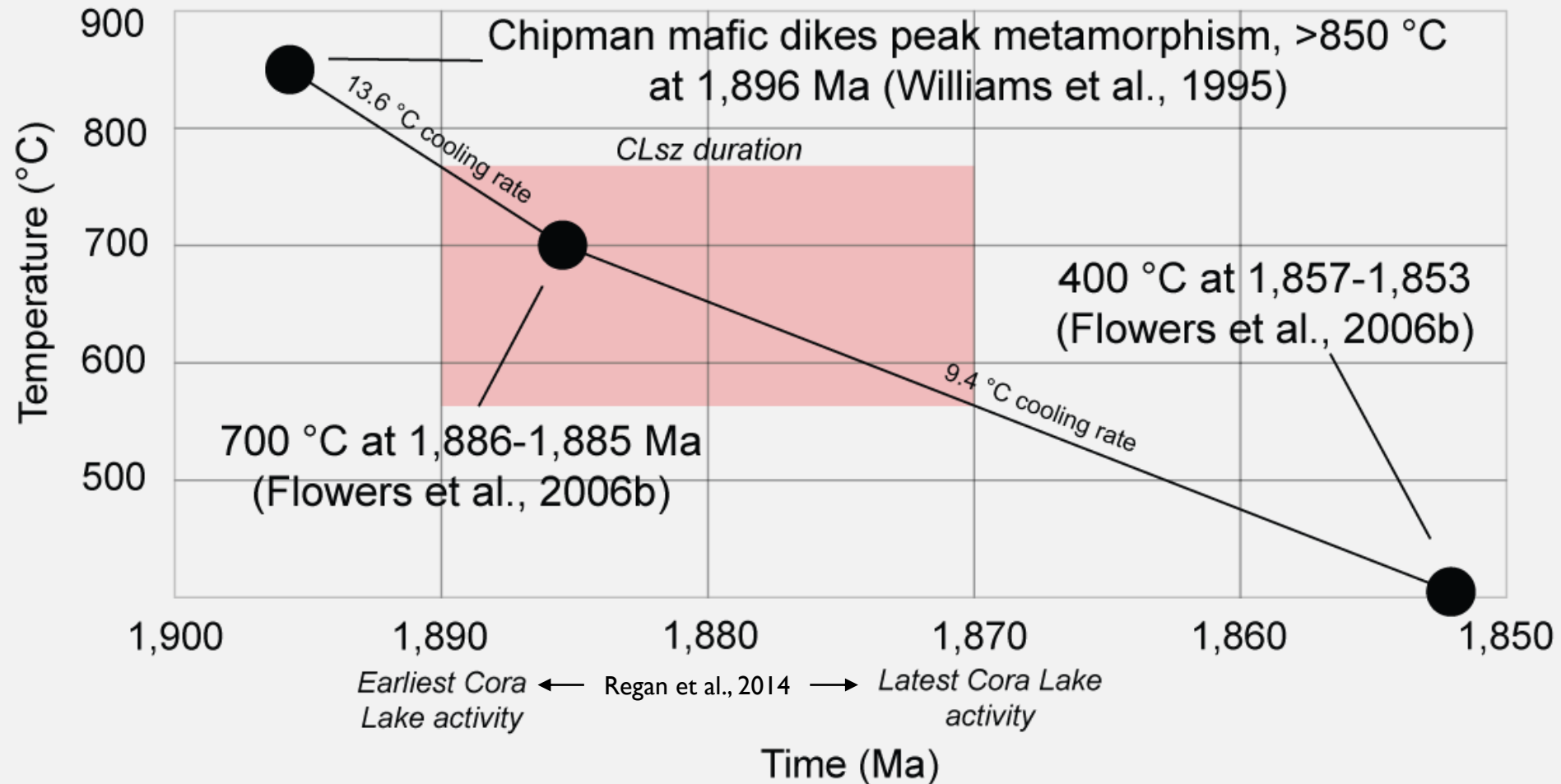


Using temperature to understand ductile flow



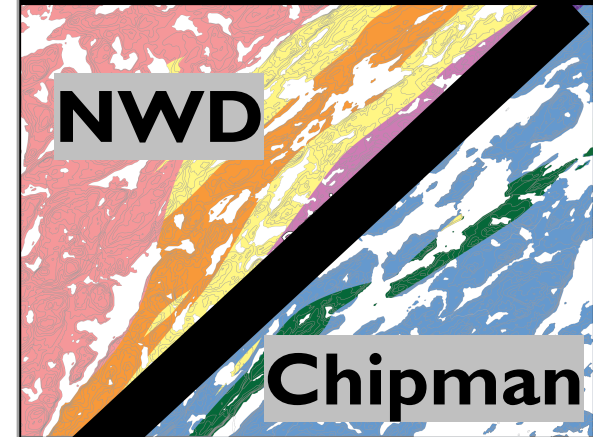
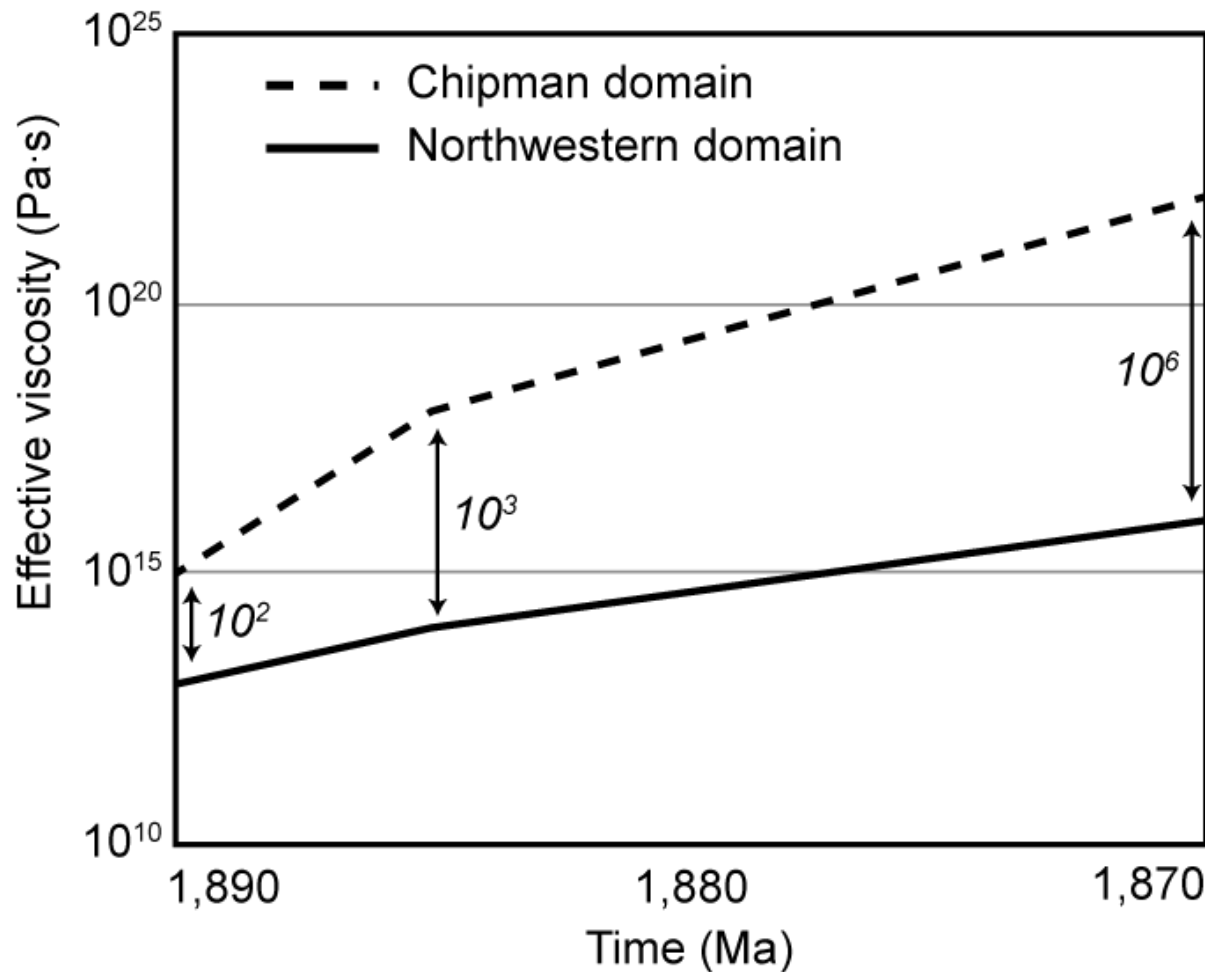
- Rocks flow more easily at higher temperatures and lower stresses
- This relationship can be predicted thanks to deformation experiments

Temperature of Cora Lake deformation through time



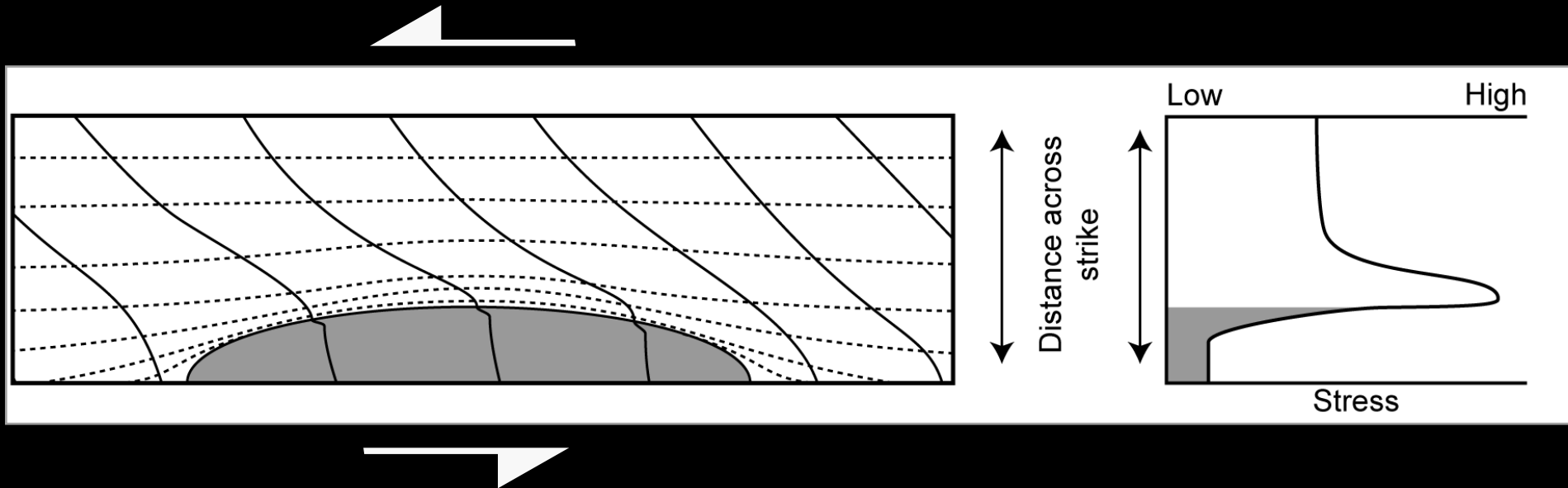
Deformation **started hot** and **cooled quickly**

Evolution of viscosity for quartz-rich hangingwall and quartz-poor footwall through time



Early stages: hangingwall is like water and footwall is like warm honey
Mid- to late-stages: like water vs peanut butter!

The 'stress riser' effect



Theoretical stress perturbations due to viscosity contrast
(schematic after Sibson, 1980; Fagerang and Sibson, 2010; Gardner et al., 2017)

The higher the viscosity contrast, the higher the stress increase!

High stresses = **closer to brittle failure**

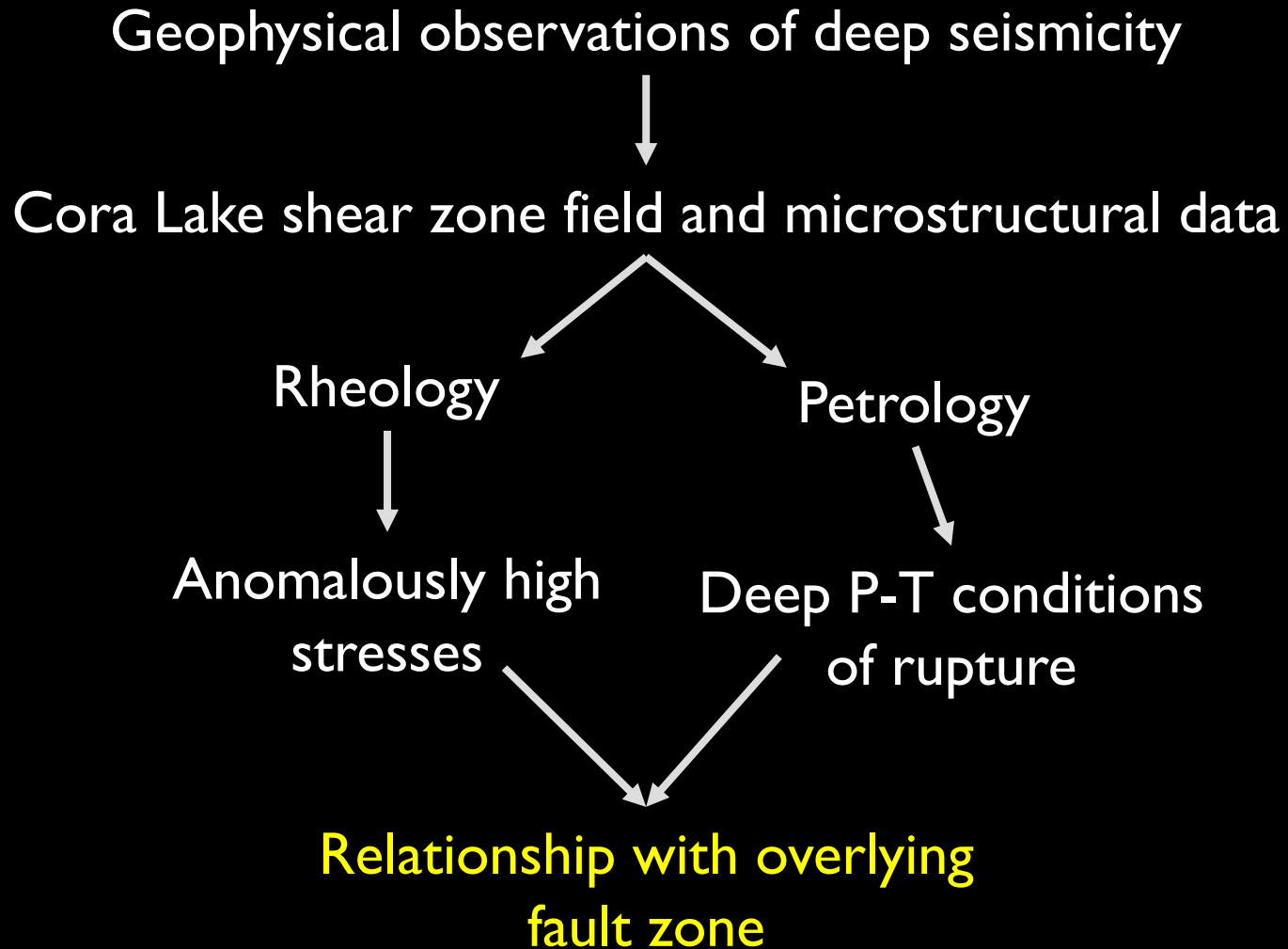
Question 2:

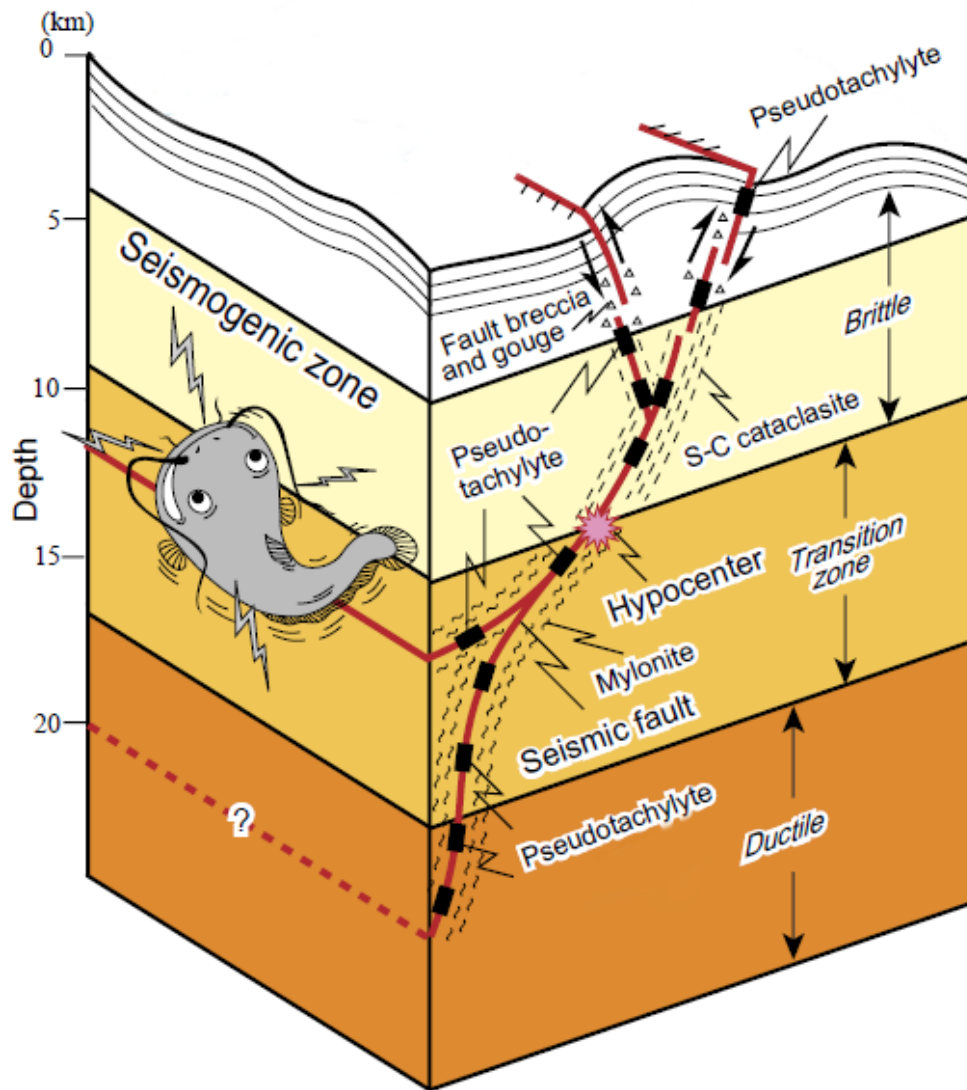
What is the relationship between the pseudotachylyte and the hosting shear zone?

- Plagioclase-rich footwall **stiffened** significantly during deformation
- Km-scale contact between footwall and hangingwall became **stress riser**
- High stresses in a narrow region near contact **allows the formation of PST**

Final question:

Does our PST translate into the deep seismicity we started with?





Deformation can span
the entire crust of the
Earth

Currently exposed
Cora Lake shear zone
was 30-40 km deep

The Cora Lake shear zone very likely had an active
overlying fault system >70 km long

Final question:

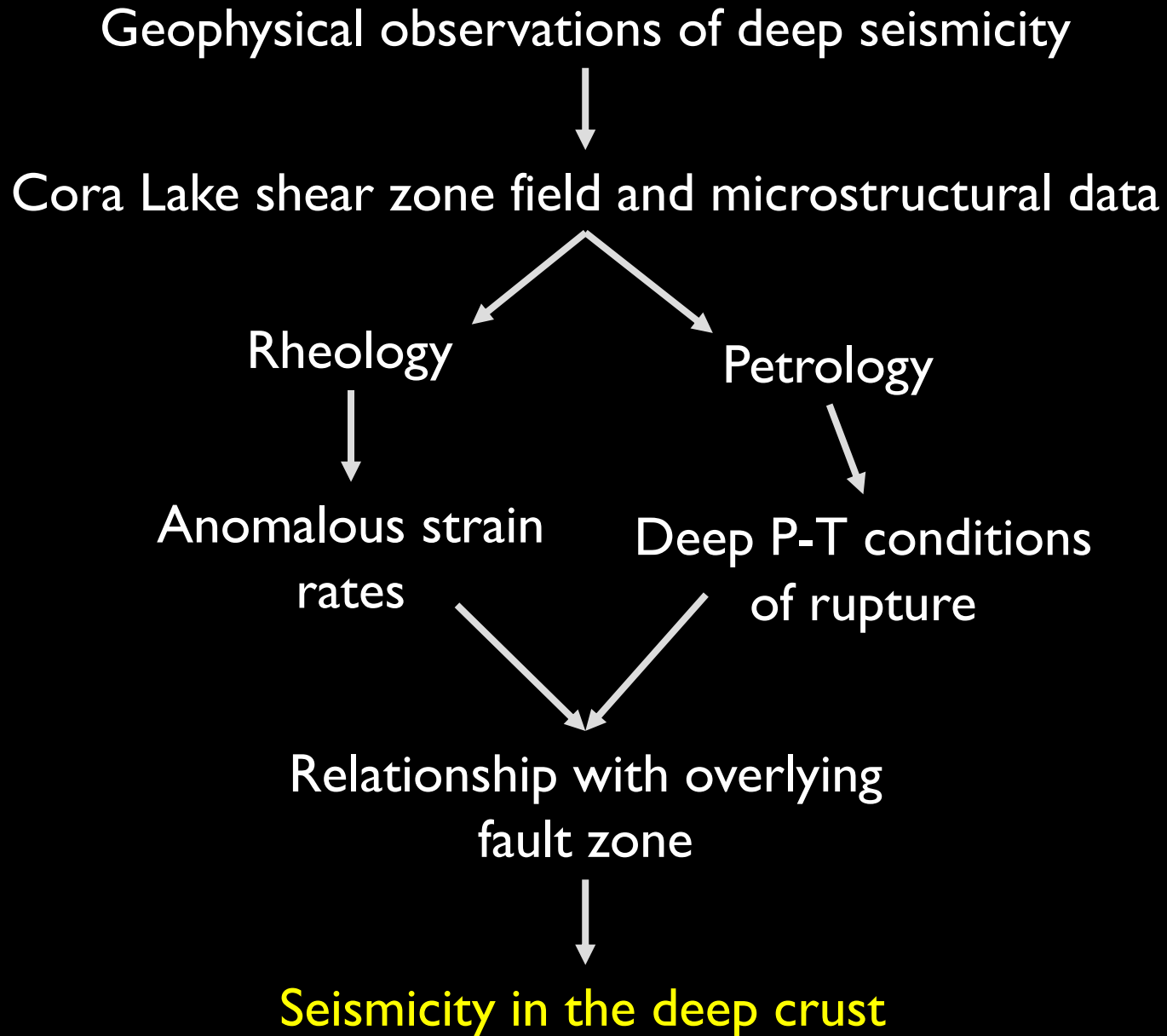
Does our PST translate into the deep seismicity we started with?

- PST seems to be from many small ruptures over 20 My (thickness $\approx M_w$)
- Deep aftershocks from big fault ruptures are much more common than big deep earthquakes
- Our shear zone is >70km long, and likely had a big fault system sitting right on top of it

Final question:

Does our PST translate into the deep seismicity we started with?

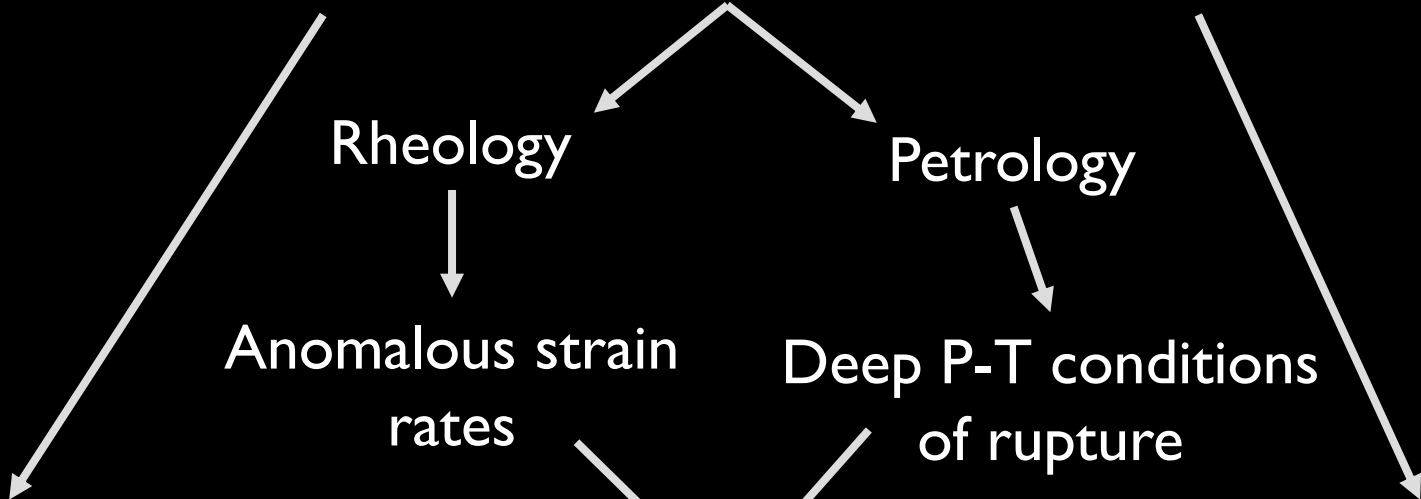
- PST seems to be from many small ruptures over 20 My (thickness $\approx M_w$)
- Deep aftershocks from big fault ruptures are much more common than big deep earthquakes
- Our shear zone is >70km long, and likely had a big fault system sitting right on top of it
- Cora Lake PST is most likely evidence of **deep aftershocks from overlying fault system**



Geophysical observations of deep seismicity



Cora Lake shear zone field and microstructural data



Rheology

Petrology

Anomalous strain
rates

Deep P-T conditions
of rupture

Neural network
prediction of
crystal orientation

Relationship with overlying
fault zone

Seismic anisotropy
of ductile
deformation

Seismicity in the deep crust

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