The rheology and mechanical anisotropy of a foliated blueschist

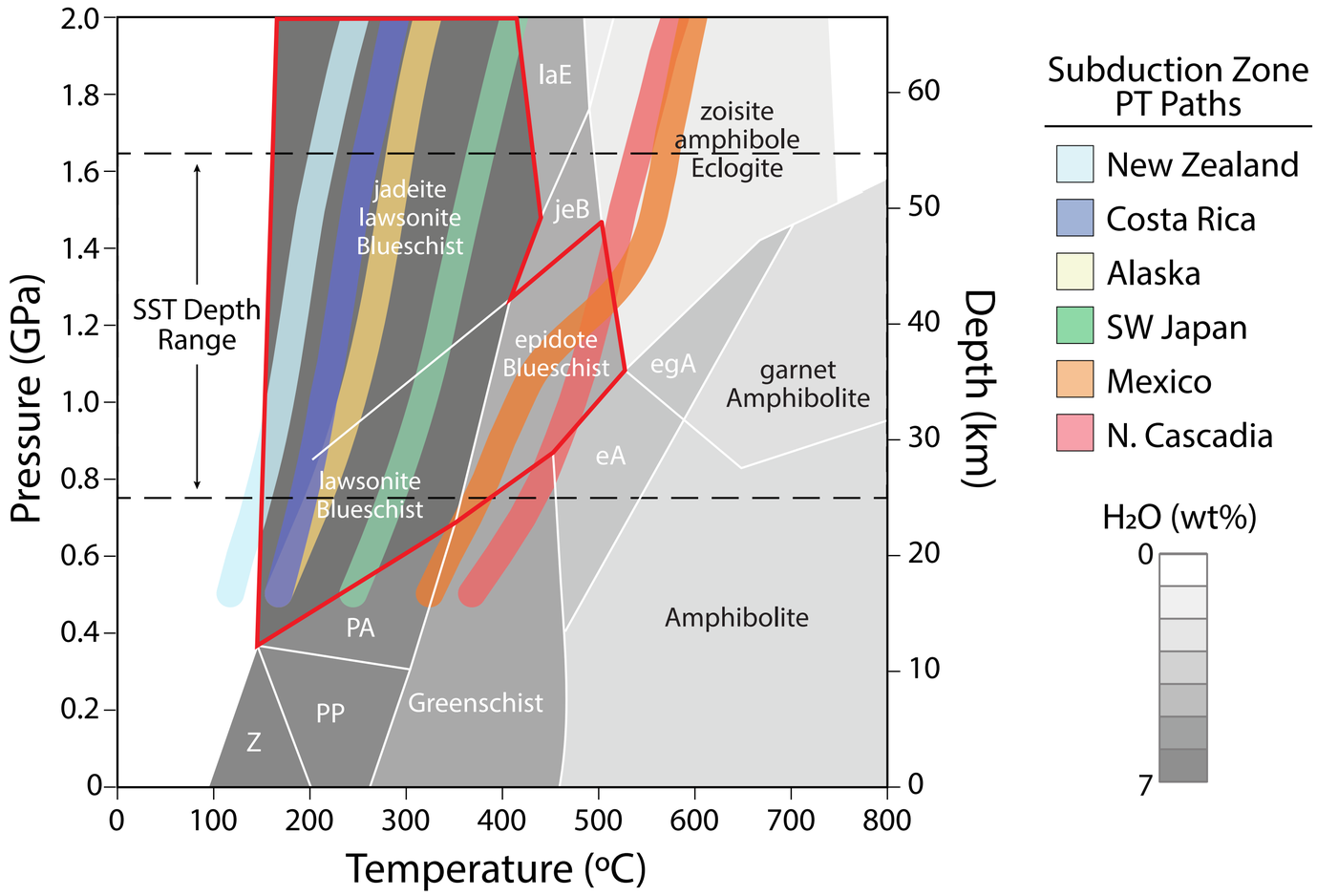
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[1]ETH Zürich (Structural Geology and Tectonics Group)
vEGU 2021

Motivation

- Blueschist rocks are a major constituent rock type along the subduction zone interface and critical to our understanding of subduction zone dynamics.
- Blueschist rocks are also the rock type that occurs at conditions where Slow Slip and Tremor (SST) occur.
- However, the mechanical properties of blueschist rocks are poorly constrained, especially at viscous deformation conditions.

Goal: To quantify the rheology of a glaucophane-bearing blueschist with and without a foliation using rock deformation experiments



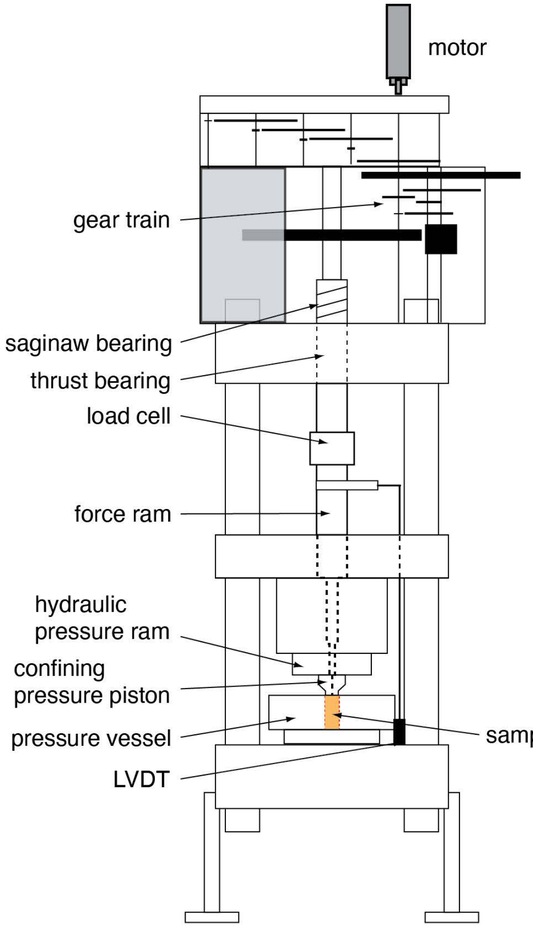
Modified from Behr & Burgmann (*2021*)

Griggs Apparatus

- Rock deformation experiments are performed in the Griggs apparatus at ETH Zurich
- The Griggs apparatus can deform samples at high-T and high-P relevant to conditions observed along the subduction zone interface.

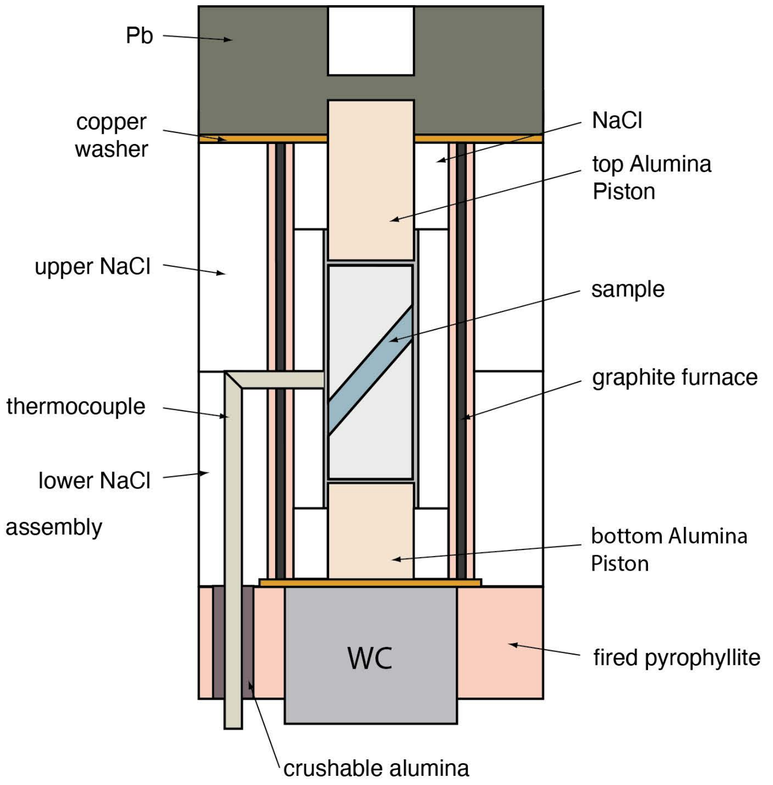


ETH Zurich Griggs

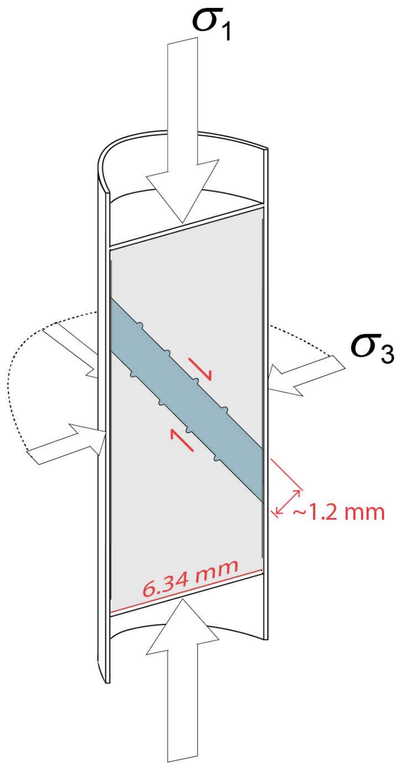


Griggs Rig

Sample Assembly

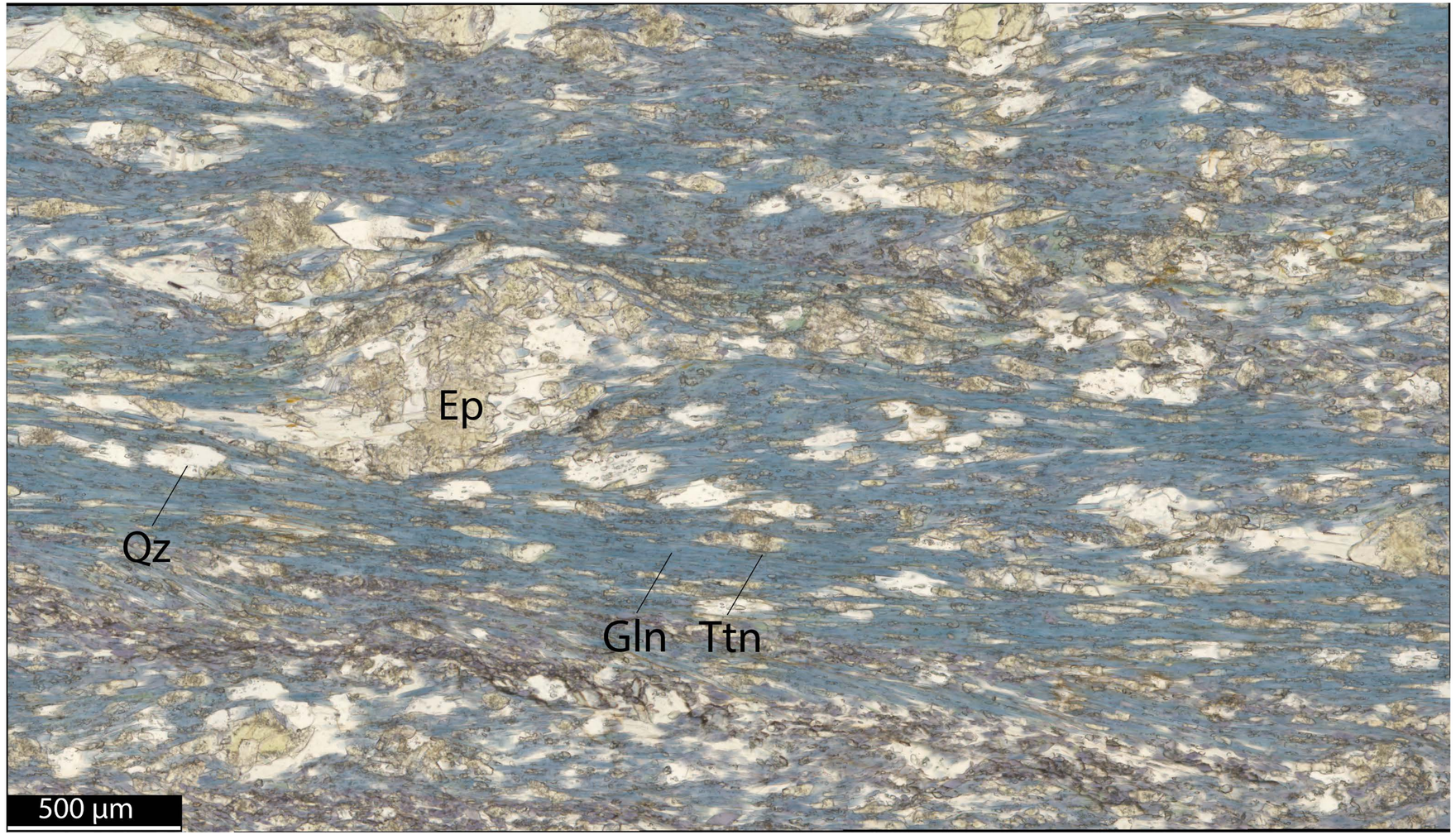


Cross-section of Jacketed Sample



Starting material

- Starting material is a foliated epidote blueschist from the Condrey Mountain Window (CMW).



Photomicrograph taken in plane light

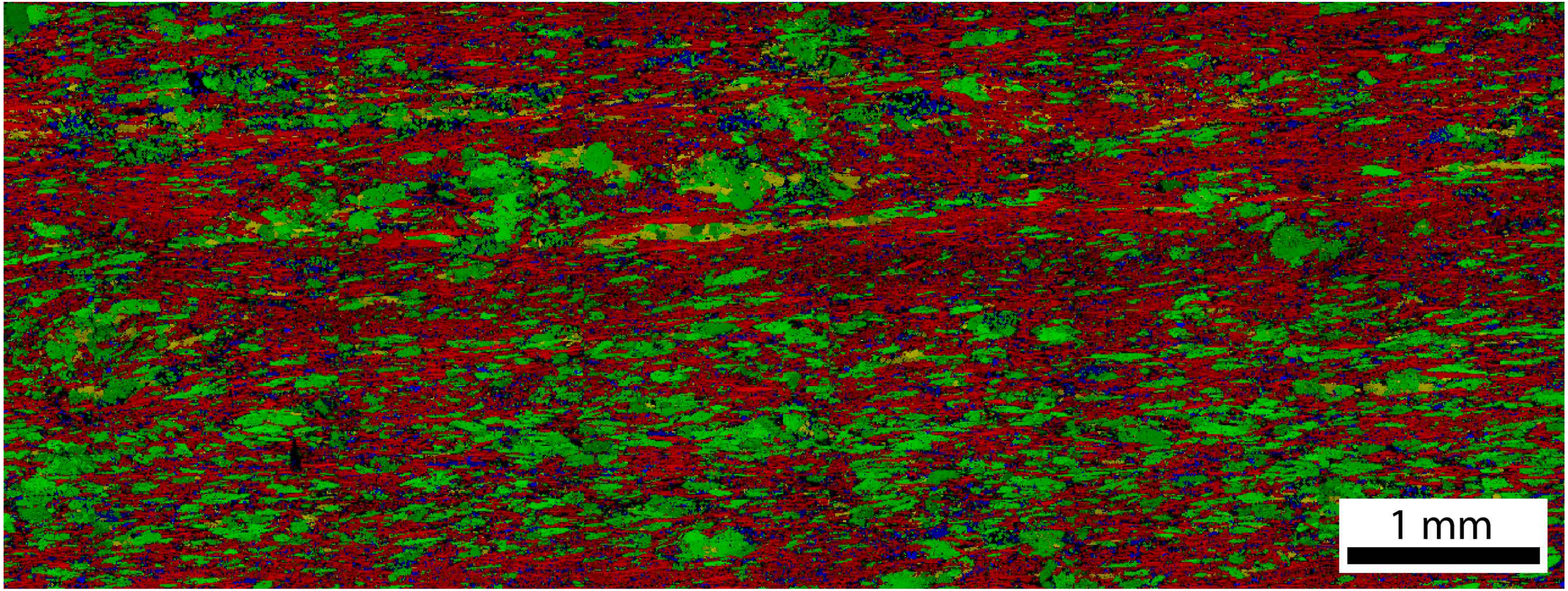
Gln - glaucophane (blue mineral)
Ep - epidote (light yellow)
Qz - quartz (clear)
Ttn - titanite (clear to yellow)

The starting sample was collected by Carolyn Tewksbury-Christle in the Klamath Mountains, CA,USA.

Starting material

~40% glaucophane
~40% epidote
~7% titanite
~7% quartz
~6% accessories

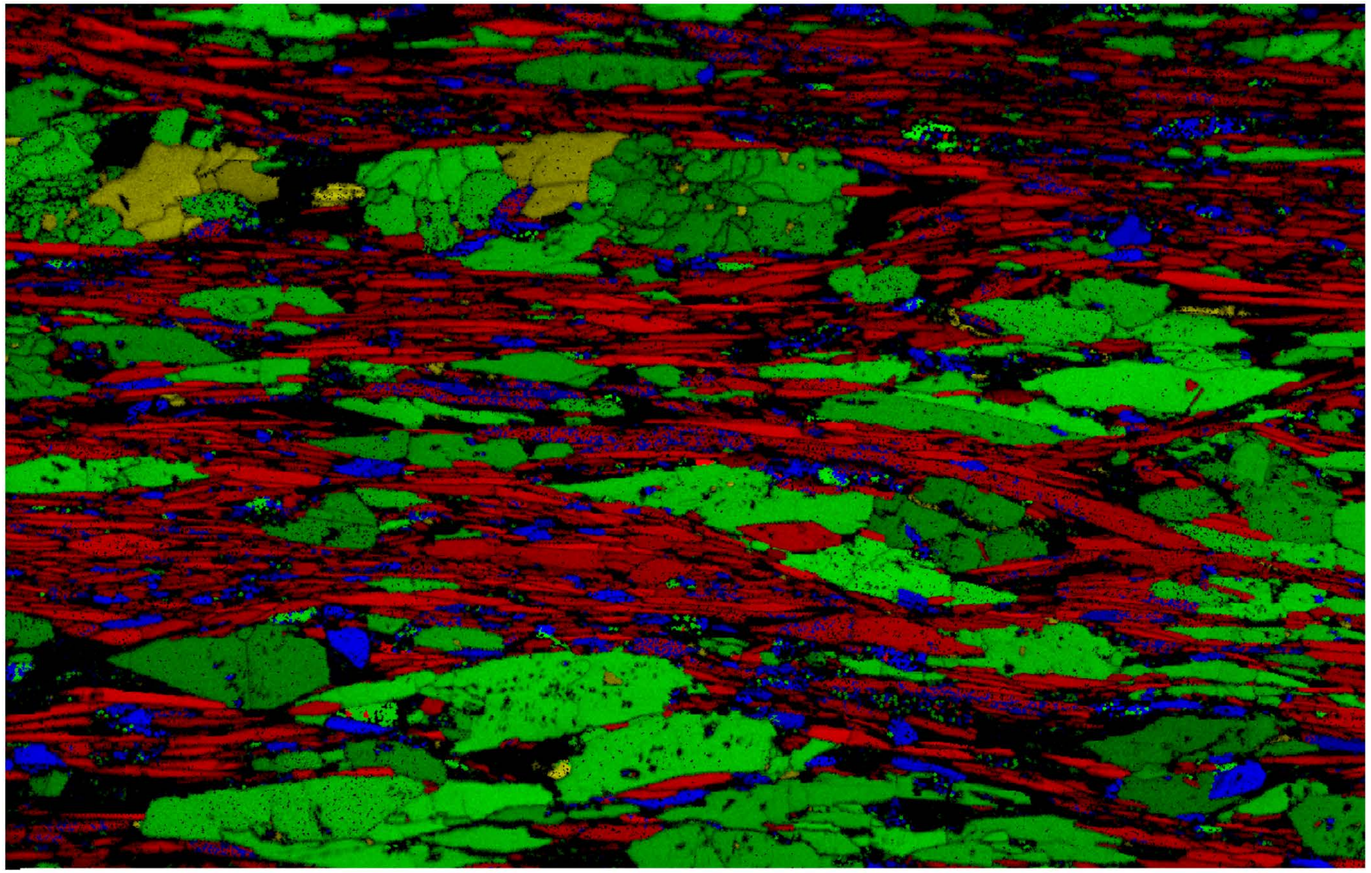
- EBSD map approximately the length of a general shear sample, illustrating the heterogeneity in the starting material



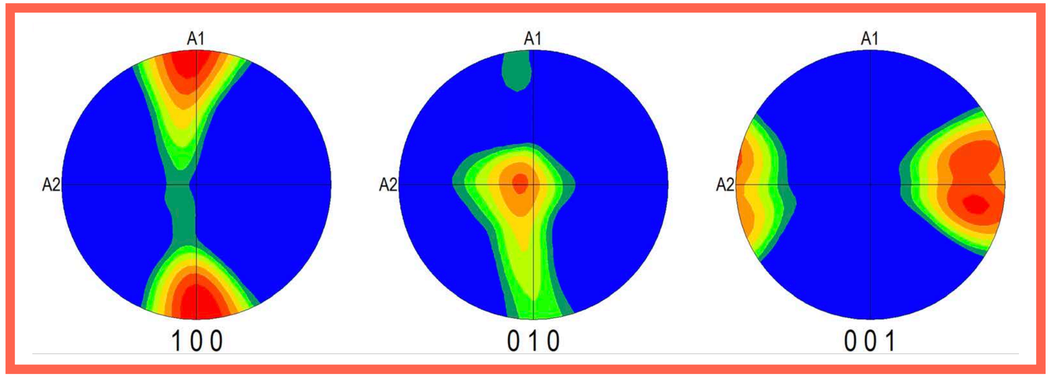
Starting material

~40% glaucophane
~40% epidote
~7% titanite
~7% quartz
~6% accessories

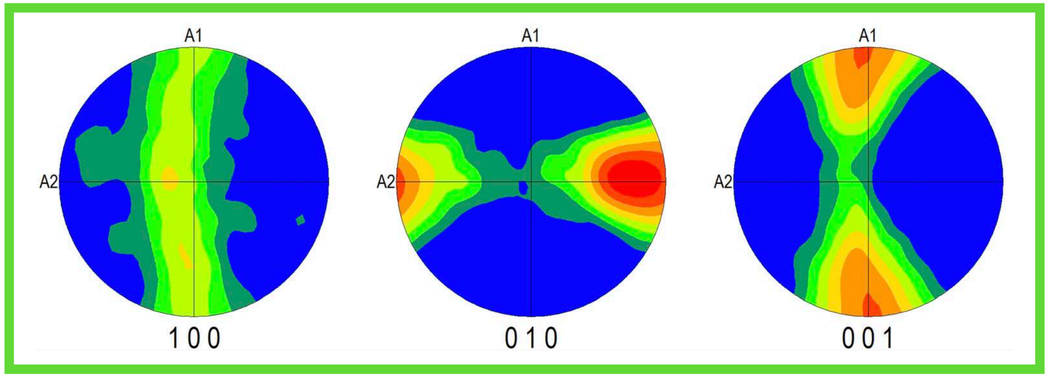
- Strong SPO and CPO in the glaucophane and epidote



Glaucophane

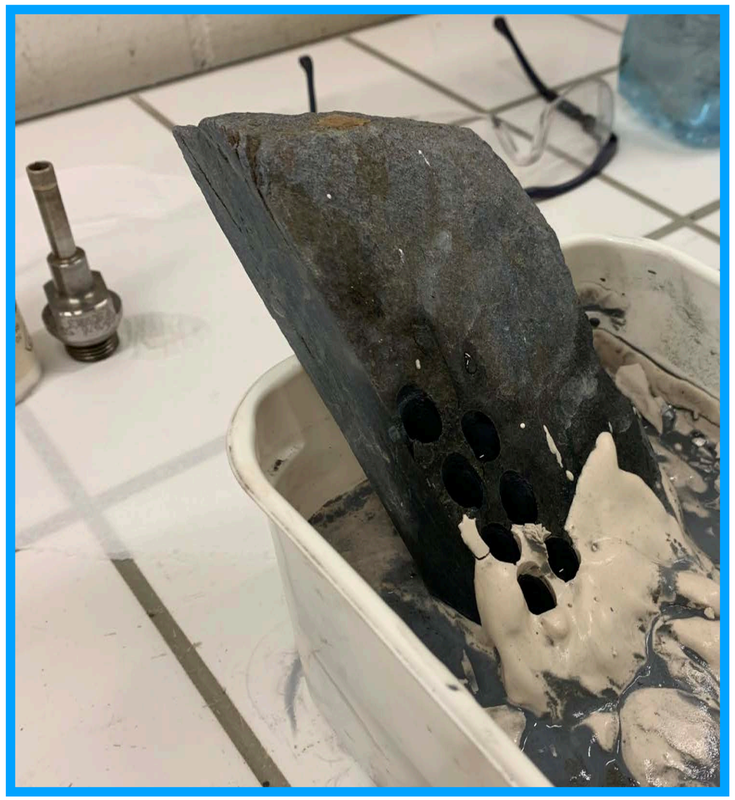


Epidote

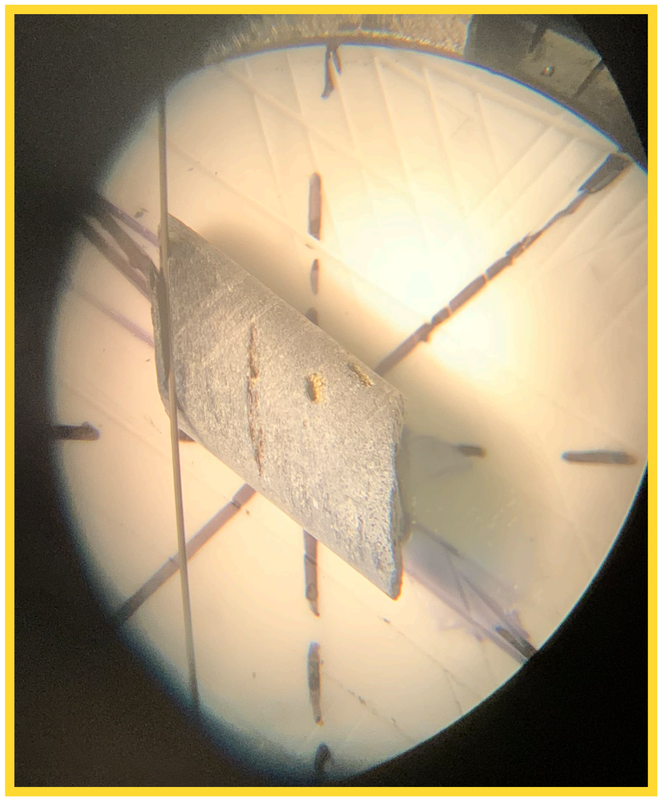


Starting material

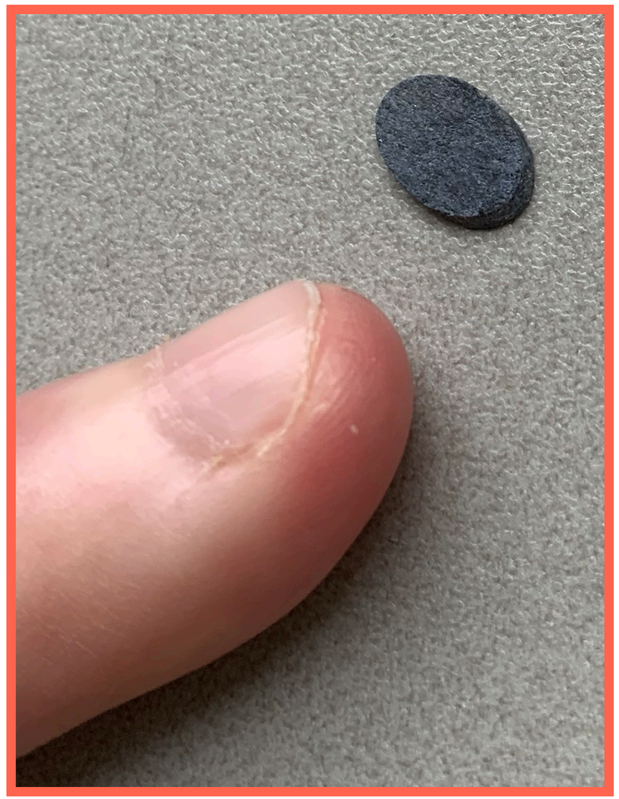
1. Core from oriented CMW sample



2. Use wire saw to cut oriented cores



3. Oriented samples

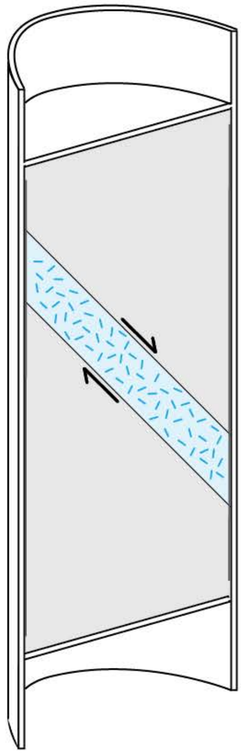


Thickness varies from 1.2 to 1.4 mm

For deformation experiments using a powder starting material, the starting material comes from the same foliated rock sample and was lightly crushed in a mortar and pestle

Part 1 - Powdered CMW blue schist

Crushed and sieved powder

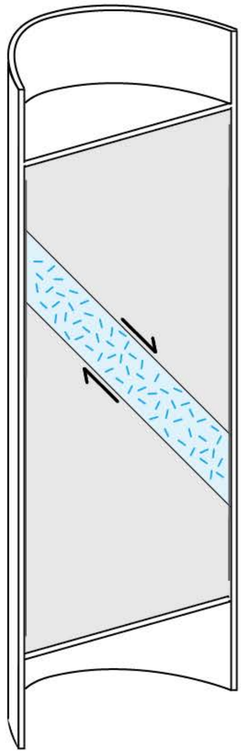


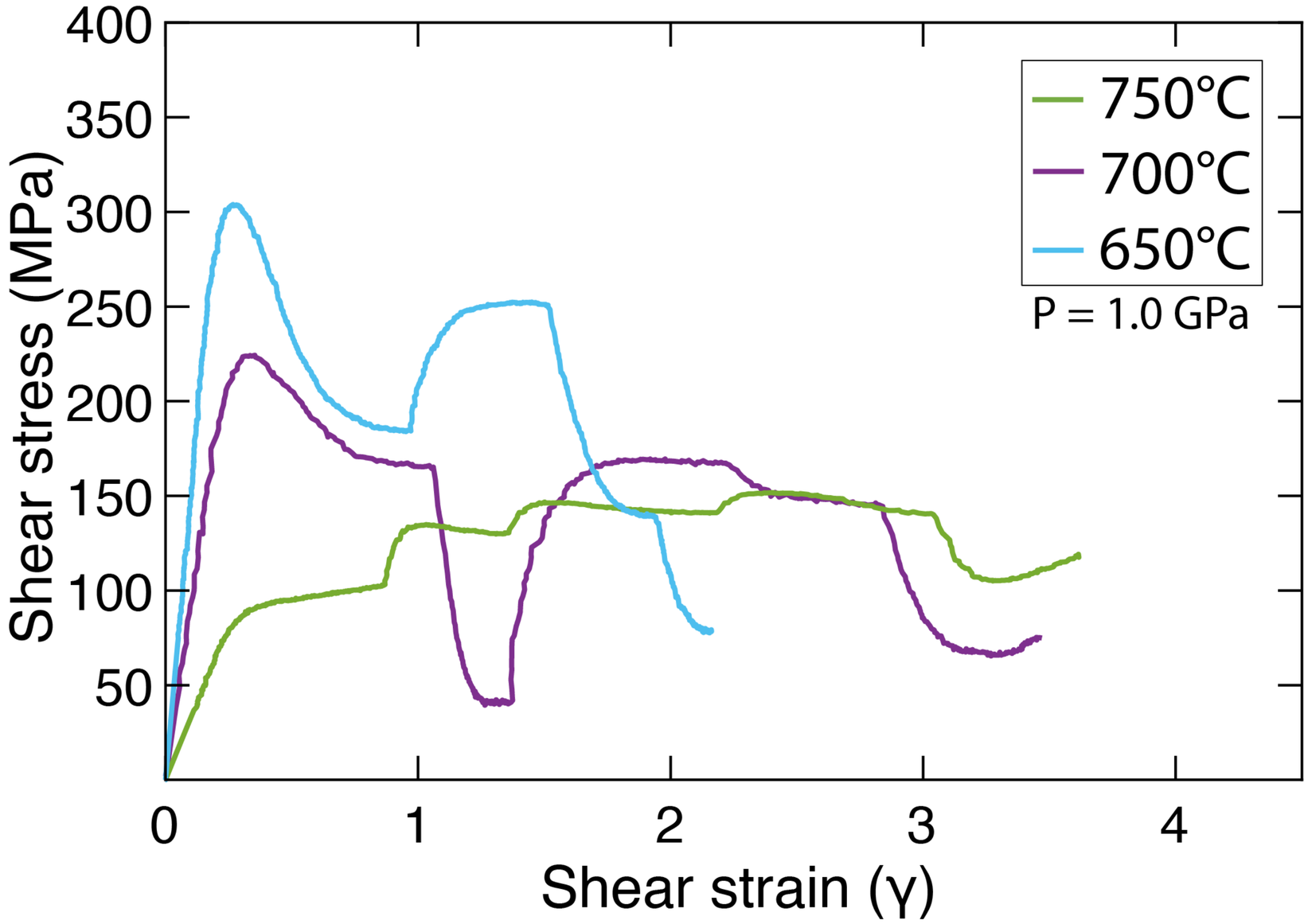
Before we assess the effect of a foliation on the rheology of a blueschist rock, we want to constrain the rheology of the same starting material without a foliation.

Therefore, in part 1 we conduct strain rate stepping experiments in the general shear geometry on powdered CMW blueschist

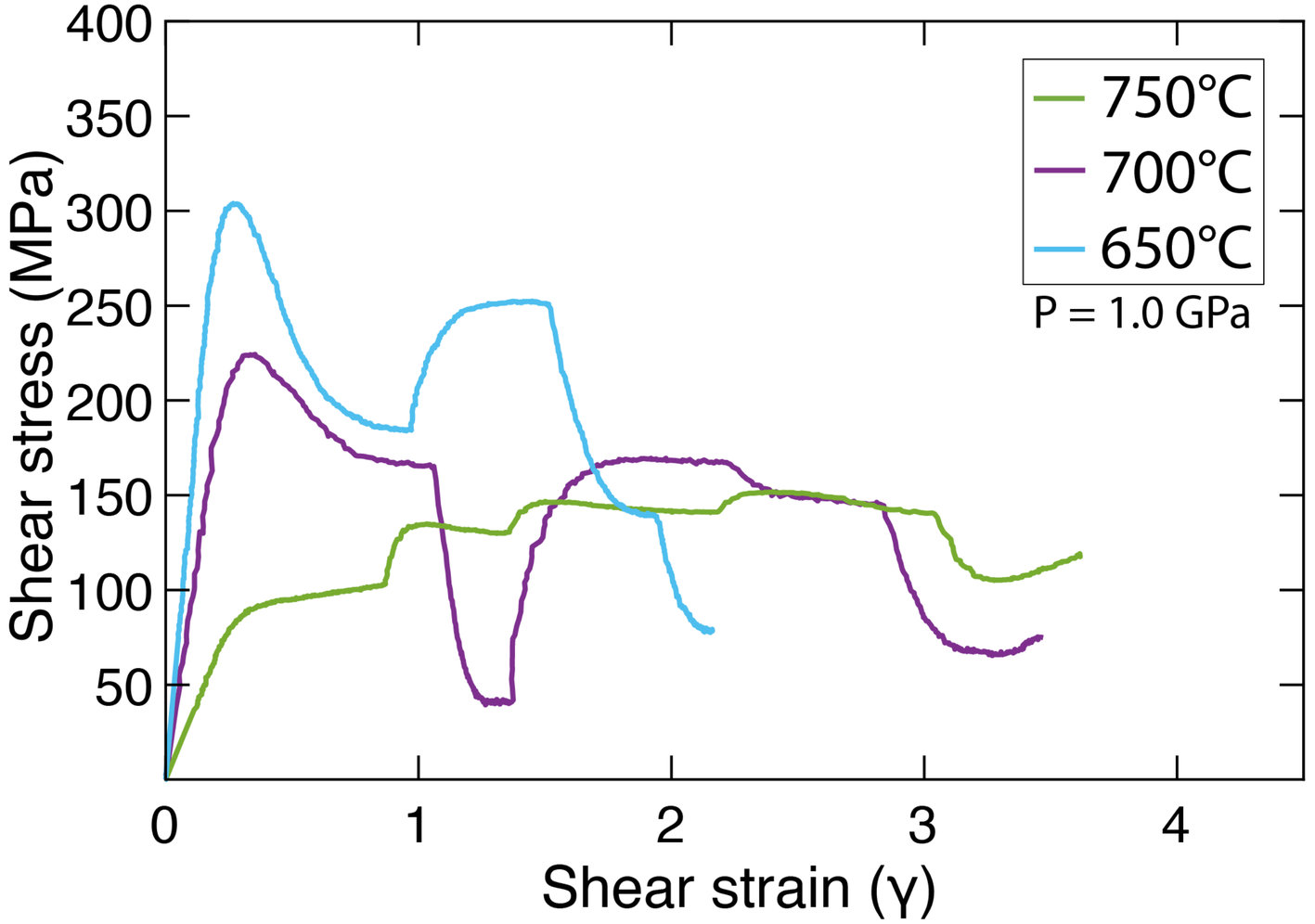
Part 1 - Powdered CMW blue schist

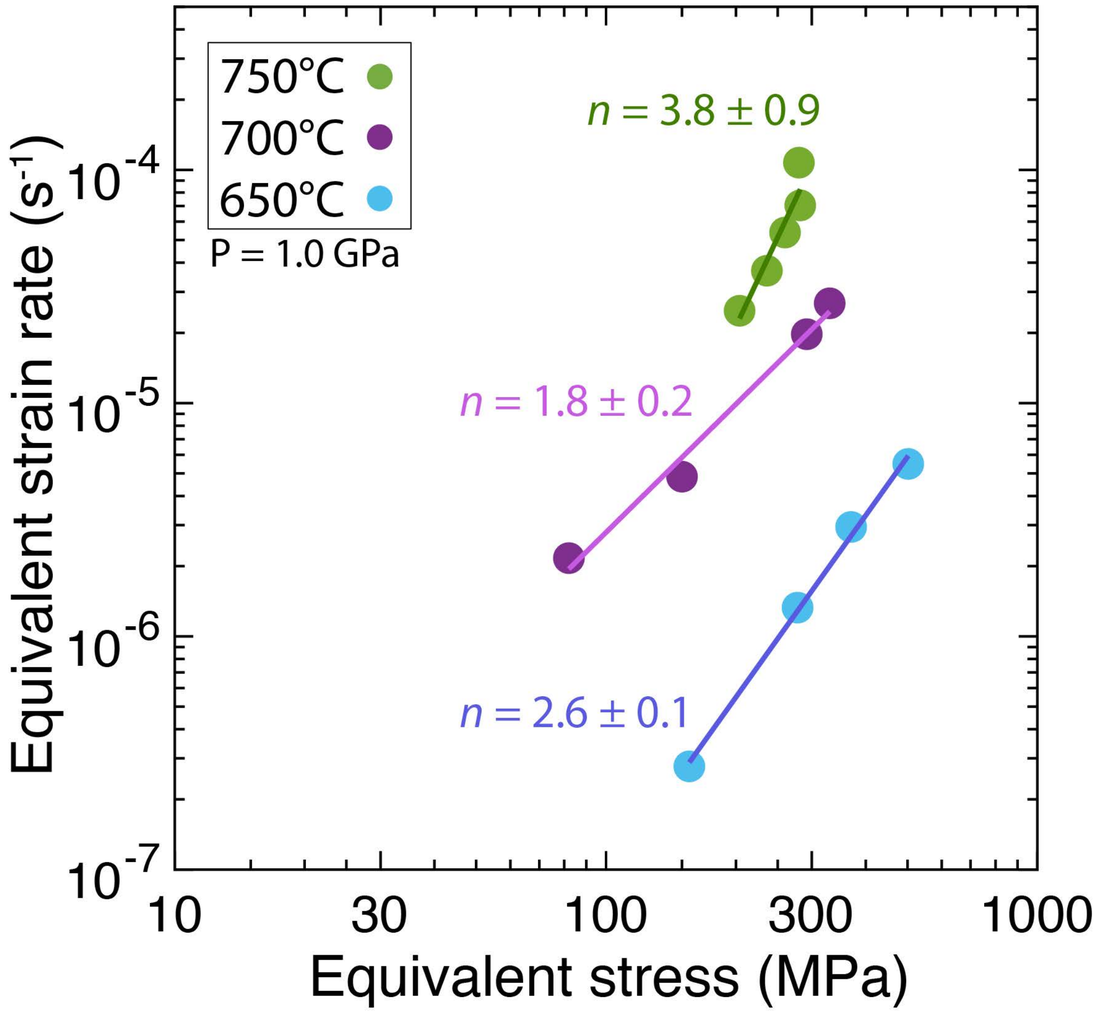
Crushed and sieved powder





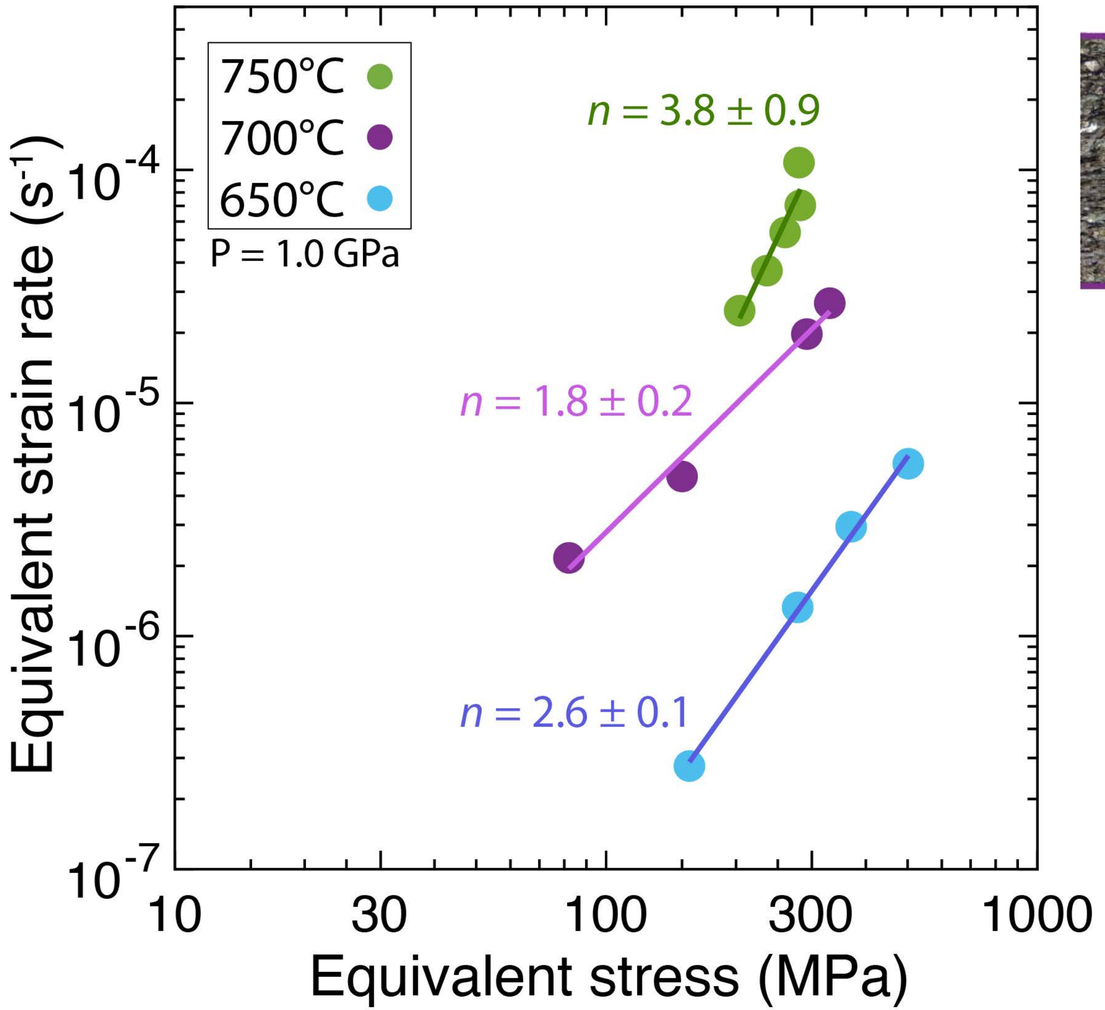
Part 1 - Powdered CMW blue schist

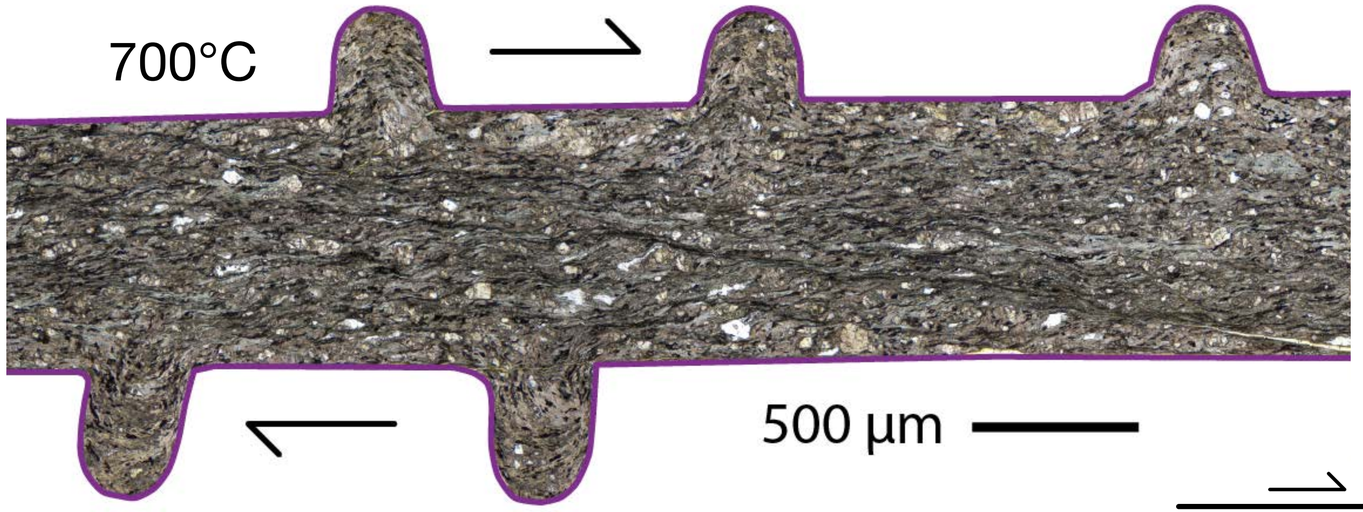


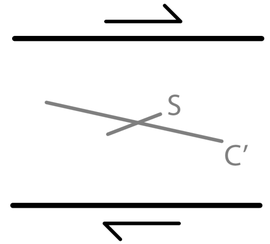


Equivalent Stress = 2*Shear stress
Equivalent Strain rate = Shear strain rate/sqrt(3)

Part 1 - Powdered CMW blue schist





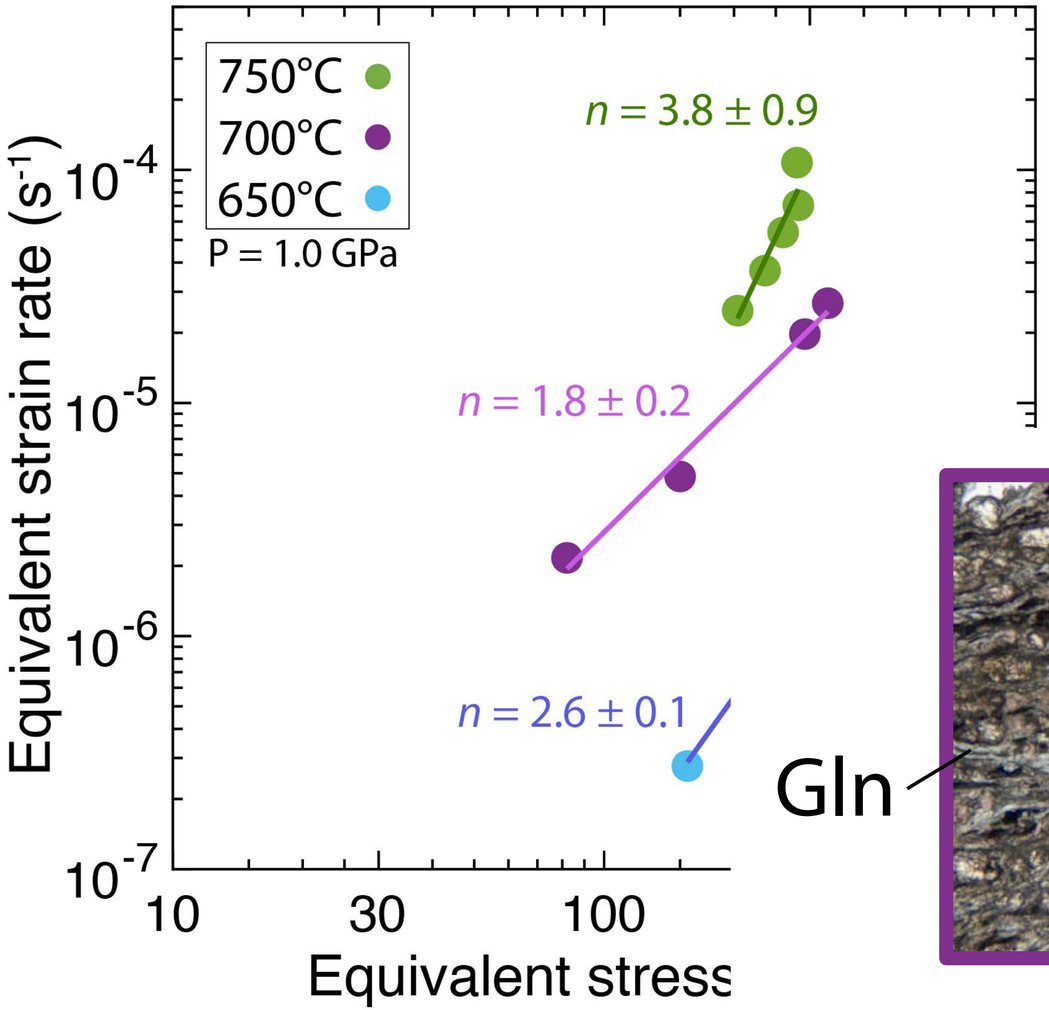


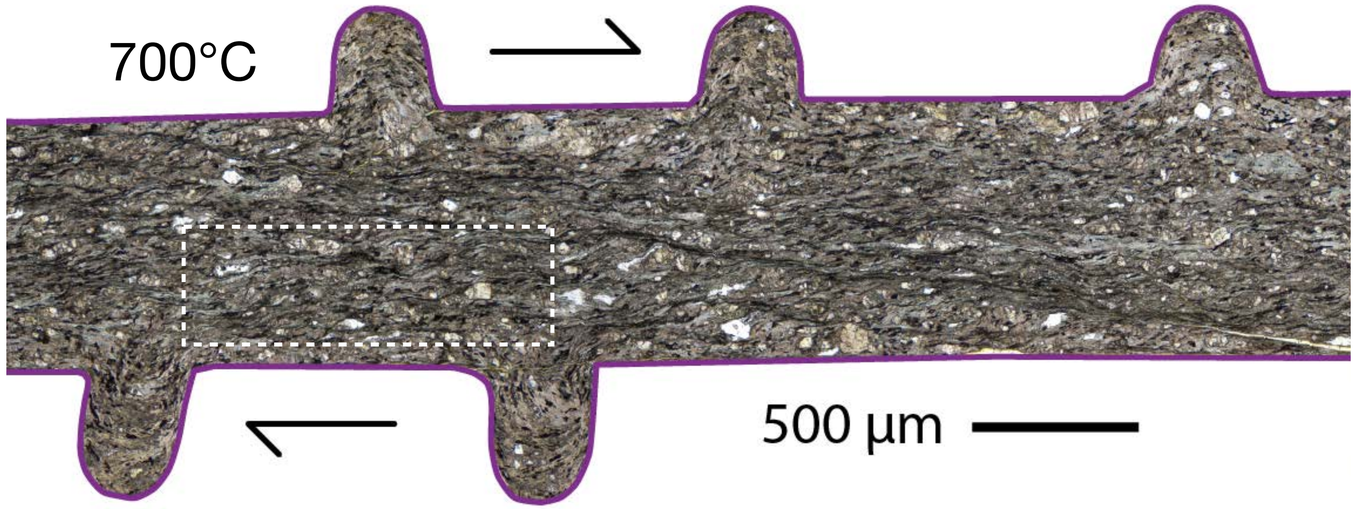
Sample develops an S-C’ mylonitic fabric.

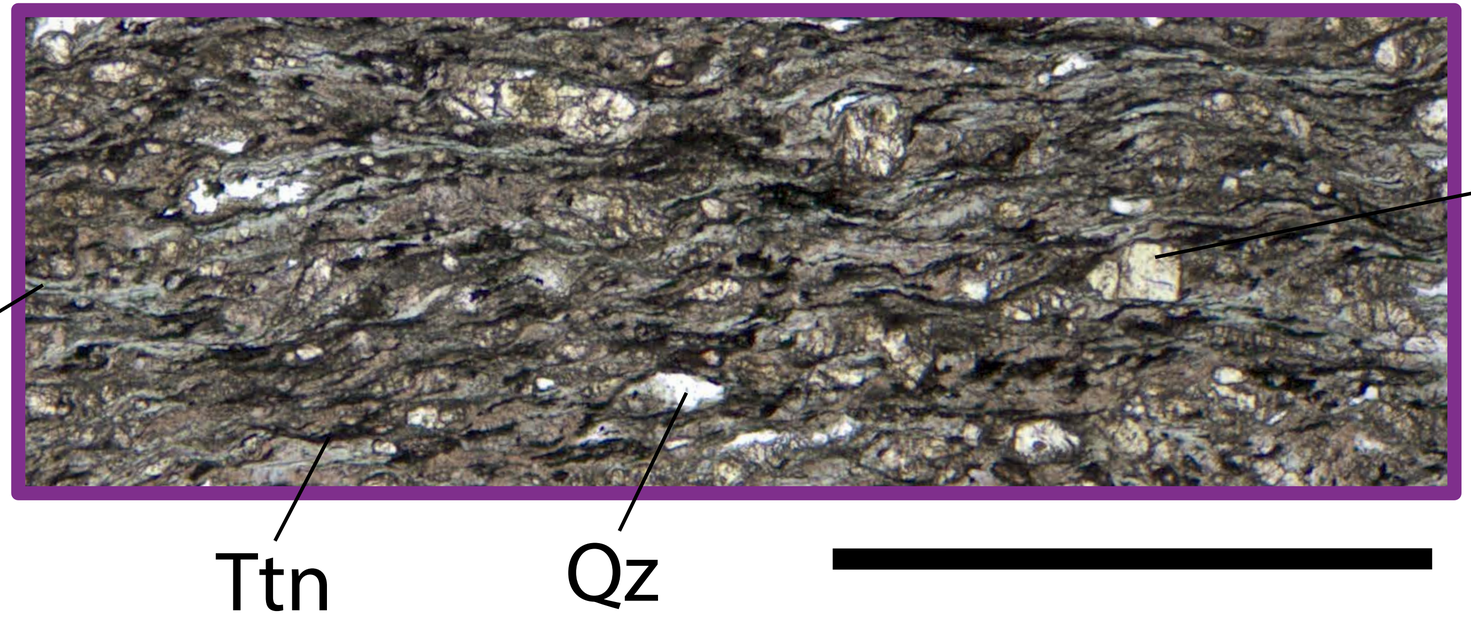
The rheologically controlling minerals are glaucophane and titanite, while quartz does not deform by ductile processes but rather deforms by rigid body rotation. Epidote deforms by brittle or cataclastic deformation processes.

* Thin sections for the 750°C and 650°C experiments are still being made.

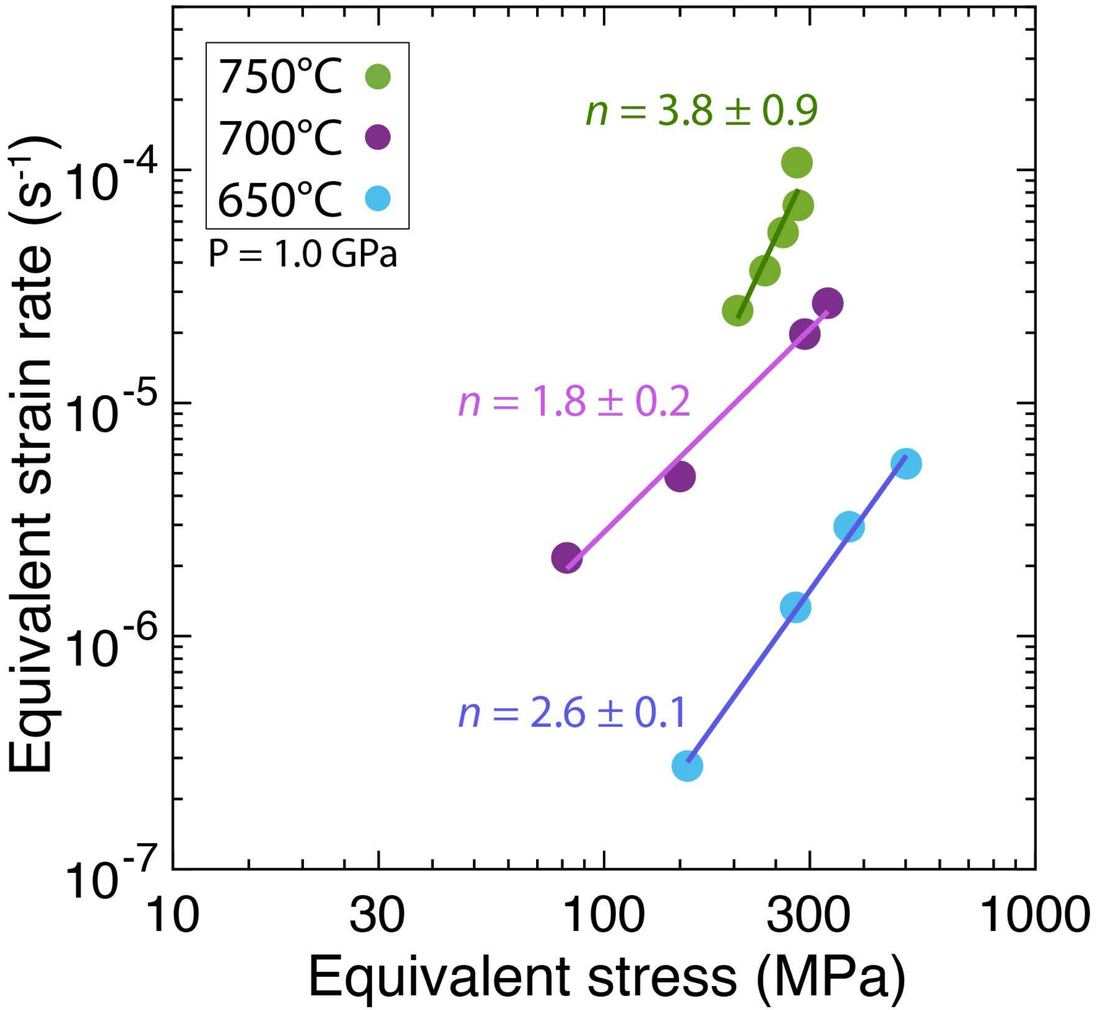
Part 1 - Powdered CMW blue schist







Part 1 - Powdered CMW blue schist

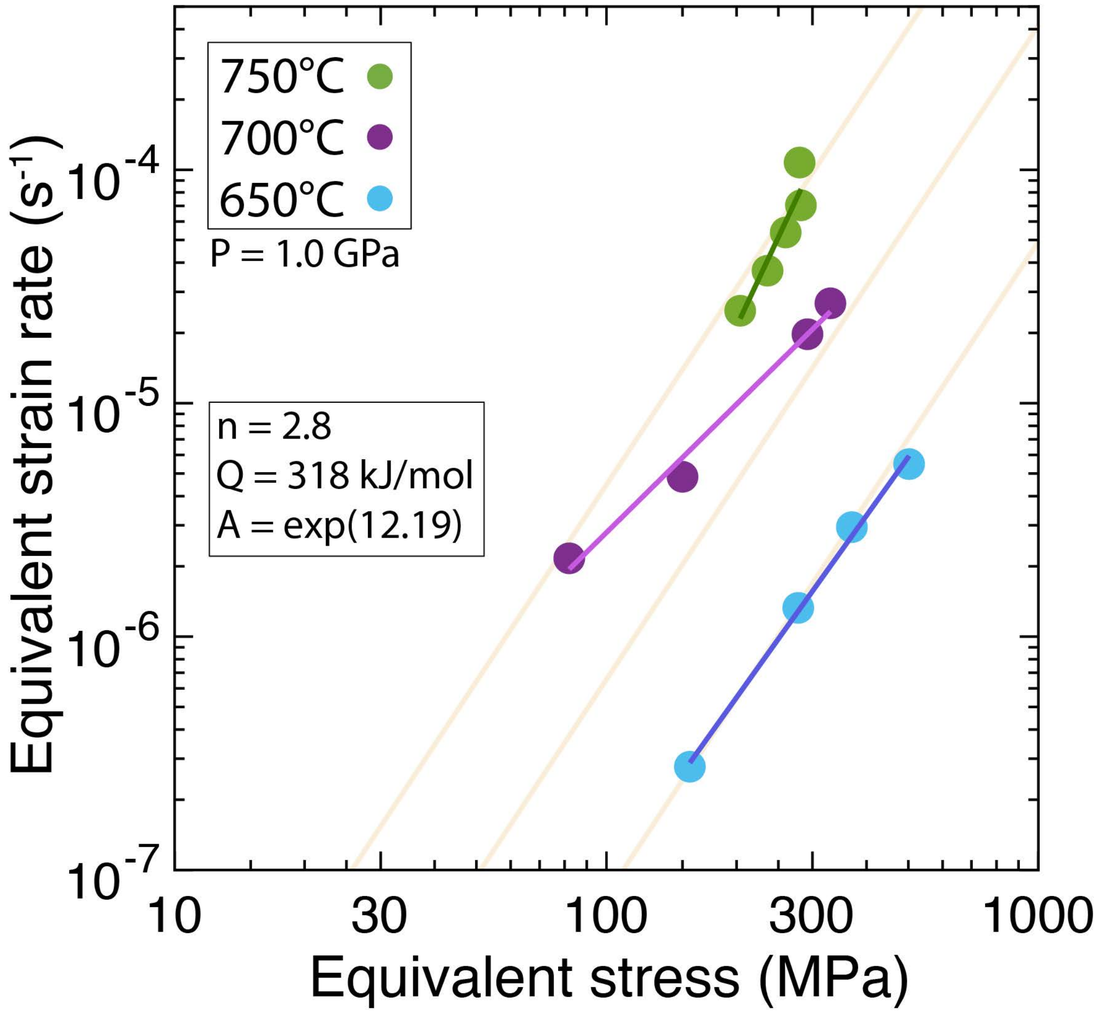


The 650°C, 700°C and 750°C strain rate stepping experiments have distinctly different stress exponents.

One interpretation is that the 650°C and the 750°C experiment are deforming by grain size insensitive deformation mechanism(s) while the strain rate steps in the 700°C experiment reflects a transition between grain size insensitive and grain size sensitive mechanisms.

Future experiments will be conducted at 700°C and 750°C to explore this interpretation.

Part 1 - Powdered CMW blue schist

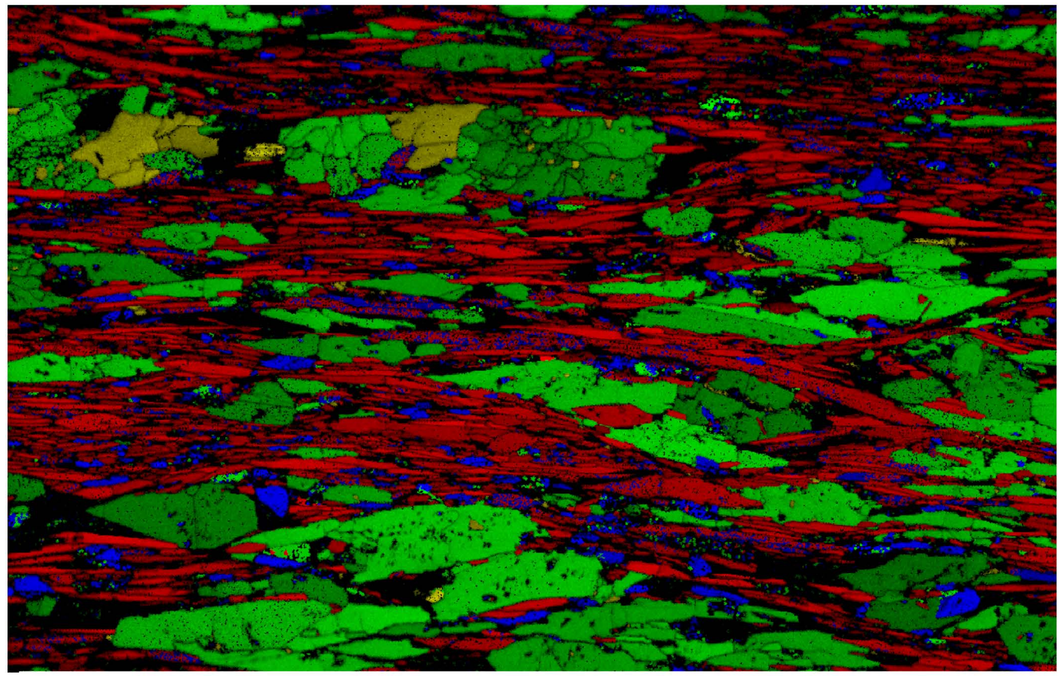


As a simple first-order test, we calculated flow law parameters from the three strain rate stepping experiments. We did not include the two lowest stress experiments from the 700°C experiment.

Additional experiments are needed to calculate more robust flow law parameters.

Part 2 - Foliated CMW blueschist

~40% glaucophane
~40% epidote
~7% titanite
~7% quartz
~6% accessories

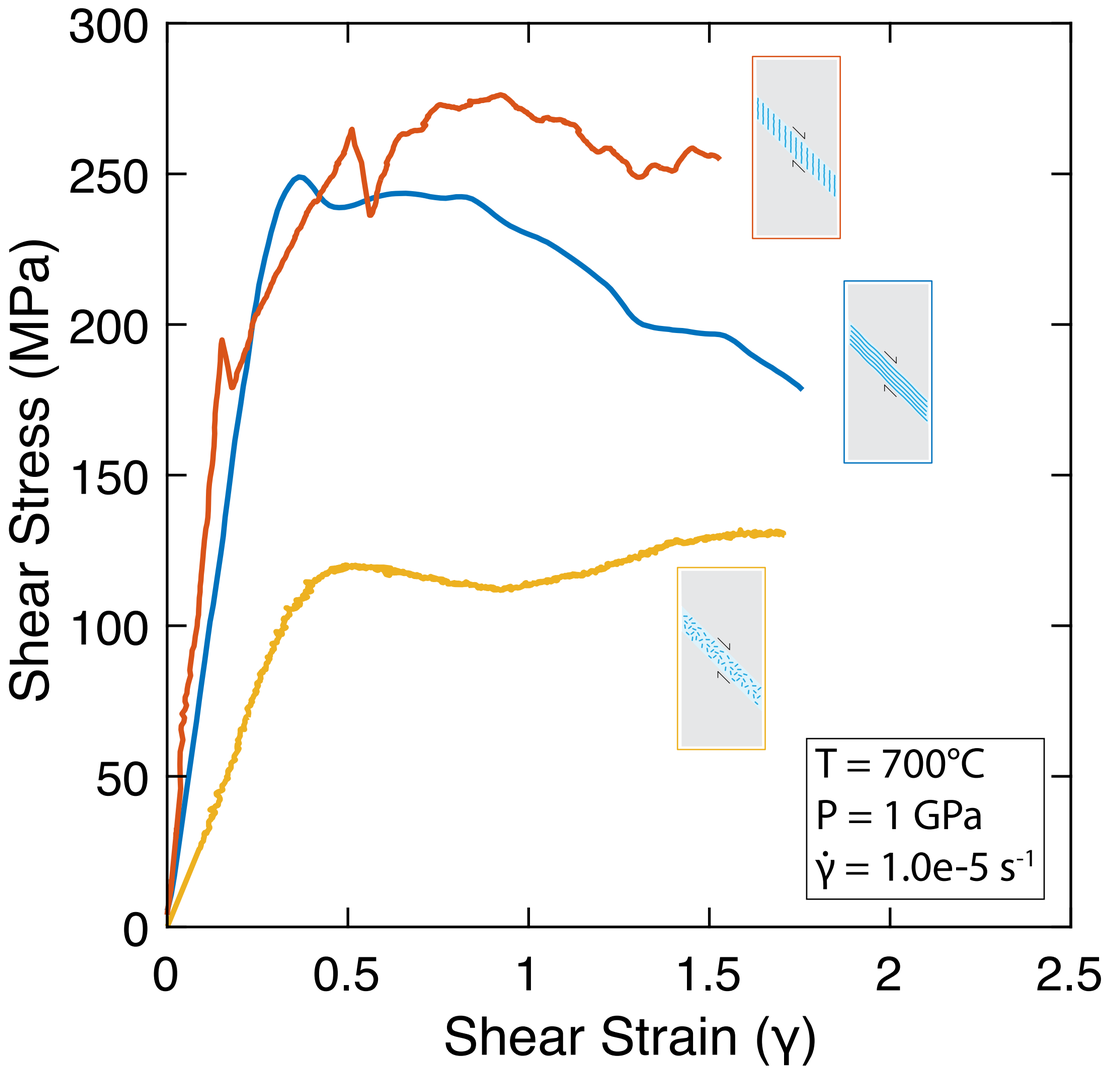


Many naturally deformed glaucophane-rich rocks develop a strong foliation where the glaucophane grains have a high aspect ratio on the order of 5:1 - 10:1.

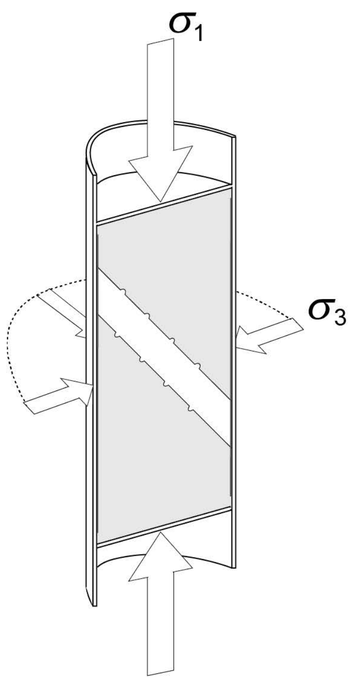
In Part 2, we want to assess the effect of the foliation on the rheology of a glaucophane-rich aggregate and the implications for subduction zone dynamics.

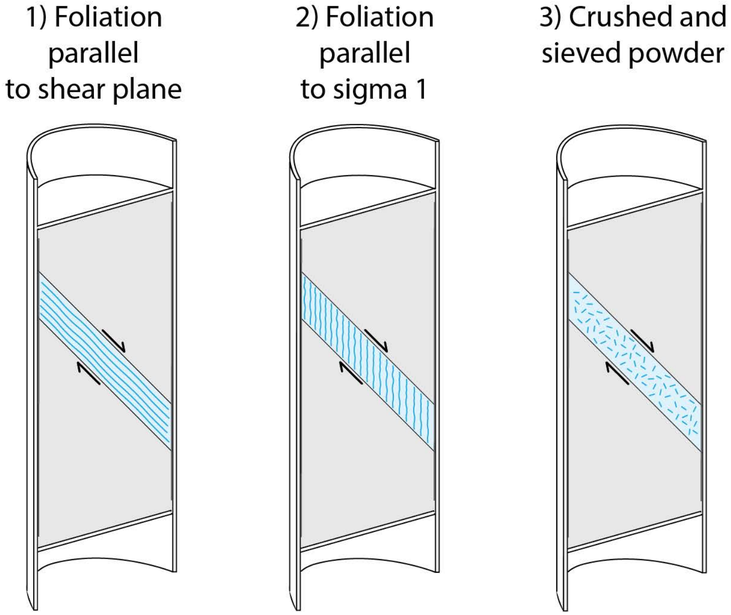
<- Here is a phase map highlighting the strong foliation defined by the high aspect ratio in the glaucophane grains.

Part 2 - Foliated CMW blueschist

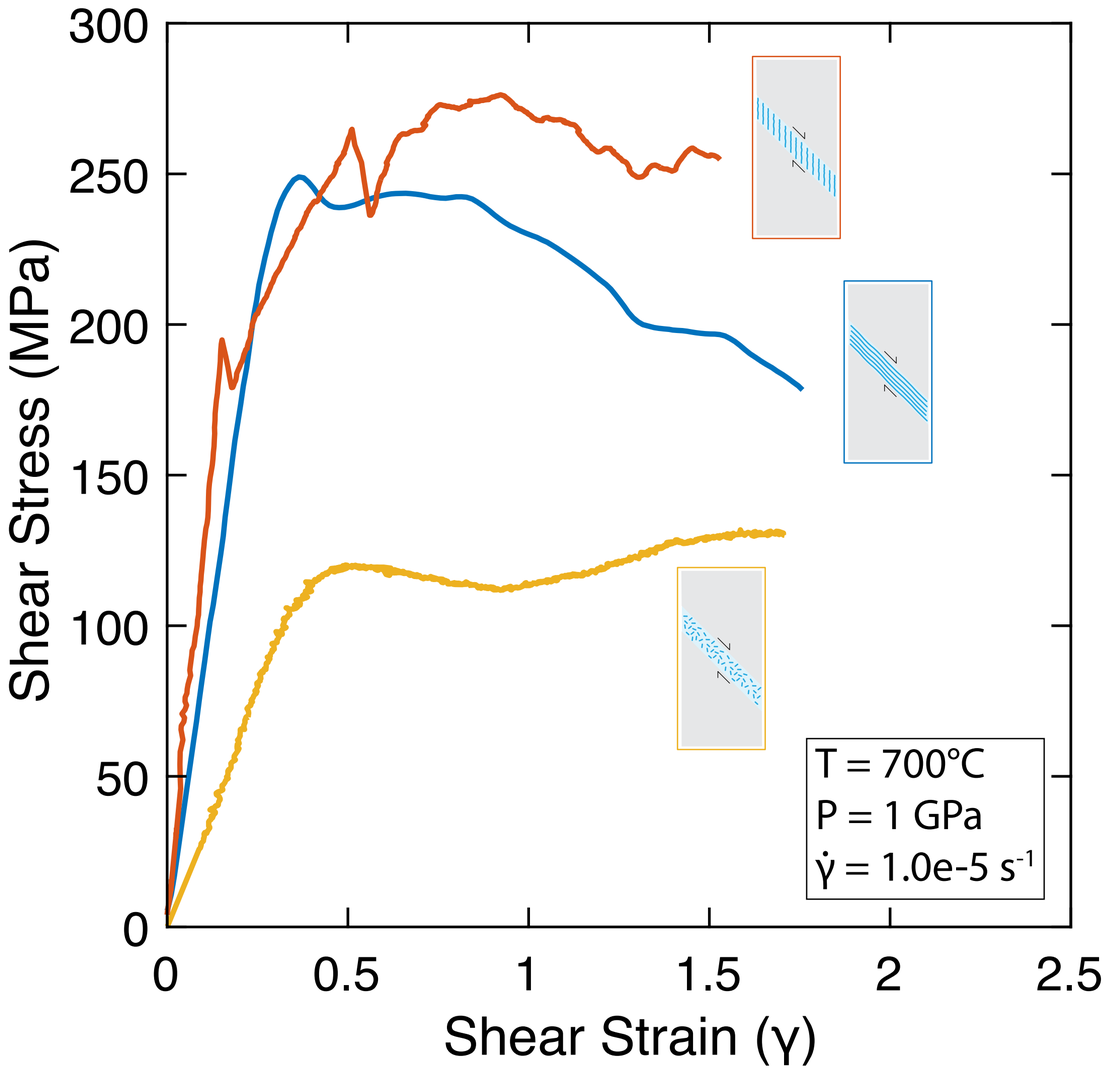


Here we deformed three different starting geometries at the same temperature, pressure, and shear strain rate.





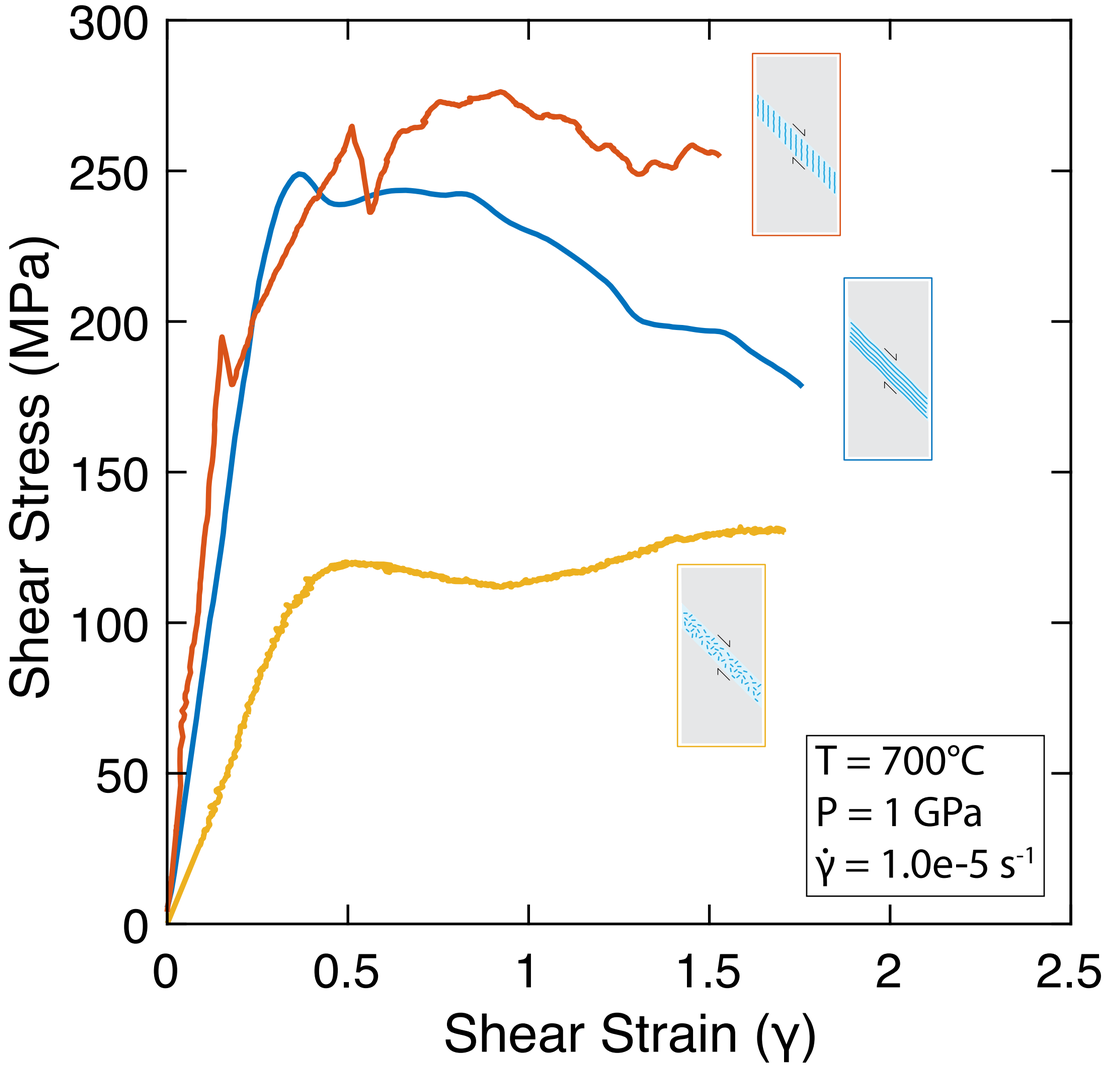
Part 2 - Foliated CMW blueschist

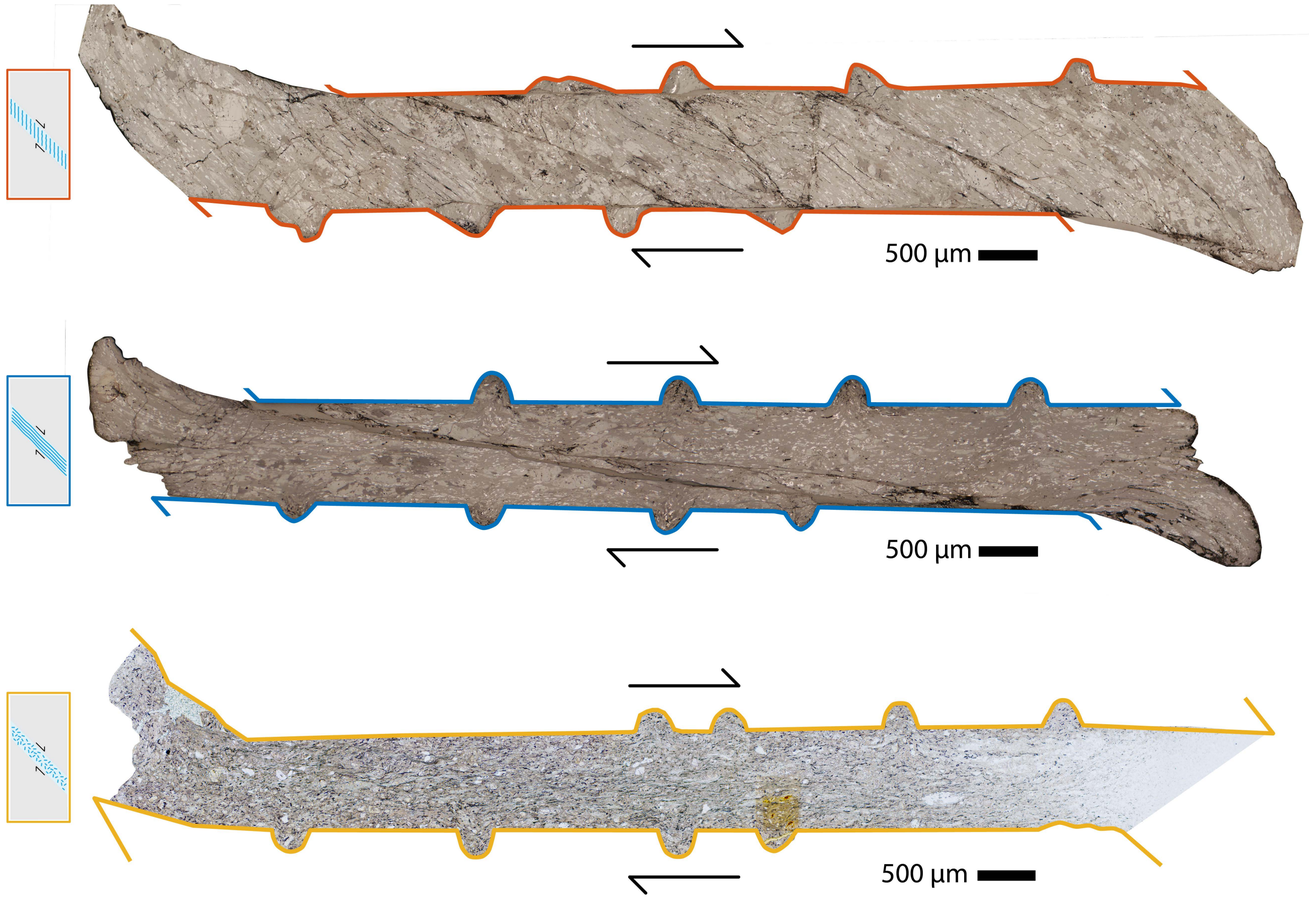


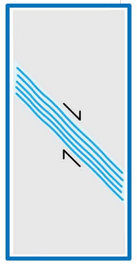
Experiments with the foliated samples are stronger than the experiment with the powdered starting material.

The foliated samples deform largely by brittle deformation processes at relatively low shear stresses, while the powdered sample is weaker and deforms by ductile processes.

Part 2 - Foliated CMW blueschist

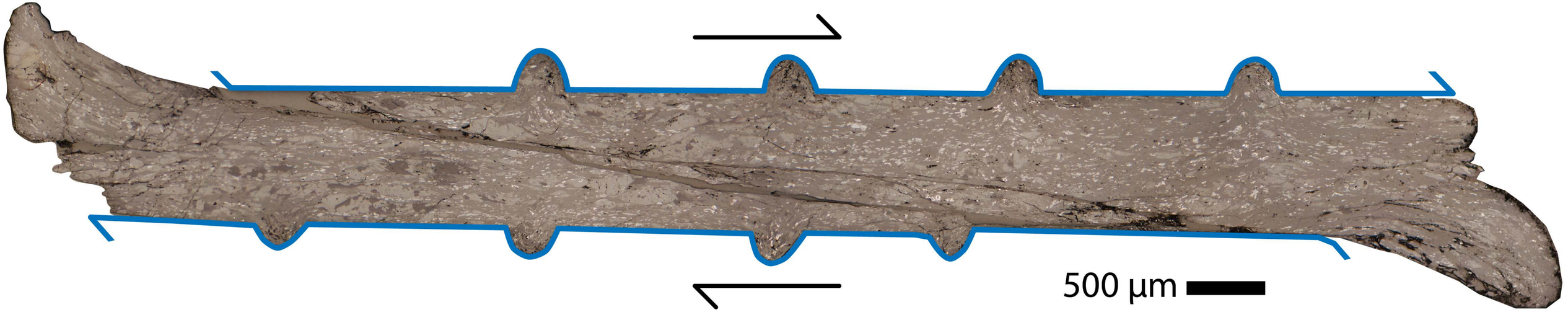






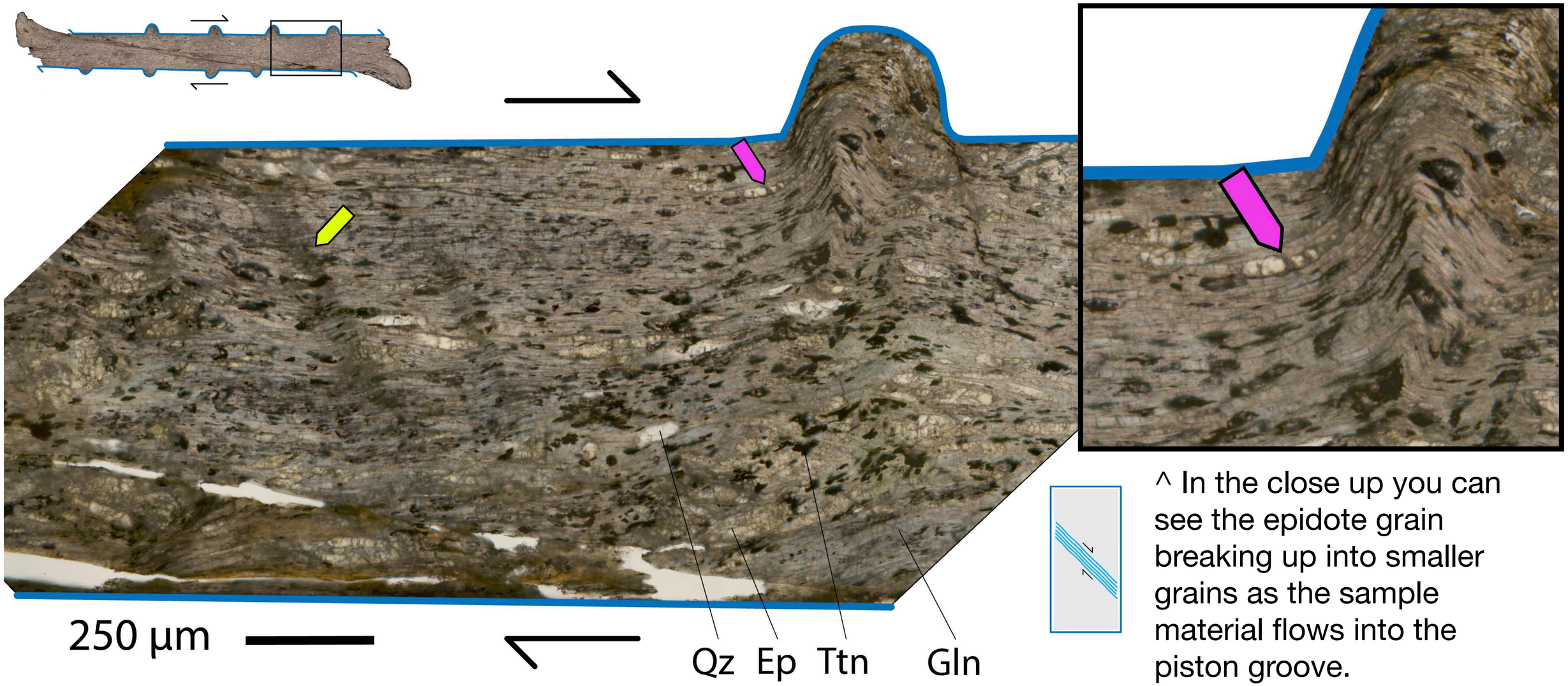
Foliation parallel to shear plane

T = 700°C
P = 1 GPa
$\dot{\gamma}$ = 1.0e-5 s^{-1}



A single brittle feature develops in the C’-orientation, accommodating the majority of the strain.

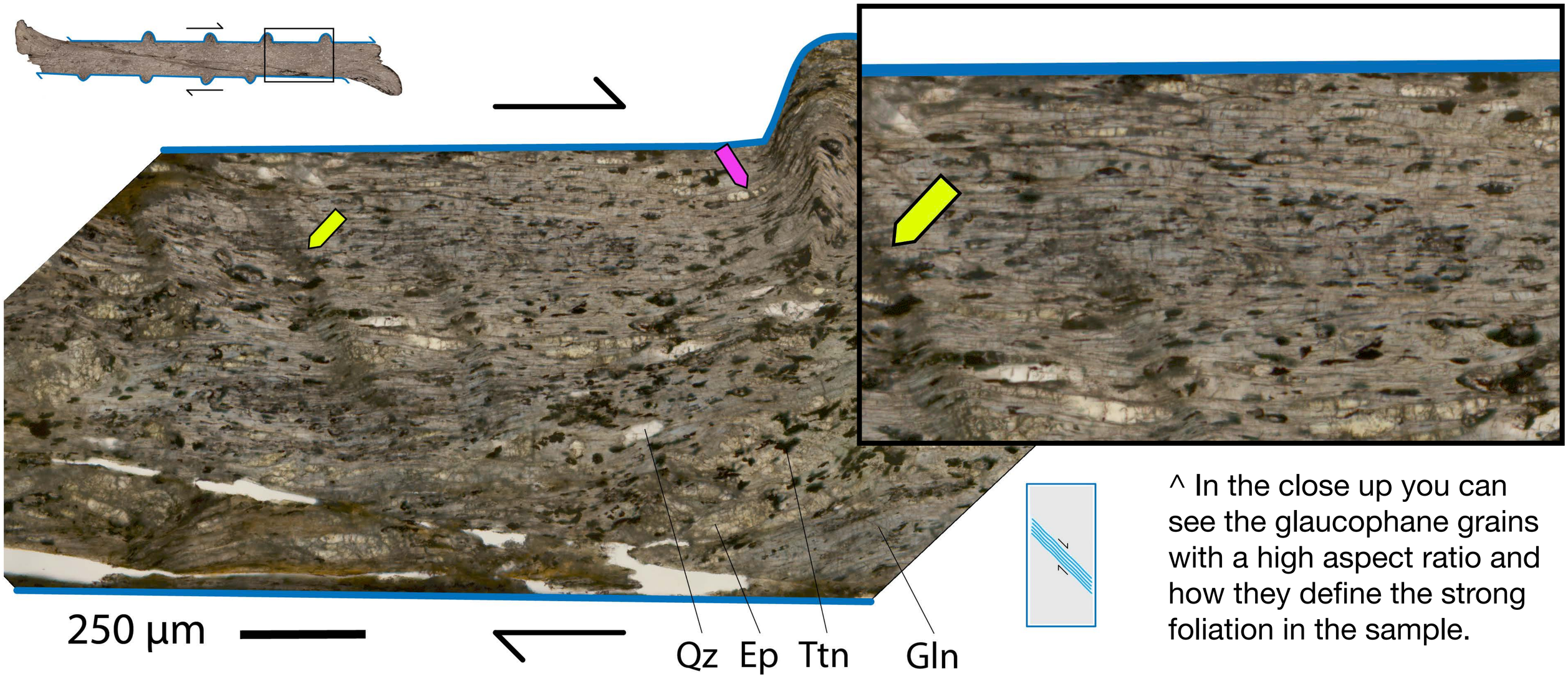
Foliation parallel to shear plane



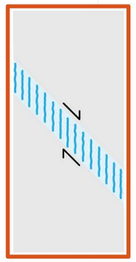
^ In the close up you can see the epidote grain breaking up into smaller grains as the sample material flows into the piston groove.

Yellow arrow highlights the development of a crenulation. The crenulations repeat at a spacing of ~200 um.
Purple arrow highlights the breakup of an epidote grain when material is deformed into the piston groove.

Foliation parallel to shear plane

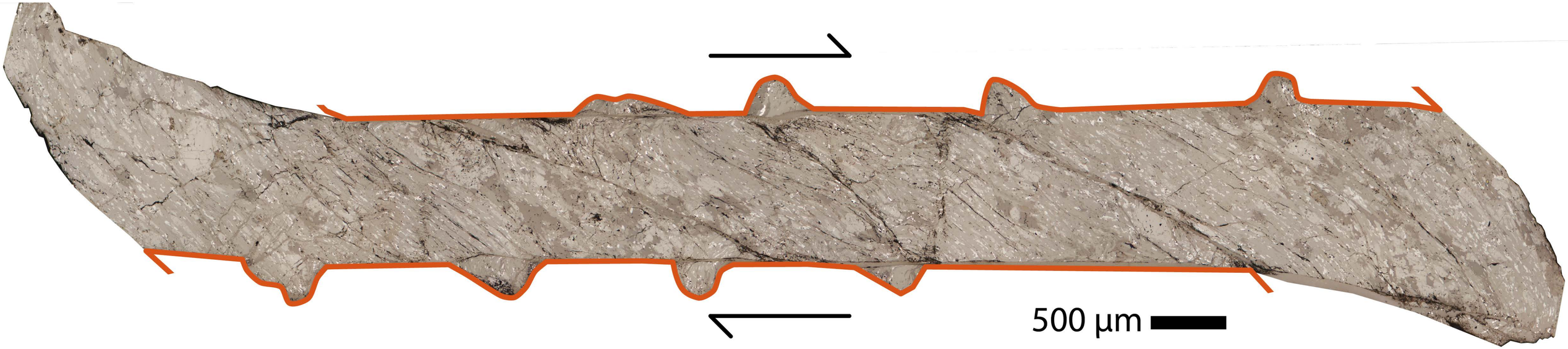


^ In the close up you can see the glaucophane grains with a high aspect ratio and how they define the strong foliation in the sample.



Foliation parallel to sigma1

T = 700°C
P = 1 GPa
$\dot{\gamma}$ = 1.0e-5 s^{-1}

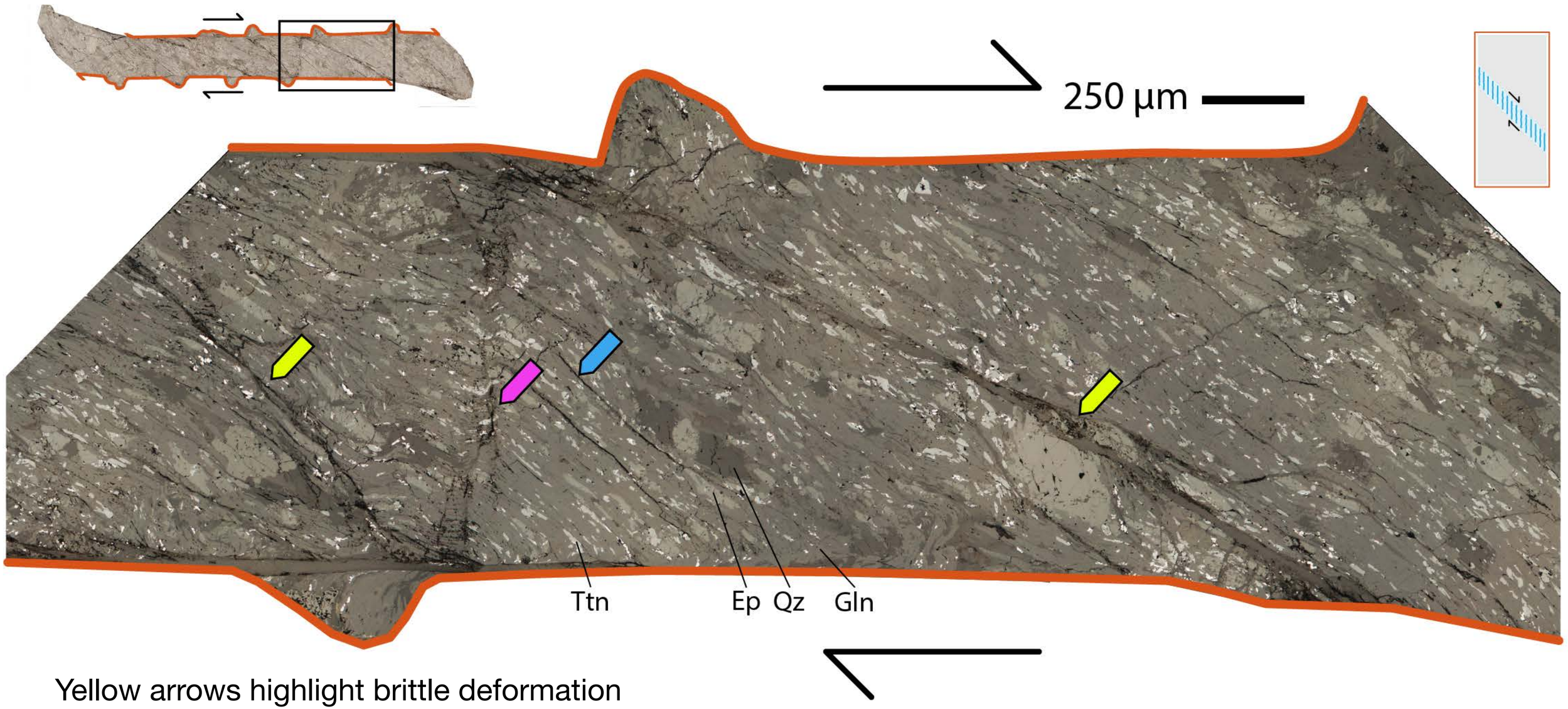


-Several brittle features develop ~parallel to the sigma1 orientation. The brittle features cut through all mineral phases.

-A kink band develops and spans the thickness of the sample. (Next 2-3 slides).

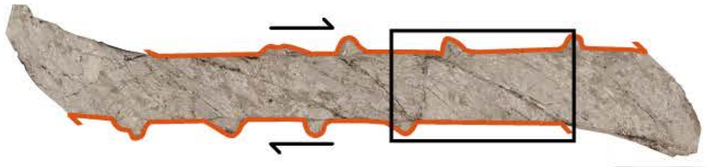
-Cracks open up between the glaucophane grains with high aspect ratios. This likely occurs during decompression, as no offset is observed (Close up in 3 slides).

Foliation parallel to sigma1

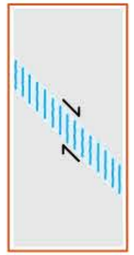


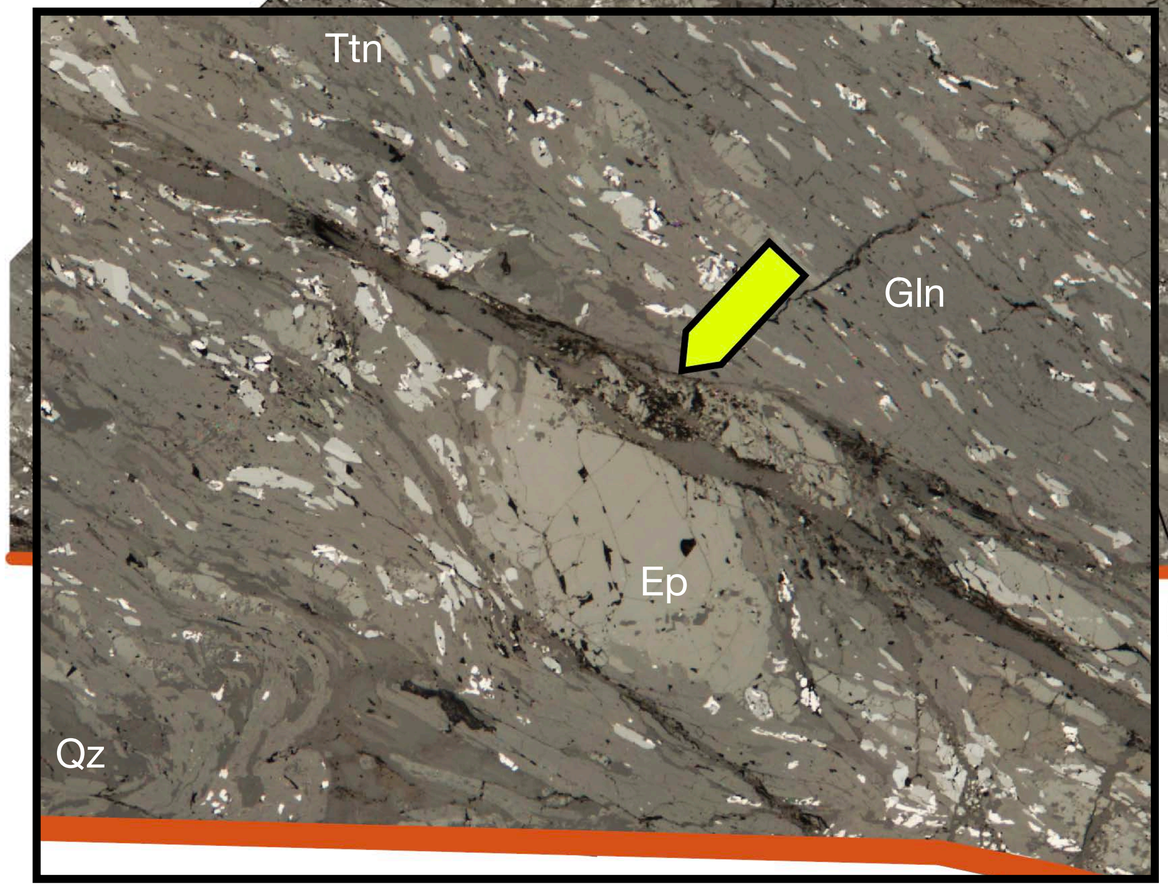
Yellow arrows highlight brittle deformation
Purple arrow highlights the kink band
Blue arrow highlights decompression cracks (no observable offset)

Foliation parallel to sigma1



250 µm

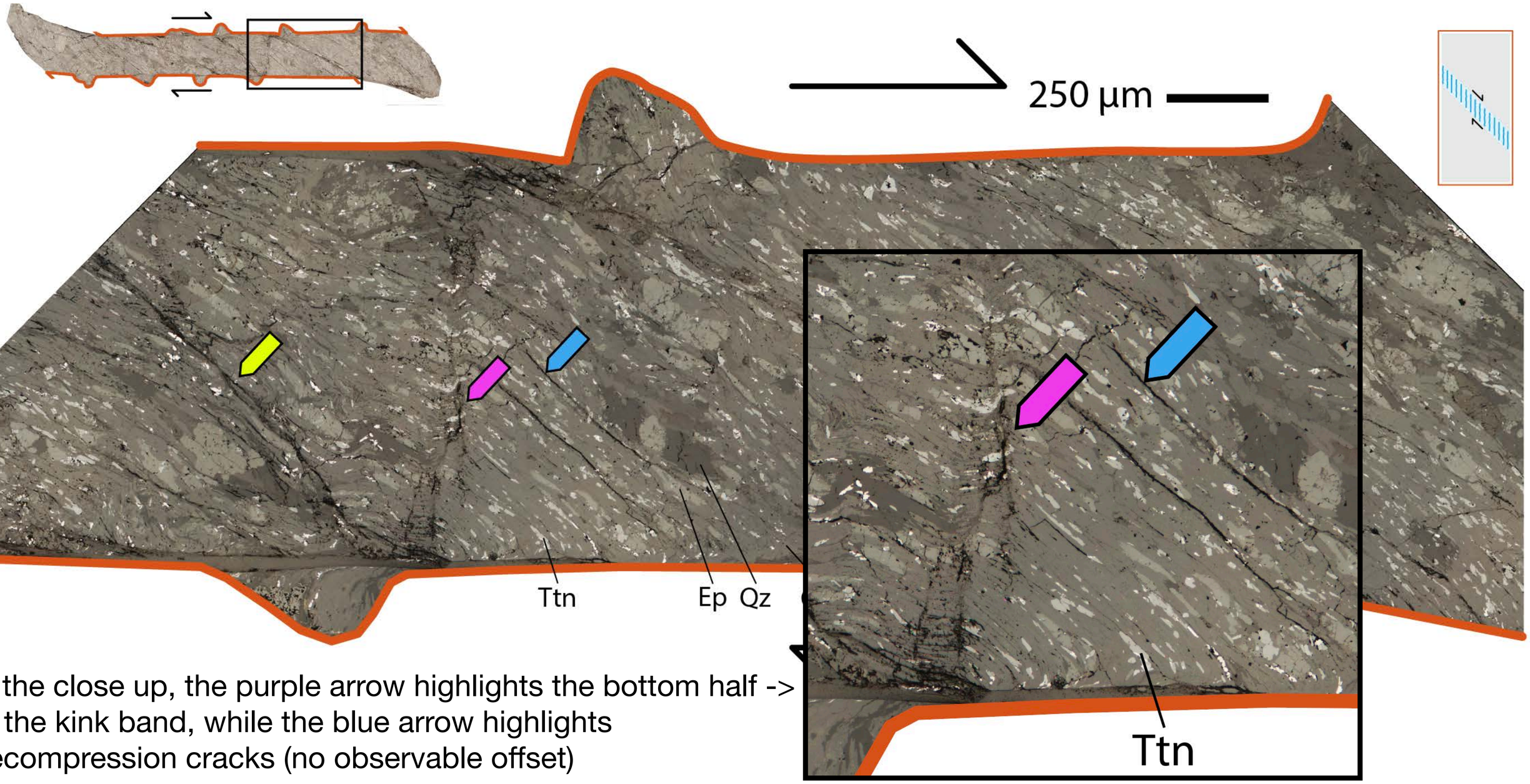




Ep Qz Gln

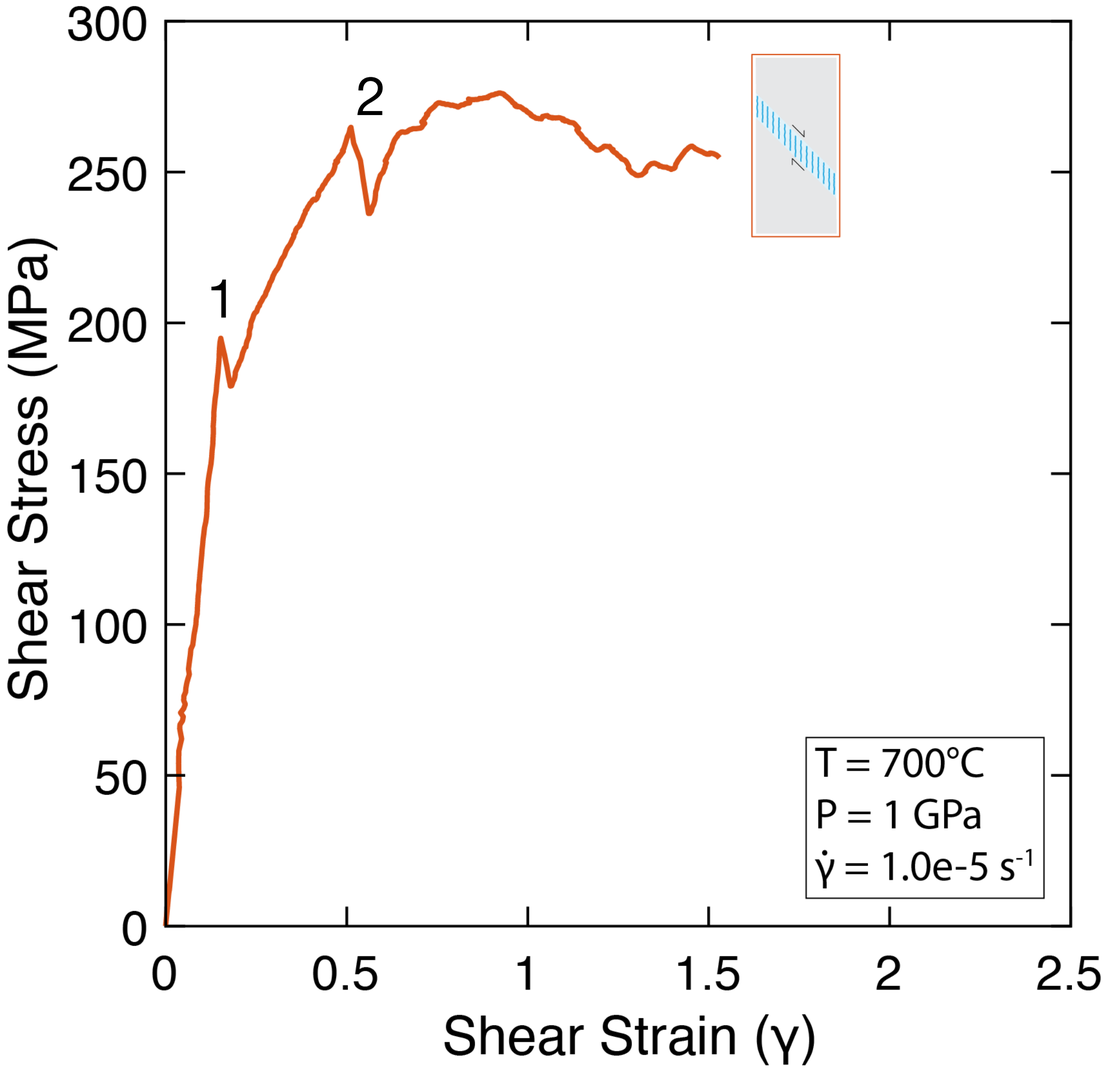
<- In the close up, the yellow arrow highlights a brittle feature cutting through both glaucophane and a large epidote grain

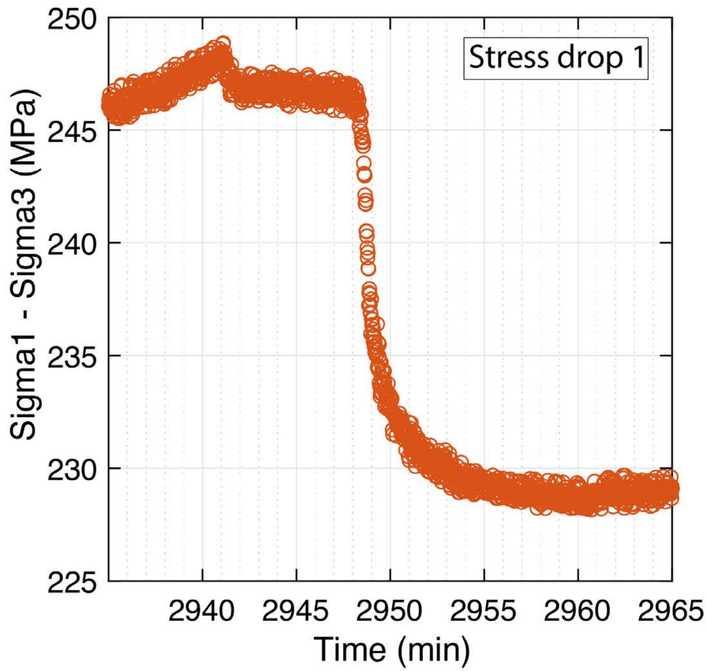
Foliation parallel to sigma1

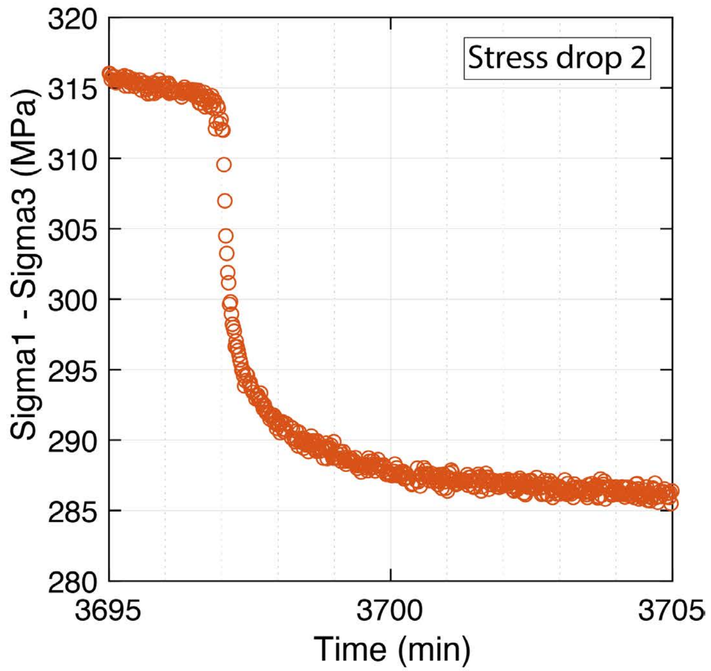


In the close up, the purple arrow highlights the bottom half -> of the kink band, while the blue arrow highlights decompression cracks (no observable offset)

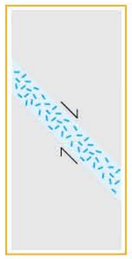
Mechanical Data





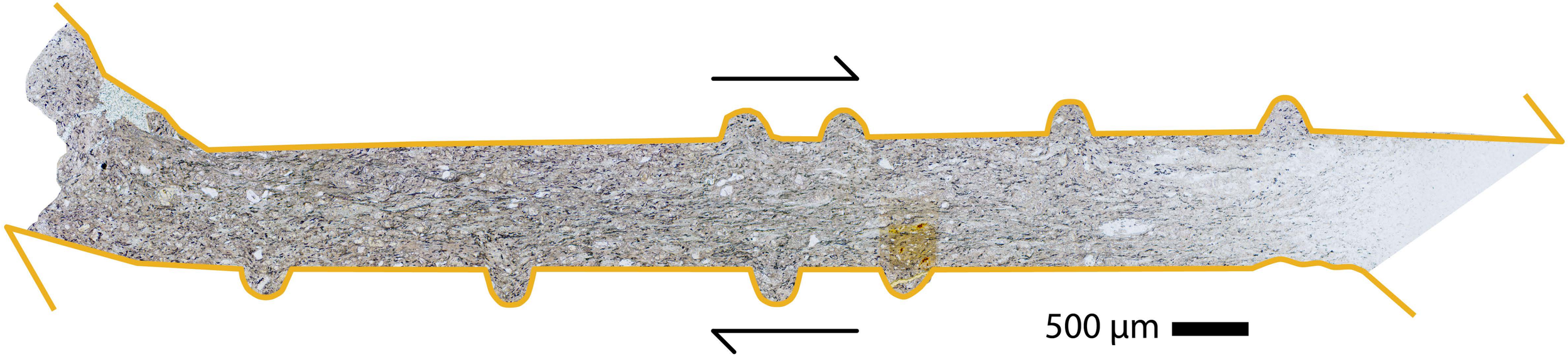


Plots of time versus the raw data sigma1-sigma3 showing two major stress drops from the experiment where the sample foliation is parallel to the sigma1 direction. Sampling for the experiment is 1 Hz, therefore each data point represents a time step of 1 second.

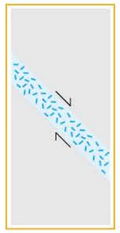


Powdered sample

T = 700°C
P = 1 GPa
$\dot{\gamma}$ = 1.0e-5 s^{-1}

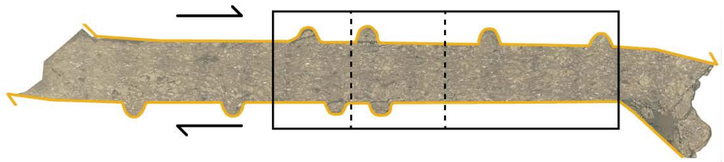


At the sample-scale, brittle deformation features do not develop.
Glaucophane and titanite accommodate the majority of the strain and deform by ductile processes.
Epidote deforms by brittle processes often breaking into smaller grains (next 2 slides), while quartz grains deform by rigid body rotation.



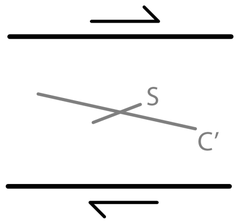
Powdered sample

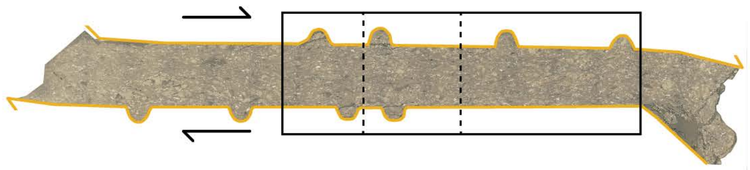
T = 700°C
P = 1 GPa
$\dot{\gamma}$ = 1.0e-5 s^{-1}





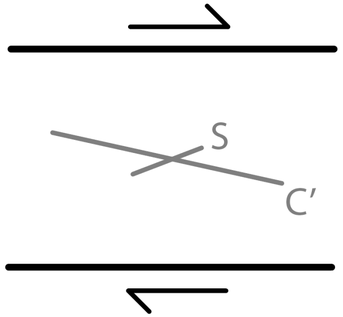
An S-C’ foliation develops across the sample, where C’-shear bands are several hundred microns in length



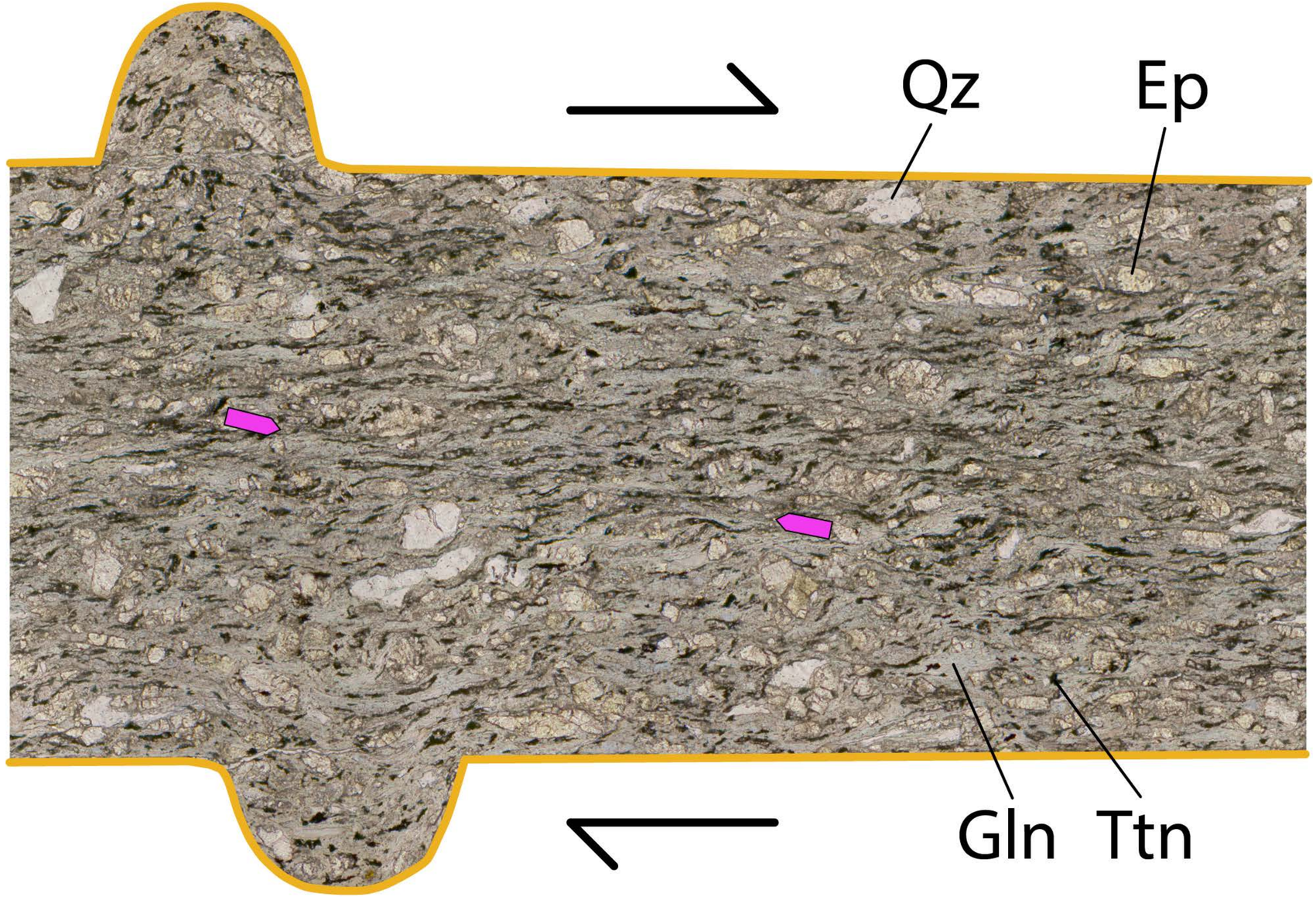


Powdered sample

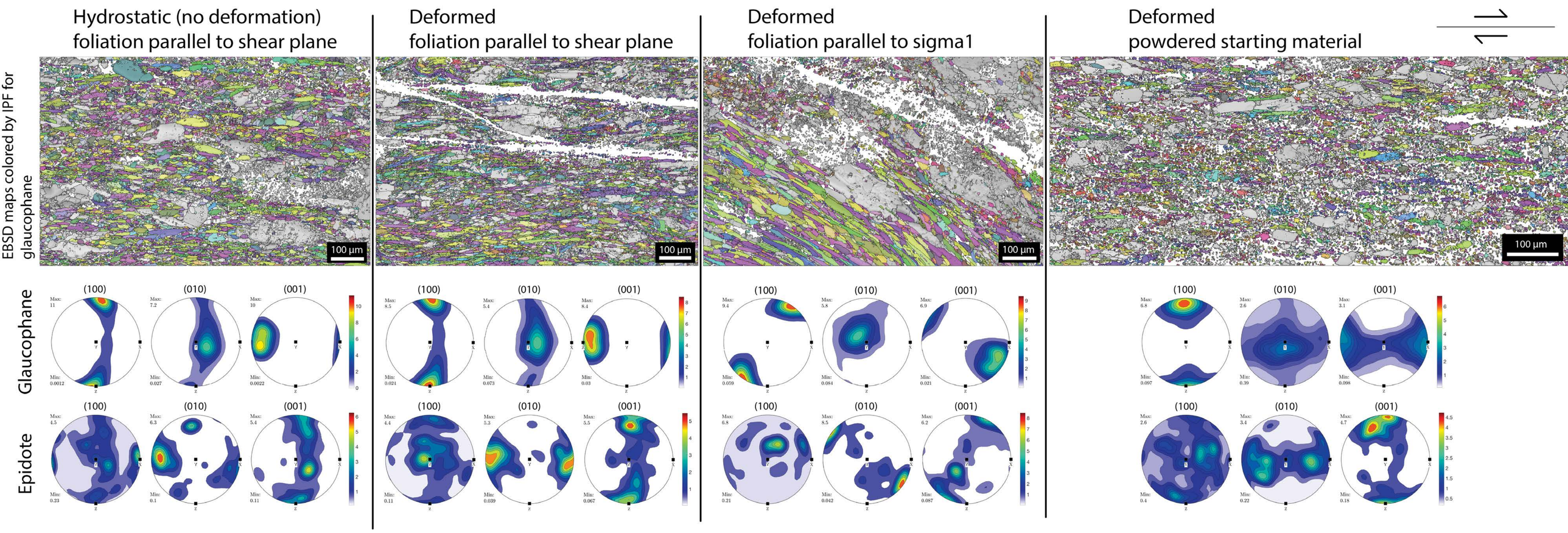
Purple arrows highlight a C’-shear band at a low antithetic angle to the shear plane ->



The Epidote grains can often be seen breaking up into smaller grains. ->



EBSD



- Hydrostatically annealing the cored CMW sample does not change the CPO.
- In both foliation samples, the sample did not deform plastically therefore the CPO remains consistent with the original sample foliation.
- The powdered sample develops a CPO pattern consistent with that observed in the natural sample, although there is more scatter in the b- and c-axes.

Even though the microstructures suggest the aggregate is chemically stable (i.e. no reactions or melting), we conducted microprobe analysis on glaucophane, epidote, and titanite between the natural sample, a 700°C hydrostatic, and two 700°C deformed samples to further highlight that our experimental samples are stable and 'happy'.

Glaucophane	SiO2	Al2O3	Na2O	MgO	CaO	Cr2O3	K2O	TiO2	FeO	MnO	TOTAL
Natural sample	55.82	8.43	6.77	7.81	0.98	0.01	0.02	0.09	16.88	0.15	96.96
Exp (hydrostatic)	55.63	8.30	6.41	7.65	0.93	-0.01	0.02	0.07	17.11	0.16	96.27
Exp (deformed)	55.26	8.60	6.53	7.86	1.16	0.01	0.03	0.06	16.92	0.16	96.58
Exp (deformed)	55.62	8.96	6.80	7.82	1.05	0.00	0.03	0.06	16.43	0.15	96.93

Epidote	SiO2	Al2O3	Na2O	MgO	CaO	Cr2O3	K2O	TiO2	FeO	MnO	TOTAL
Natural sample	38.05	22.59	0.00	0.02	22.95	0.03	0.00	0.10	14.53	0.31	98.58
Exp (hydrostatic)	37.58	22.40	0.01	0.01	23.08	0.02	0.00	0.15	14.25	0.30	97.80
Exp (deformed)	37.92	22.68	0.01	0.02	22.96	0.04	0.00	0.10	14.45	0.33	98.52
Exp (deformed)	37.87	22.89	0.01	0.02	22.87	0.02	0.00	0.08	13.85	0.34	97.95

Titanite	SiO2	Al2O3	Na2O	MgO	CaO	Cr2O3	K2O	TiO2	FeO	MnO	TOTAL
Natural sample	31.09	0.87	0.01	0.00	28.23	0.04	0.02	38.38	0.81	0.05	99.49
Exp (hydrostatic)	30.96	0.97	0.03	0.00	28.12	0.02	0.00	38.05	1.14	0.06	99.34
Exp (deformed)	30.94	0.81	0.02	0.00	28.24	0.03	0.01	38.70	0.98	0.06	99.80
Exp (deformed)	30.96	0.91	0.02	0.00	28.13	0.02	0.01	38.40	1.02	0.06	99.53

Summary - Future Work

Part 1

- Conducted general shear deformation experiments on glaucophane-bearing blueschist powder and observe stress exponents between 1.8 and 3.8.

- A possible explanation for the lower stress exponent is the sample was deforming by multiple deformation mechanisms, likely involving a sensitivity to grain size.

- FUTURE work will focus on running strain rate stepping experiments assessing the potential switch in deformation mechanisms at low stresses and the further constrain the flow law parameters.

Part 2

- Conducted general shear deformation experiments on foliated and powder glaucophane-bearing blueschist. The foliated samples localize through brittle deformation at the sample-scale. The powdered sample deforms plastically at the sample-scale but shows ductile deformation in glaucophane and titanite and brittle deformation in epidote.

- FUTURE work will focus on running slower strain rate experiments on the foliated samples to achieve more ductile deformation within the samples.