Fluid mediated deformation controls slip behaviors at the base of the subduction seismogenic zone

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Structural Petrology of the Lithosphere
At the University of Washington

NSF

UNIVERSITY *of* WASHINGTON

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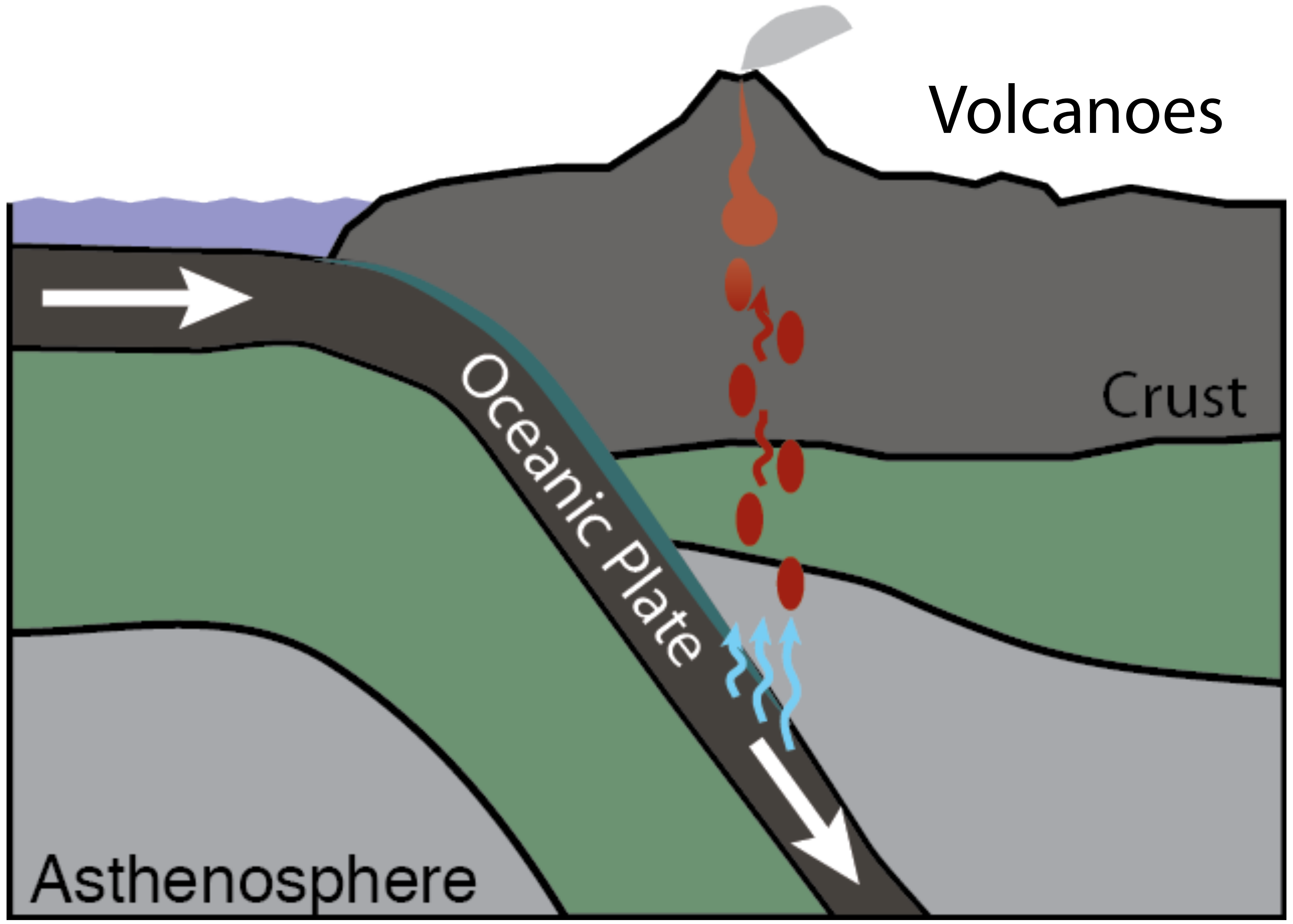
Subduction zones



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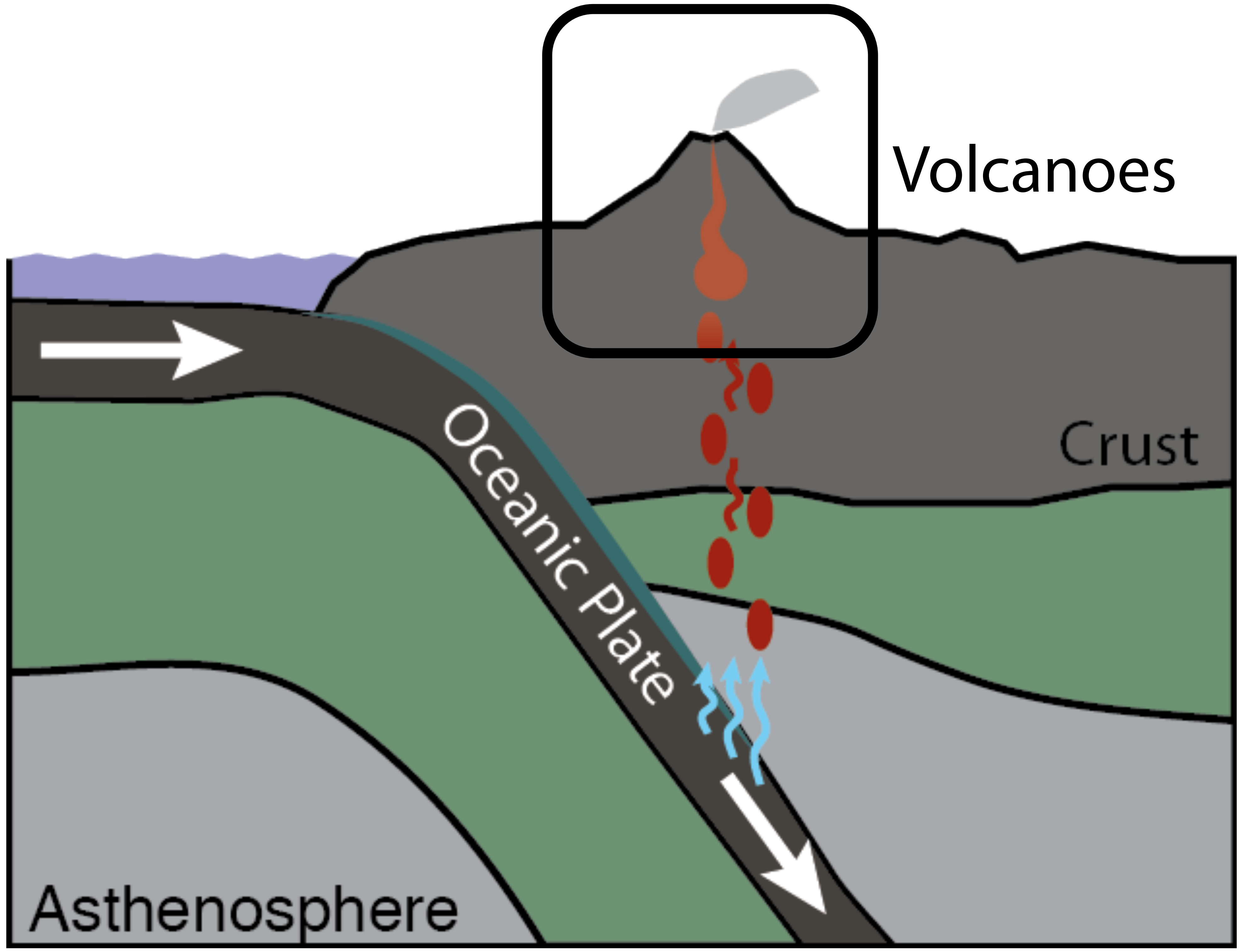
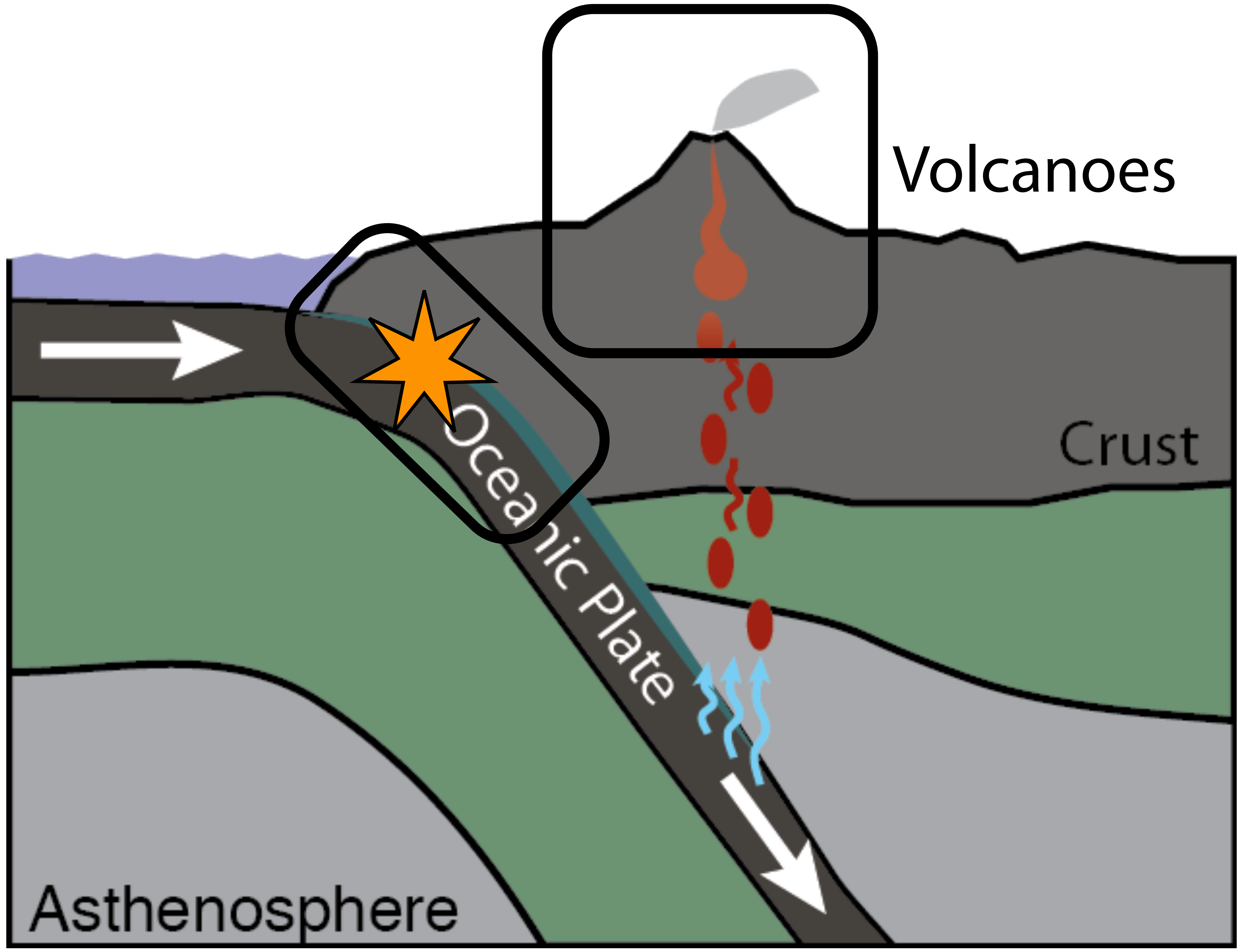


Most devastating volcanic eruptions

Subduction zones



Most devastating volcanic eruptions

Largest earthquakes on earth

Subduction zones: Plate boundary processes

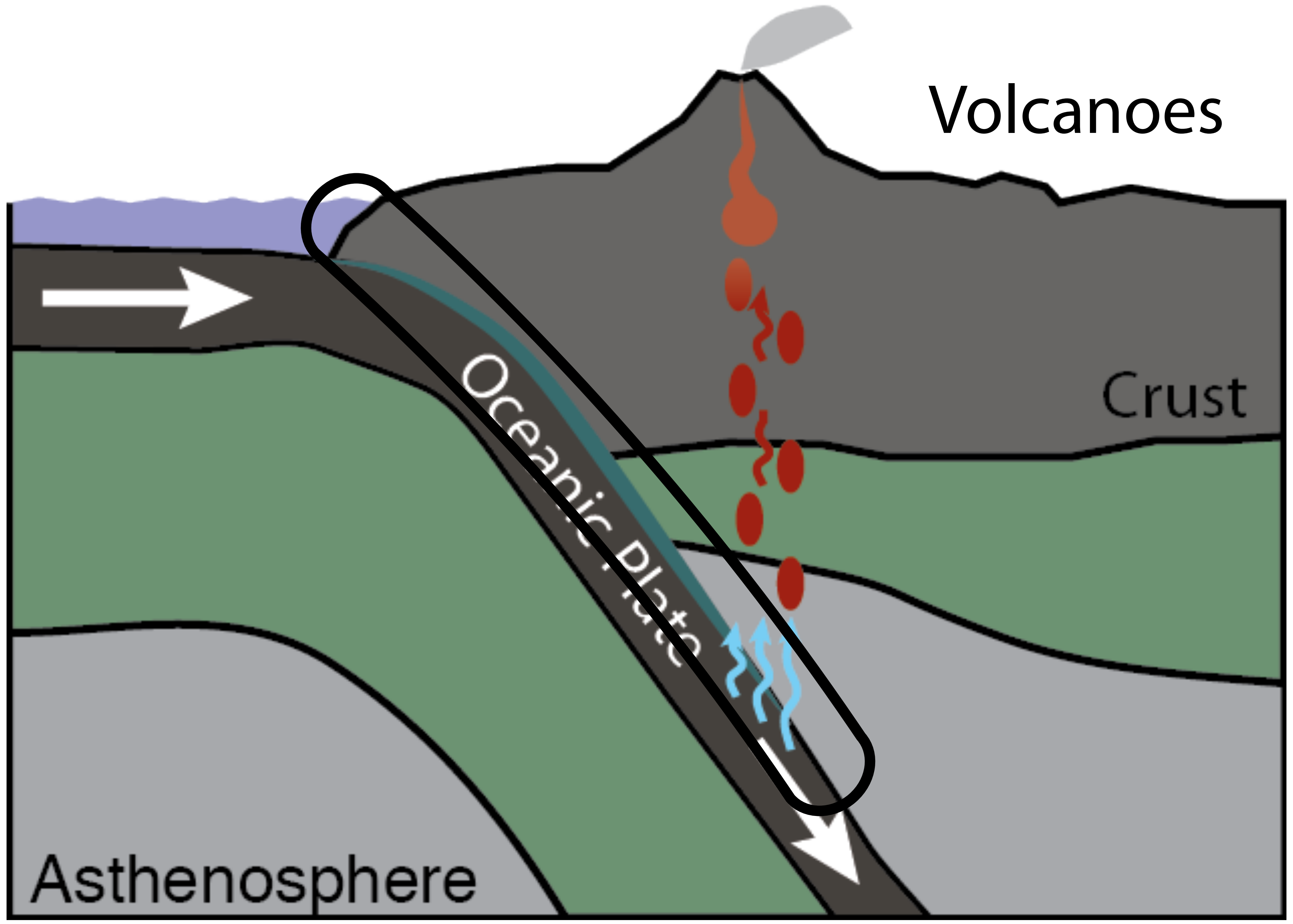


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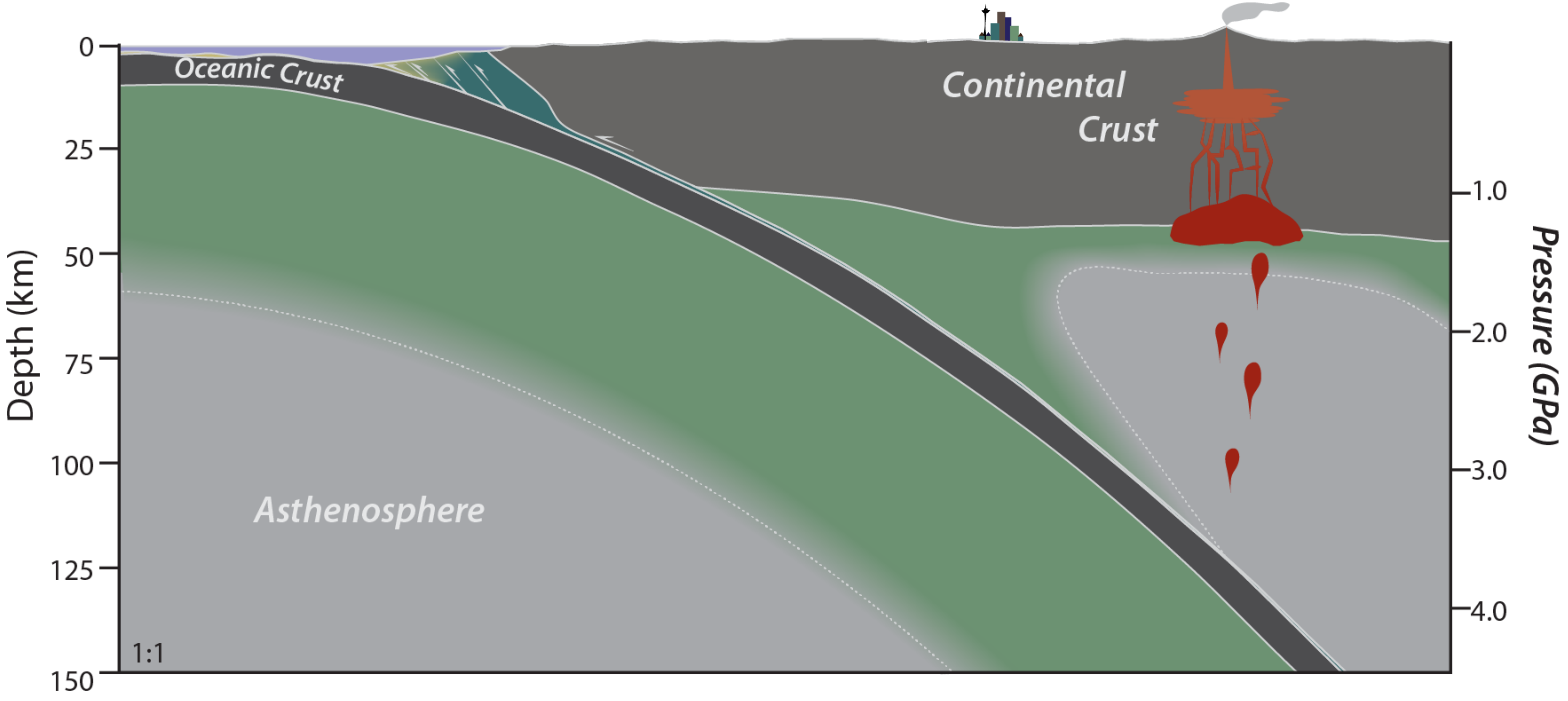
Plate interface locus of fluids, chemical & mechanical transformations



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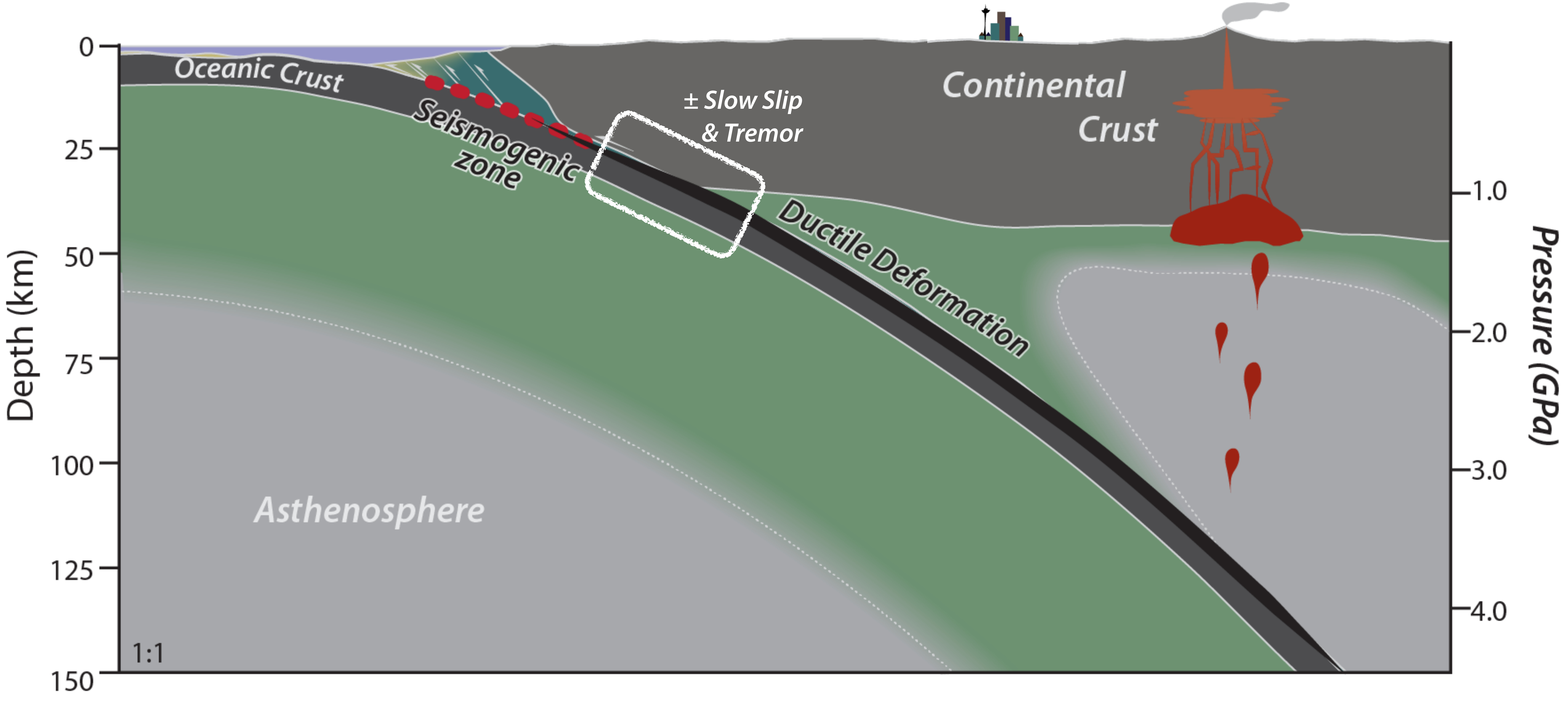

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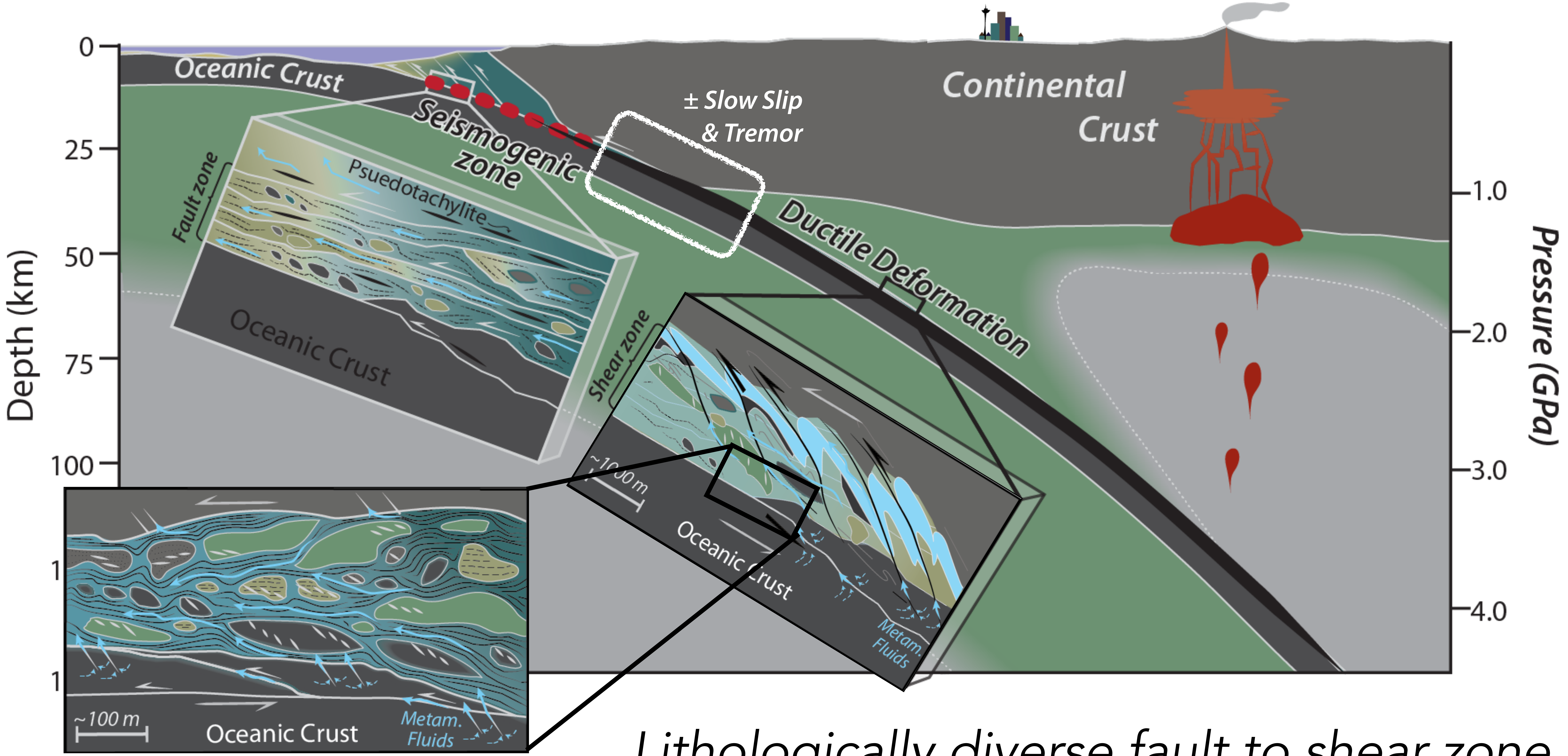
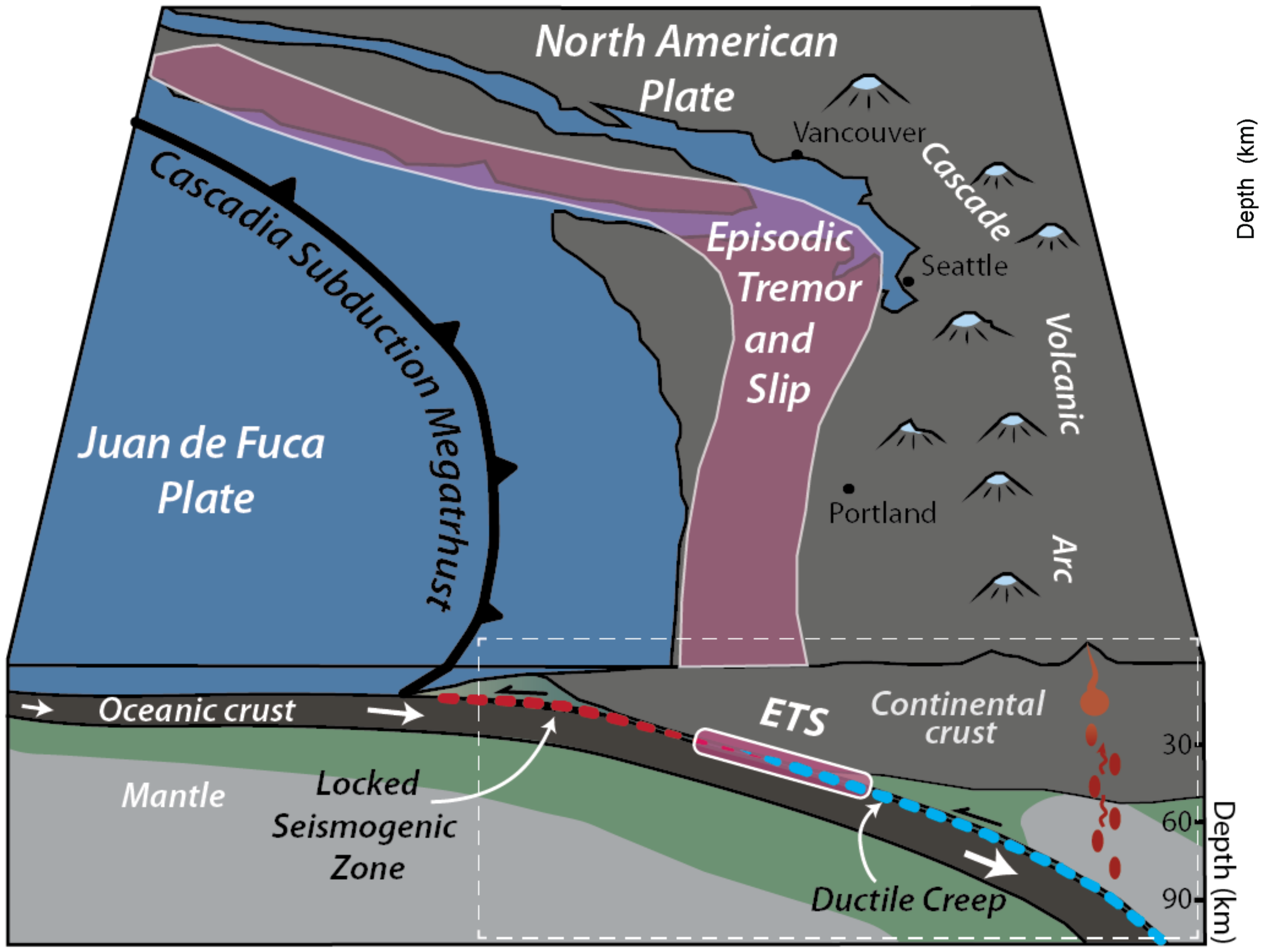


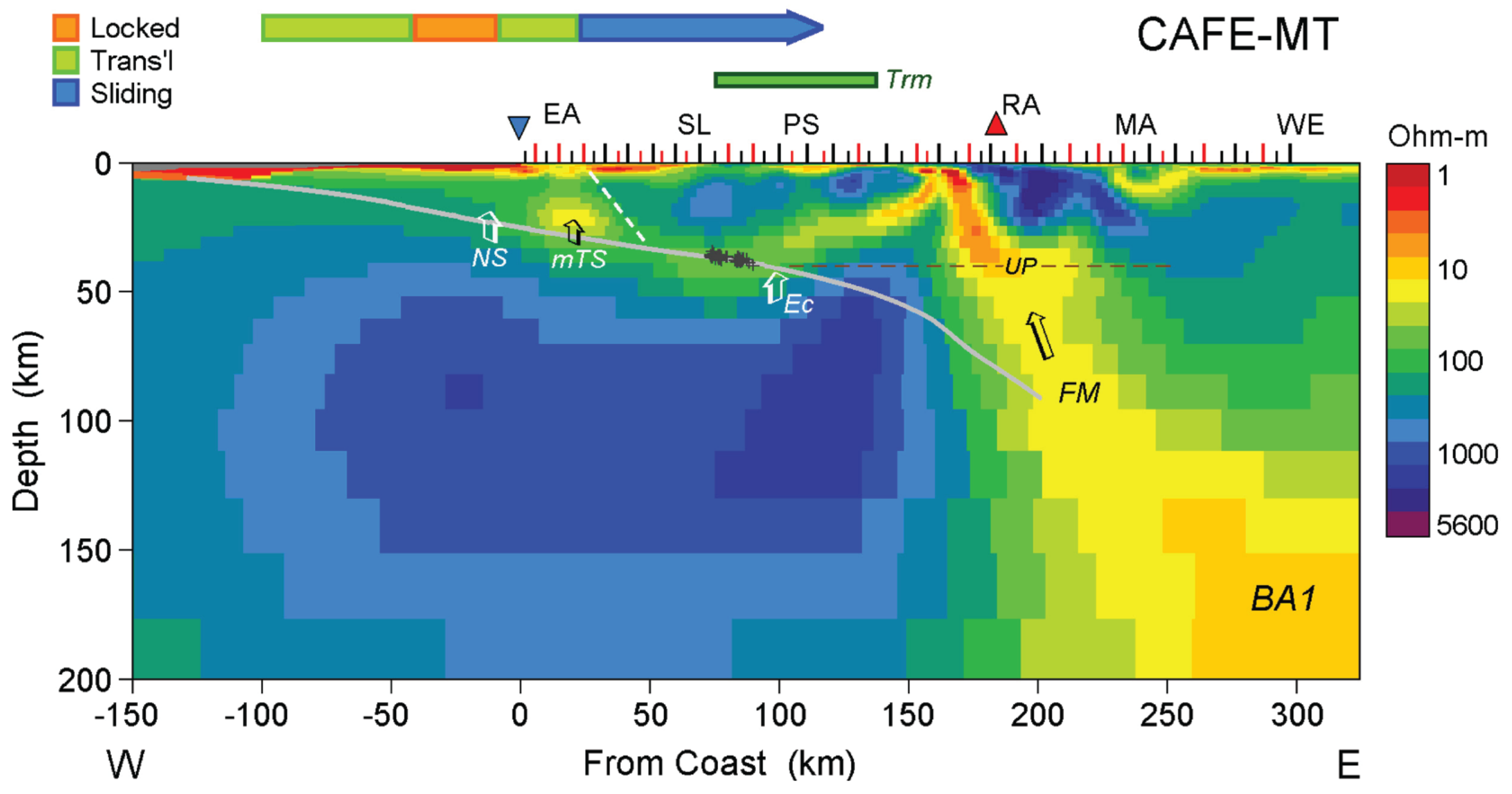
Lithologically diverse fault to shear zone

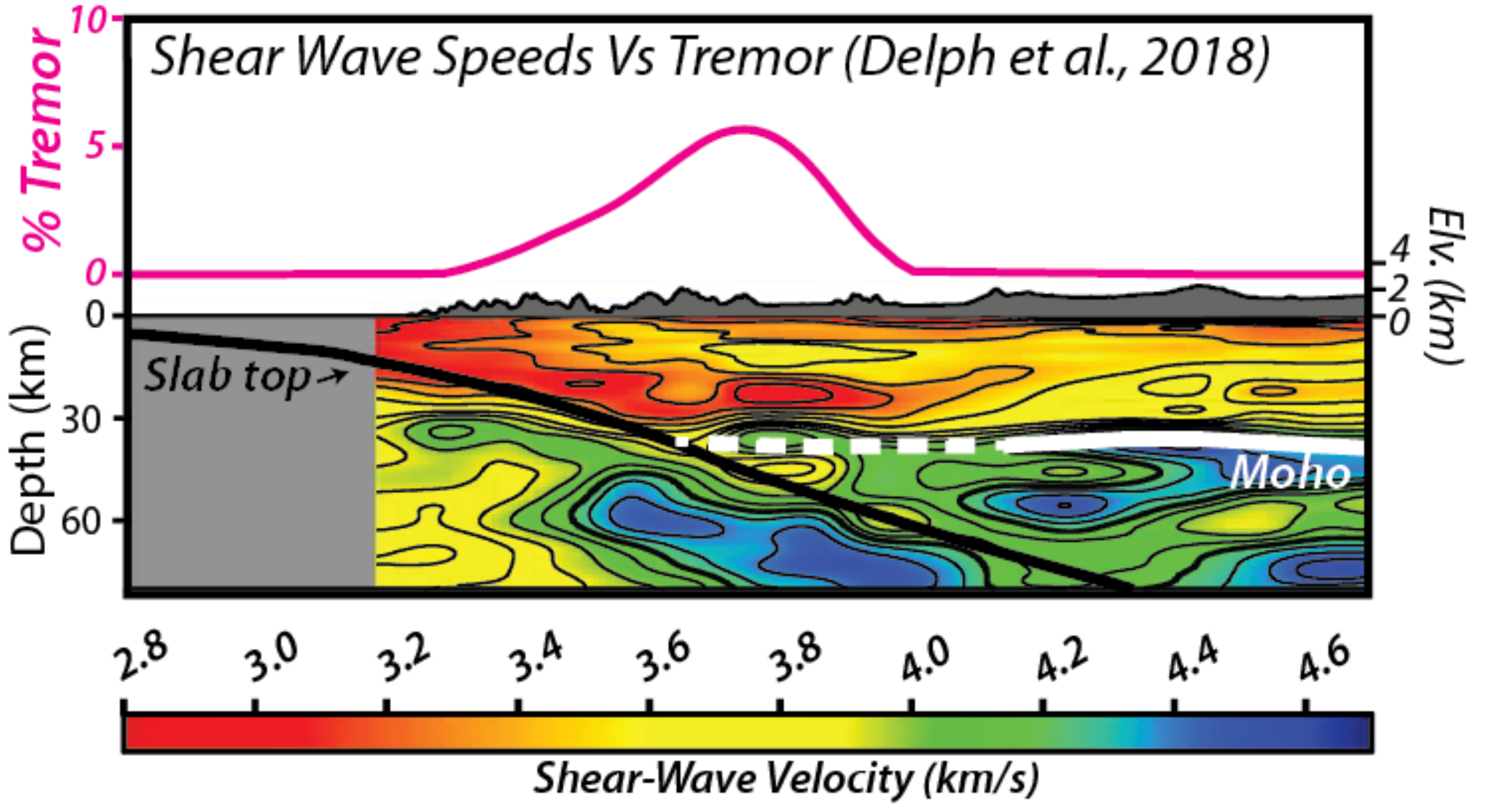
Base of the subduction seismogenic zone: EQs and slow slip events

Geophysical observations



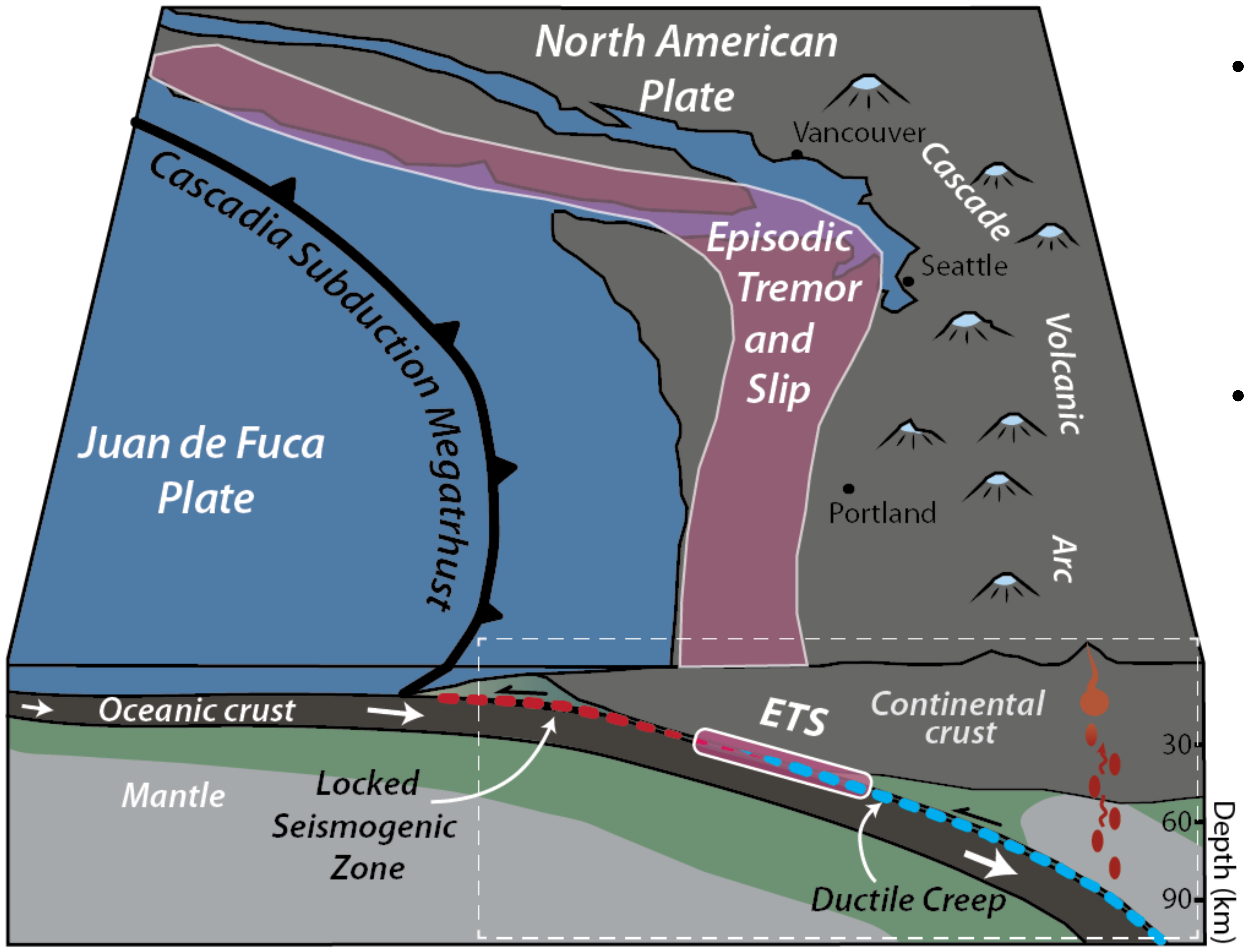
MT images conductors, inferred fluids (Wanamaker et al., 2014)





Base of the subduction seismogenic zone: EQs and slow slip events

Where deep slow slip occurs…



- **Geophysical observations → Fluid-rich environment**
  - slow Vs, conductive zones in MT, high Vp/Vs ratios
- **Tidal trigger of slow slip events**
  - **<u>very small stress perturbations (kPa) result in several order magnitude increase in slip rates</u>**
    <u>→ most consistent with low differential stress</u>
- **Inferred high pore fluid pressures (P_f)**

Deep slow slip events have preceded large megathrust earthquakes; contribute to the subduction zone slip budget; Occur down-dip* of megathrust hypocenters but in their slip patches

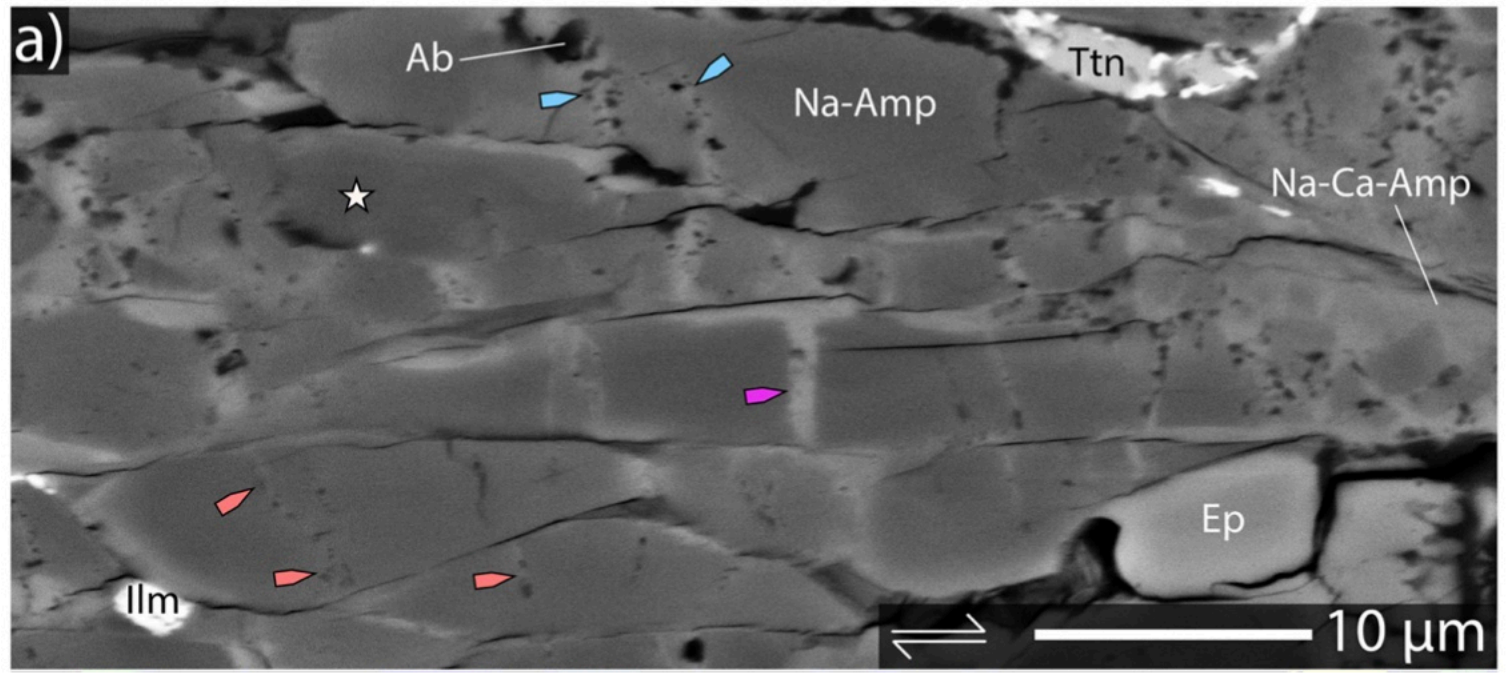
E.g., Glaucophane deformation

*Strength of the plate interface dependent on **fluid behavior and volumes***

Fluids can change def. mechanism, mineralogy, and mode of deformation

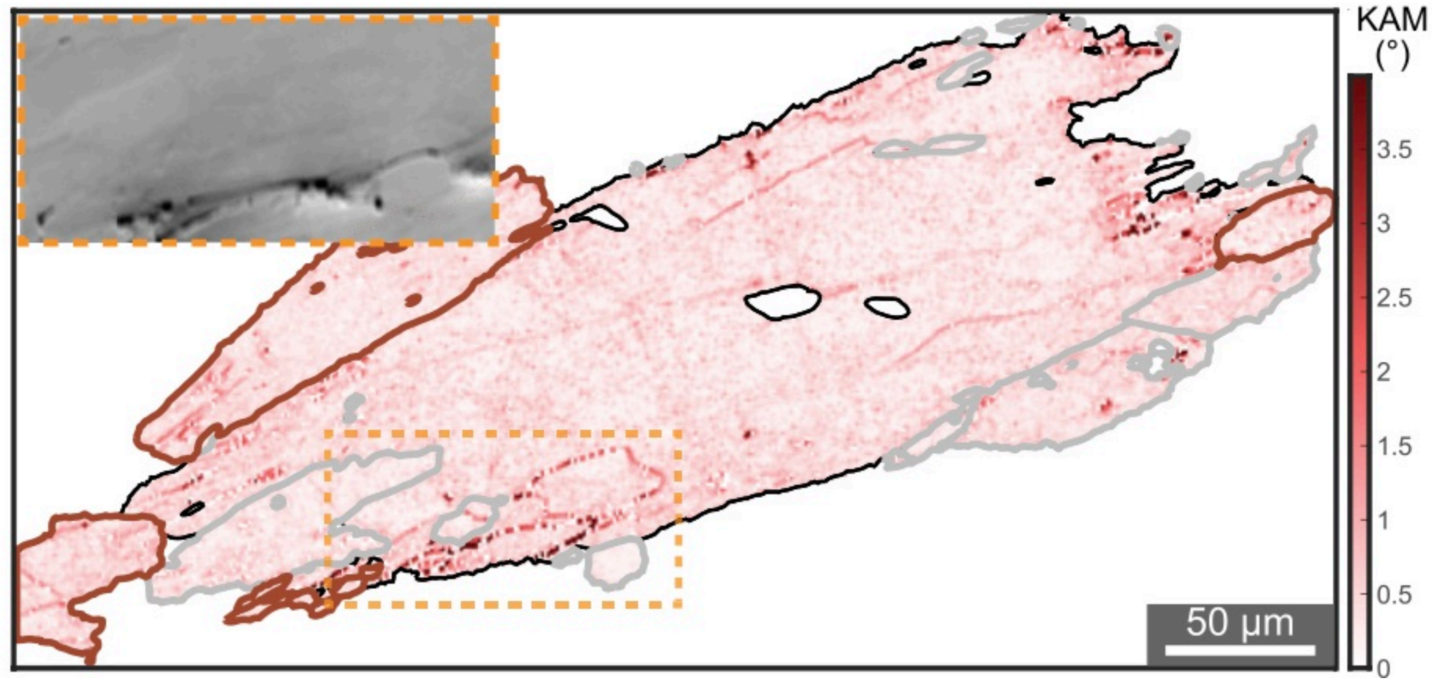
Shift in mechanism

Microboudinage (diffusive mechanism; n ~2)



Tokle et al., 2023

Dislocation creep (power law rheology; n ~3-5)



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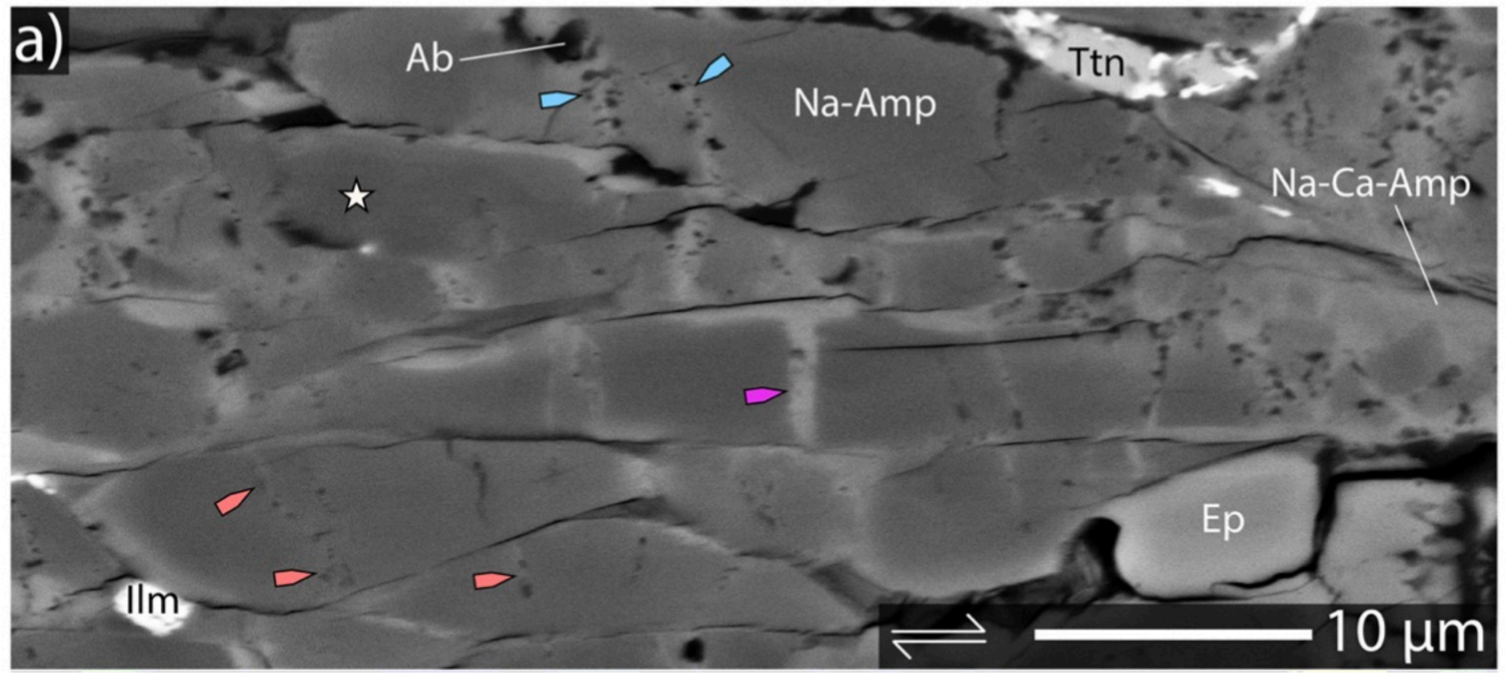

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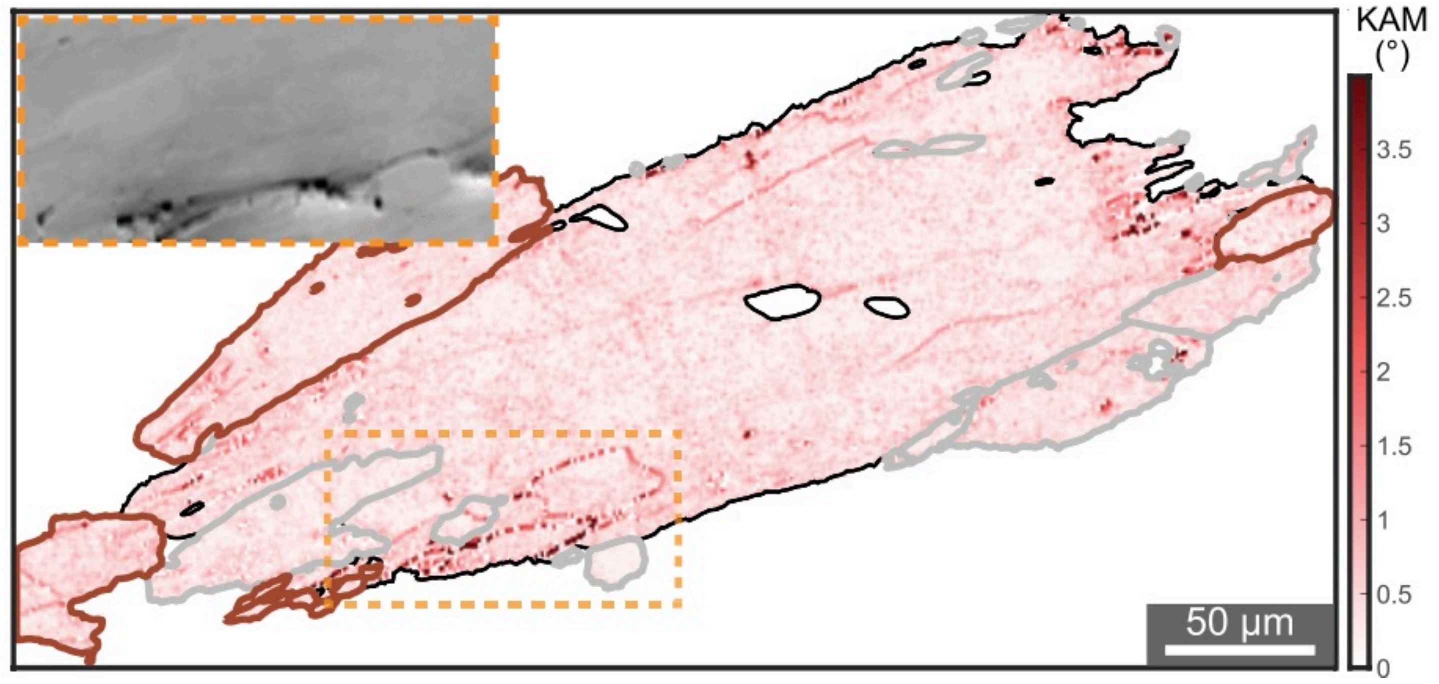

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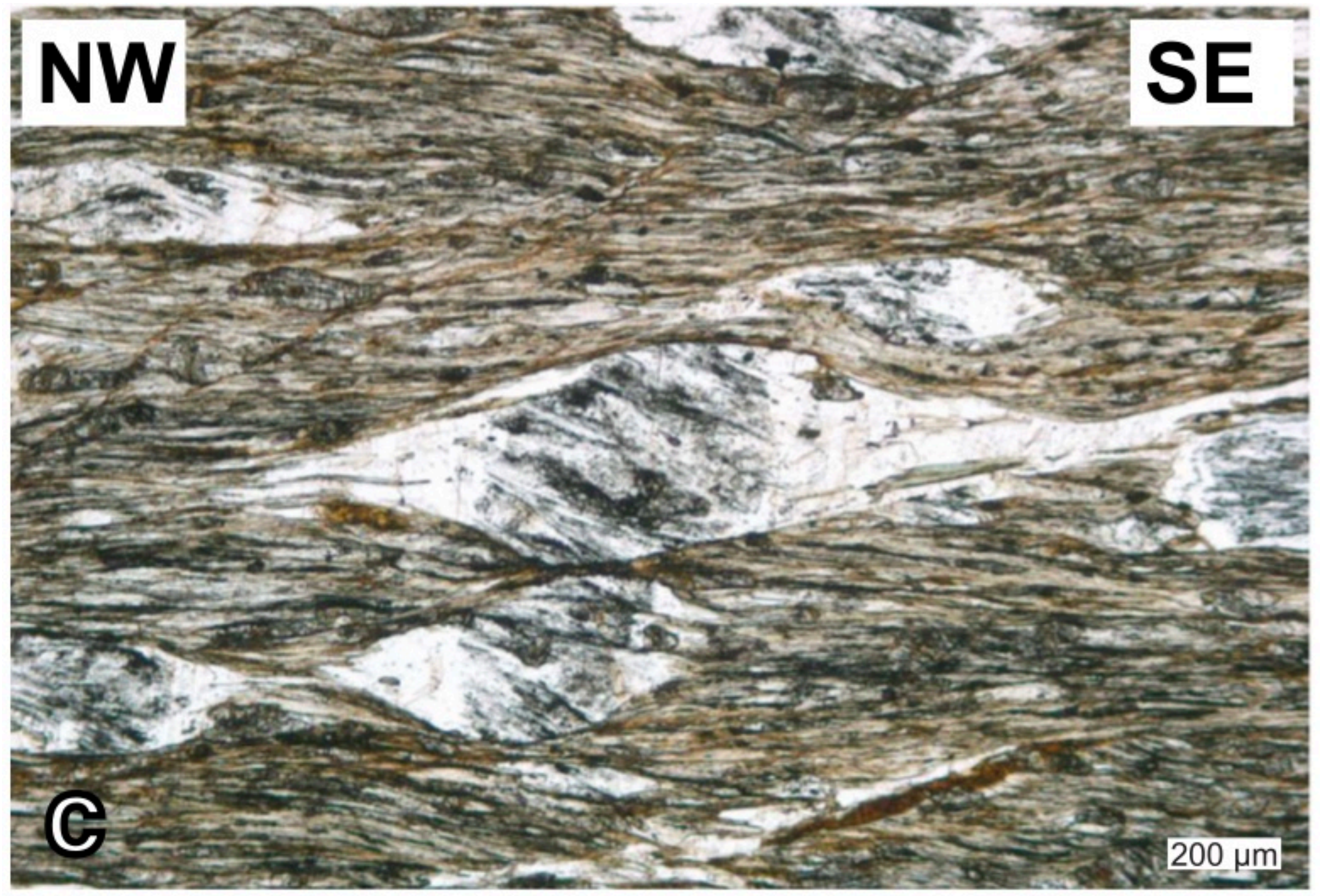
New minerals through fluid-mediated metamorphic reactions



Platt et al., 2018

Transformation-Assisted Creep, Ab porphyroblast/clasts reacting to quartz+ w/ fluid in Pelona schist

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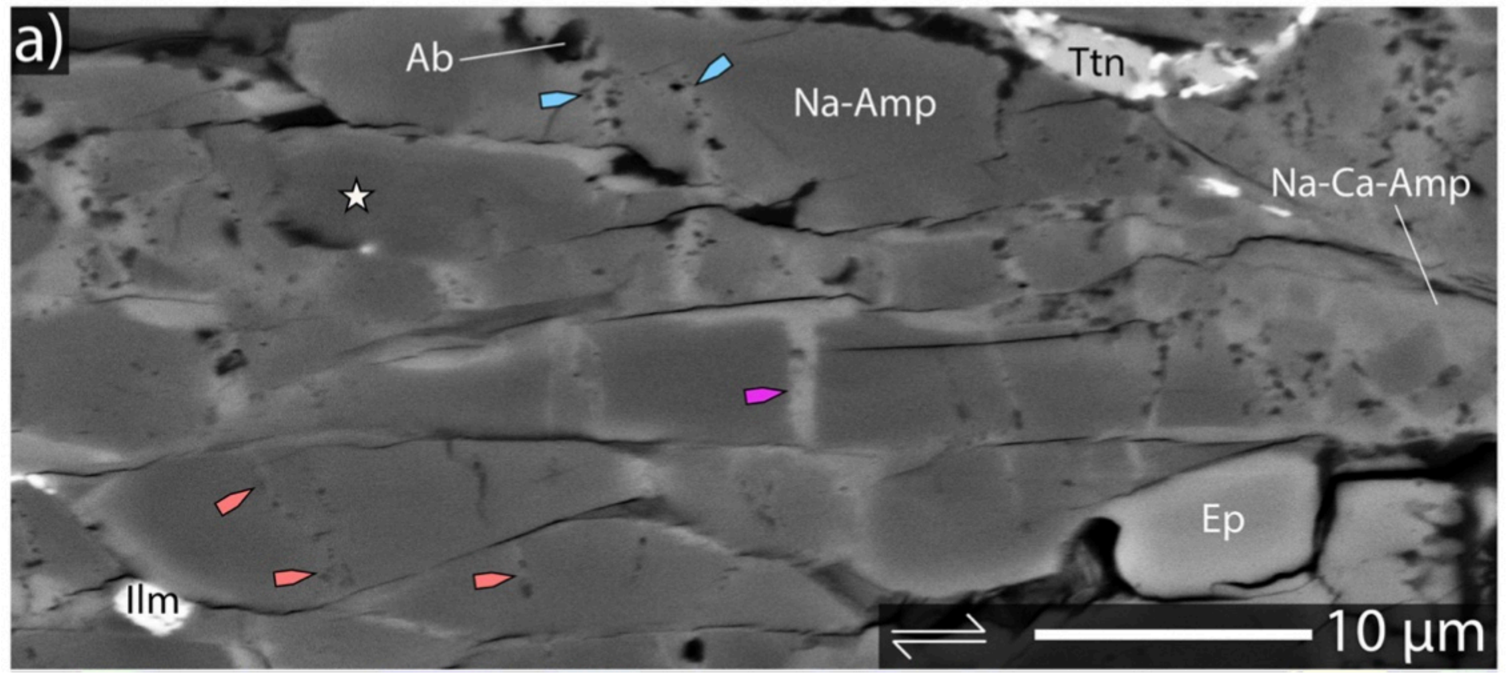

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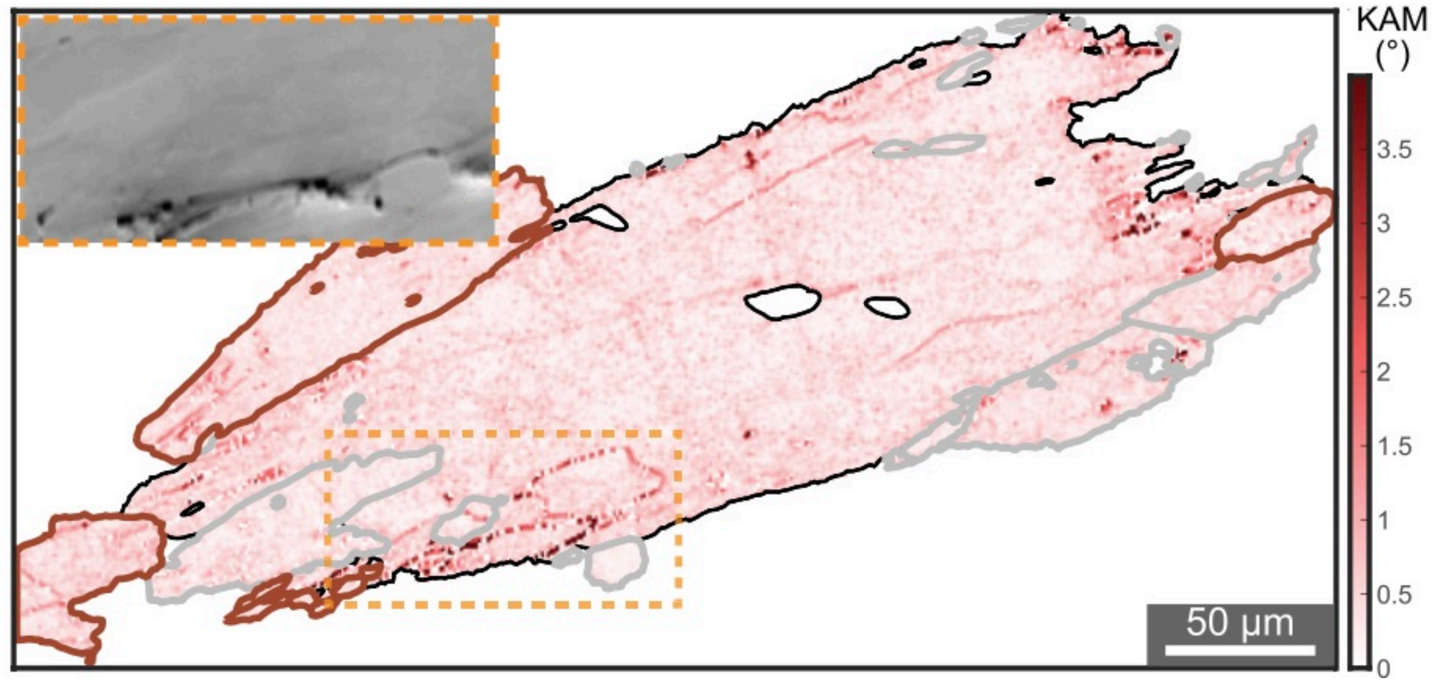

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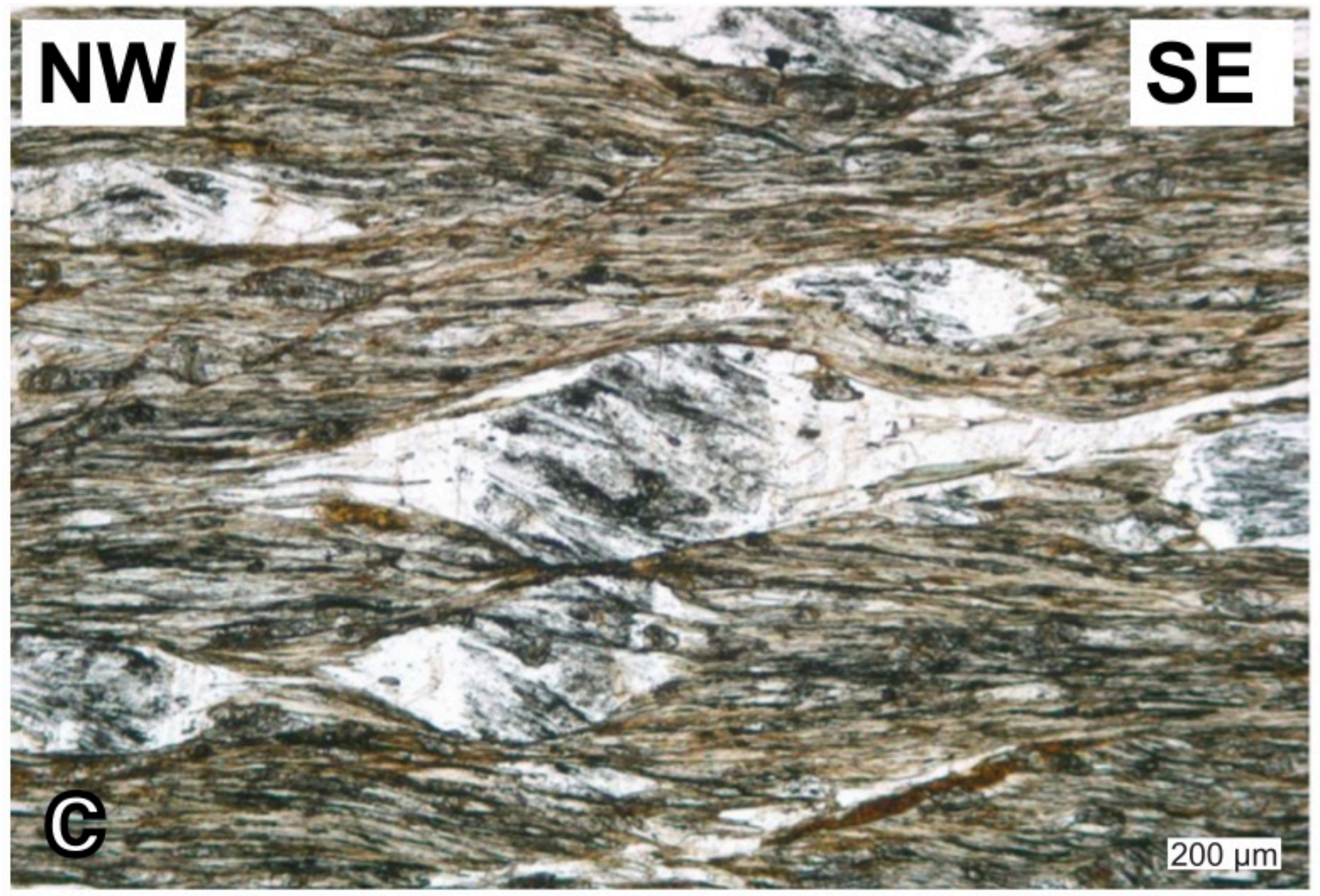

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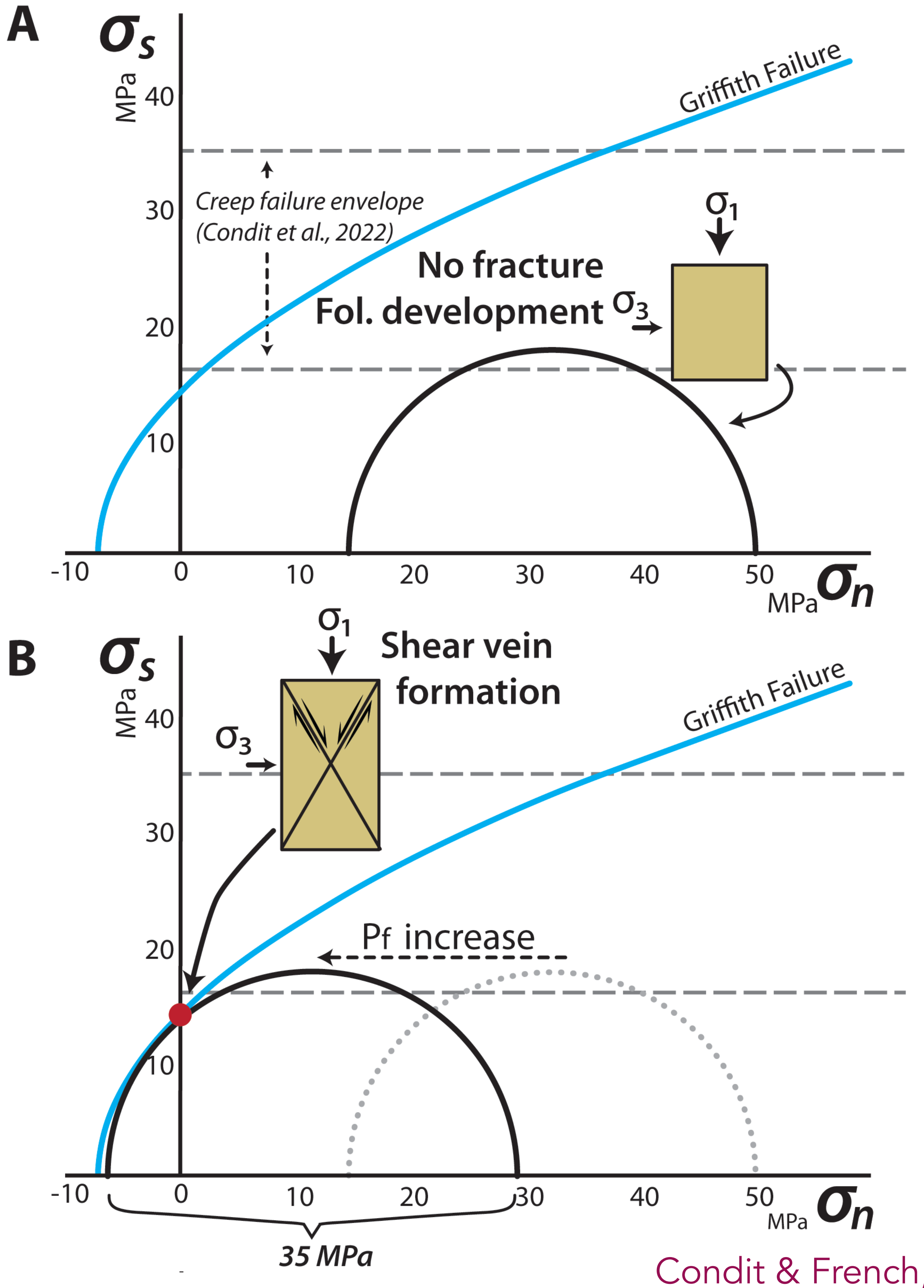

Condit & French, 2022

Activate frictional/brittle def.

Pore fluid pressure ($\sigma_n = \sigma - P_f$)

Observations from the exhumed rock record from the base of the subduction seismogenic zone

What are the phenomena we see in rocks that we need improved:

…Constitutive relations for?

…Dynamic mechanistic understanding of chemical-mechanical feedbacks?

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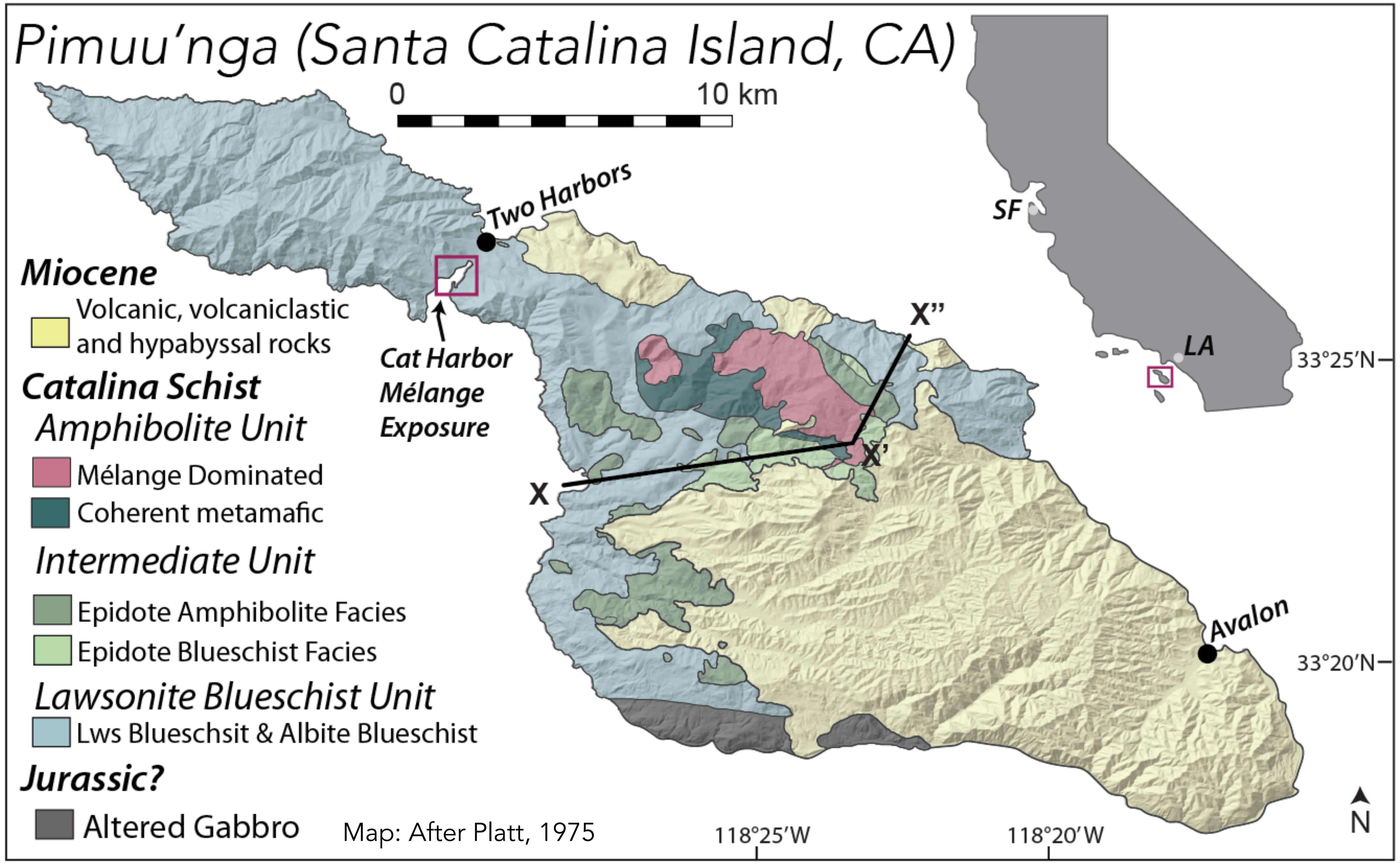
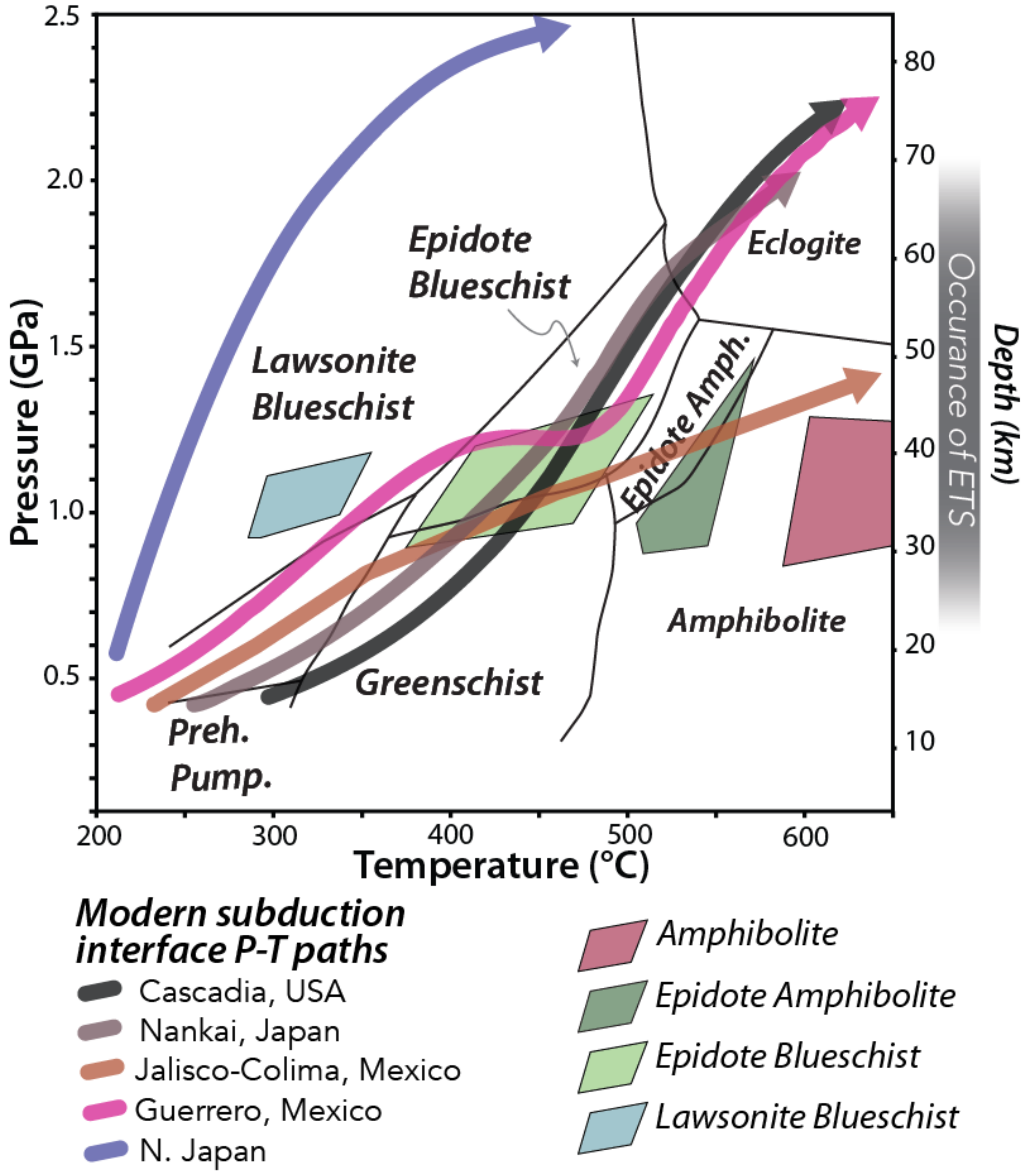
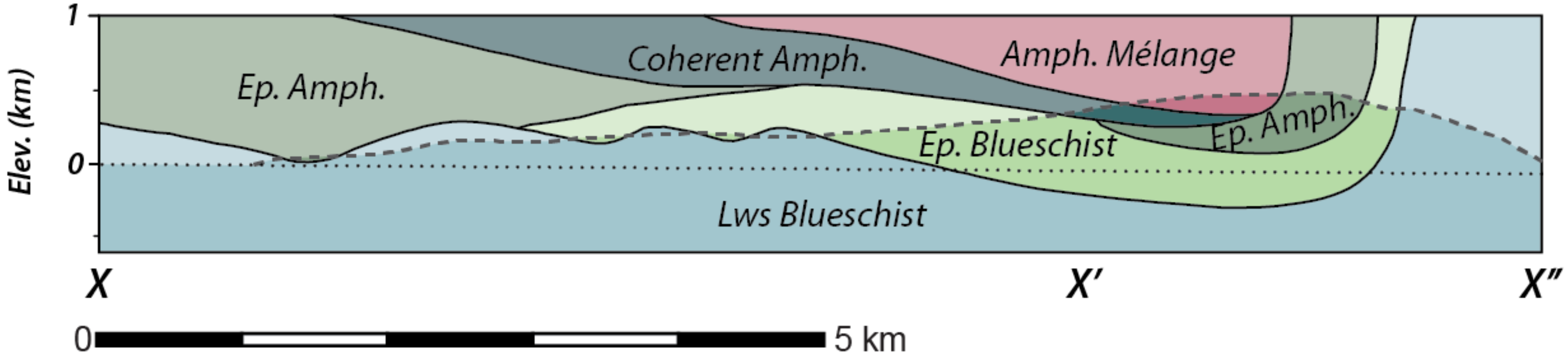
Pressure Solution Creep along the plate interface is not slow slip

Activation of frictional mechanisms with high Pf could be slow slip

Evidence for brittle deformation (seismic slip?) at these deep depths intimately related to fluid process

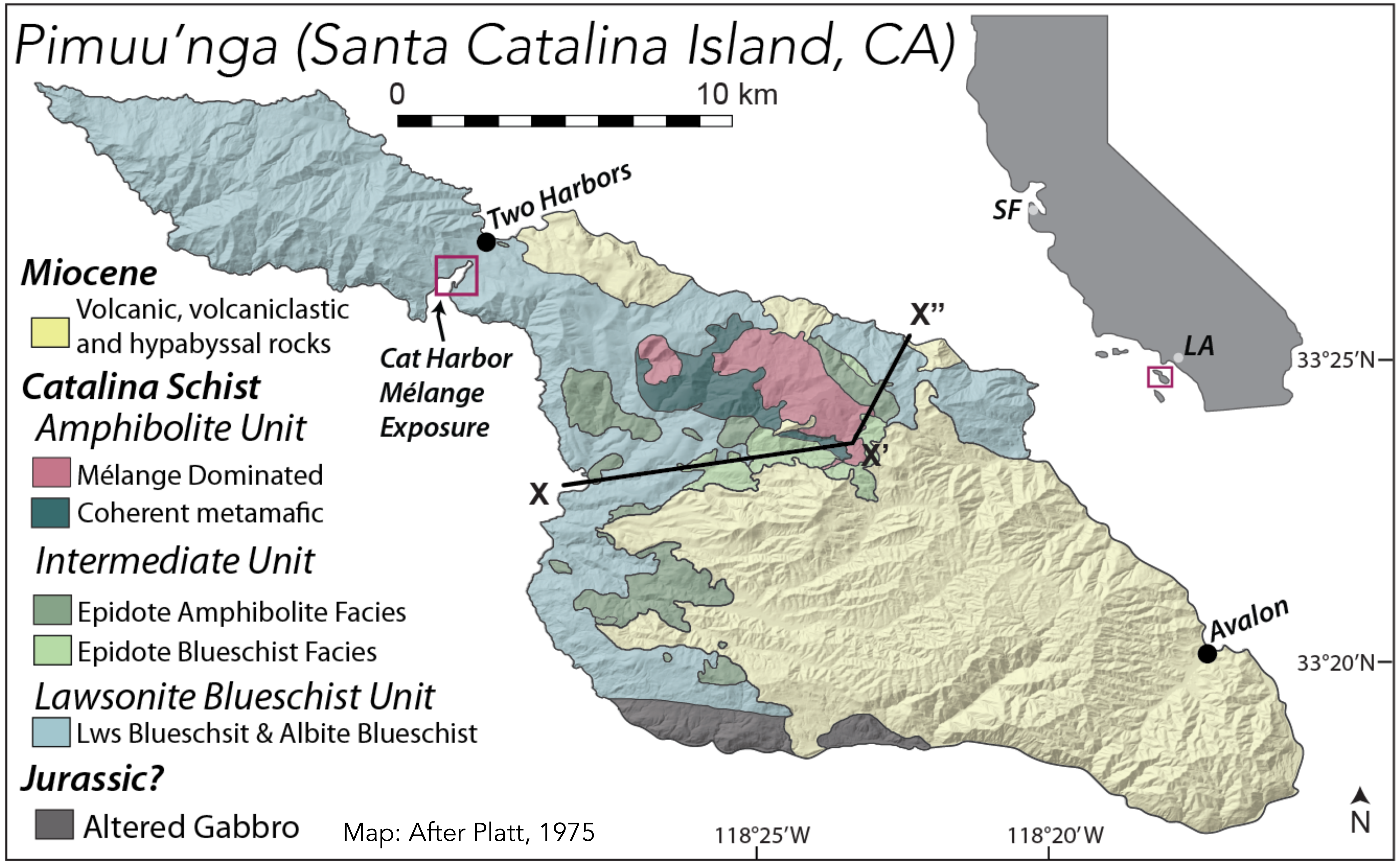


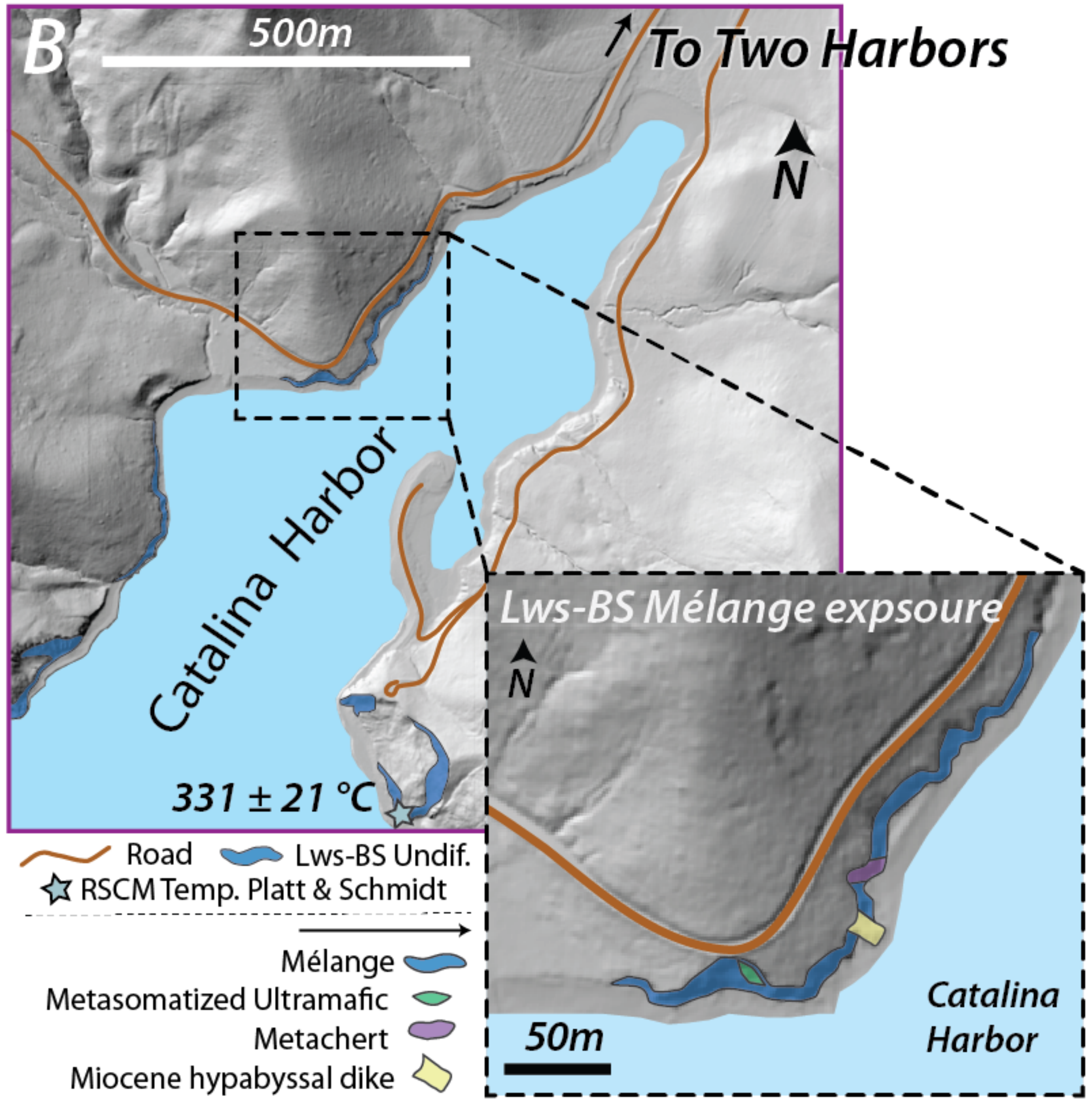




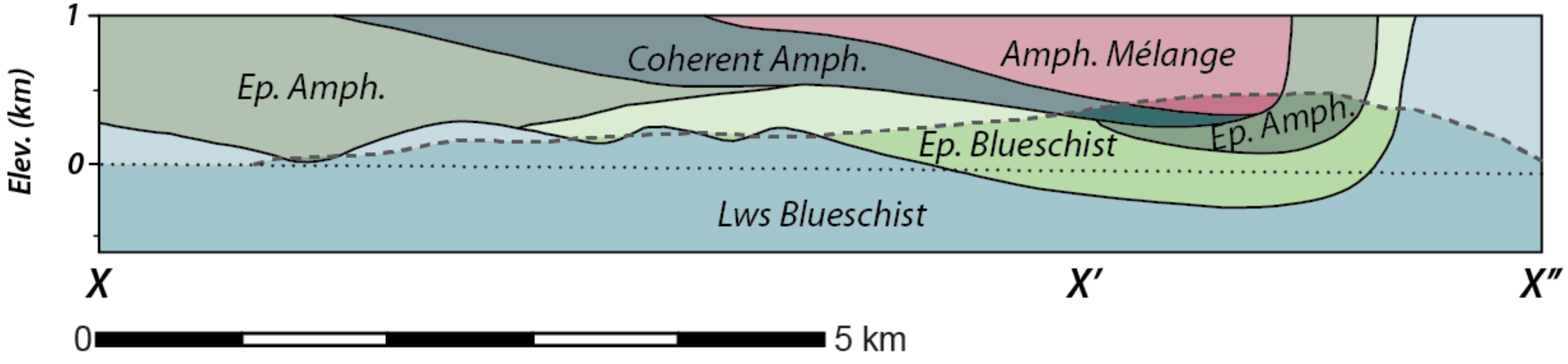
Cross-section: Platt and Schmidt, 2024

Exhumed set of terranes recording Cretaceous subduction beneath North America from 115 -95 Ma





Condit et al., 2025 Geology



Cross-section: Platt and Schmidt, 2024

Lawsonite blueschist unit - ~1.0 GPa (30-35 km) and ~320-330 °C

Temperatures: Platt and Schmidt, 2024


Looking to the WNW
Metasedimentary mélange
Block-in-matrix structure, quartz vein-rich mess
Cat Harbor Mélange · Pimuu'nga (Santa Catalina Island) · CA, USA


Looking to the WNW
Cat Harbor Melange, Pimuu'nga (Santa Catalina Island) - CA, USA

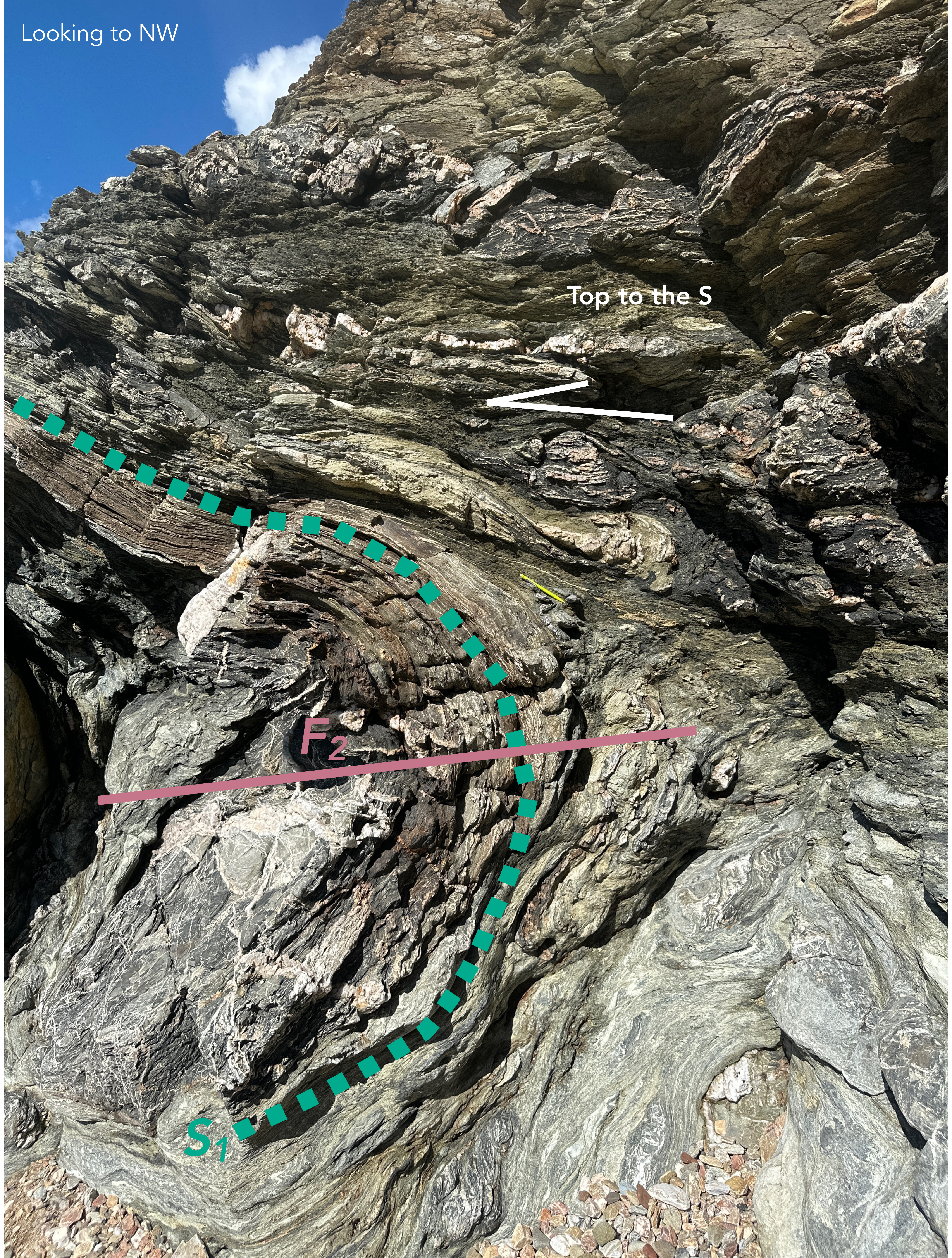
Condit et al., 2025 Geology

Metasedimentary mélange

Block-in-matrix structure, quartz vein-rich exposure

How do these structures form? How do they deform? and what slip behaviors do they accommodate?

Condit et al., 2025 Geology



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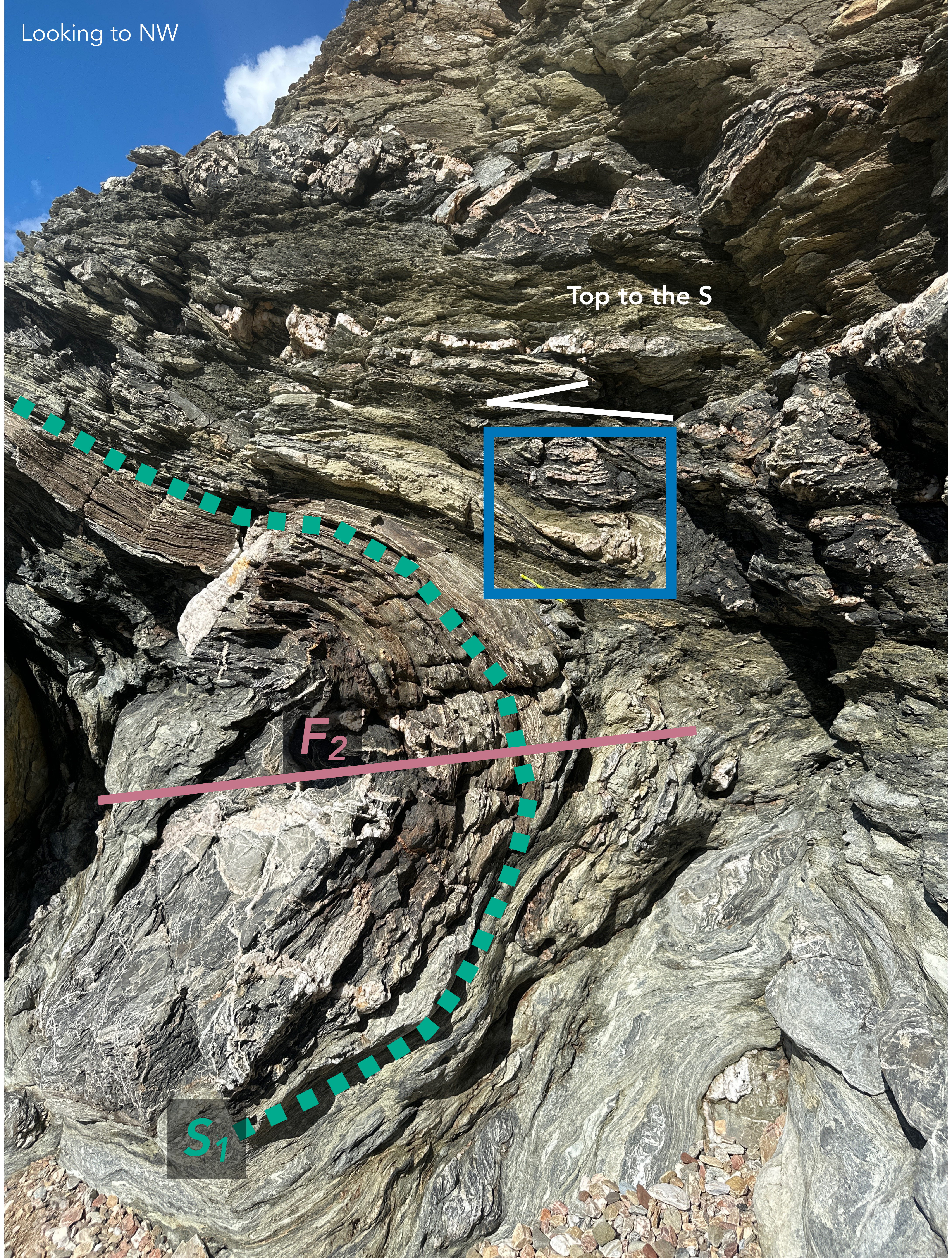
Extensional veins in fold noses

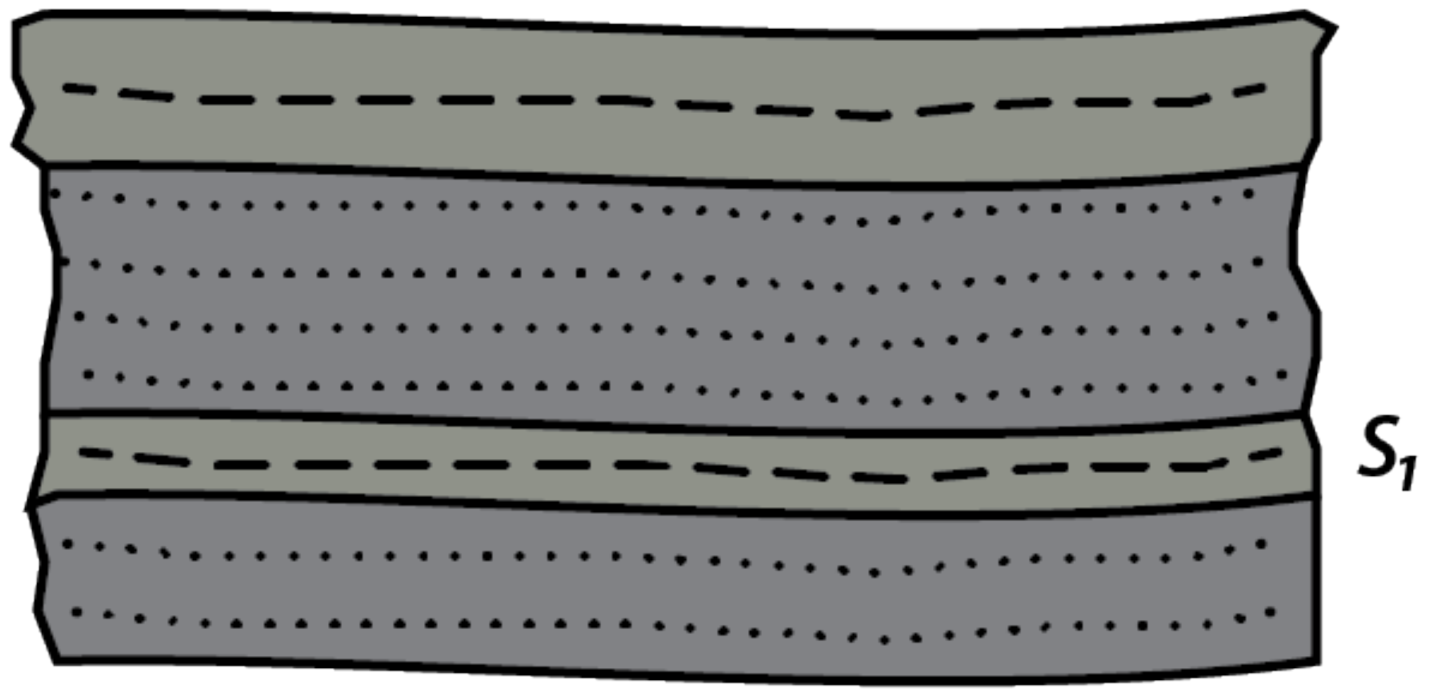
Outer-arc extension fractures precipitate quartz;
Transform into coarse grained quartz vein-mesh networks in fold noses

Extensional veins in fold noses

Vein-filled fold noses become blocks in the mélange

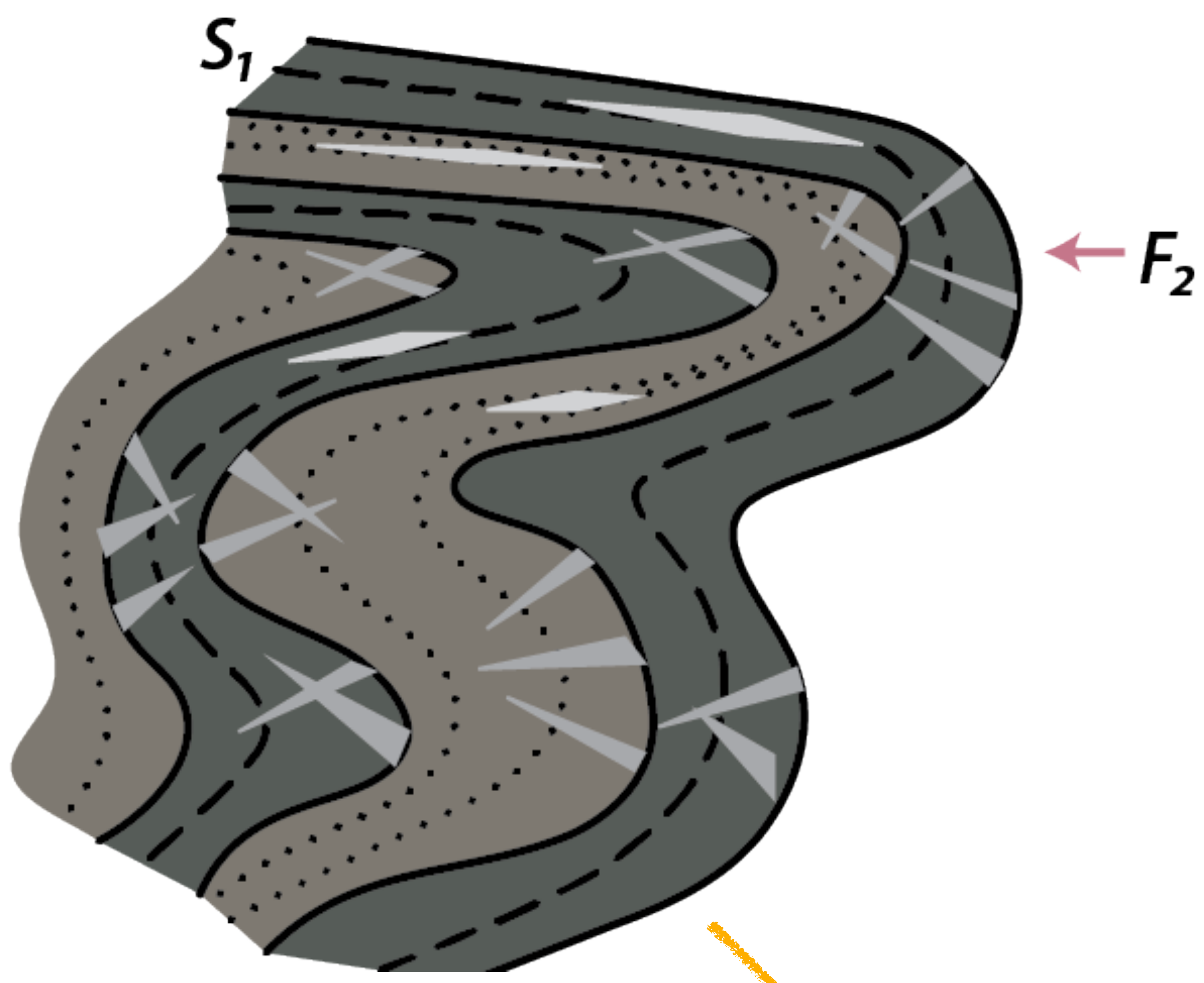


Subduction, deformation fluid infiltration & metamorphism

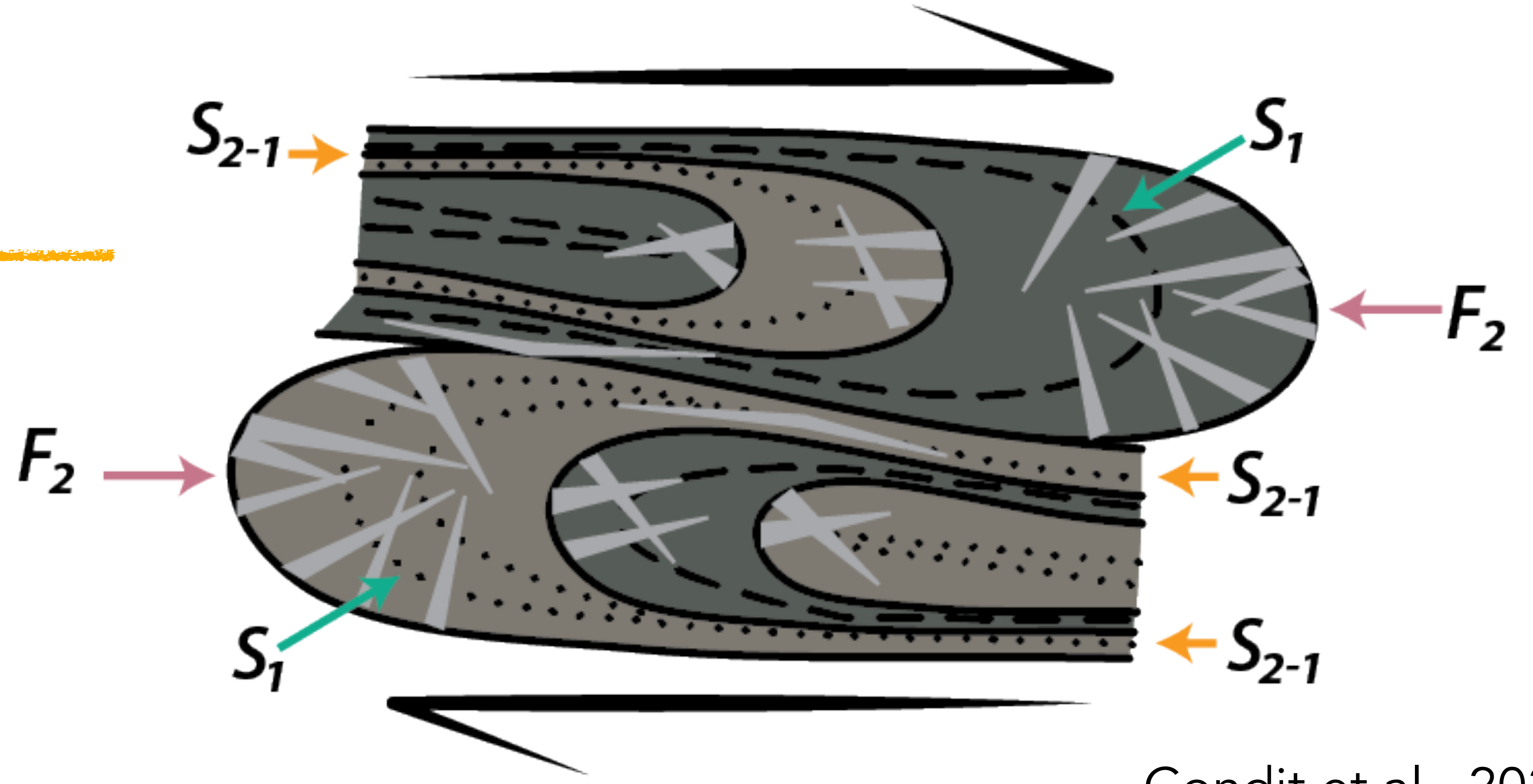


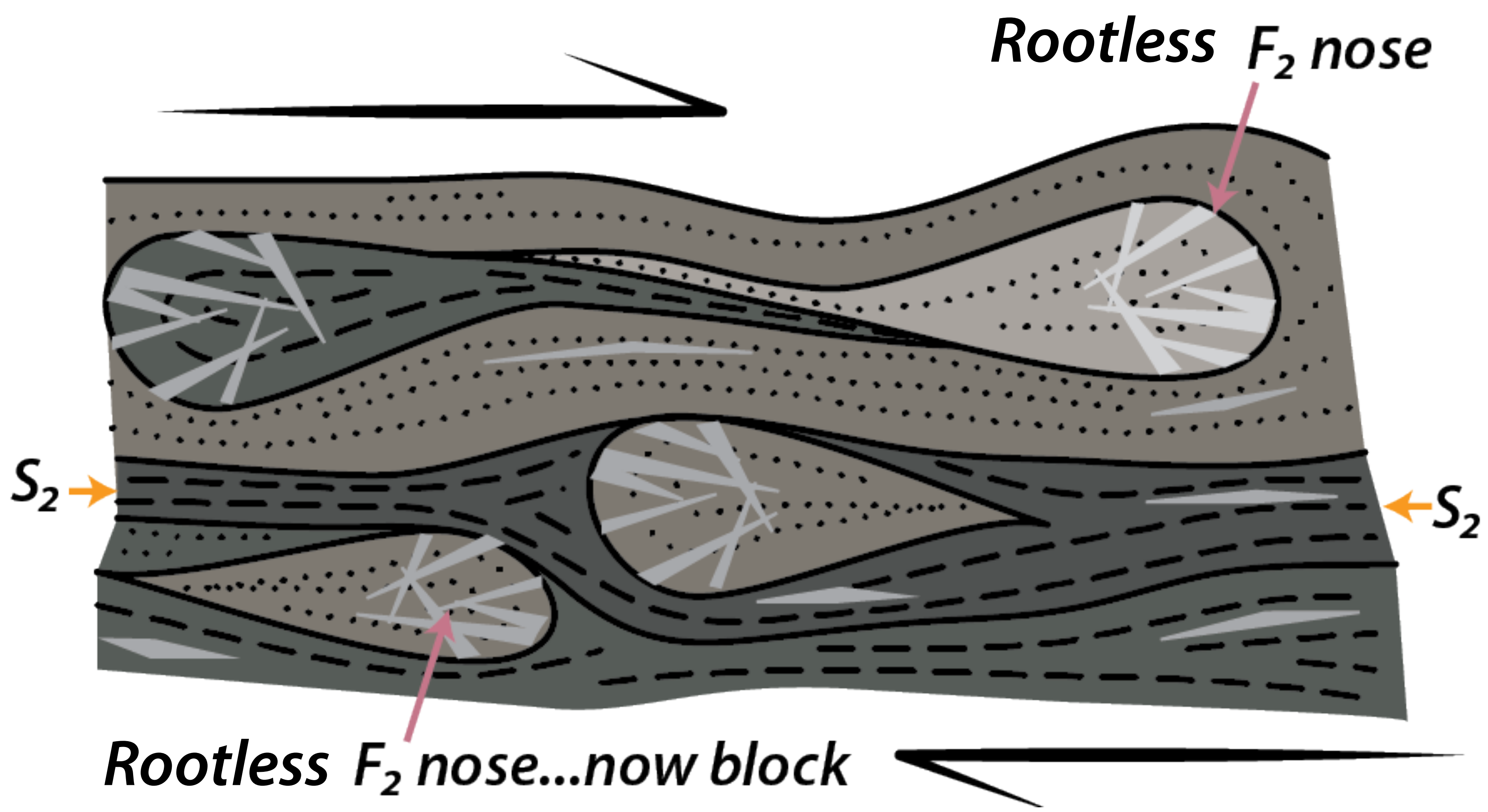
Deposition near the trench:
~100 Ma; graywackes, sandstones, shales

Folding, veining, during prograde subduction



Veins strengthen fold noses, progressive shearing
with continued subduction, strain localization in limbs/matrix

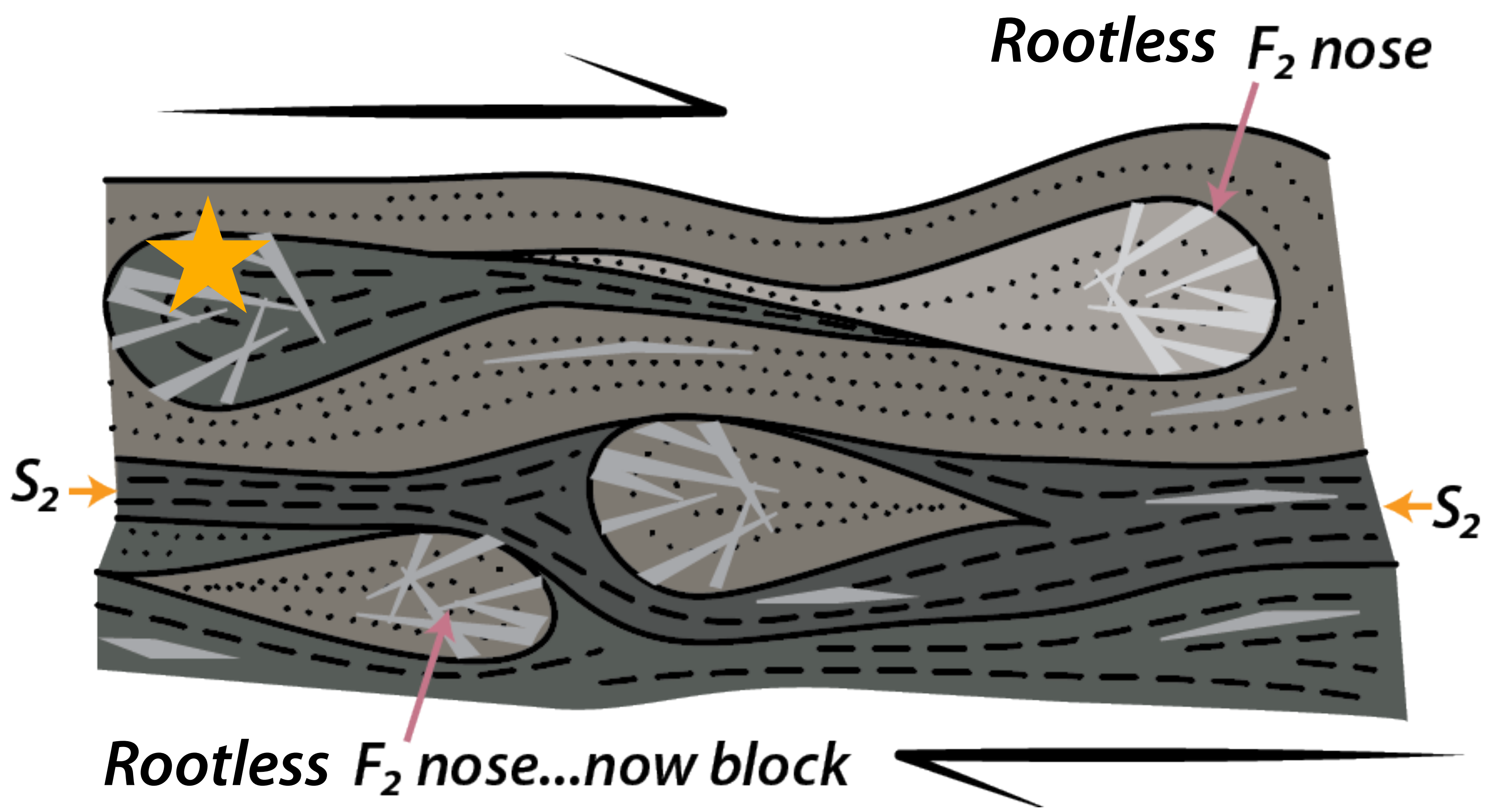


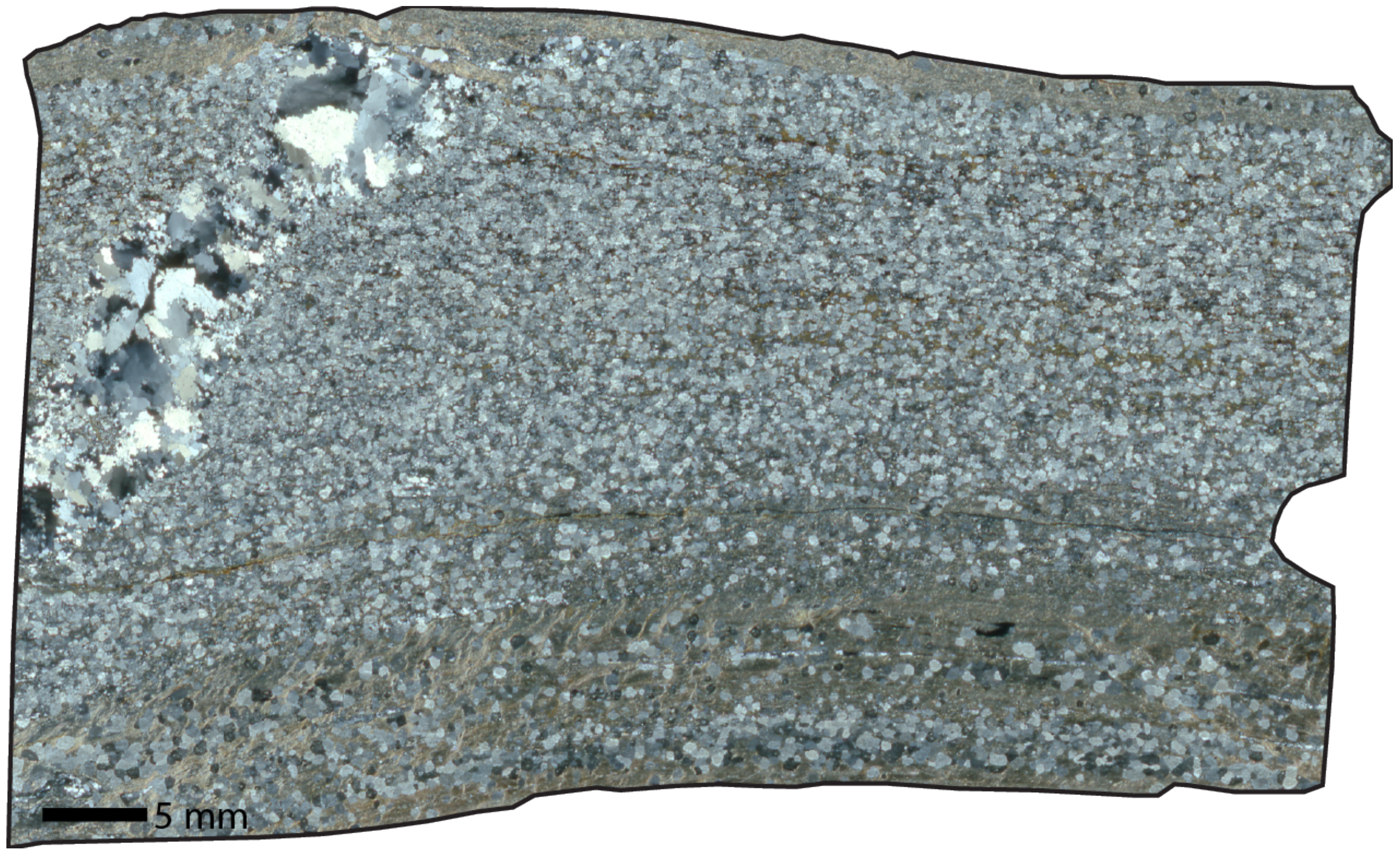


Rootless fold noses = strong blocks
Fold Limbs (F_2) = weak matrix

Condit et al., 2025 Geology

Rootless Fold Nose/Block





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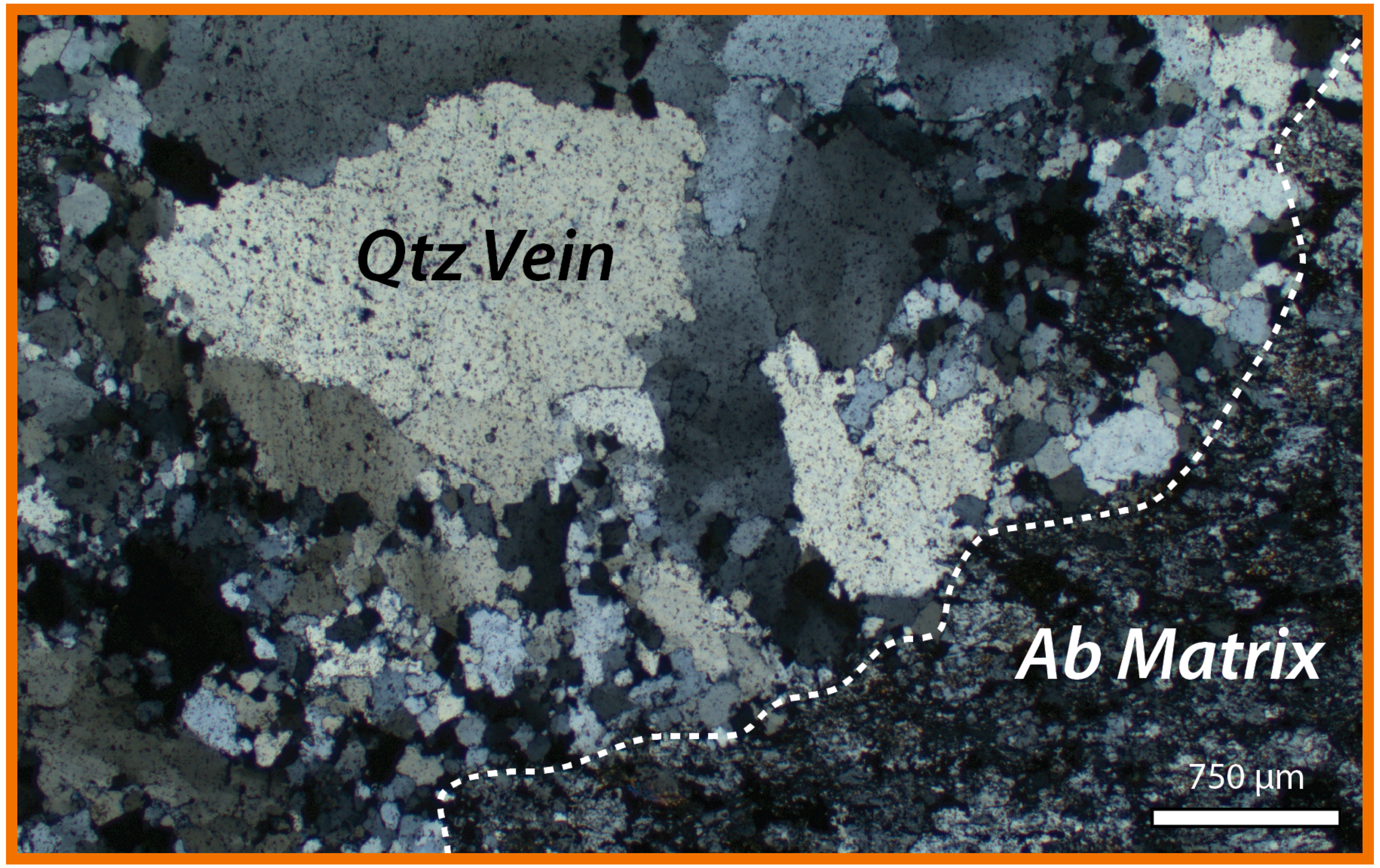

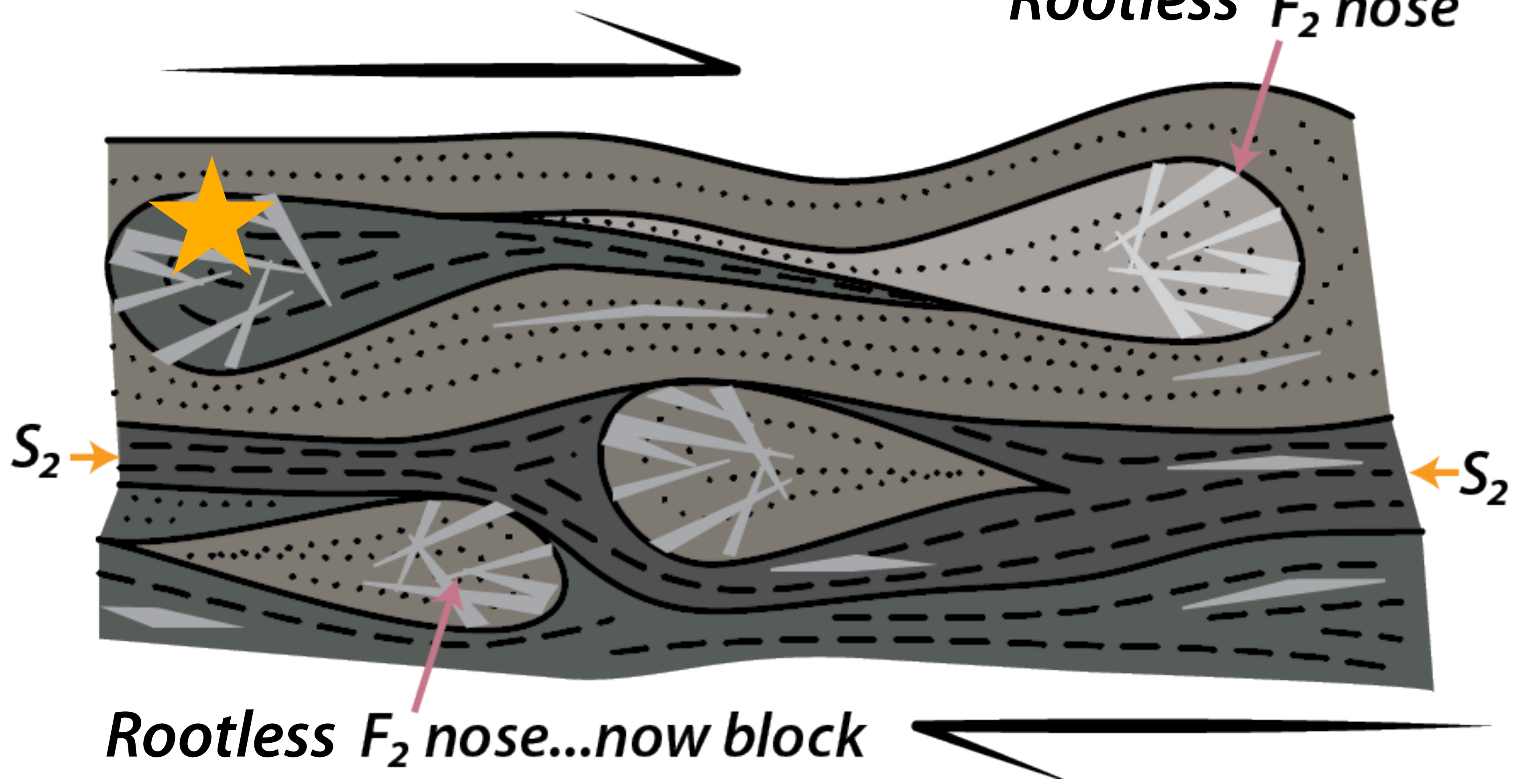

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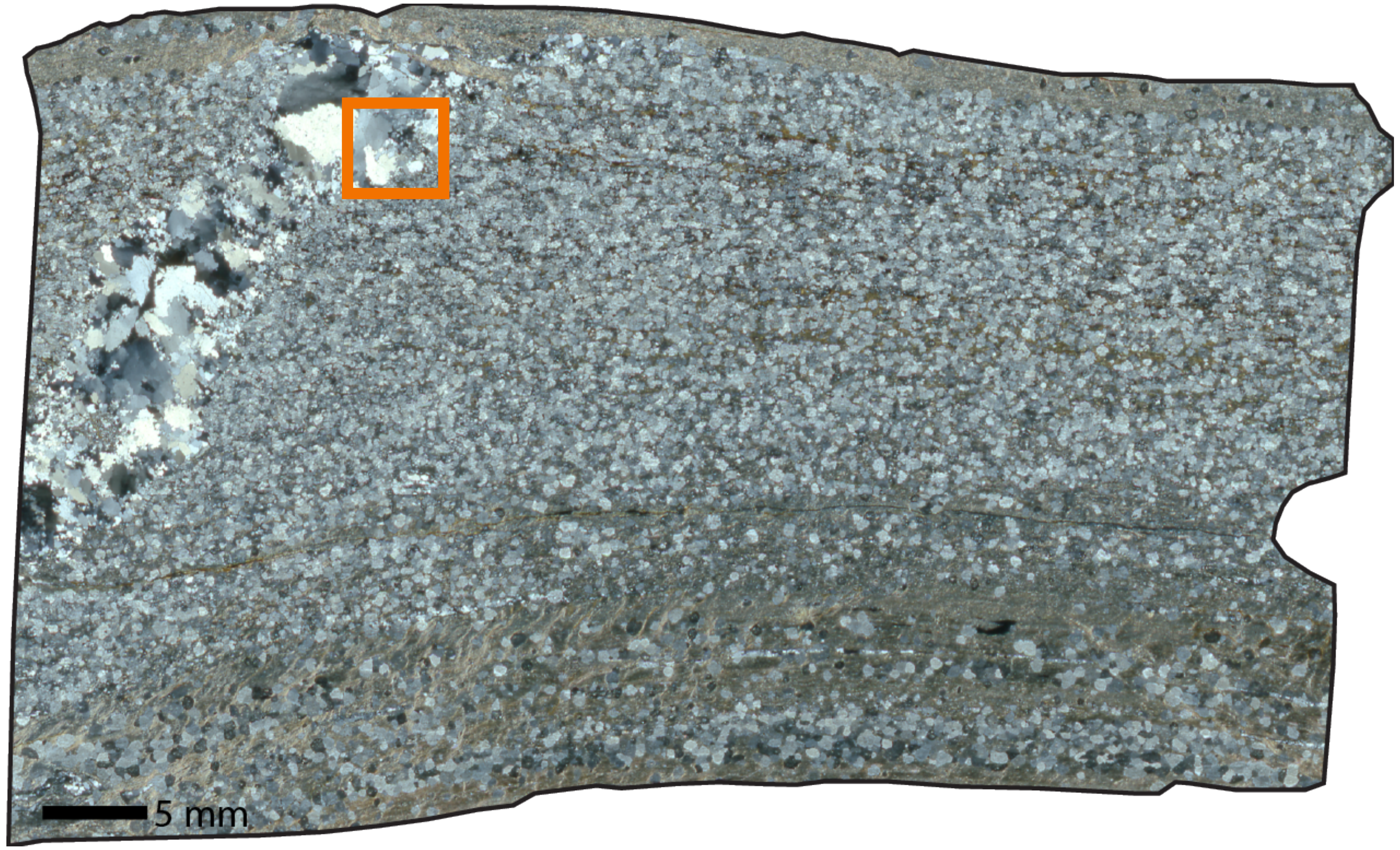
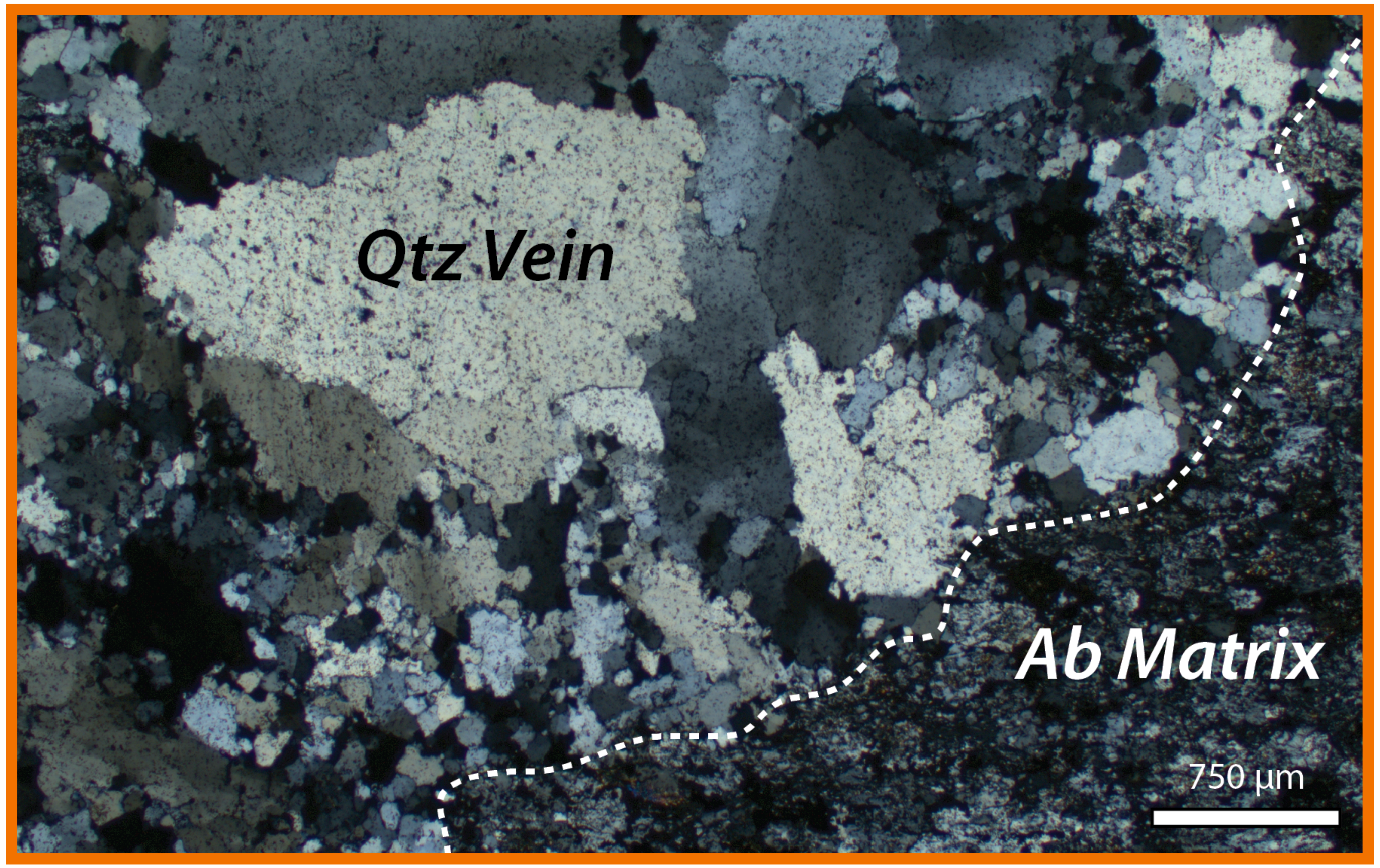


Veins - Cross-cut early fabric (S_1); deform by BLG and incipient SGR; temps of 300-350°C



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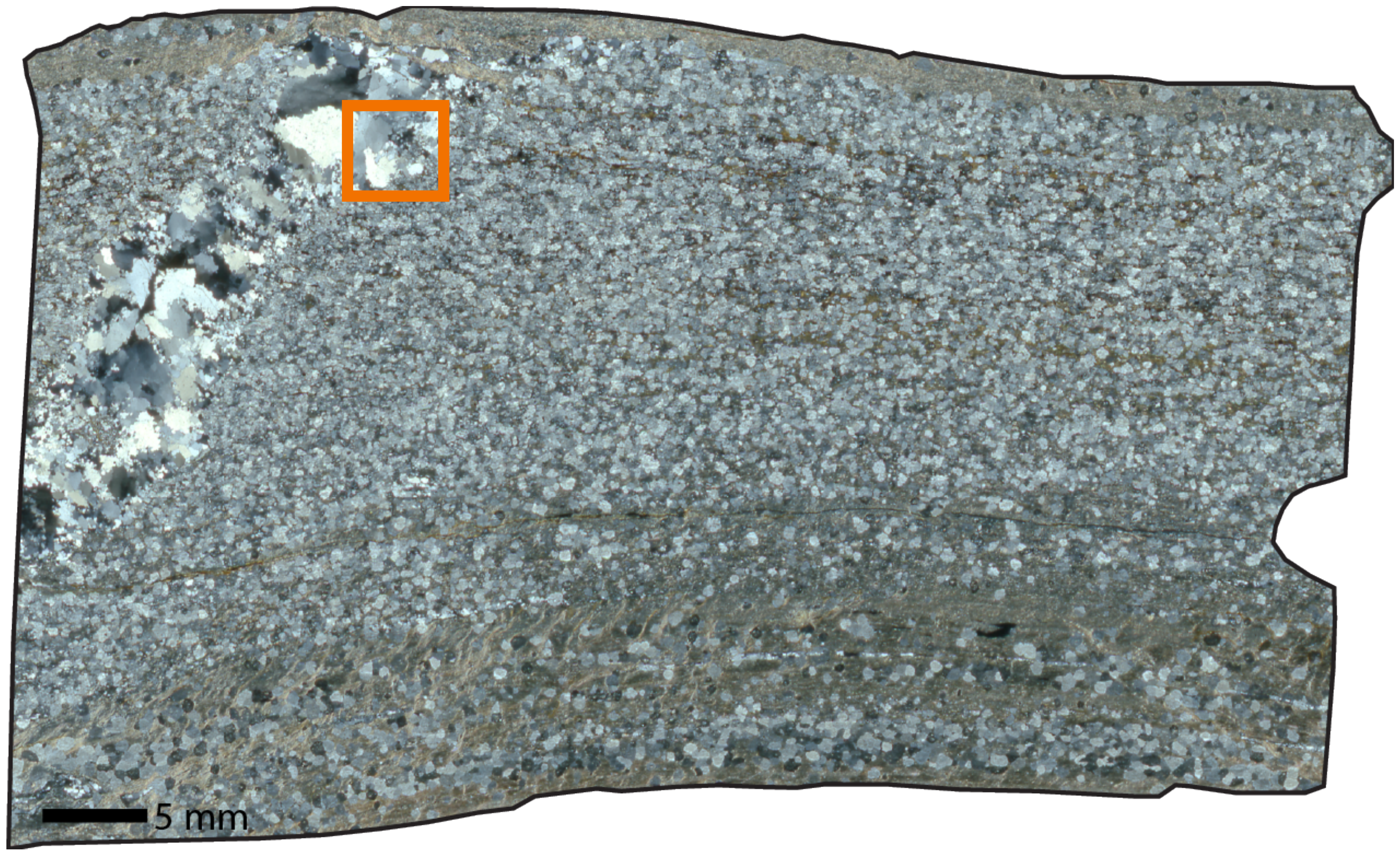

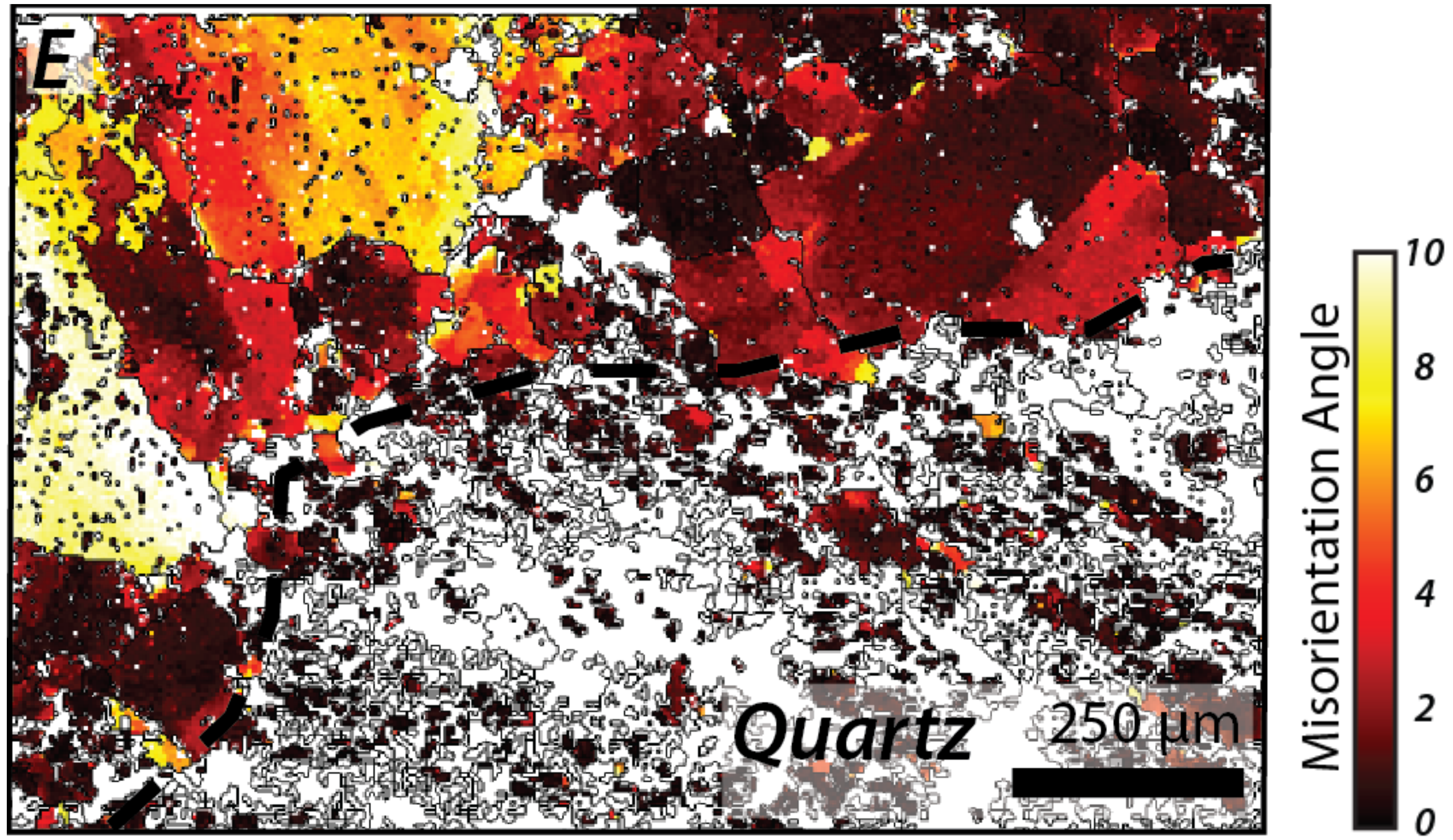

Quartz Mis2Mean EBSD map of vein

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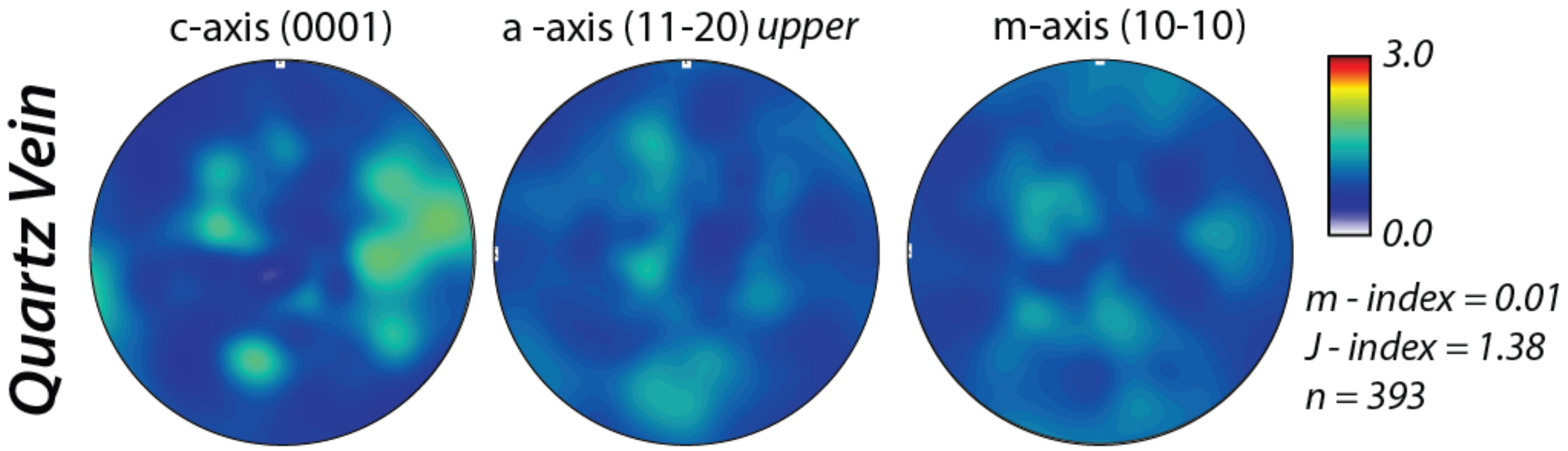

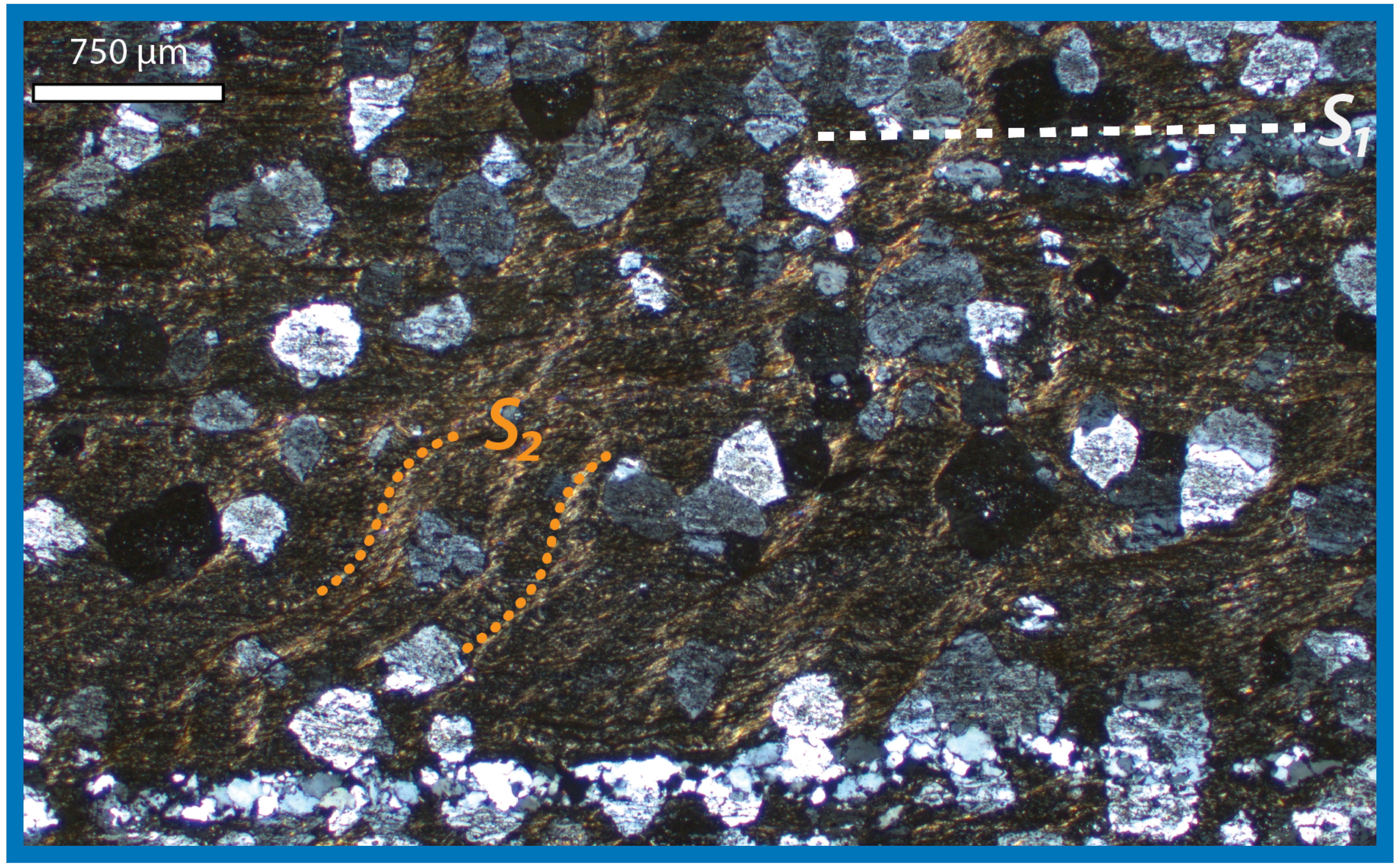

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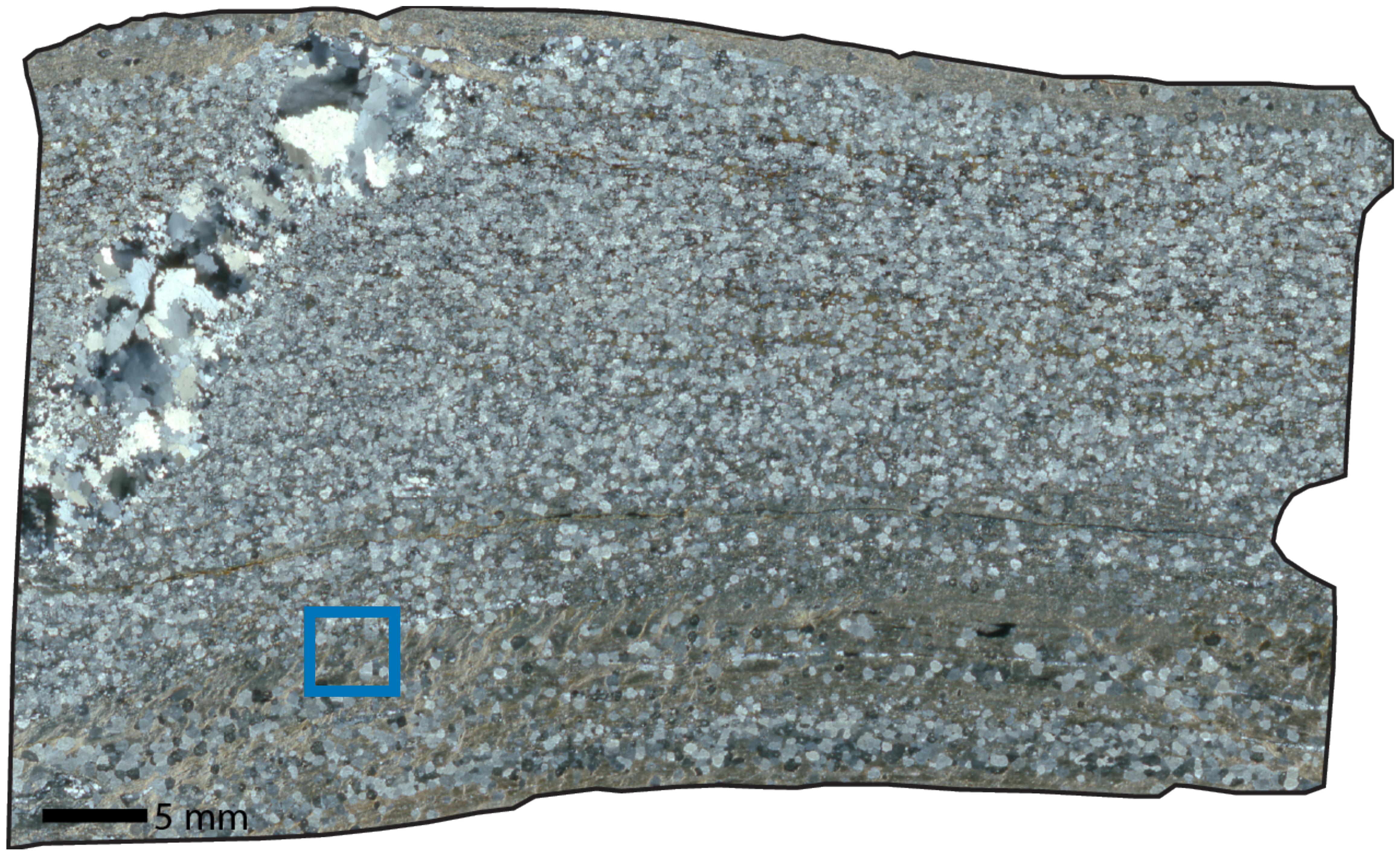

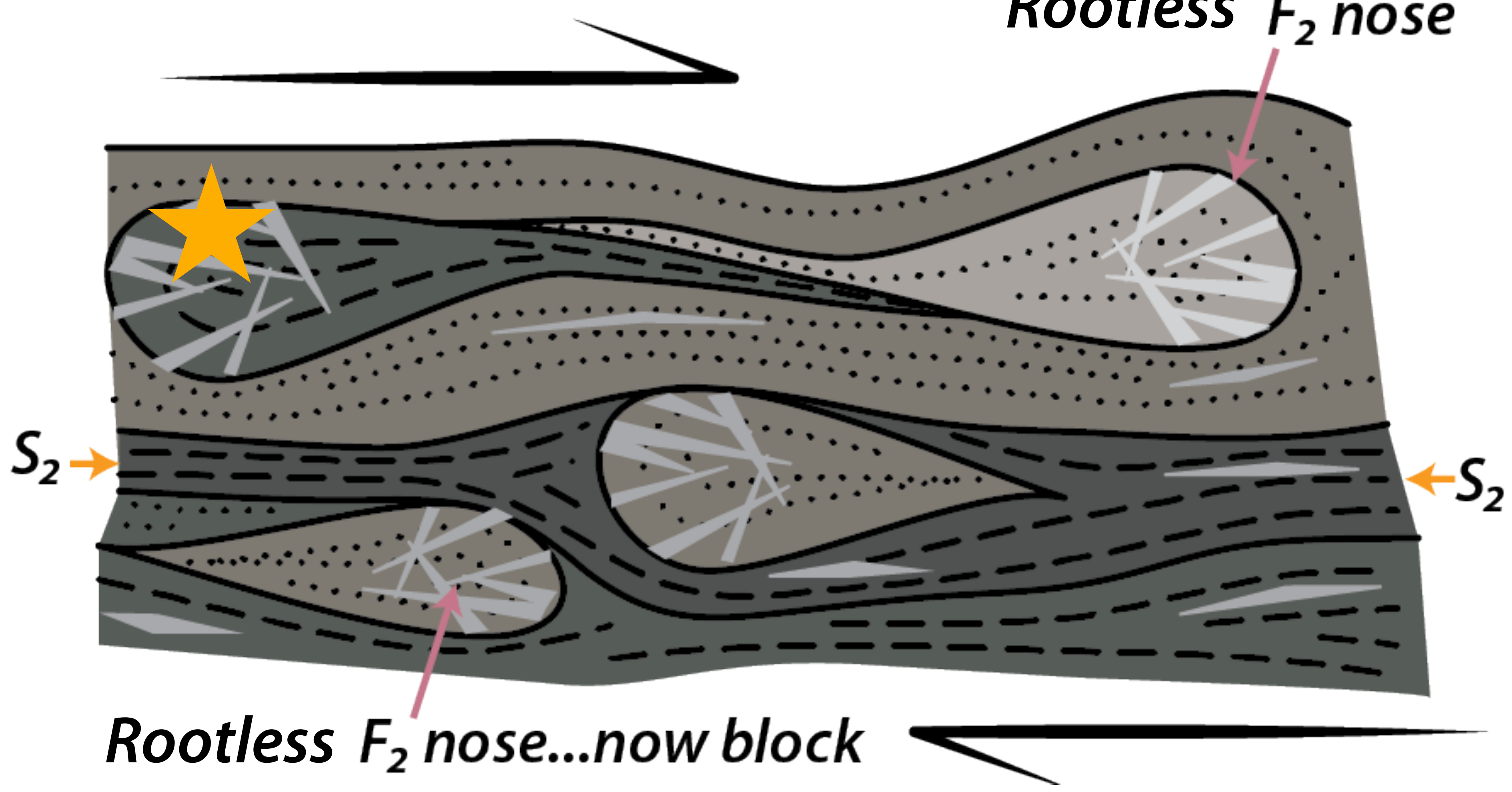

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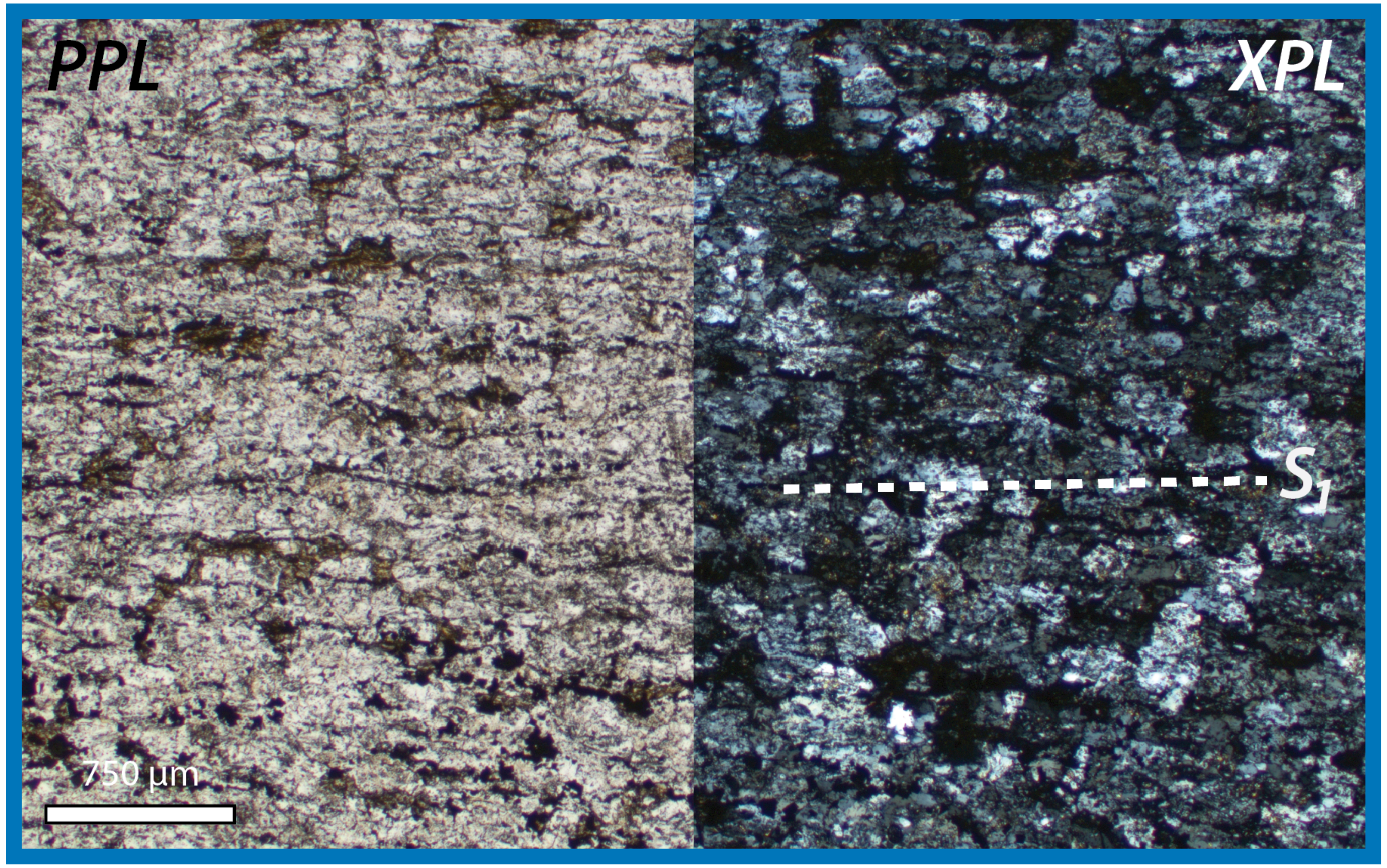

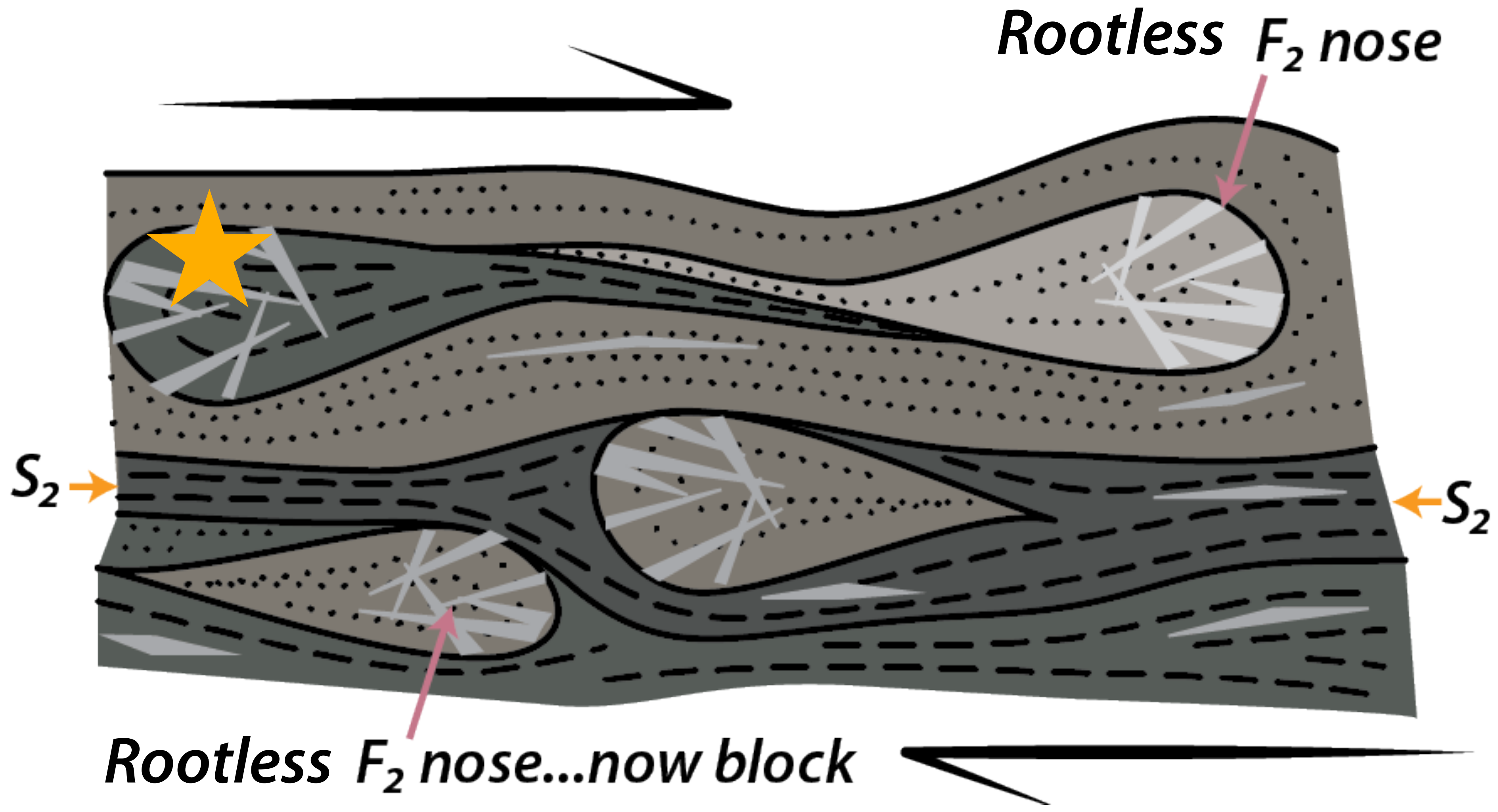

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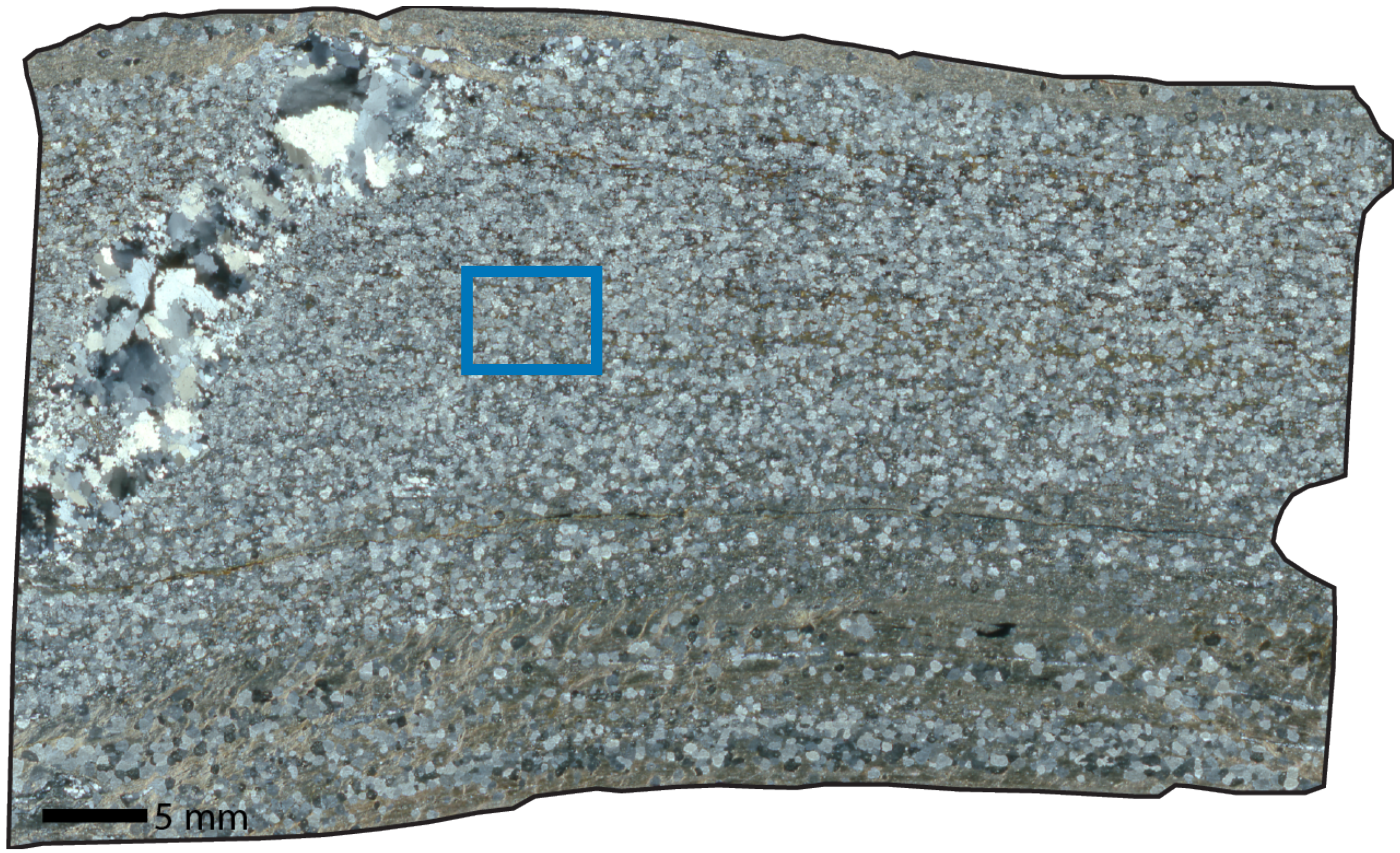

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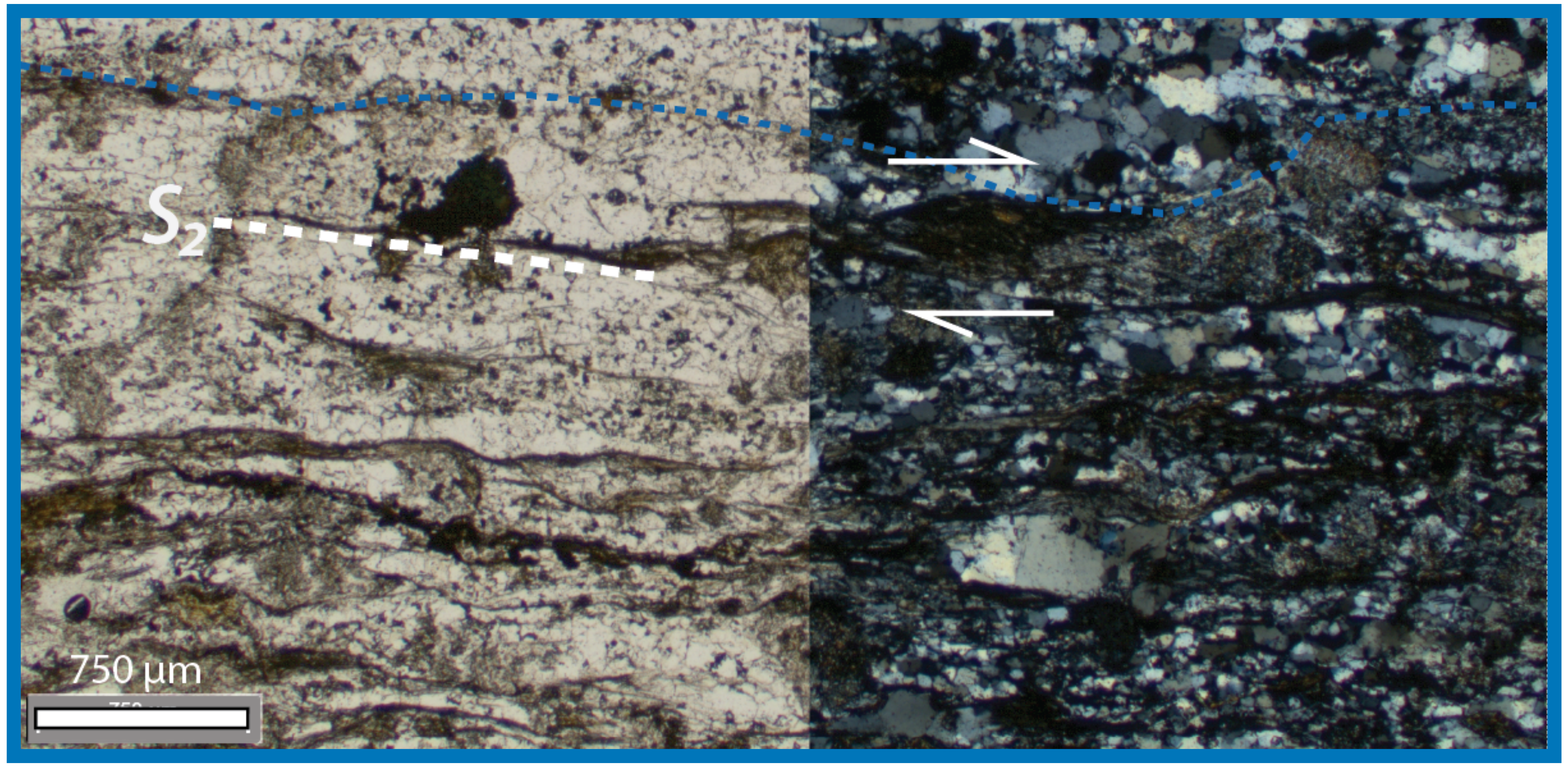
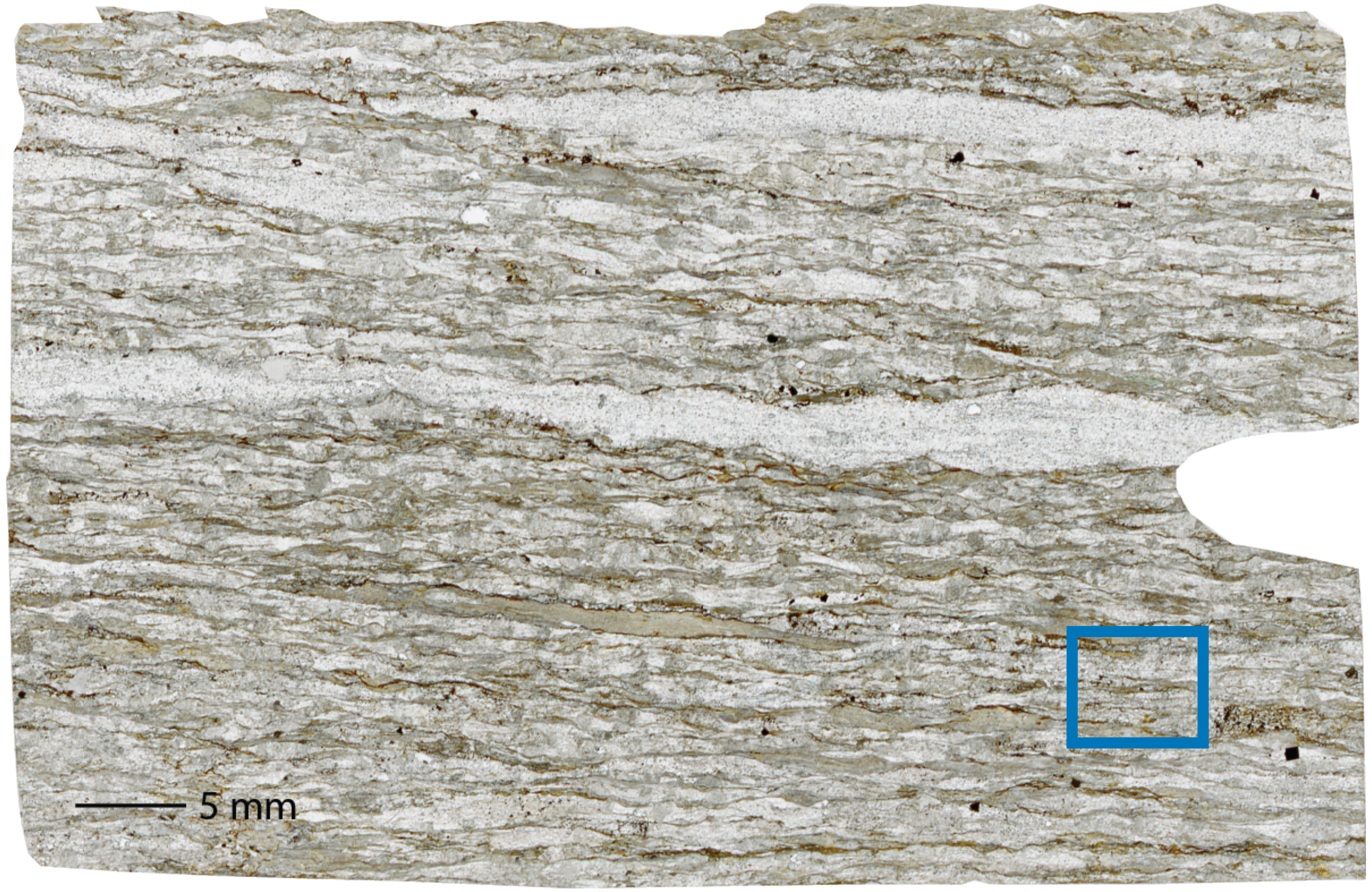
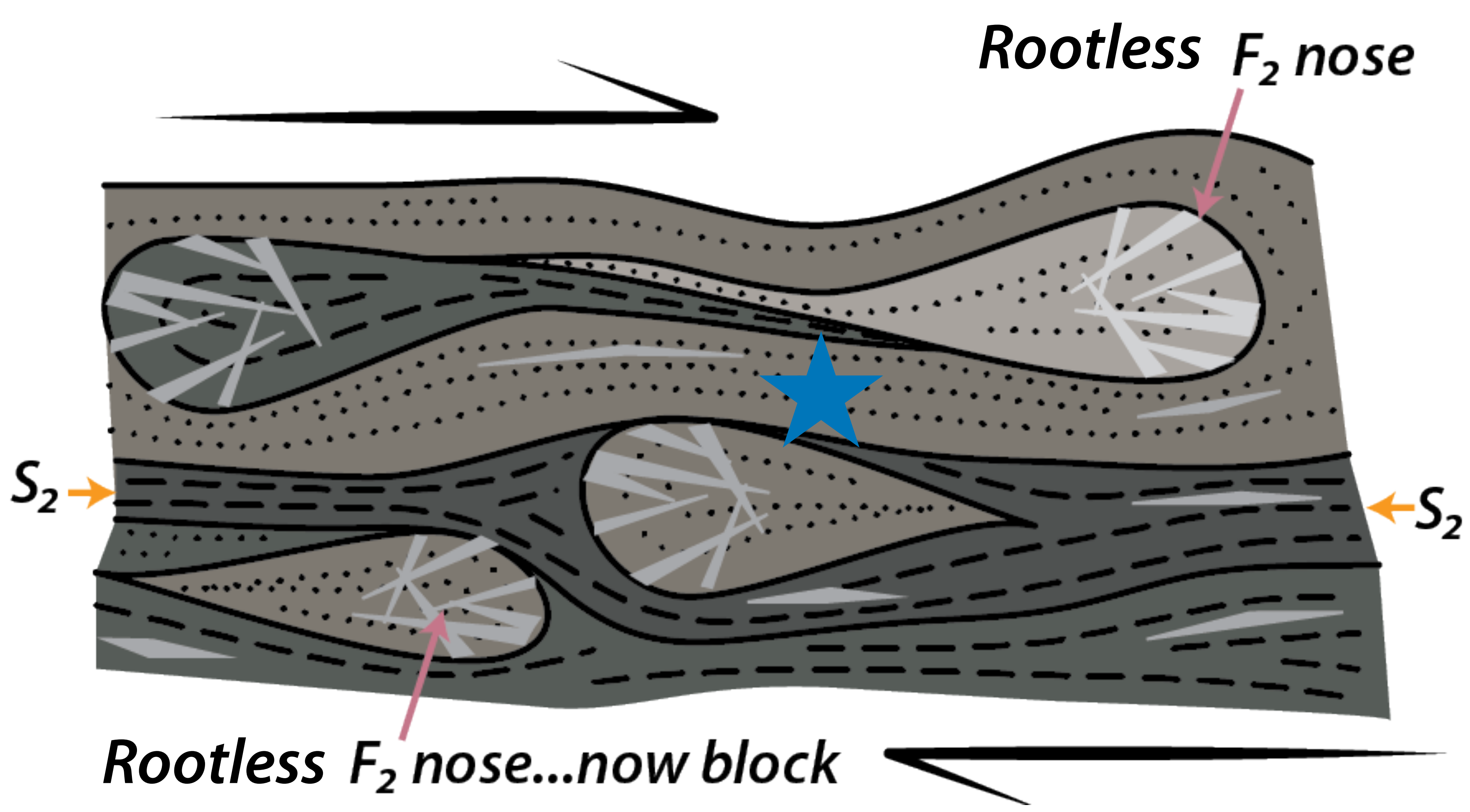


Fold Limb/Matrix





Matrix fabric - pressure-solution creep microstructures - grain size ~15 μm in both Ab and Qtz - Fluid mediated process

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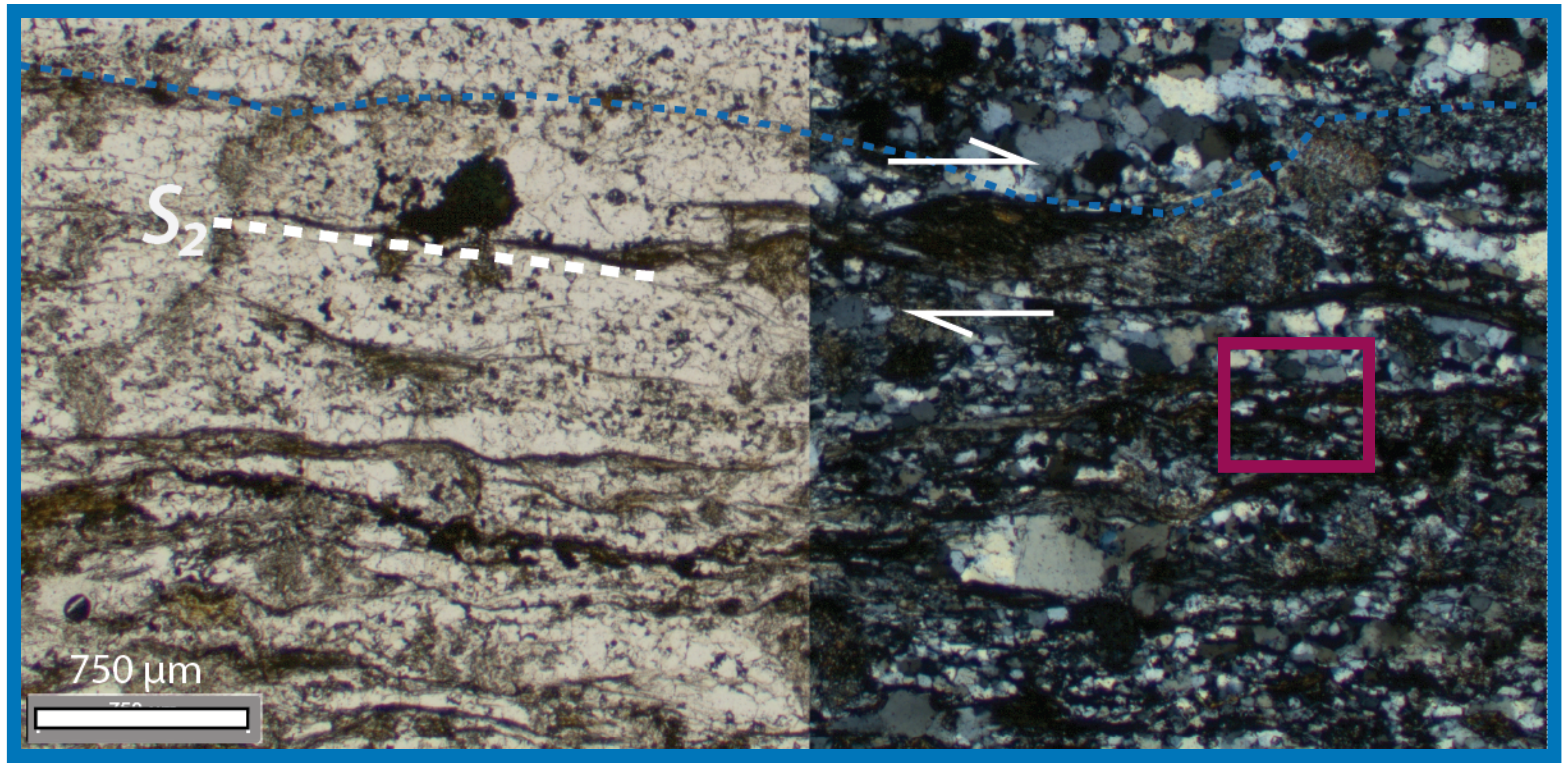
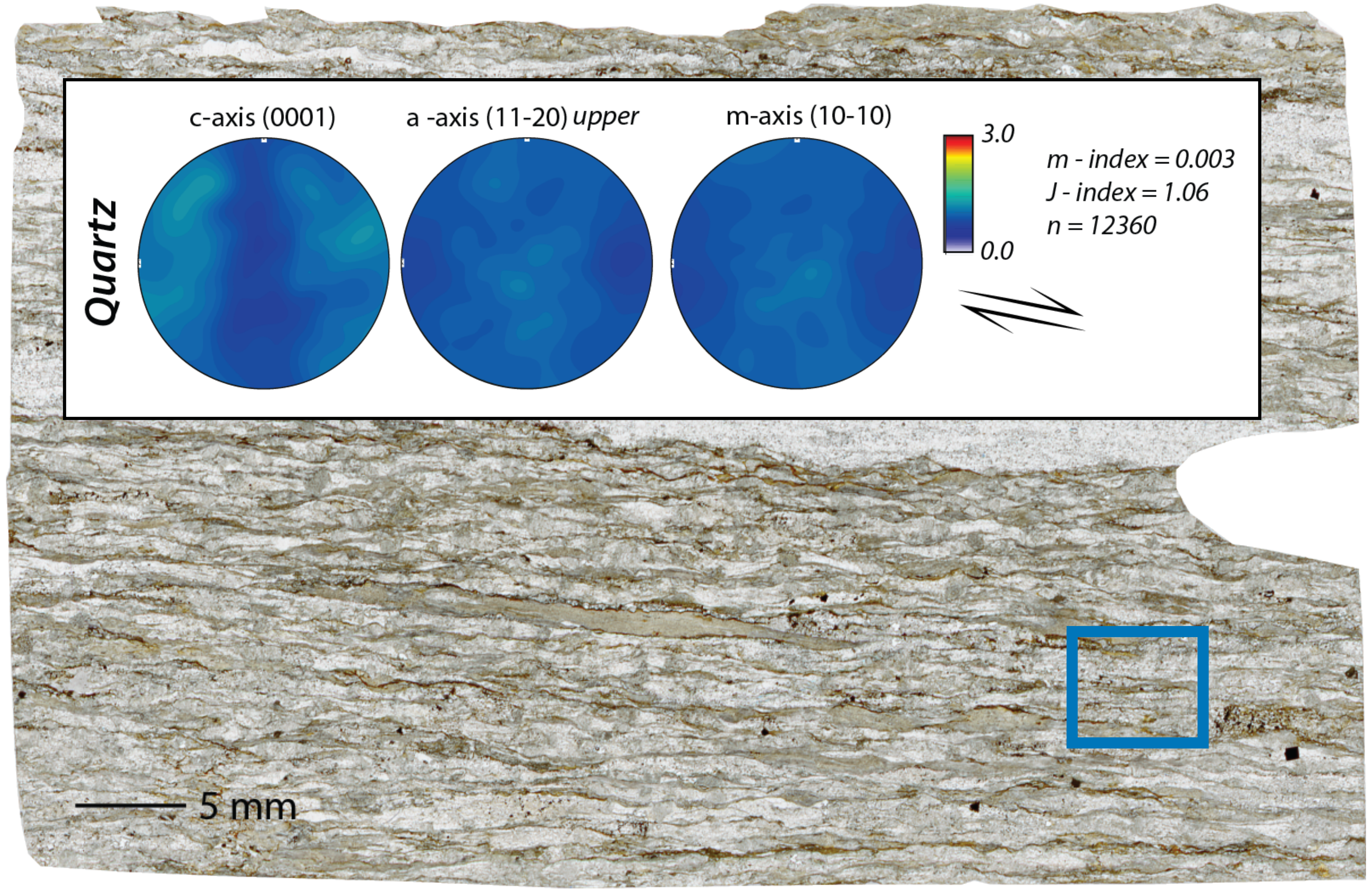
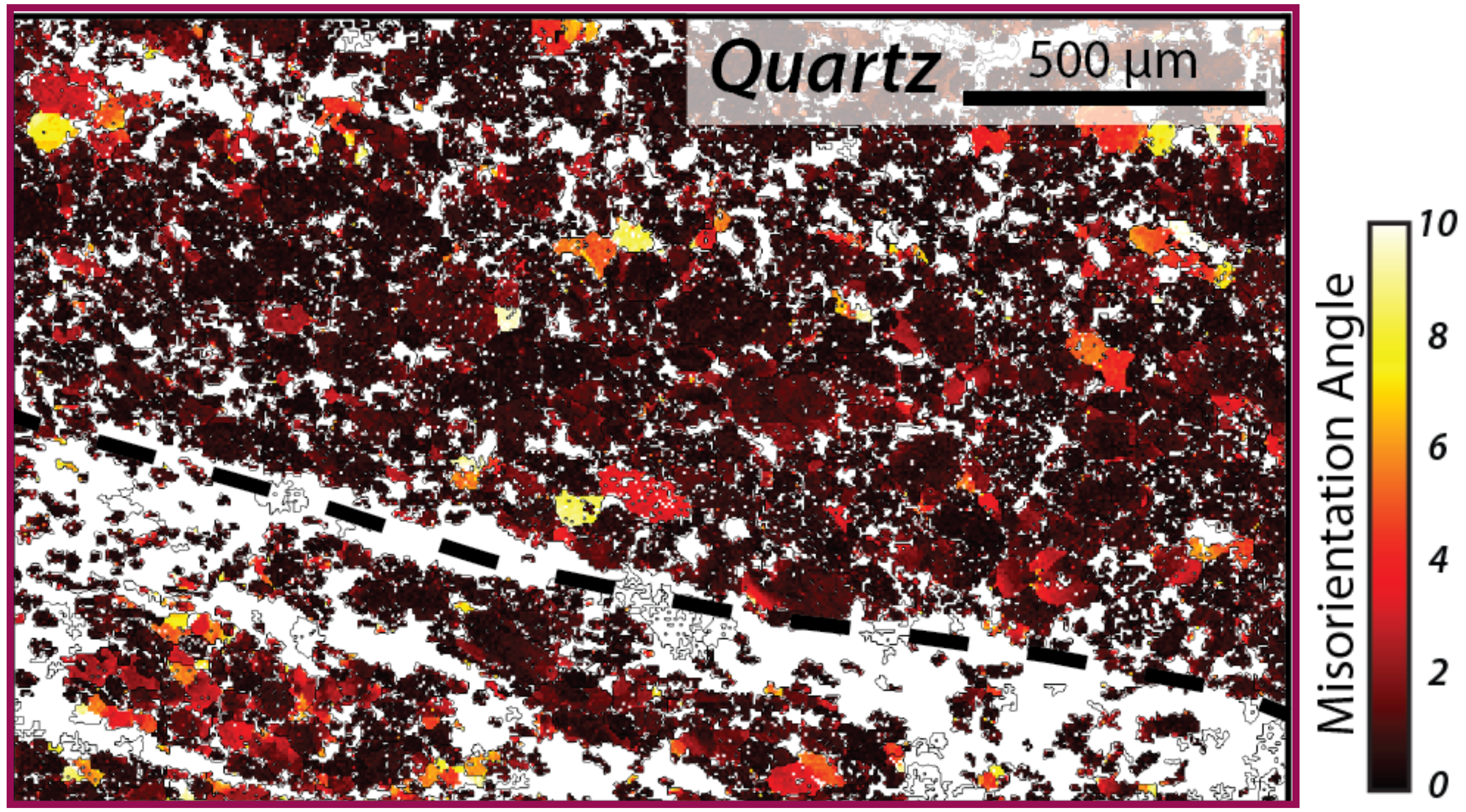
Condit et al., 2025 Geology

Fold Limb/Matrix







Quartz Mis2Mean EBSD map of matrix fabric

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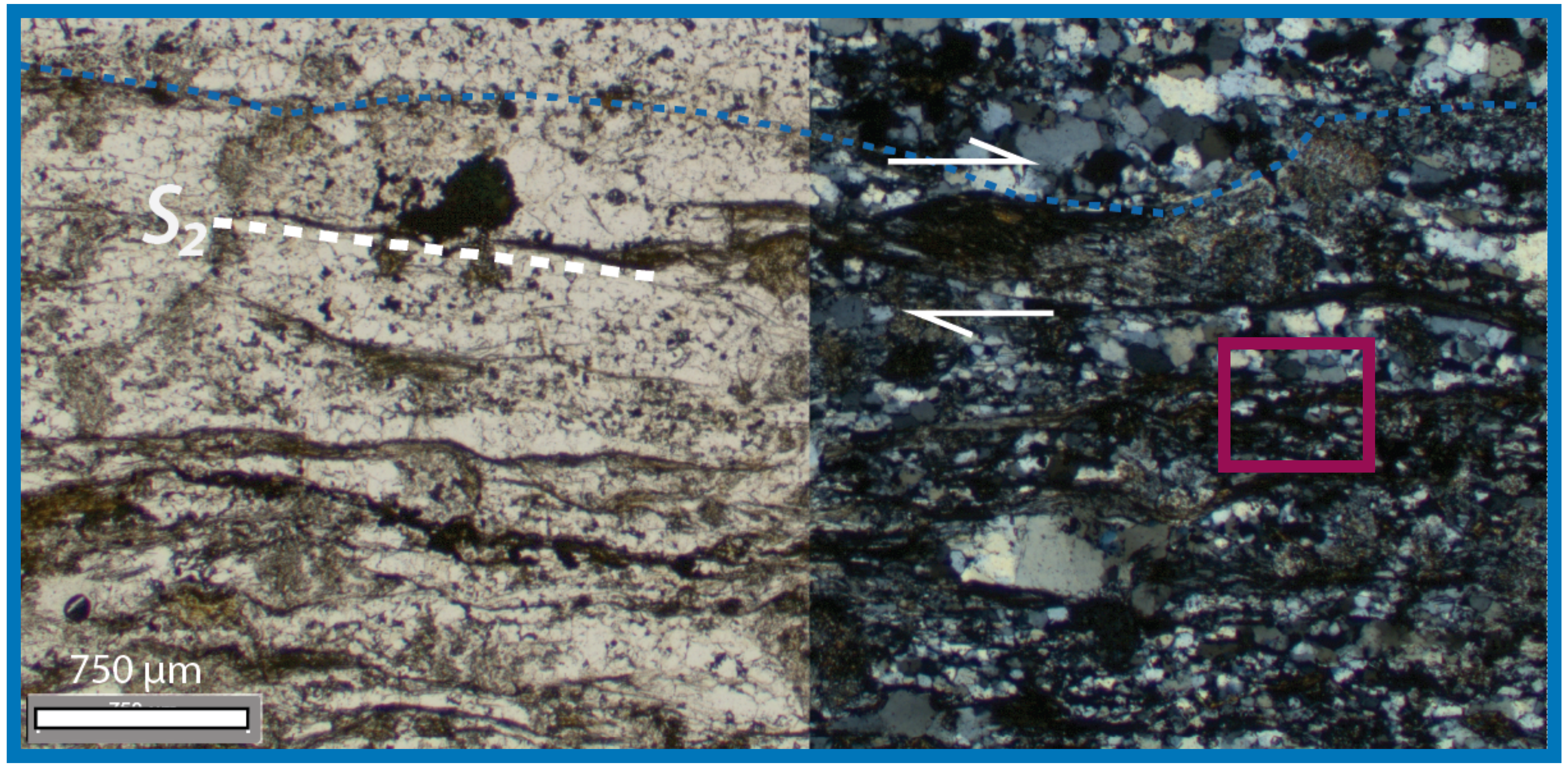

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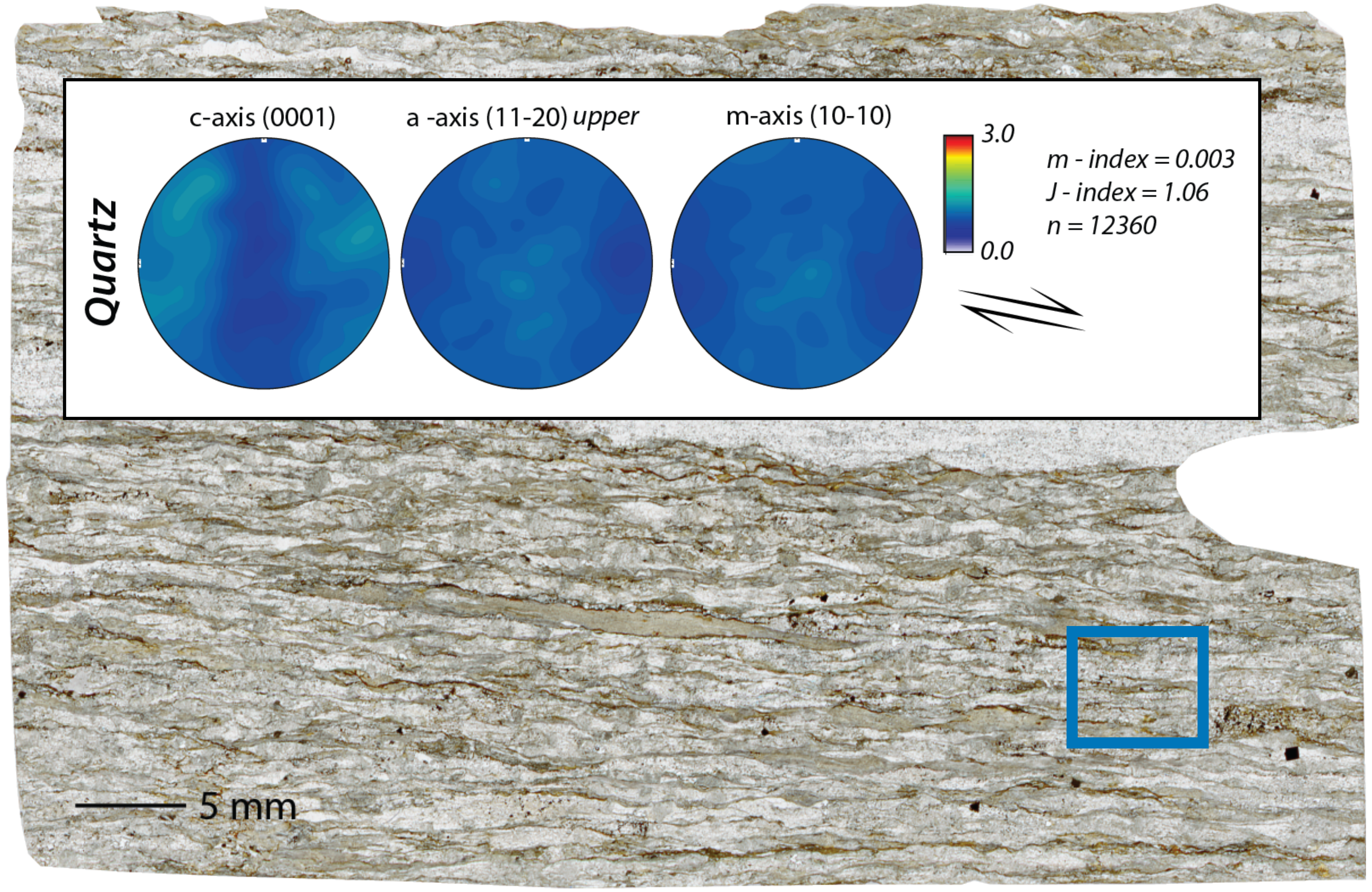

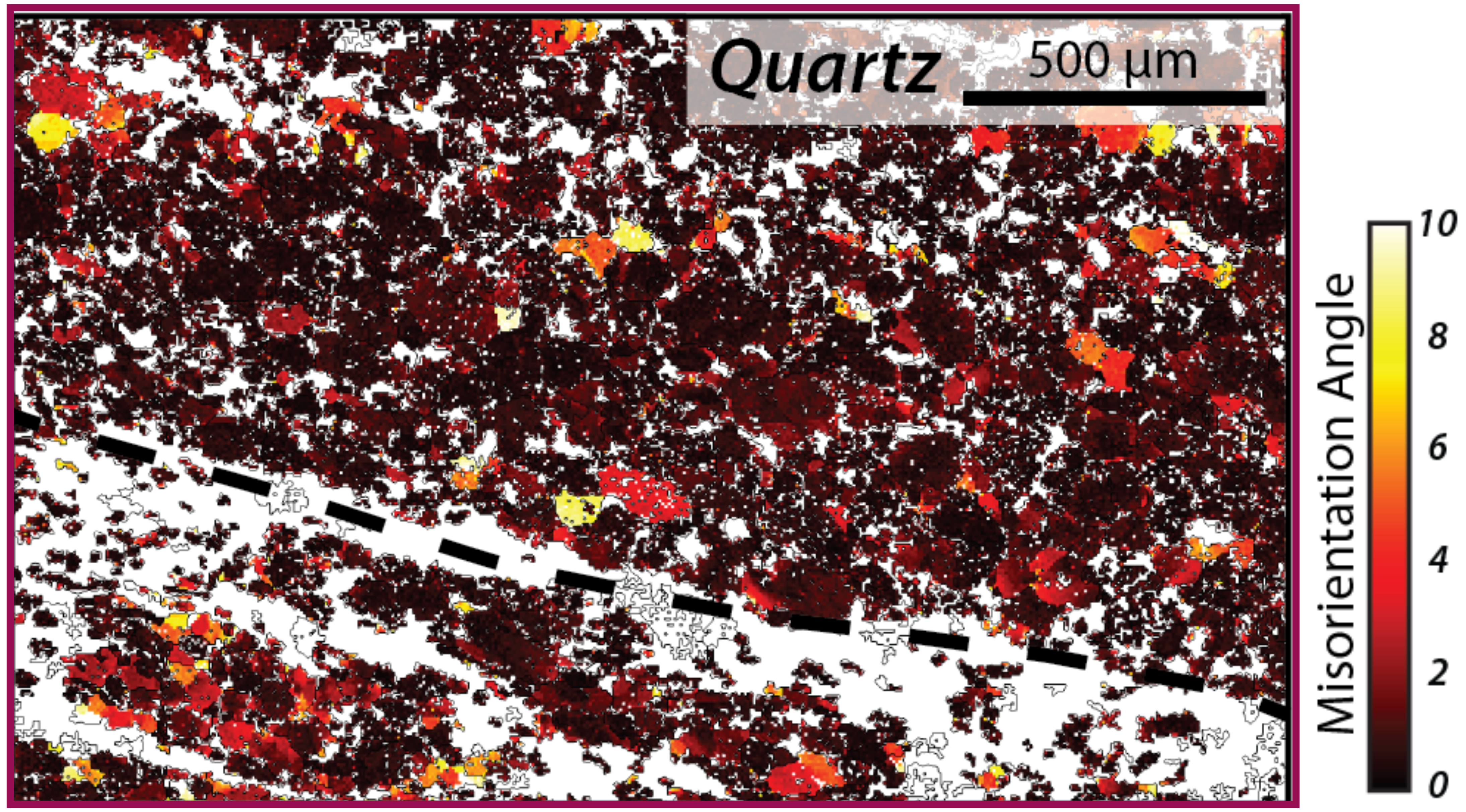

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What slip behaviors do these rocks host?

Condit et al., 2025 Geology

Thin film model for pressure solution creep of quartz

Grain size dependent

Stress exponent = 1

Rutter, 1976

$$\dot{\varepsilon} = \frac{AV_m c D_{gb} w \sigma \rho_f}{RTd^3 \rho_s}$$

Key area for improved understanding

Rheology of the metasediments

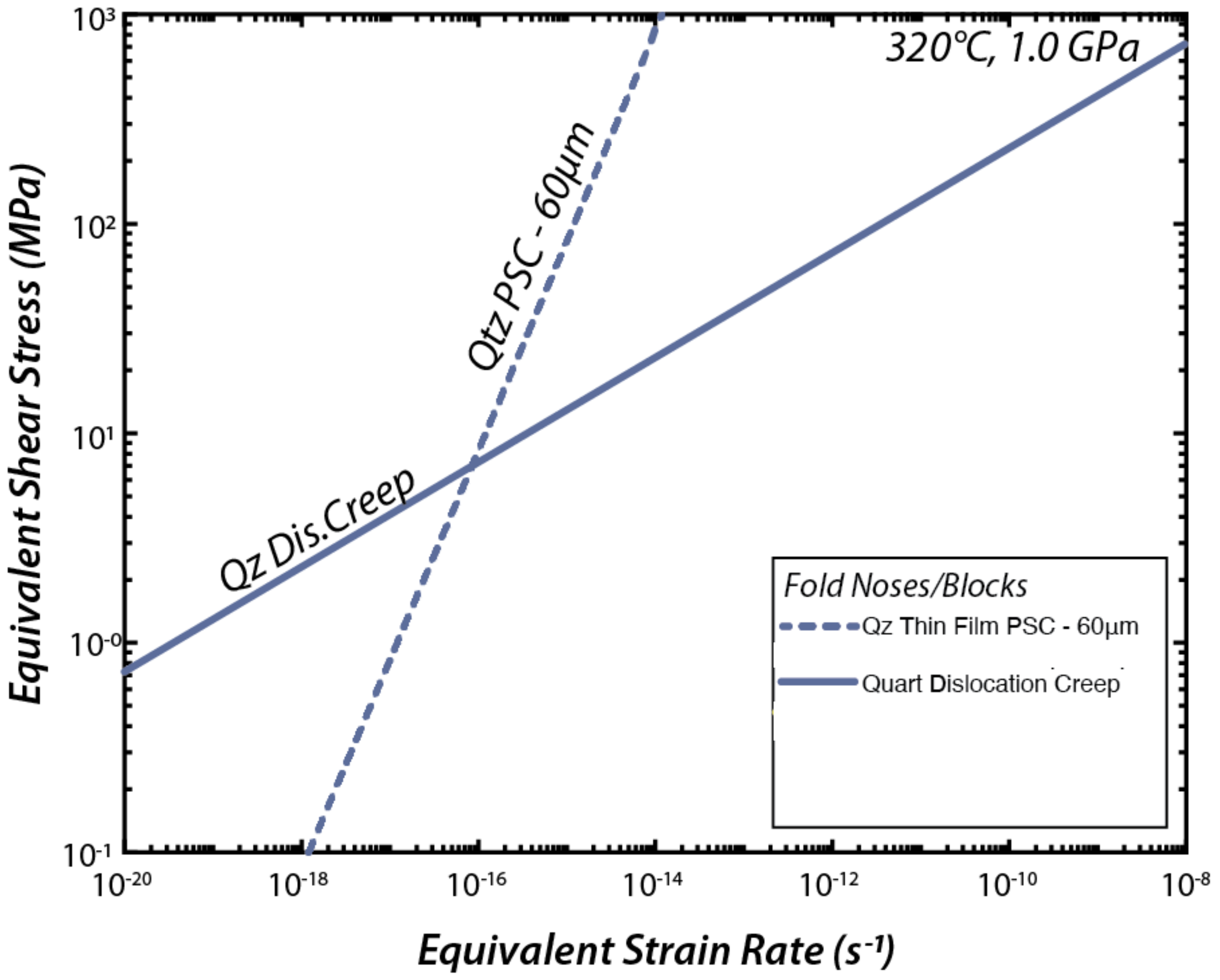
Dislocation creep of quartz

Grain size independent

Stress exponent = 4

$$\dot{\varepsilon} = A f_{H_2O} \sigma^4 \exp\left(-Q/RT\right)$$

Hirth et al., 2001; Tokle et al., 2019



Condit et al., 2025 Geology

Thin film model for pressure solution creep of quartz

Grain size dependent
Stress exponent = 1
Rutter, 1976

$$\dot{\varepsilon} = \frac{AV_m c D_{gb} w \sigma \rho_f}{RTd^3 \rho_s}$$

Key area for improved understanding

Dislocation creep of quartz

Grain size independent
Stress exponent = 4
Hirth et al., 2001; Tokle et al., 2019

$$\dot{\varepsilon} = A f_{H_2O} \sigma^4 \exp\left(-Q/RT\right)$$

Diffusion Creep of albite

Grain size dependent
Stress exponent = 1
Offerhaus, 2001

$$\dot{\varepsilon} = A\sigma d^{-3} \exp\left(\frac{-Q}{RT}\right)$$

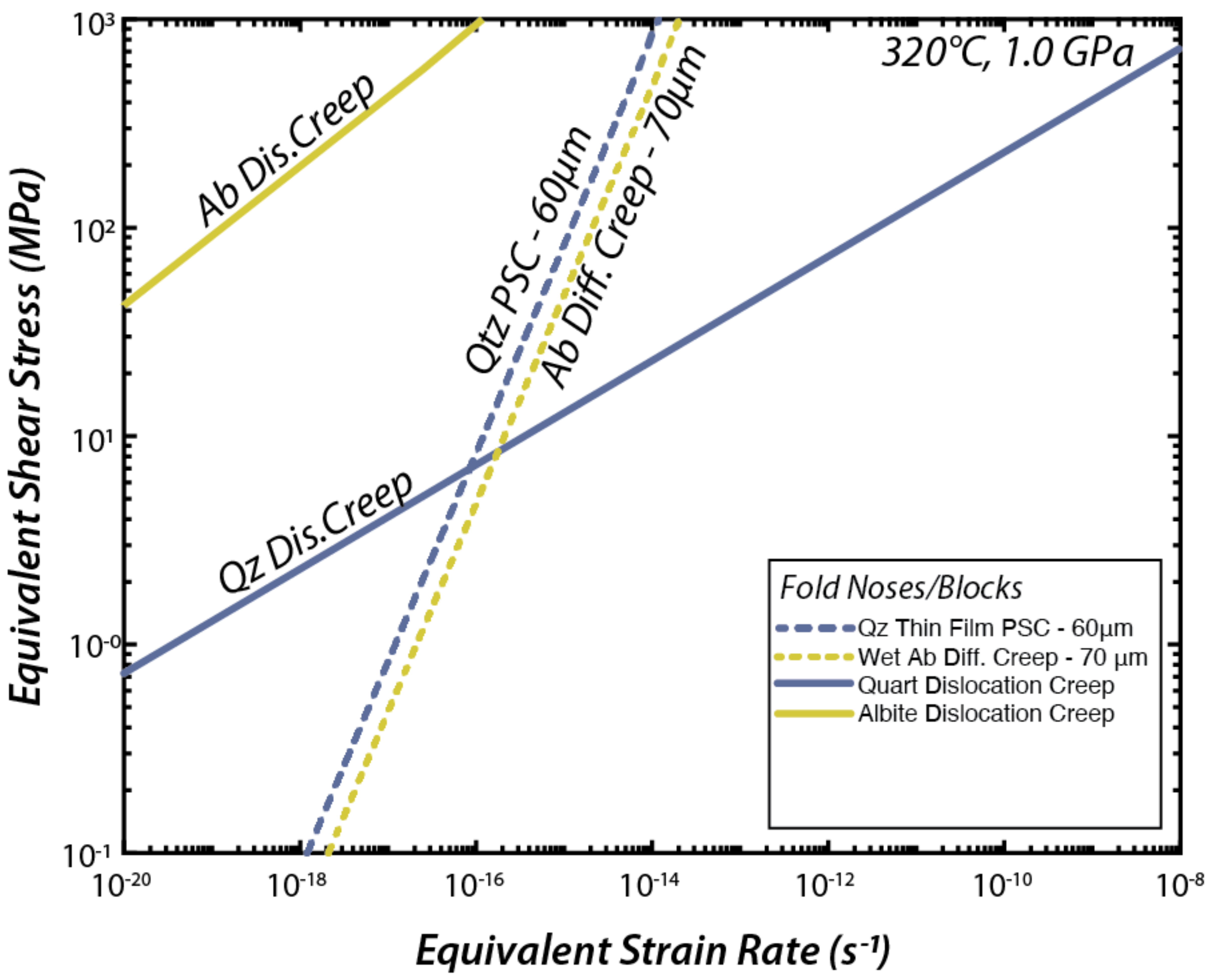
Key area for improved understanding

Dislocation Creep of feldspar

Grain size independent
Stress exponent = 3
Rybacki & Dresen, 2000

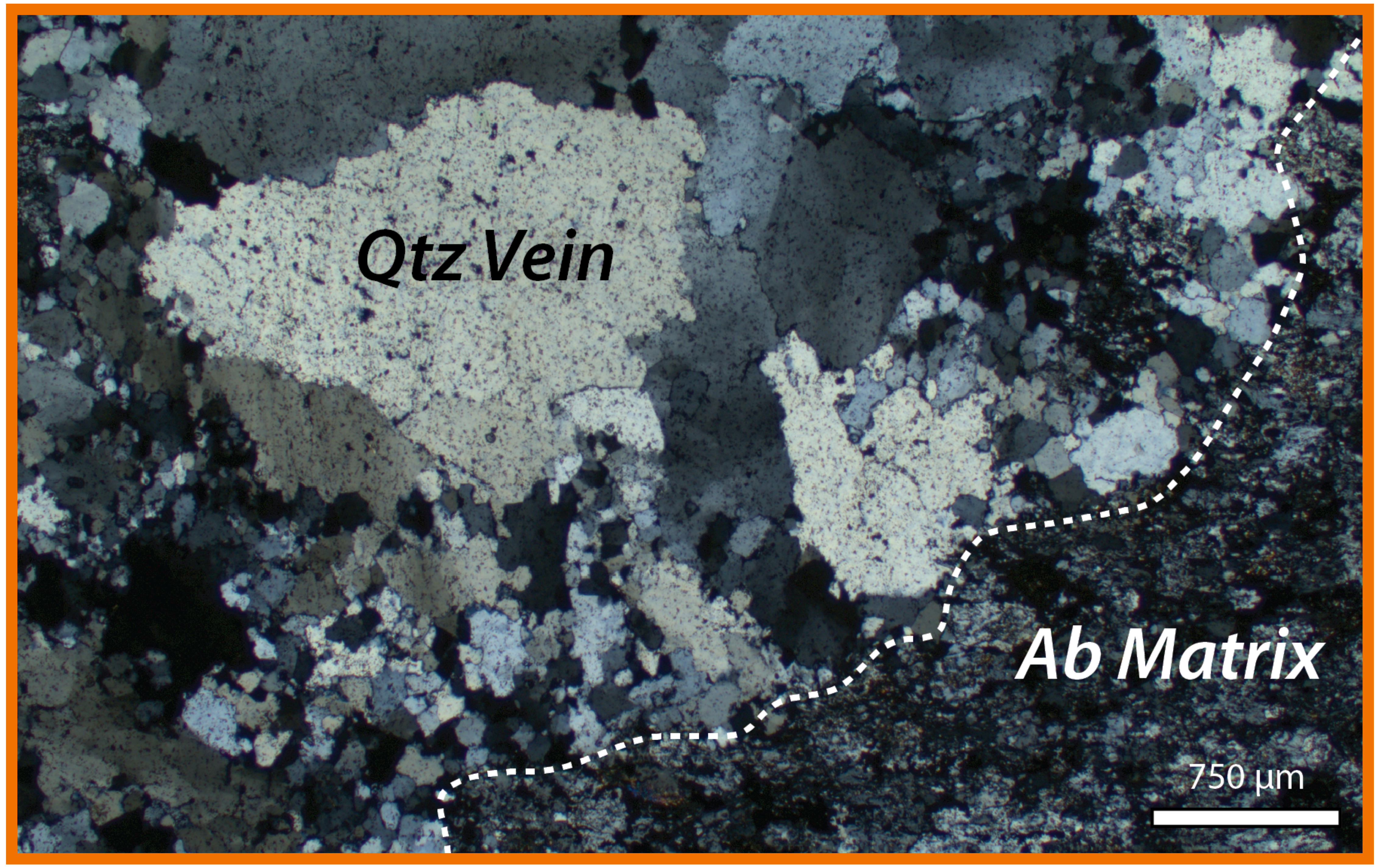
$$\dot{\varepsilon} = A\sigma^3 \exp\left(-Q/RT\right)$$

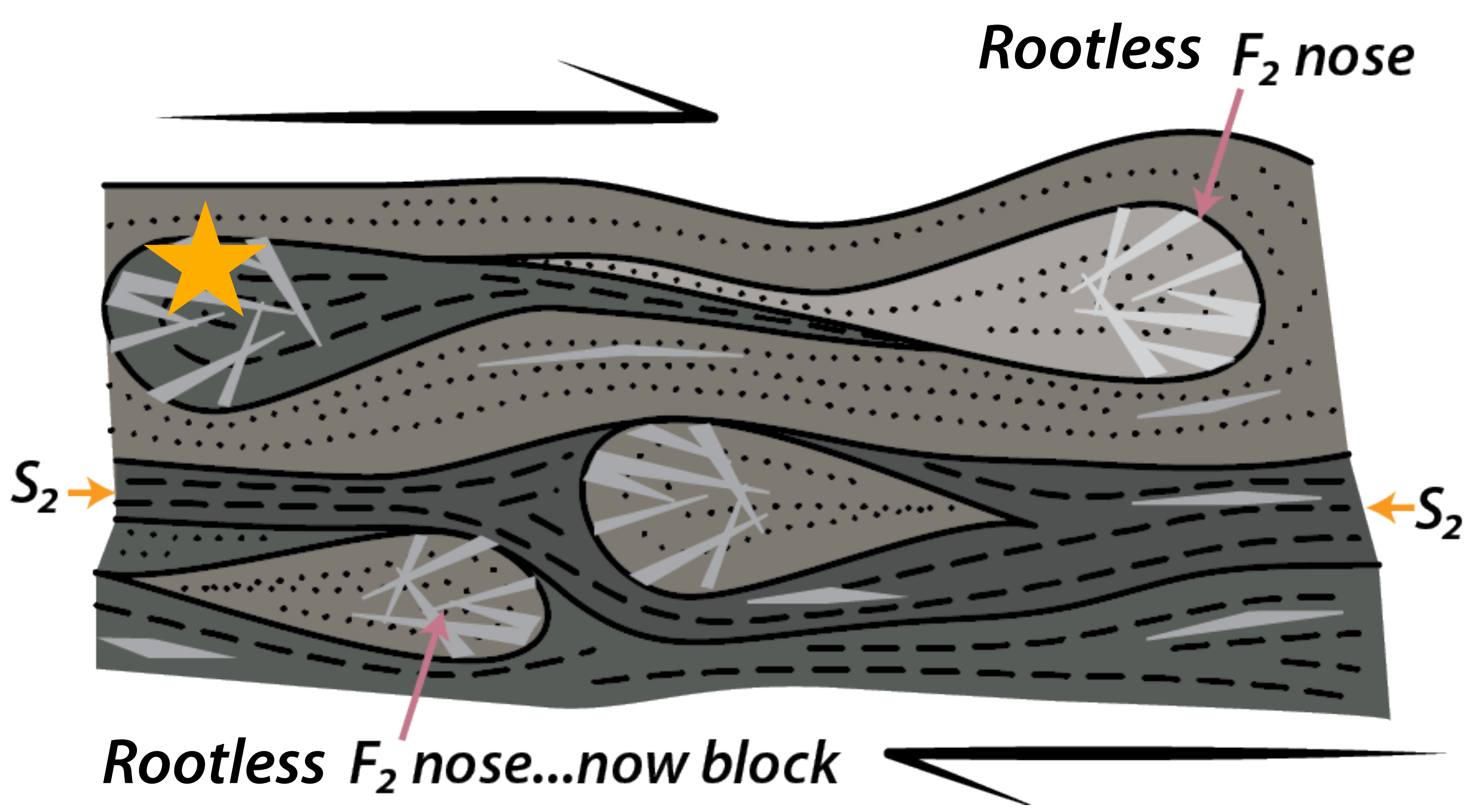
Rheology of the metasediments

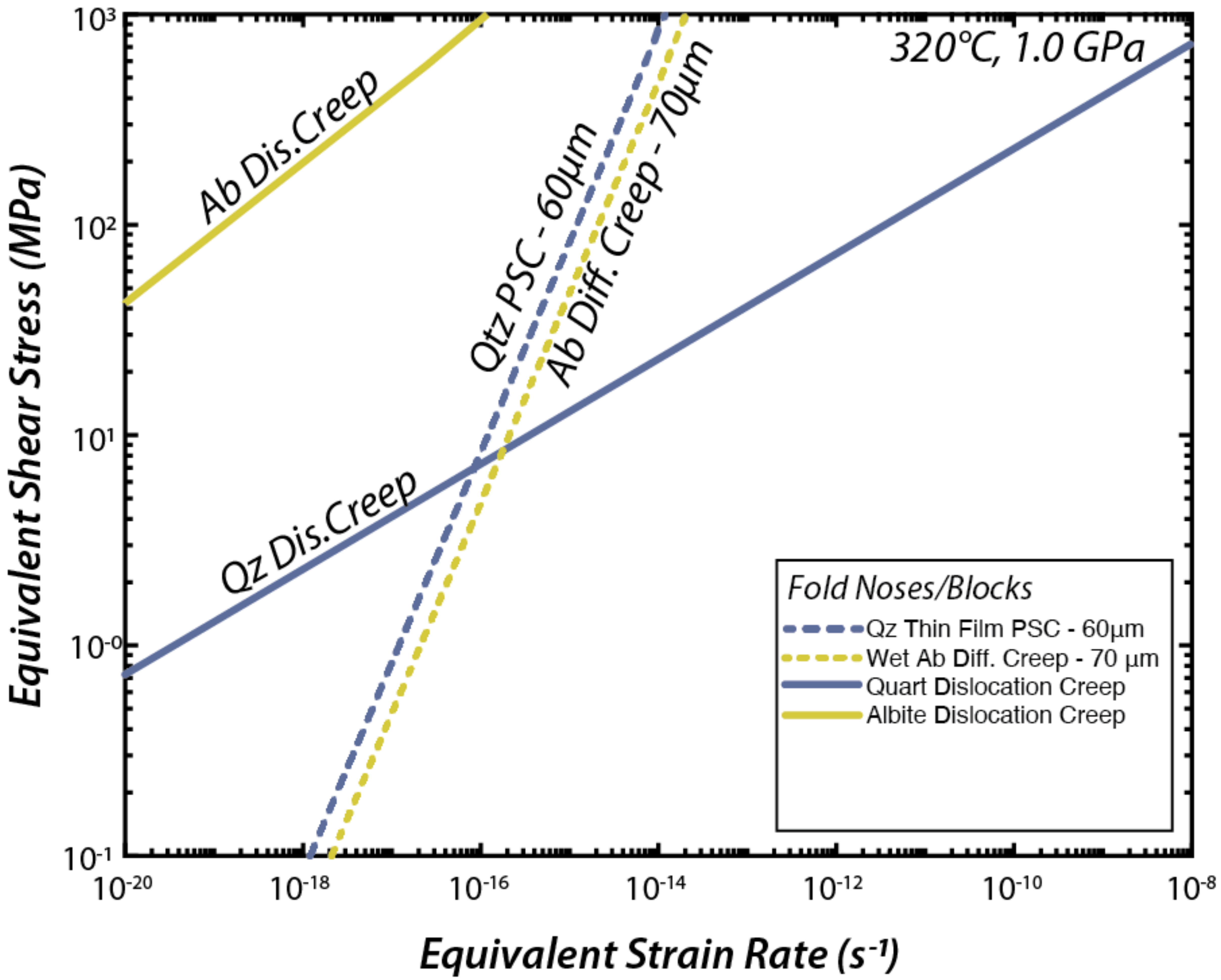


Condit et al., 2025 Geology

Rheology of the metasediments







Condit et al., 2025 Geology

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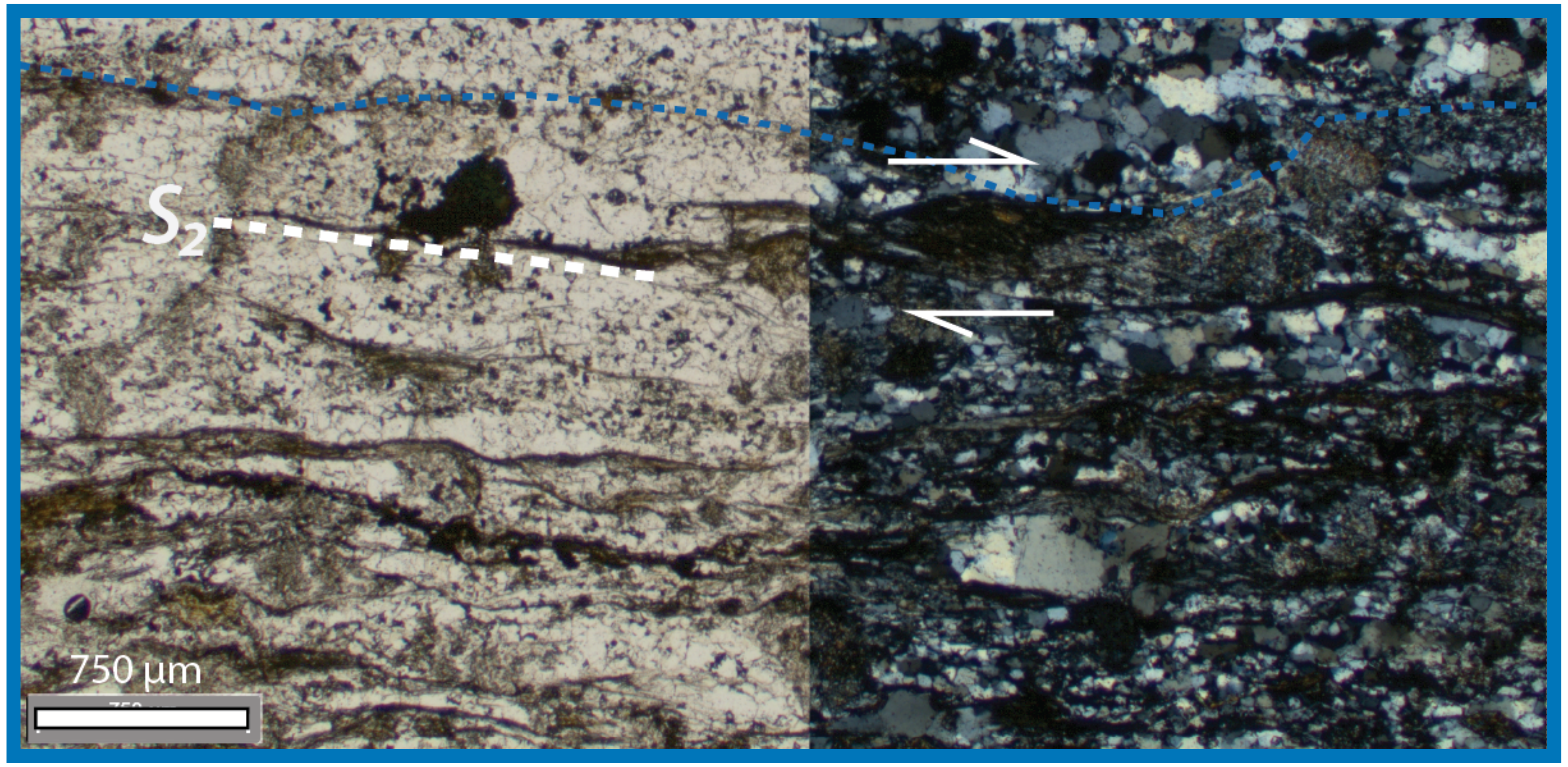

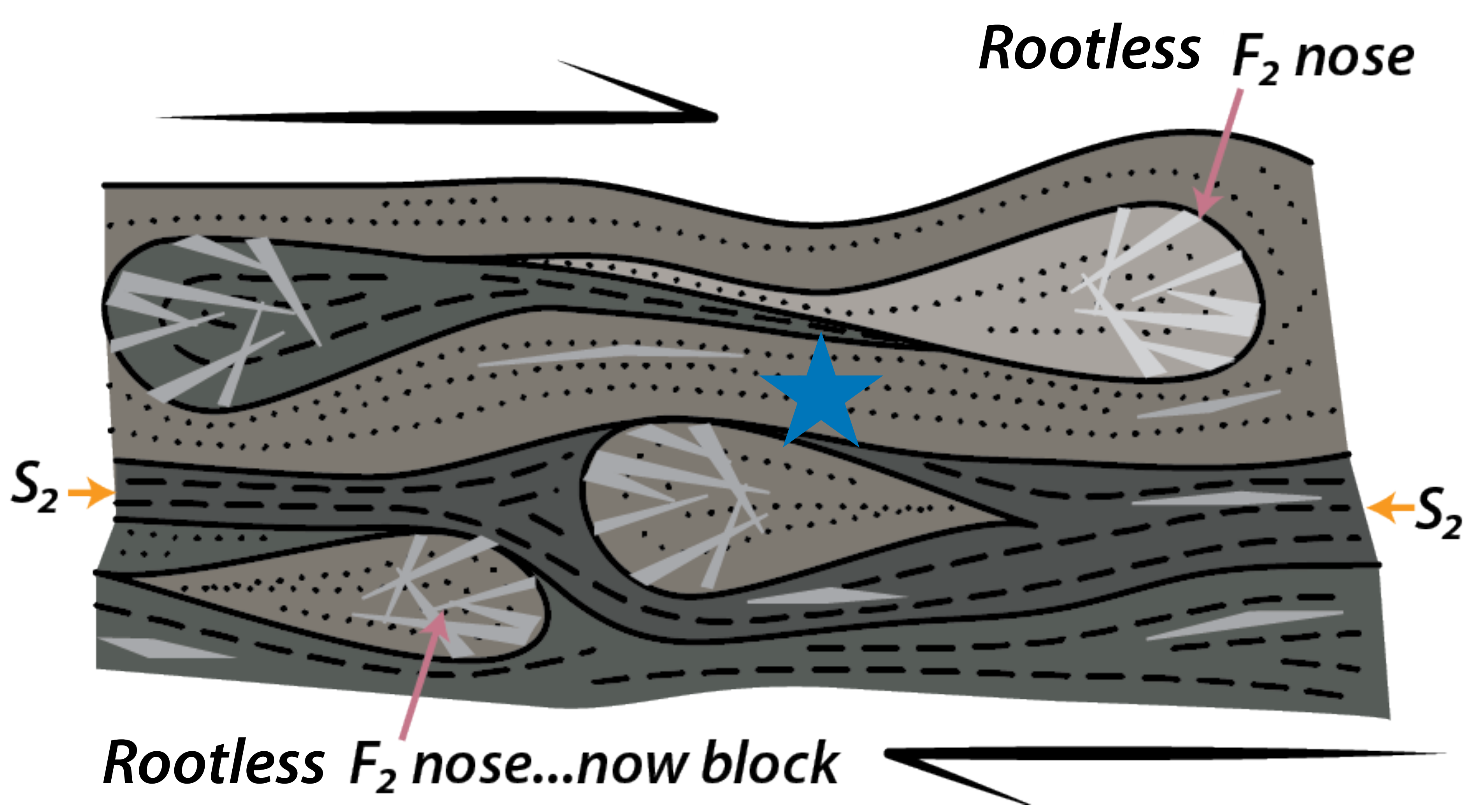

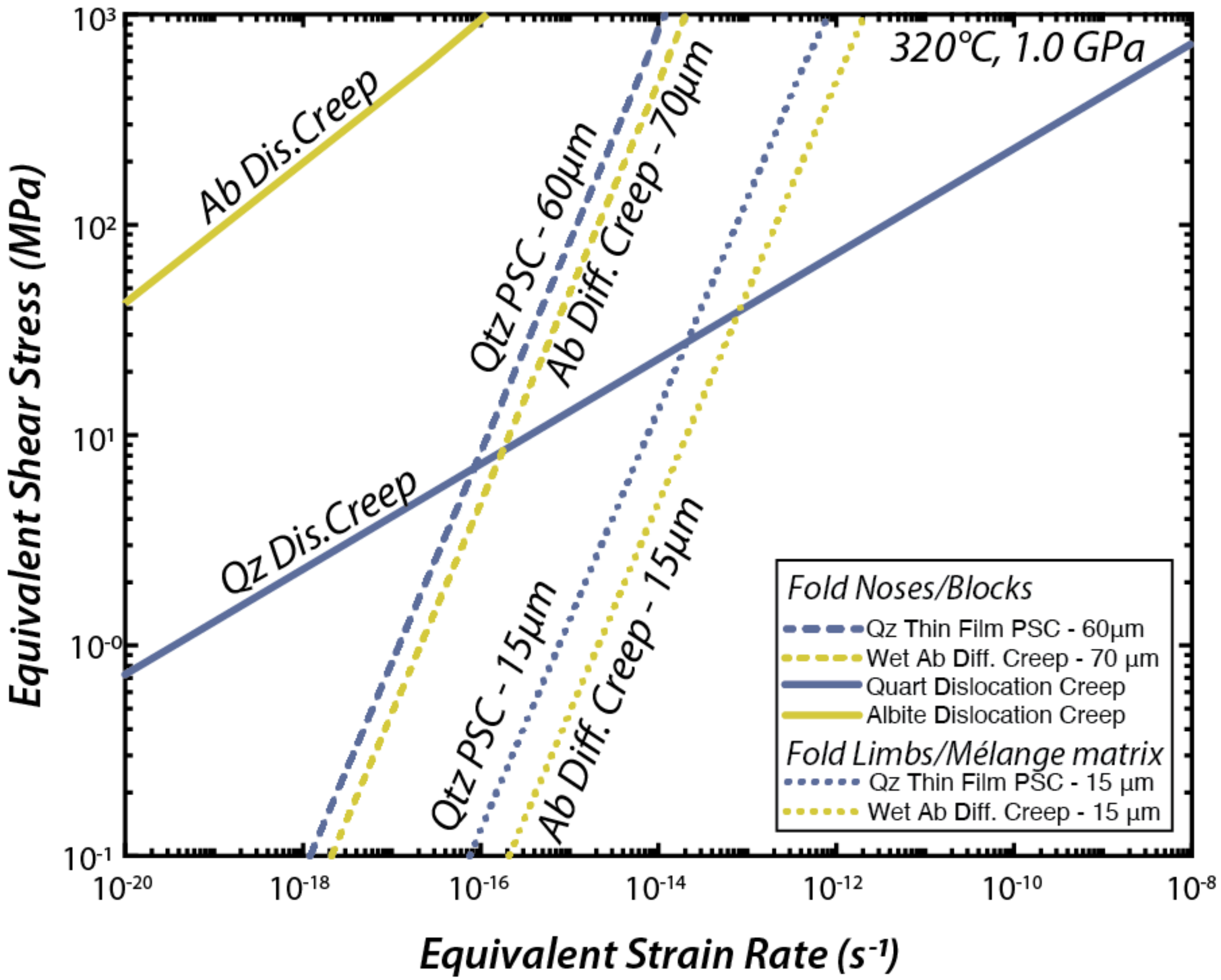

Condit et al., 2025 Geology

Requires σ <~25 MPa for PSC of matrix to be weaker than dislocation creep of the quartz veins

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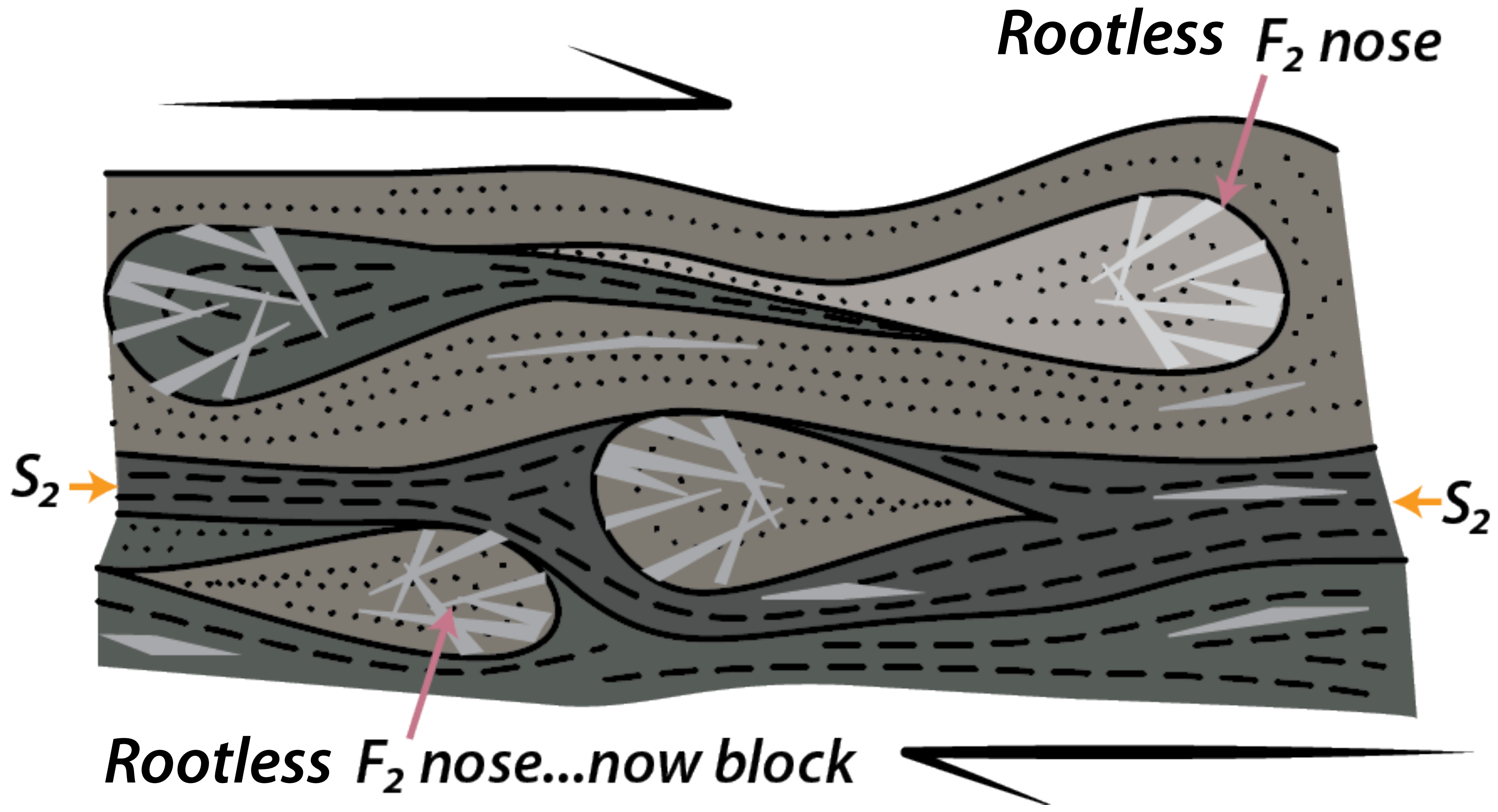

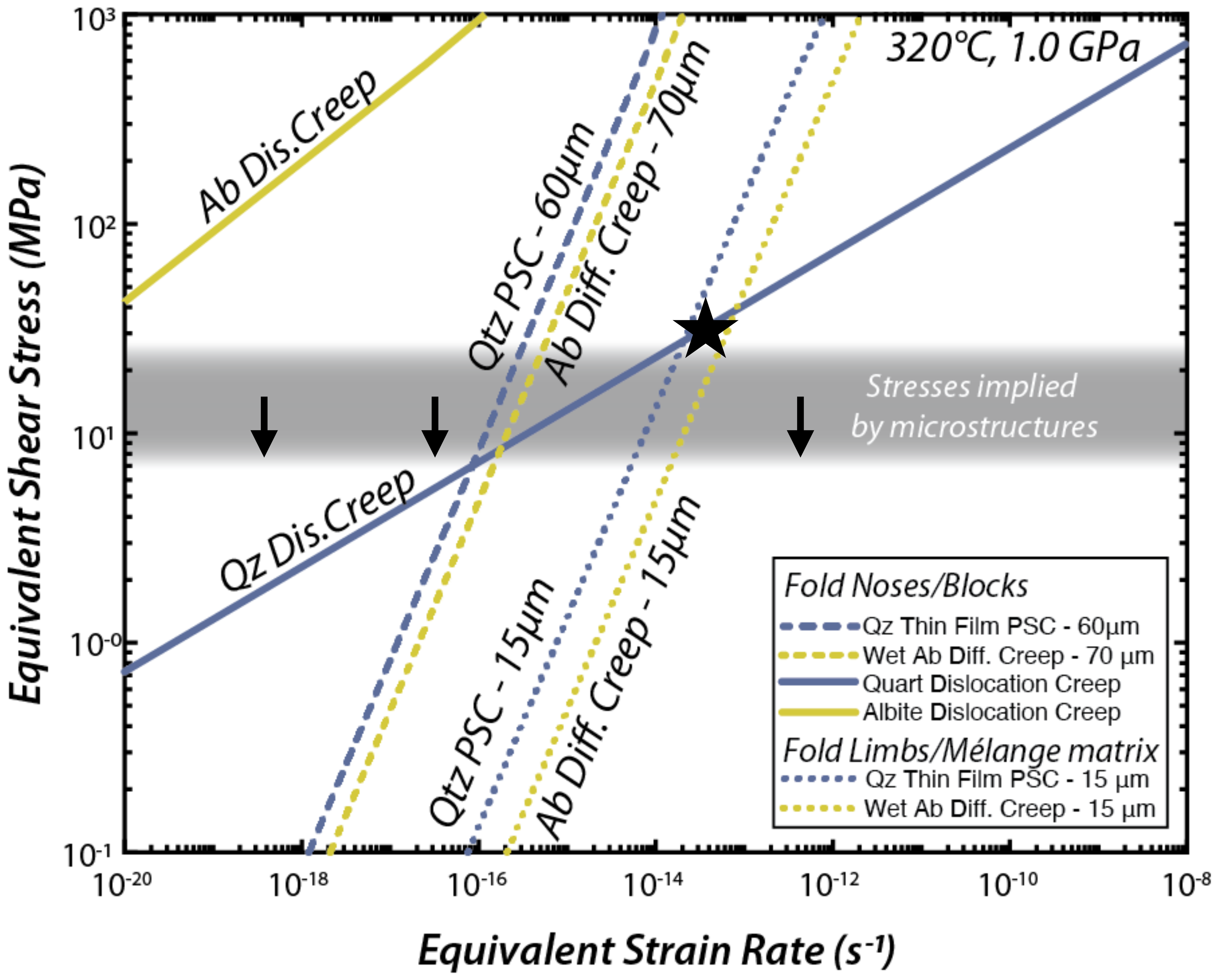

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Results in strain rates 10^{-13} s^{-1} or slower

With reasonable thicknesses (200-2000m): tectonic strain rates

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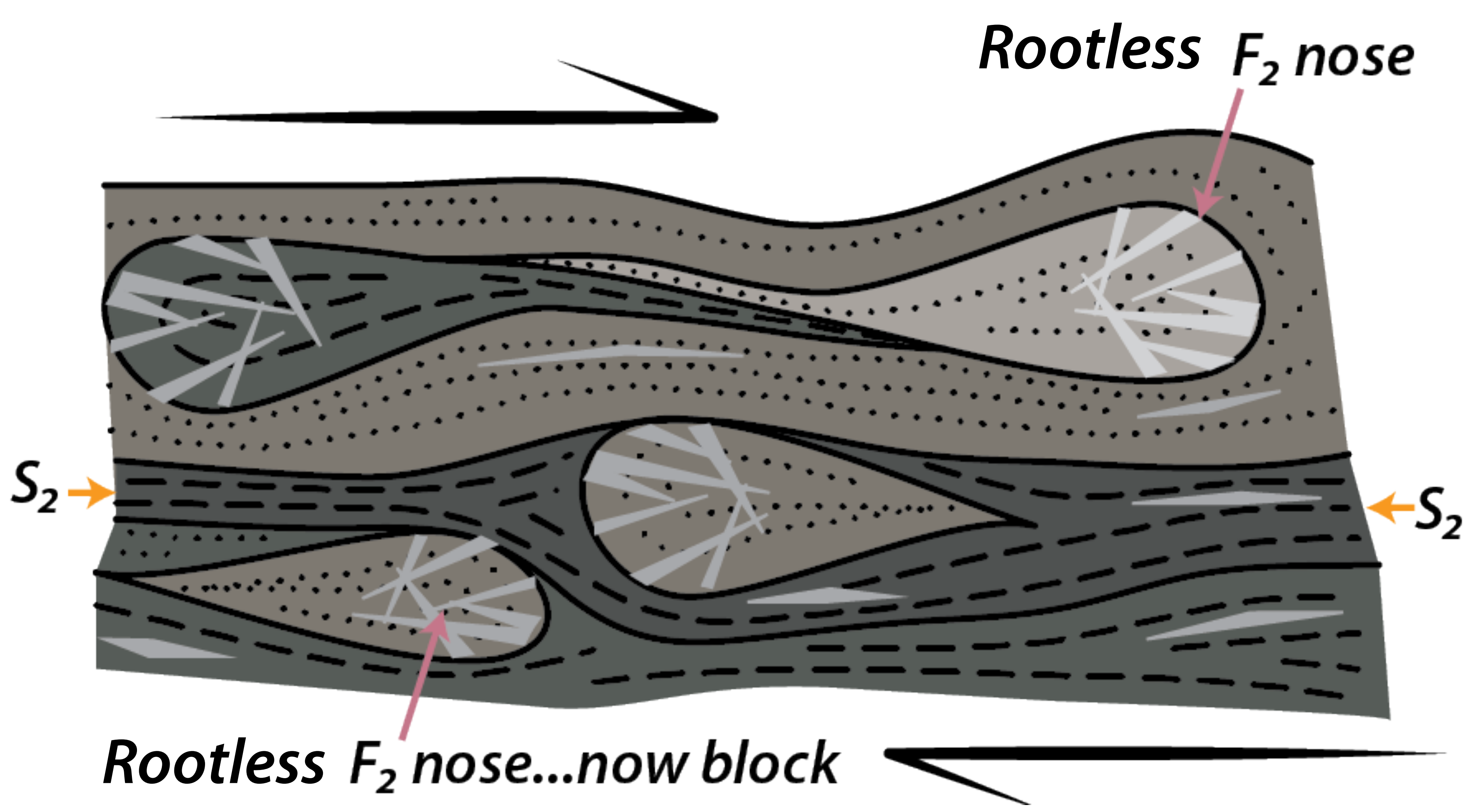

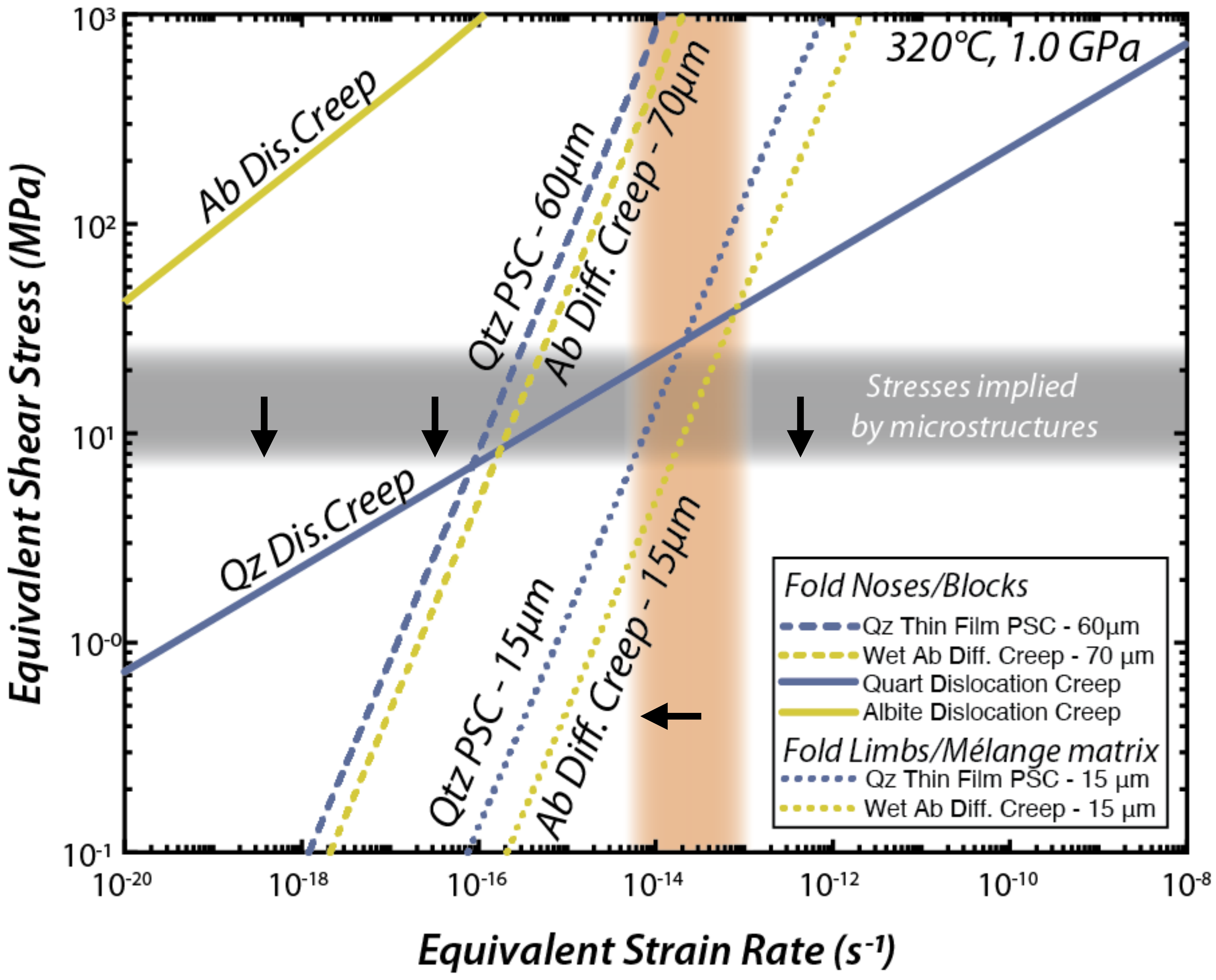

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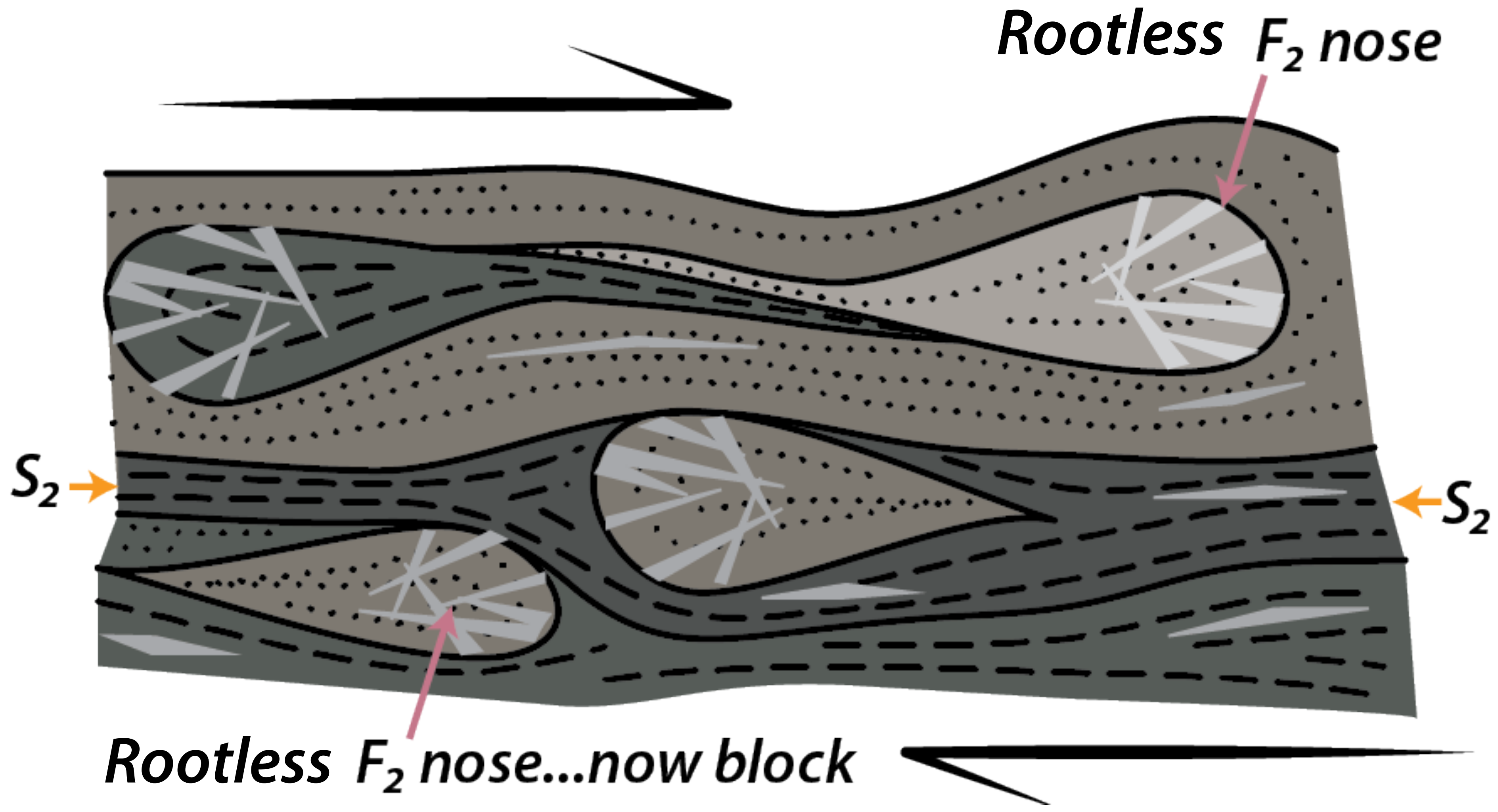
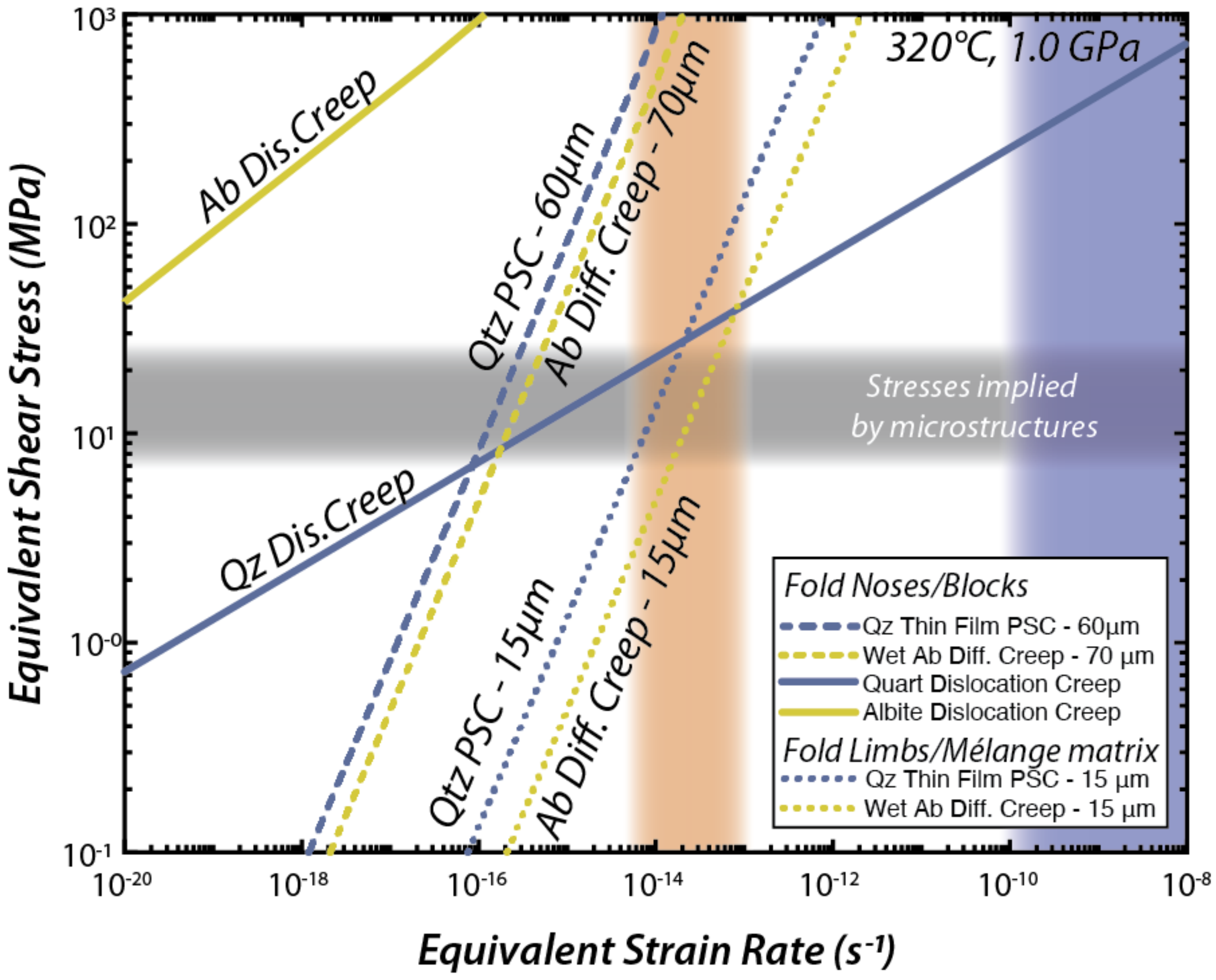
- **Slow slip rates of 10^{-10} s^{-1} or faster**

Rheology of the metasediments





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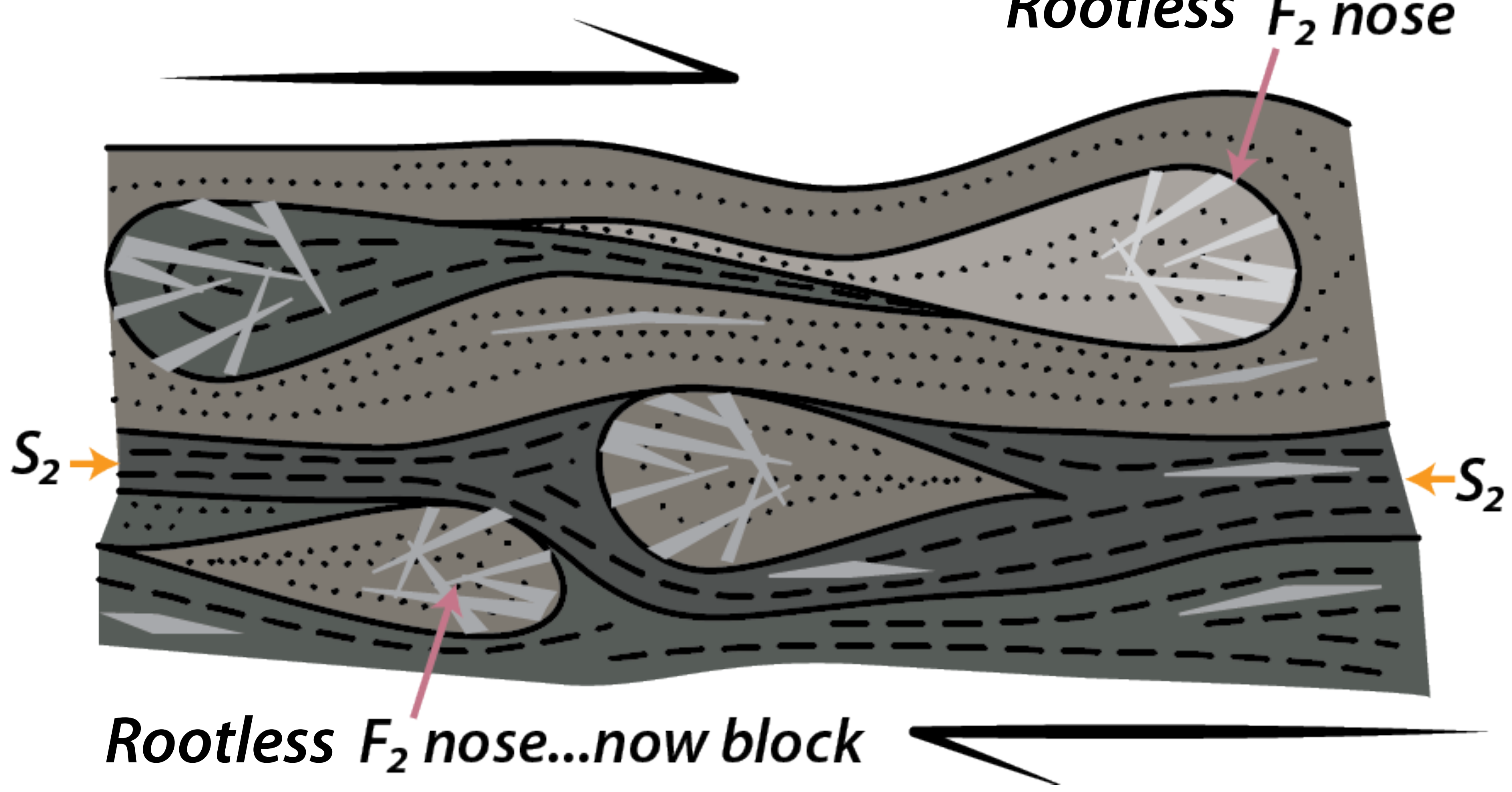
>1000 MPa for thin film pressure solution creep



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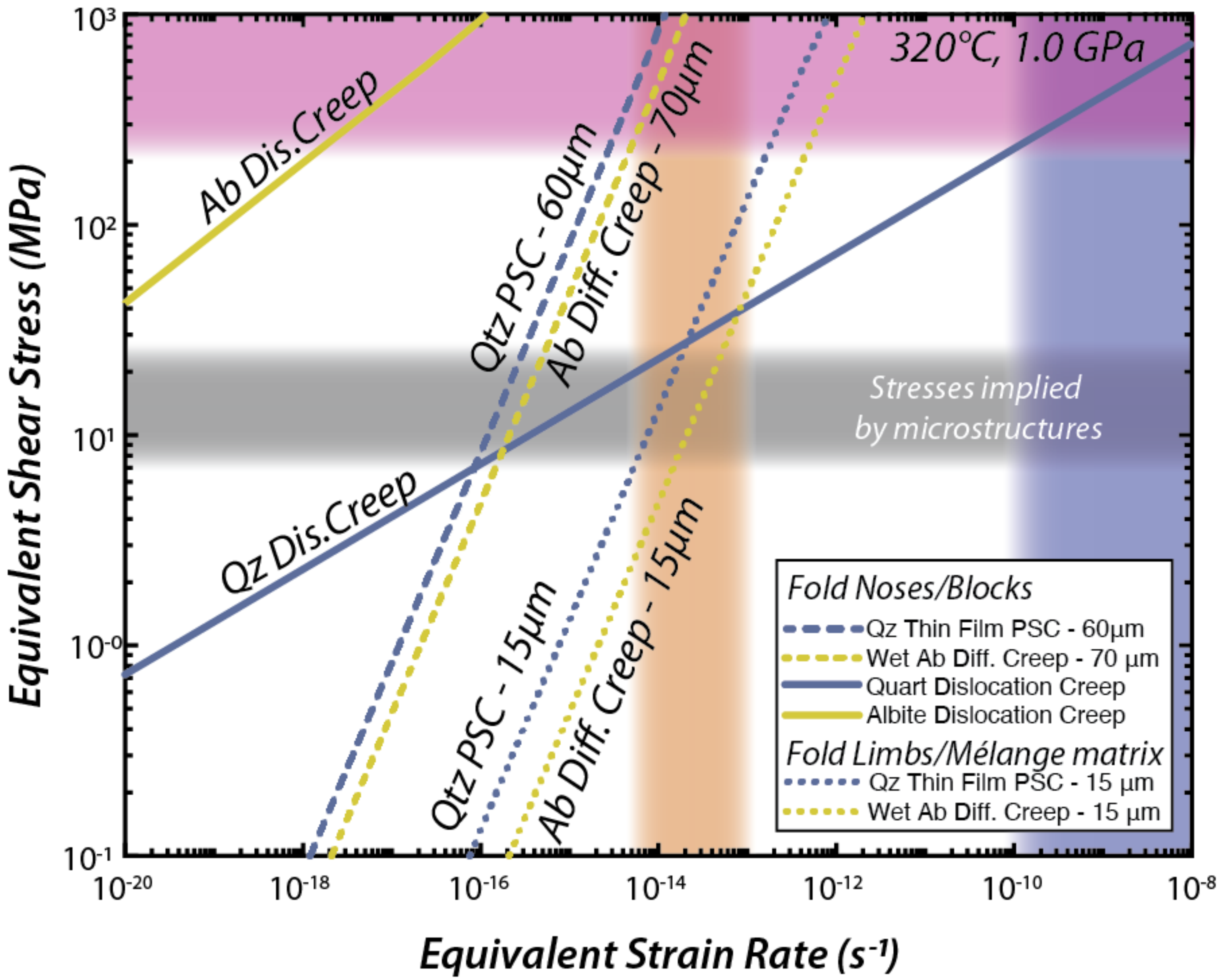

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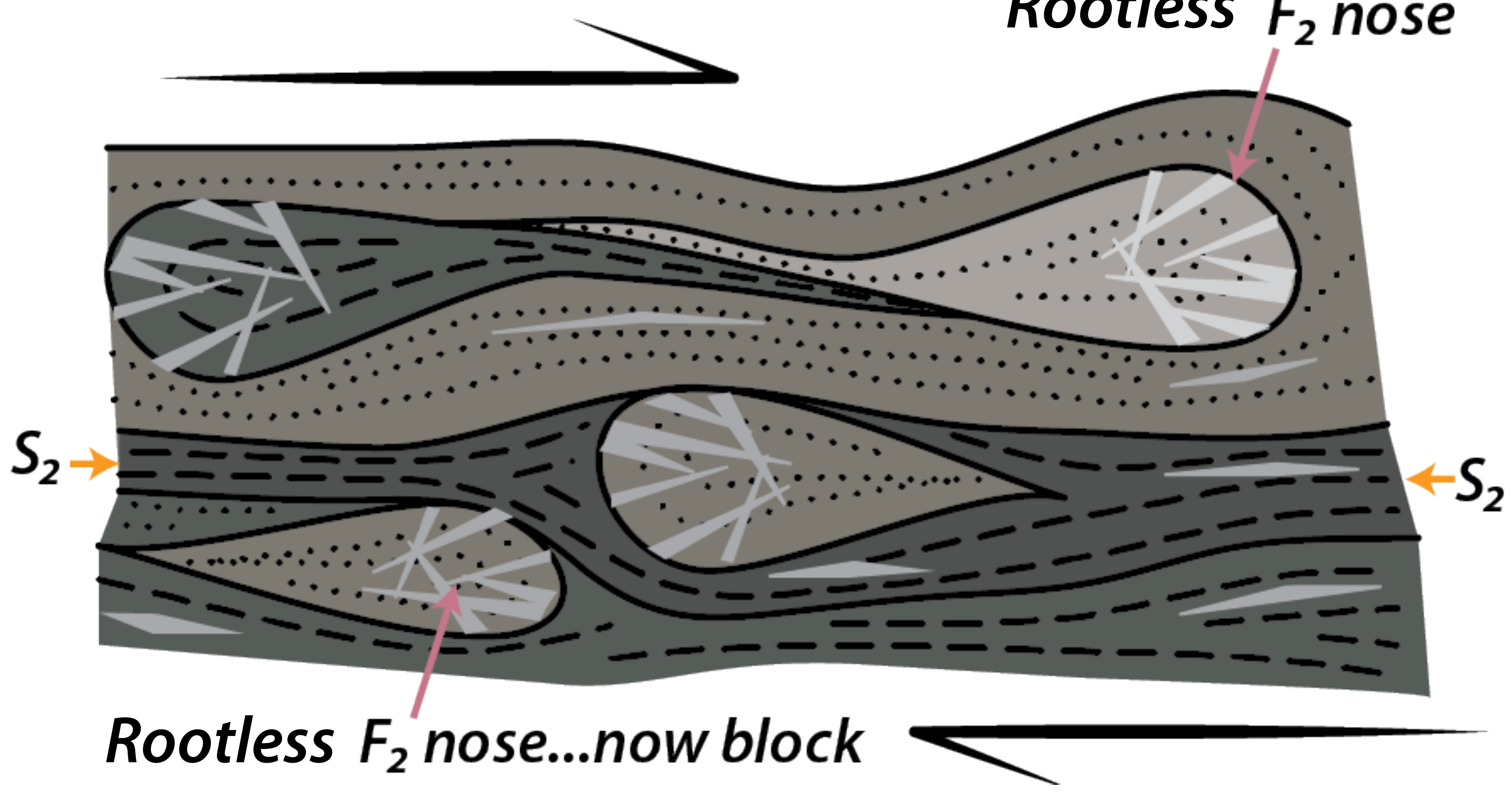

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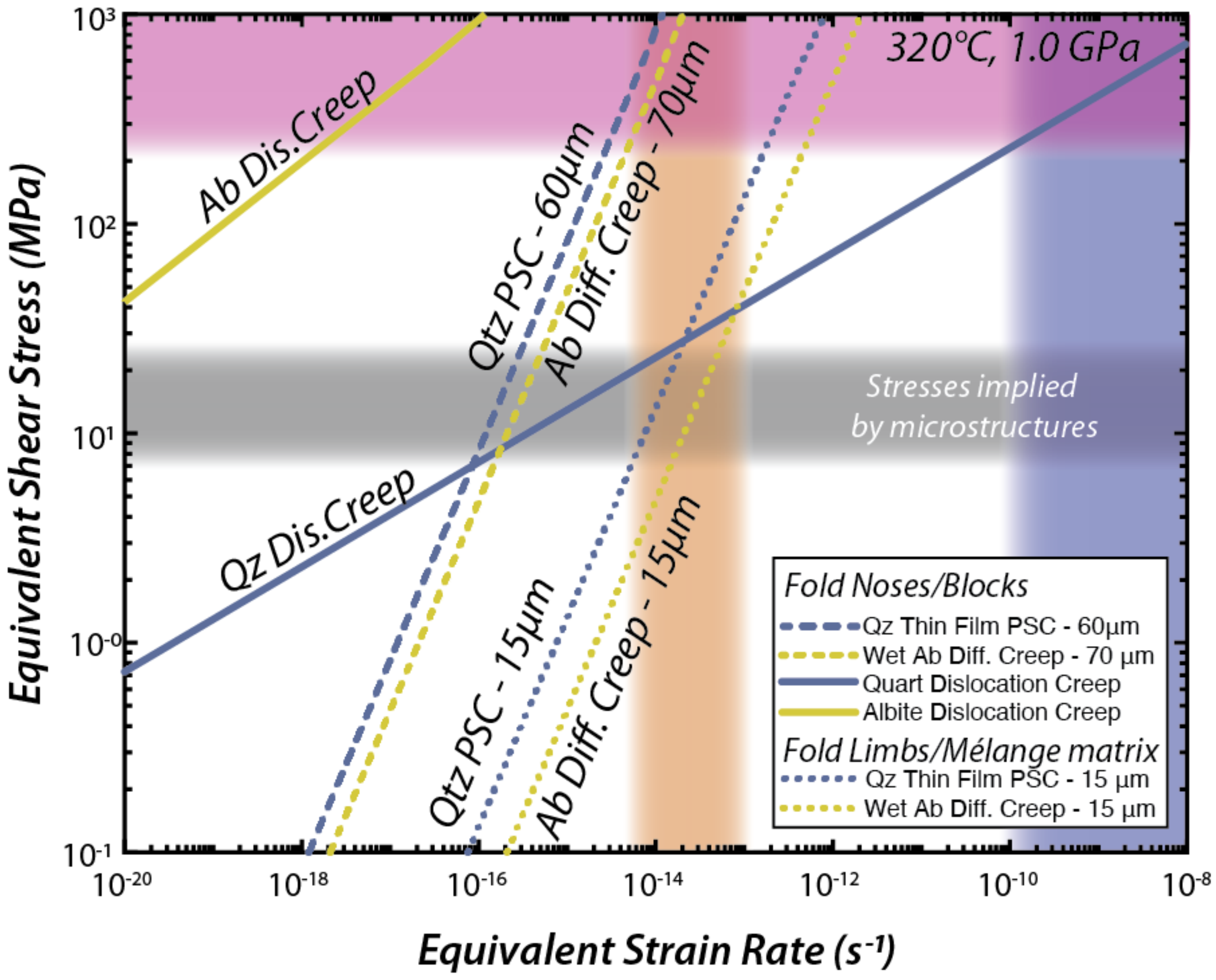

Host tectonic creeping; not slow slip

Condit et al., 2025 Geology

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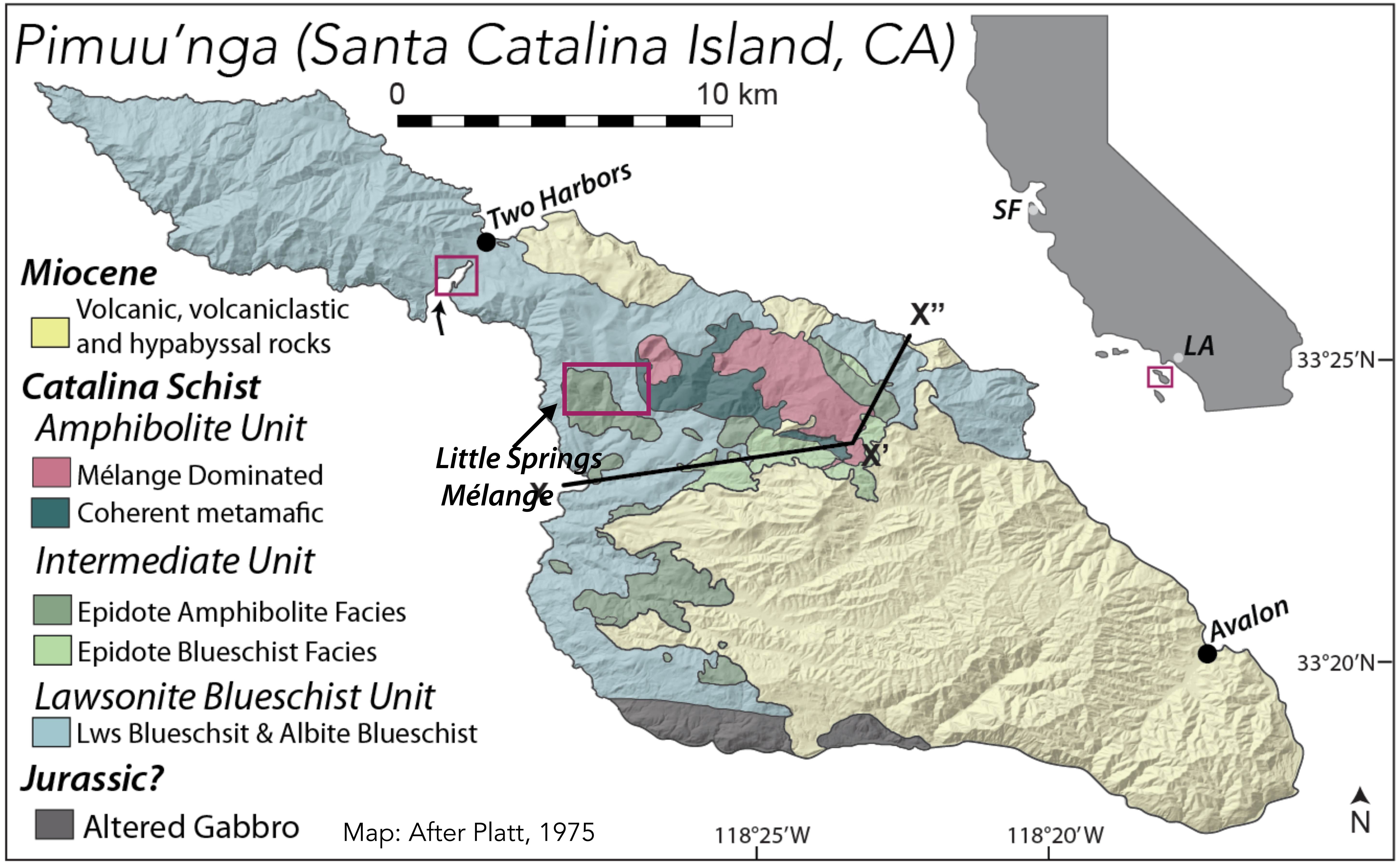
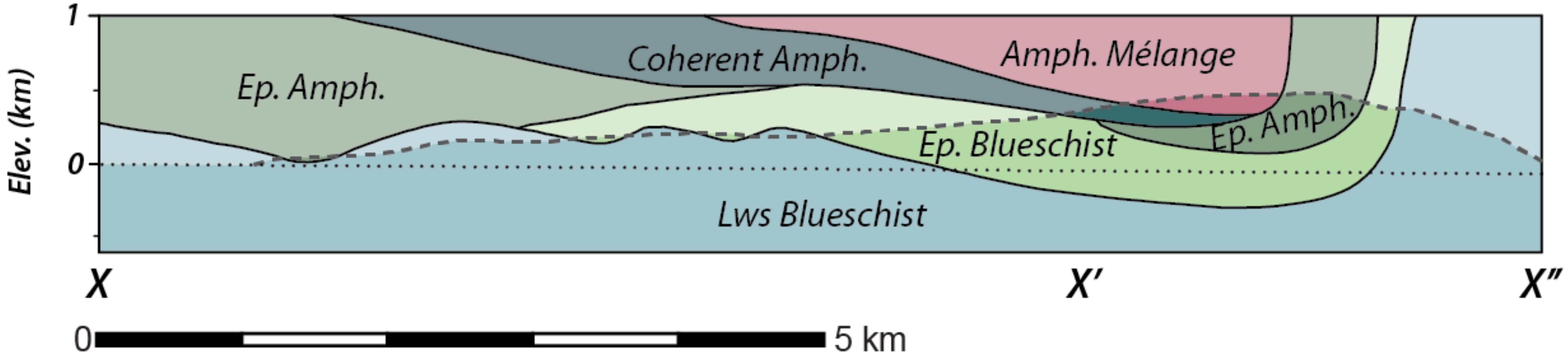
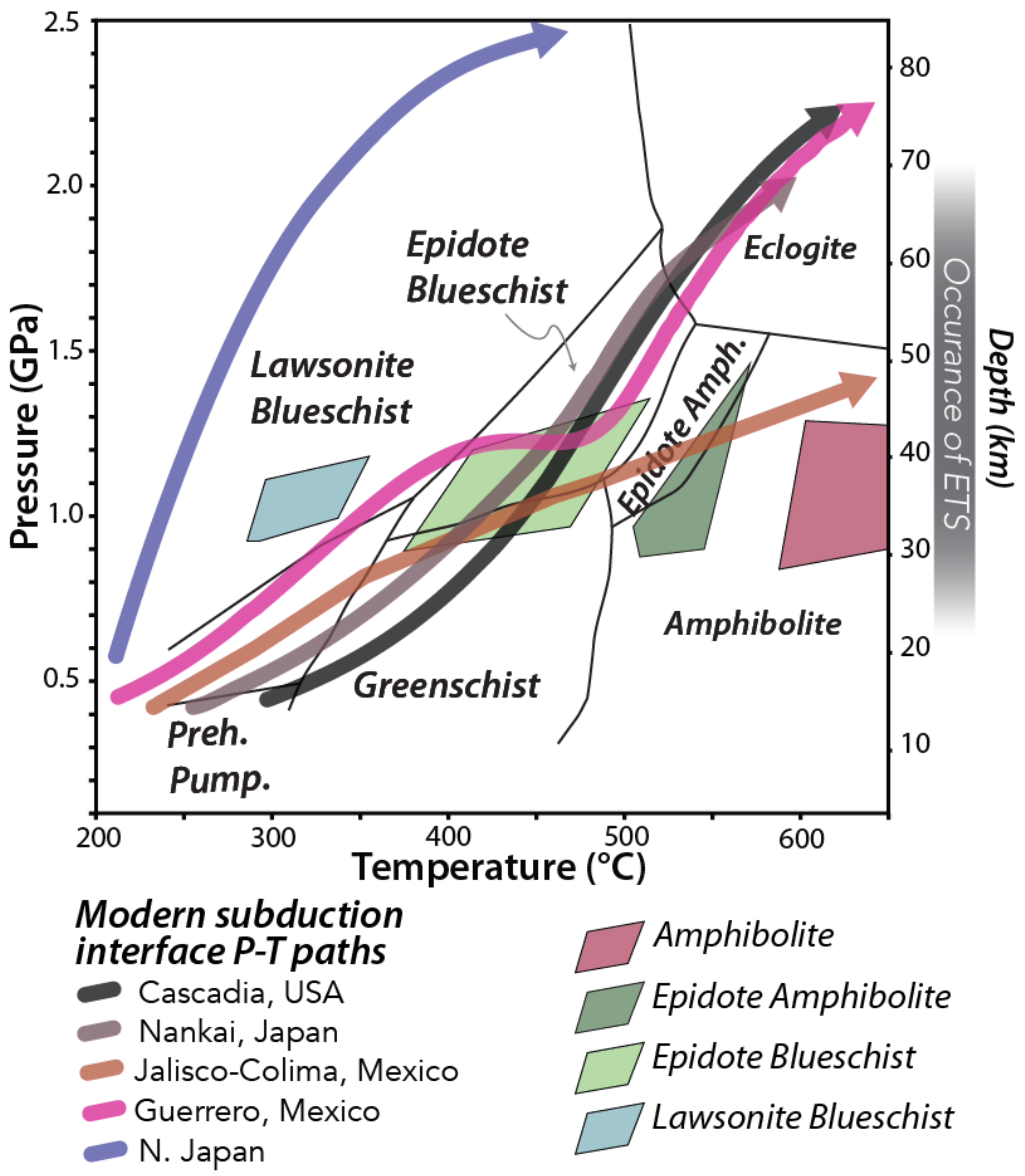
Evidence for brittle deformation (seismic slip?) at these deep depths intimately related to fluid process





Cross-section: Platt and Schmidt, 2024



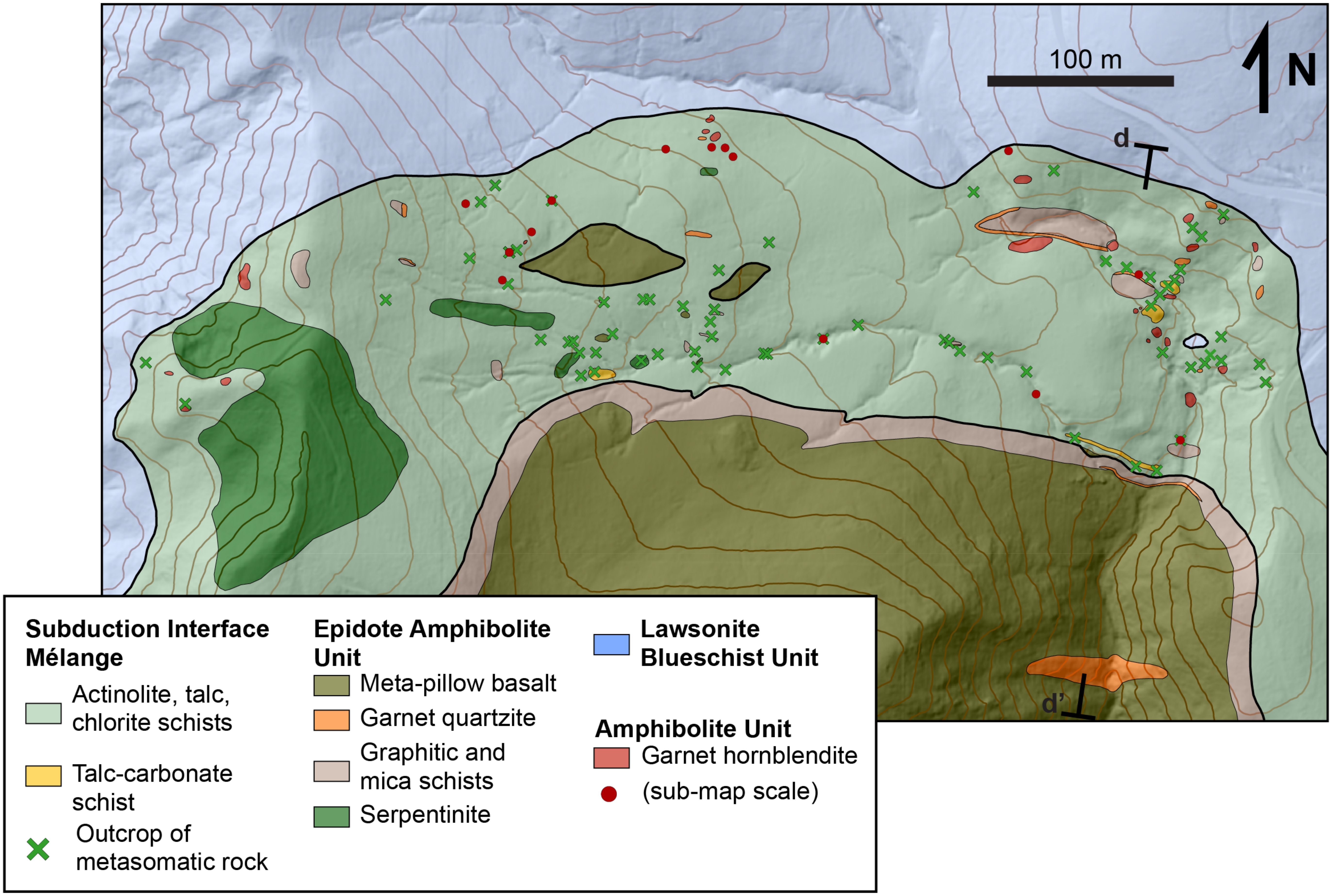
Epidote Amphibolite Unit - ~1.2 GPa (35-45) and 450-550 °C

P-T conditions: Hoover, Condit et al., *in Revision G3*

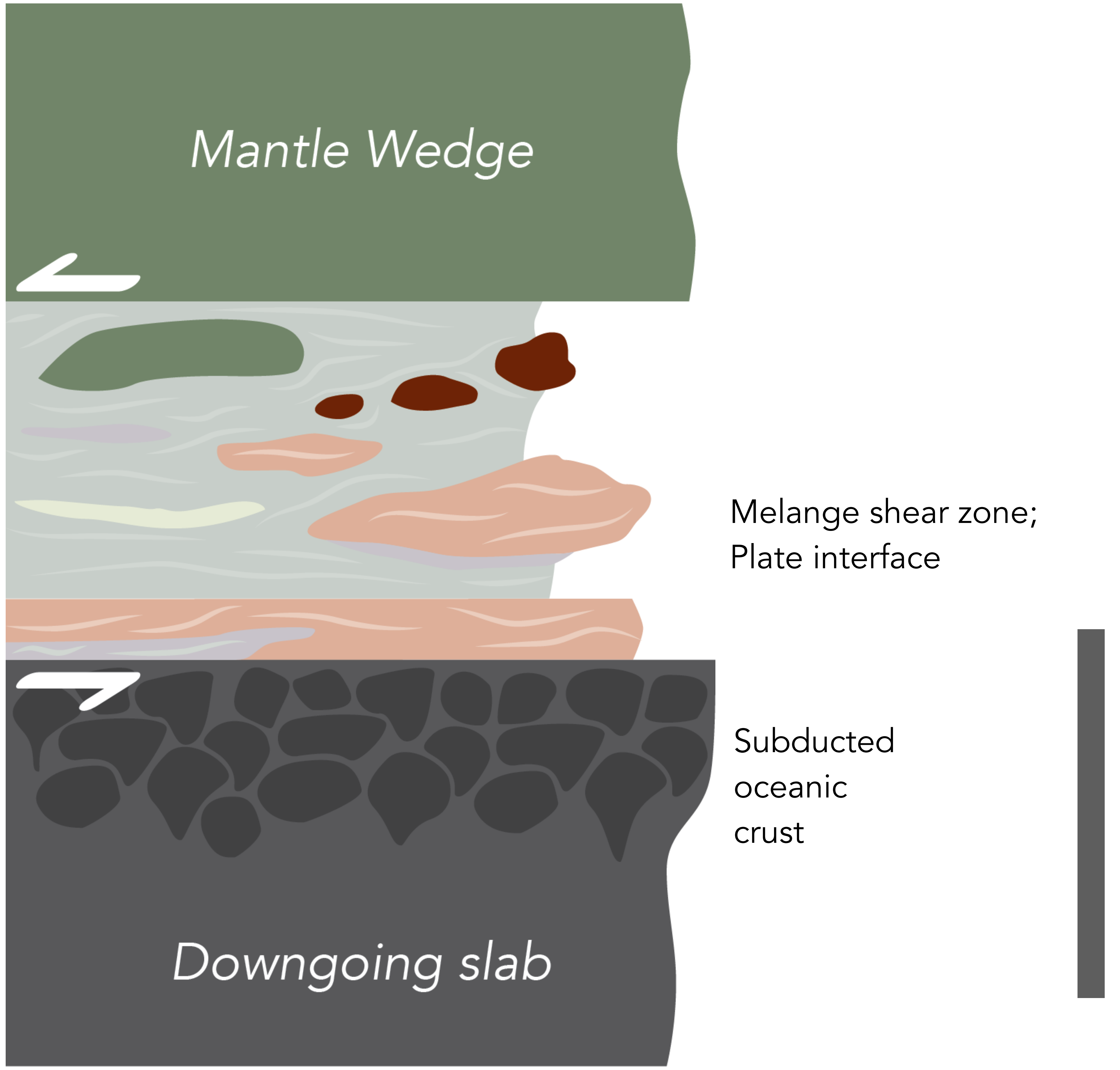
Metasomatic mélange, talc, chlorite, and actinolite schists, Serpentinized mantle blocks, metasedimentary rocks

Block-in-matrix structure underlain by lithostratigraphically intact metacherts and metabasalts from the slab

Epidote Amphibolite Facies Plate interface: 450-550°C, 1.2 GPa



Hoover, Condit et al; 2022 GRL



Adapted from Easthouse, Hoover et al., 2025, Geology

Lindquist, Condit et al., in prep

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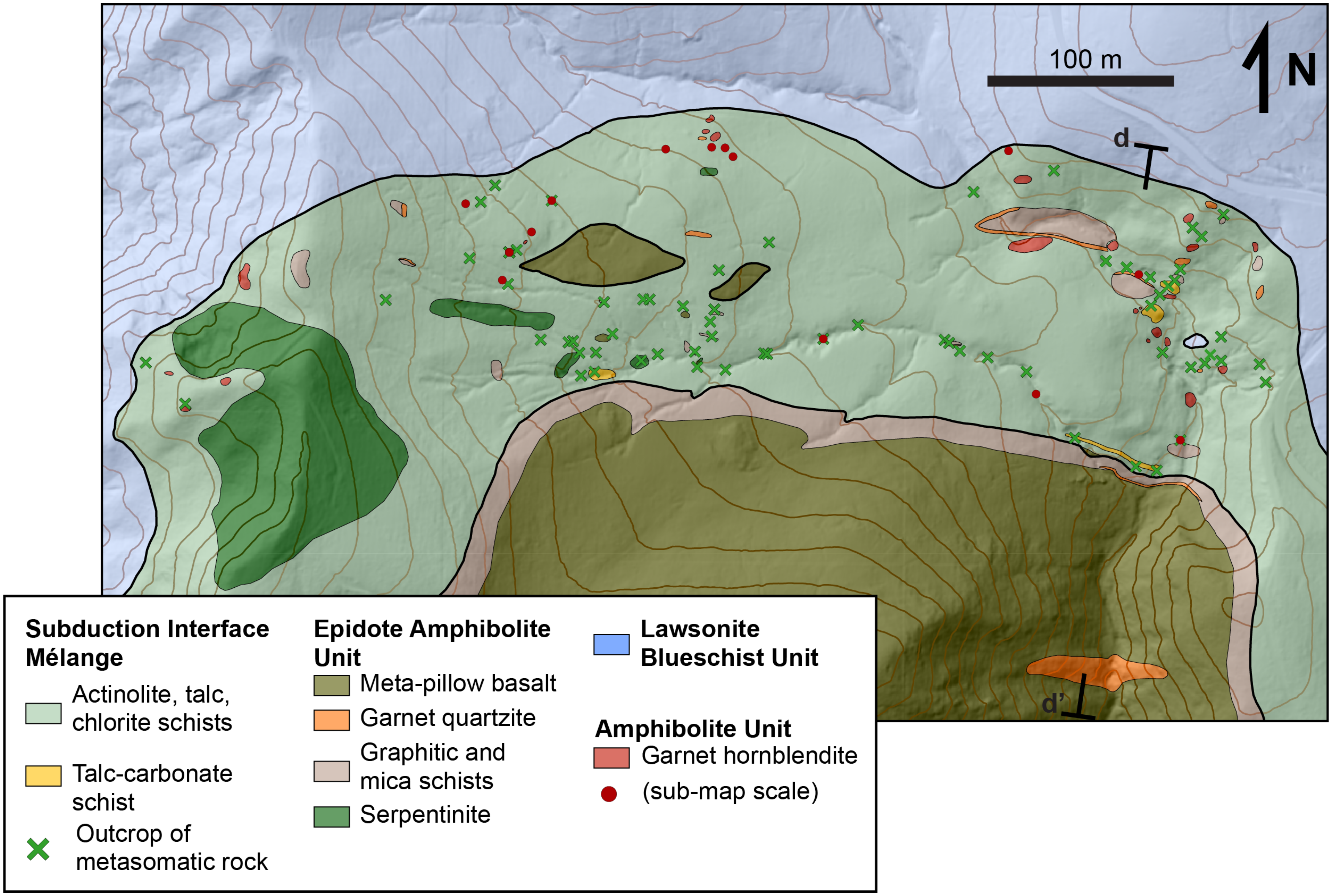
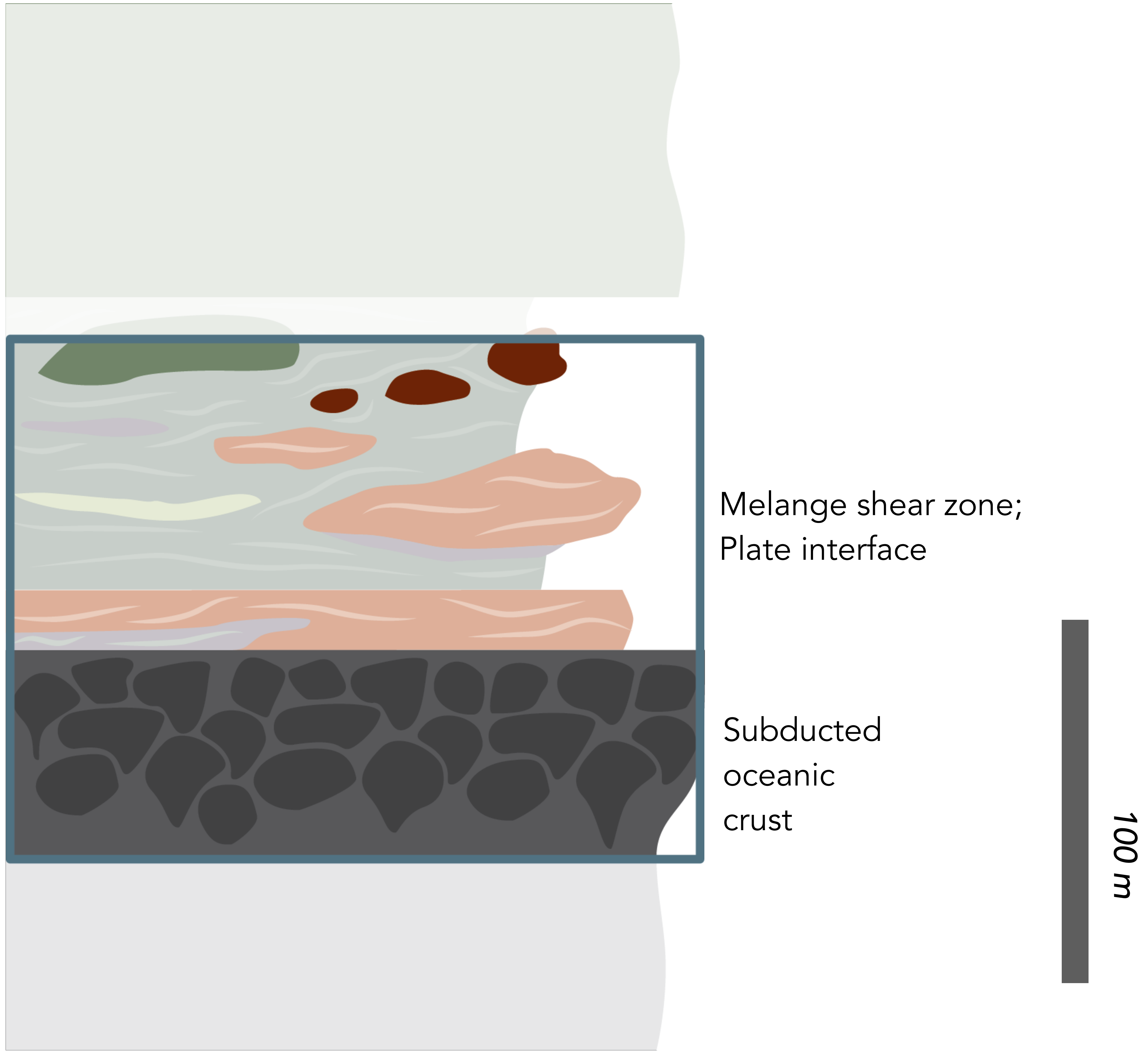


Hoover, Condit et al; 2022 GRL



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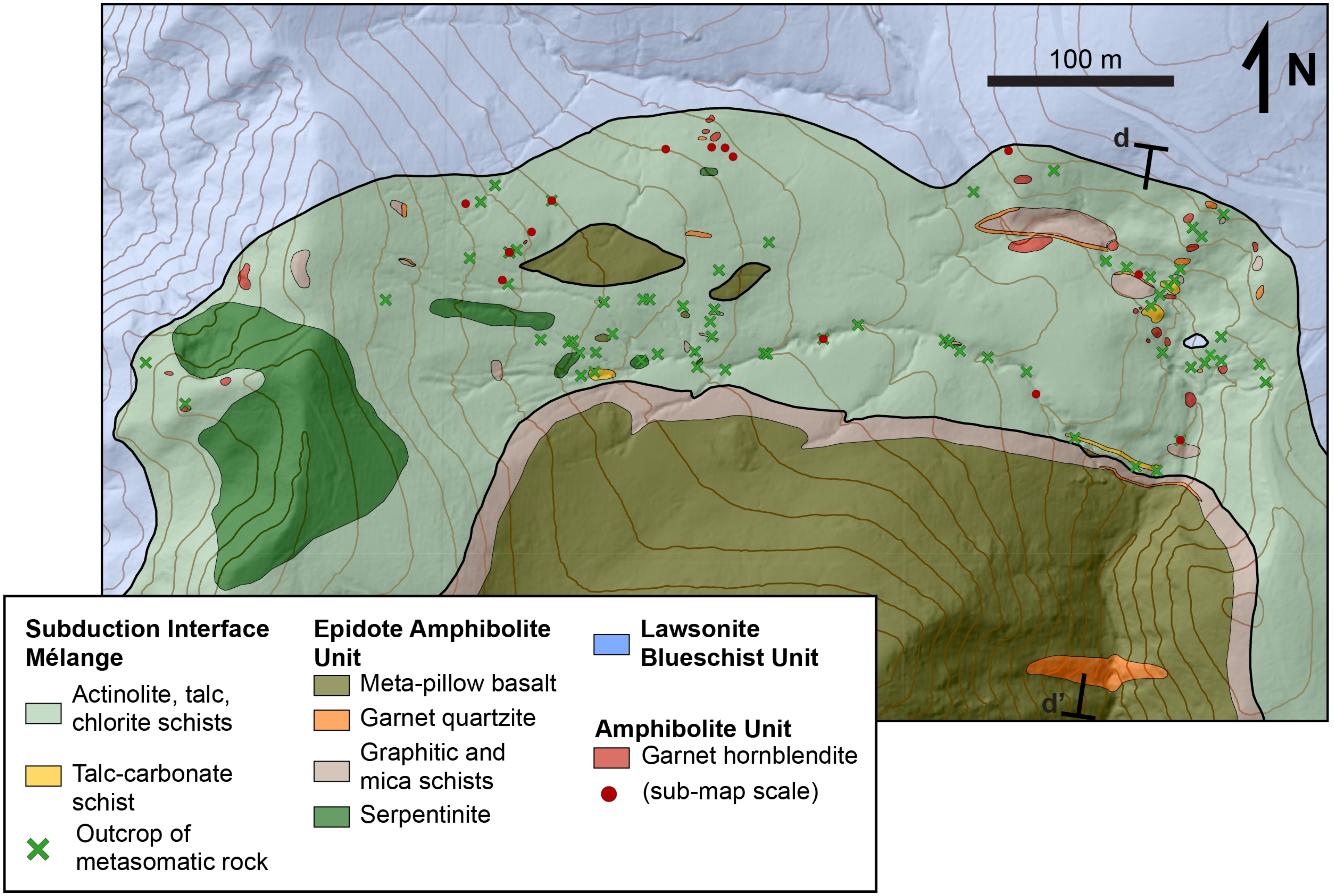
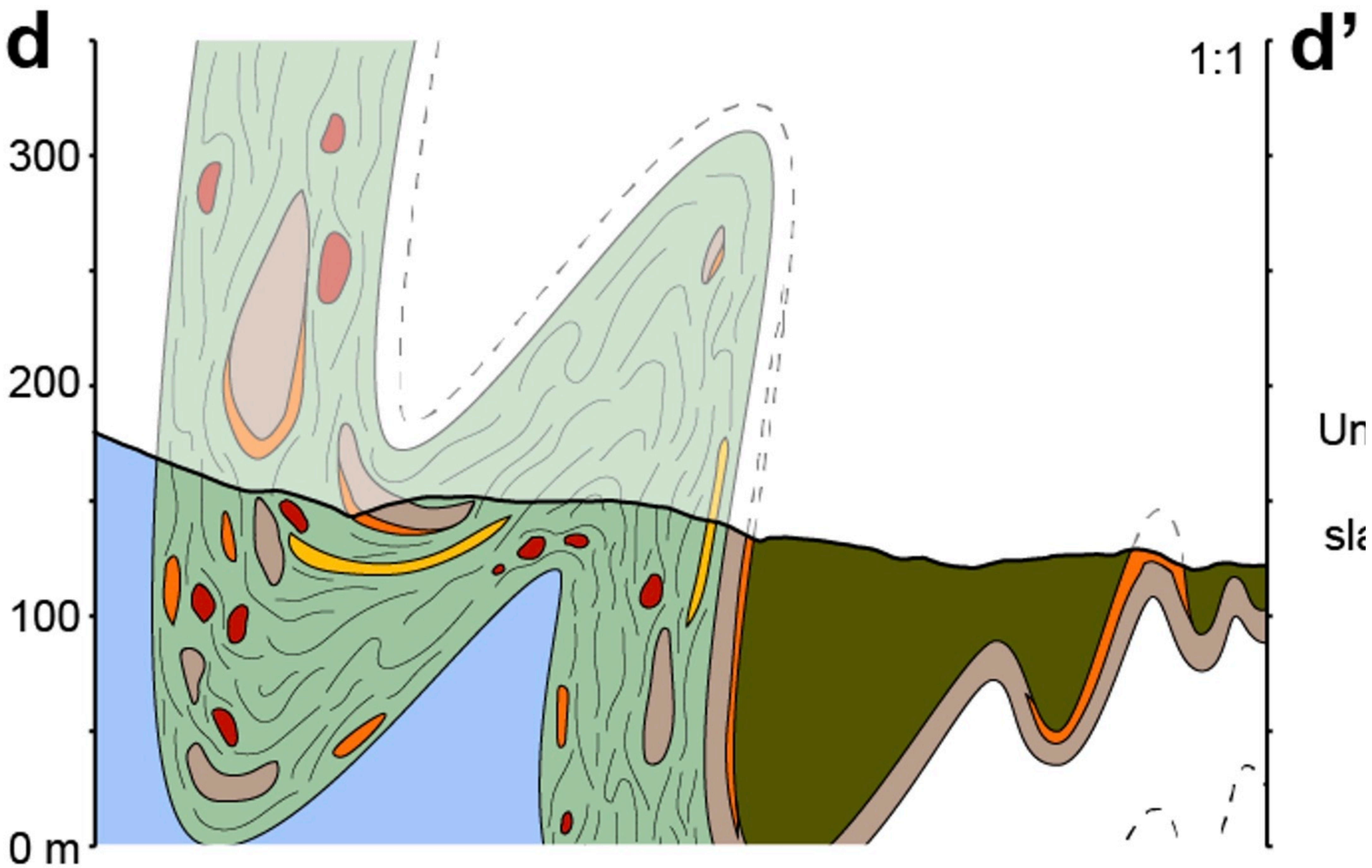
Epidote Amphibolite Facies Plate interface: 550°C, 1.0 GPa (~35 km paleodepth)



Hoover, Condit et al; 2022 GRL



Hoover, Condit et al., in Revision

Ultramafic-Metasedimentary melange matrix

Hoover, Condit et al; 2022 GRL

Easthouse, Hoover, 2025 Geology

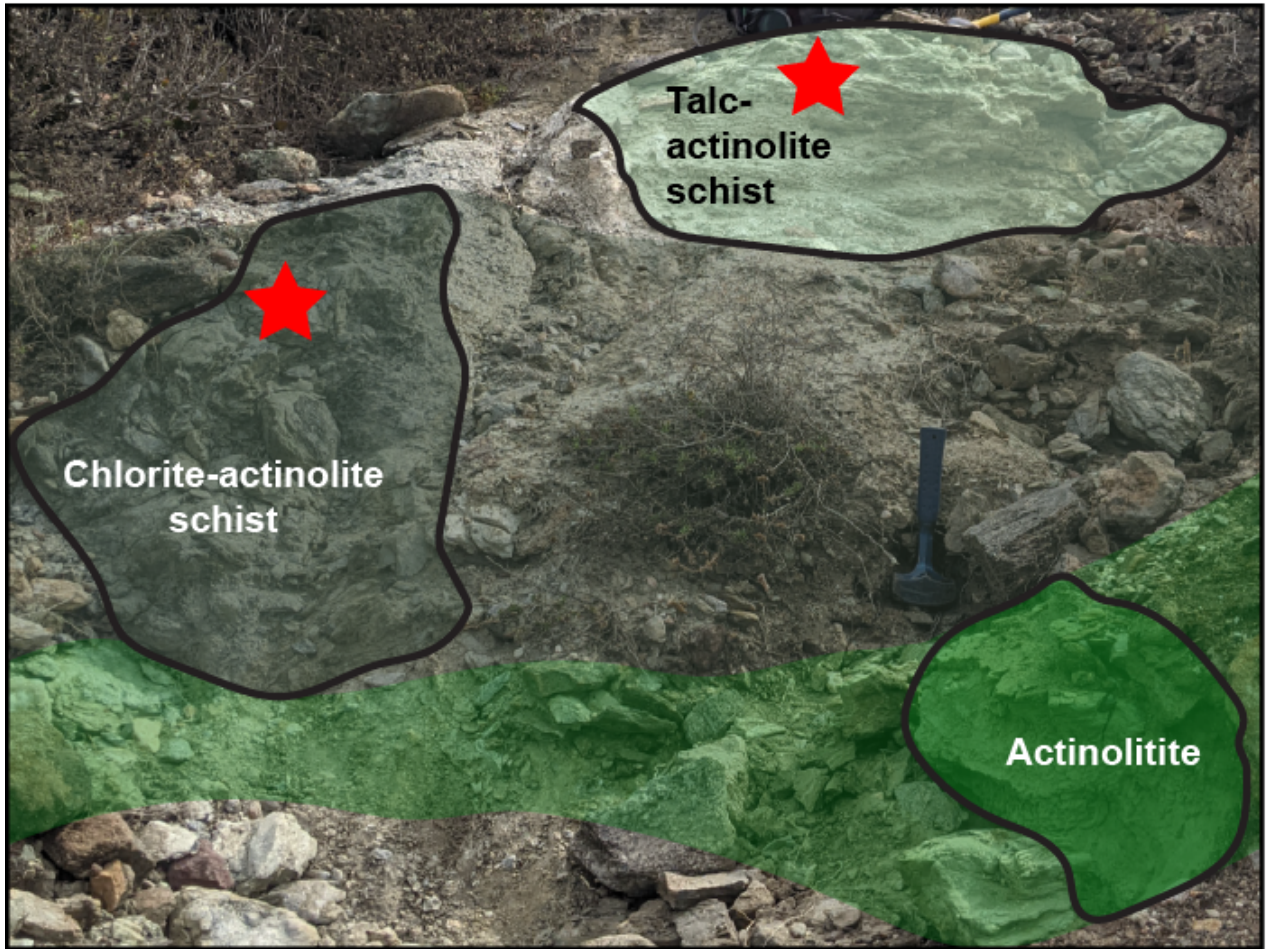
Ultramafic-pelitic melange

Mechanical and chemical mixing between

- ultramafic rocks from mantle wedge
- metasedimentary schists

Result: talc and chlorite schists

Ultramafic-Metasedimentary melange matrix



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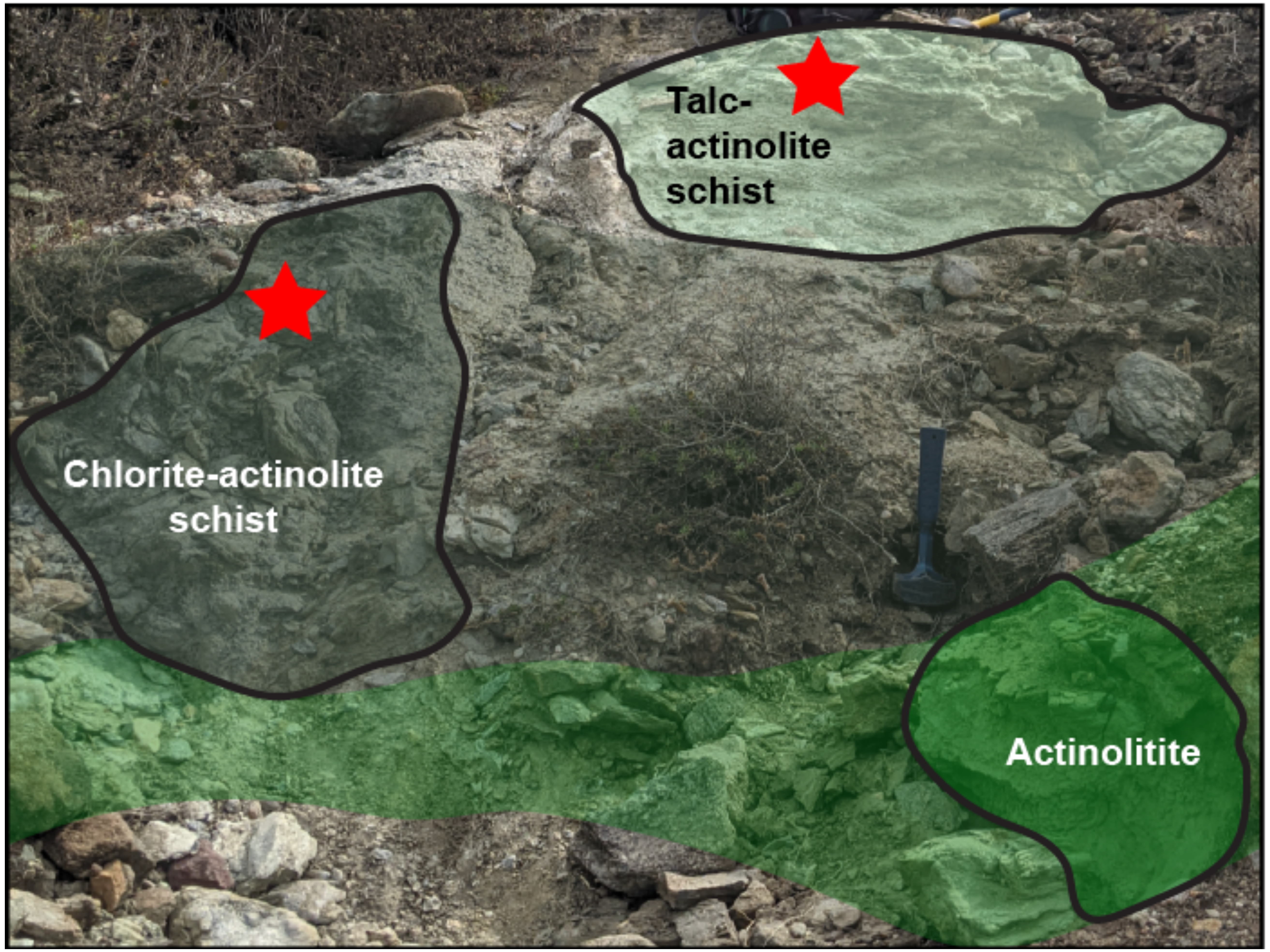

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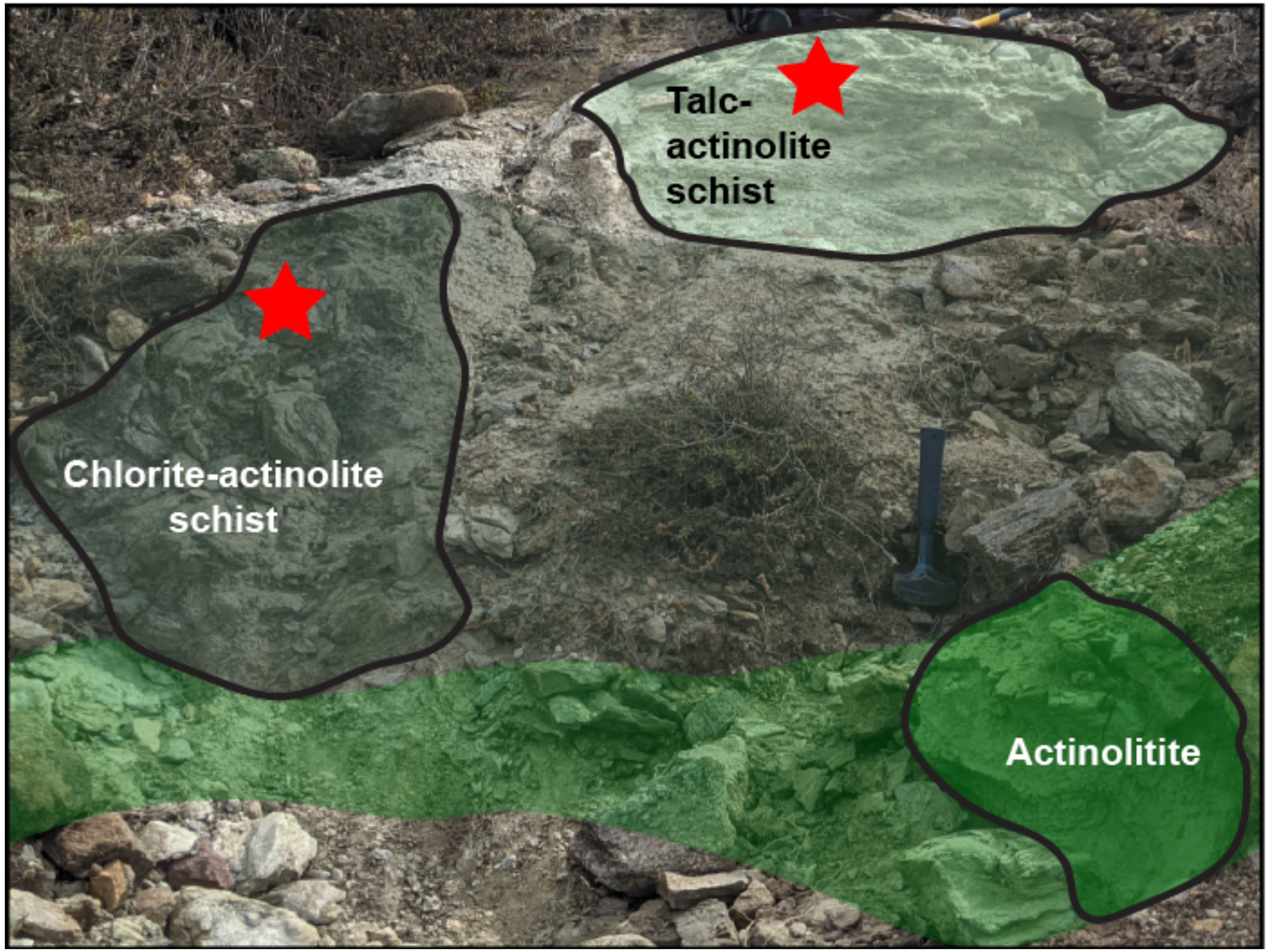
Result: talc and chlorite schists

Recent work suggests metasomatic rocks might host slow slip;

Frictionally weak and ~rate strengthening

Pore fluid pressure ($\sigma_n = \sigma - P_f$)

Ultramafic-Metasedimentary melange matrix



Hoover, Condit et al; 2022 GRL

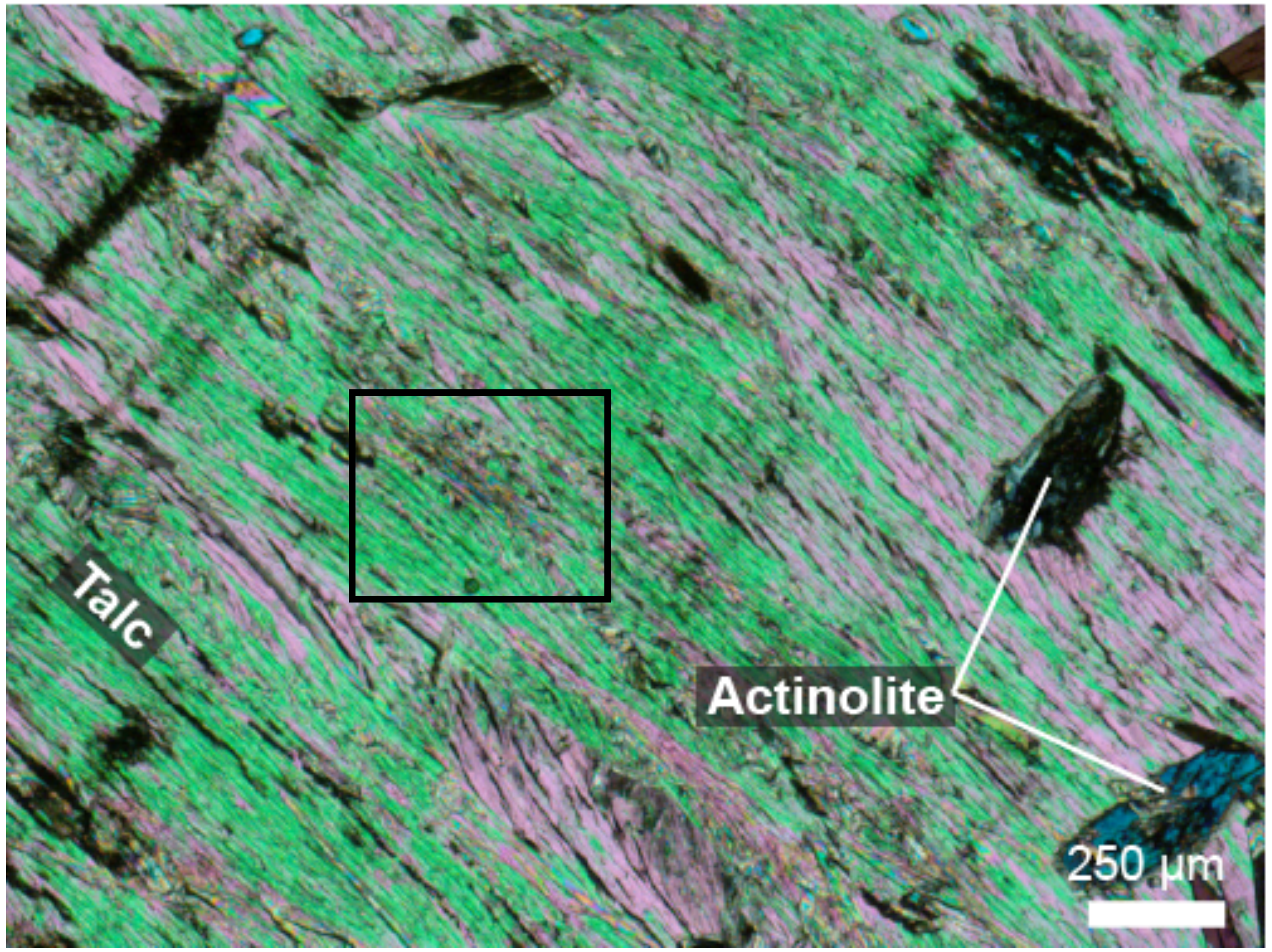
Easthouse, Hoover, 2025 Geology

Evidence of fluids

Talc-Actinolite Schist - Metasomatic with an ultramafic protolith

Talc Schist

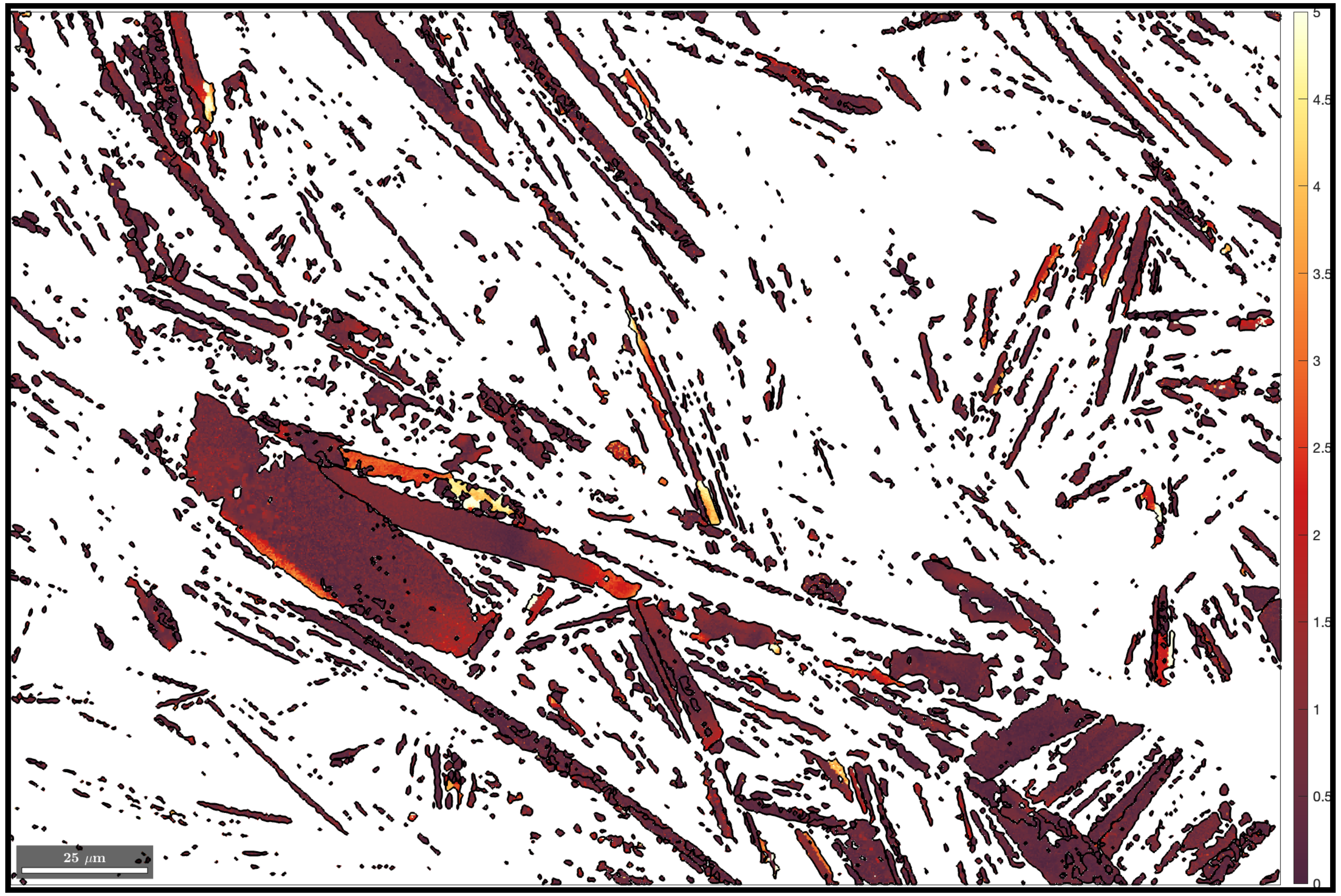
Photomicrograph



Talc strongly aligned in some places;

Hoover, Condit, et al; 2022 GRL

Talc Mis2Mean EBSD map



Hoover, Condit, Cross; In Prep

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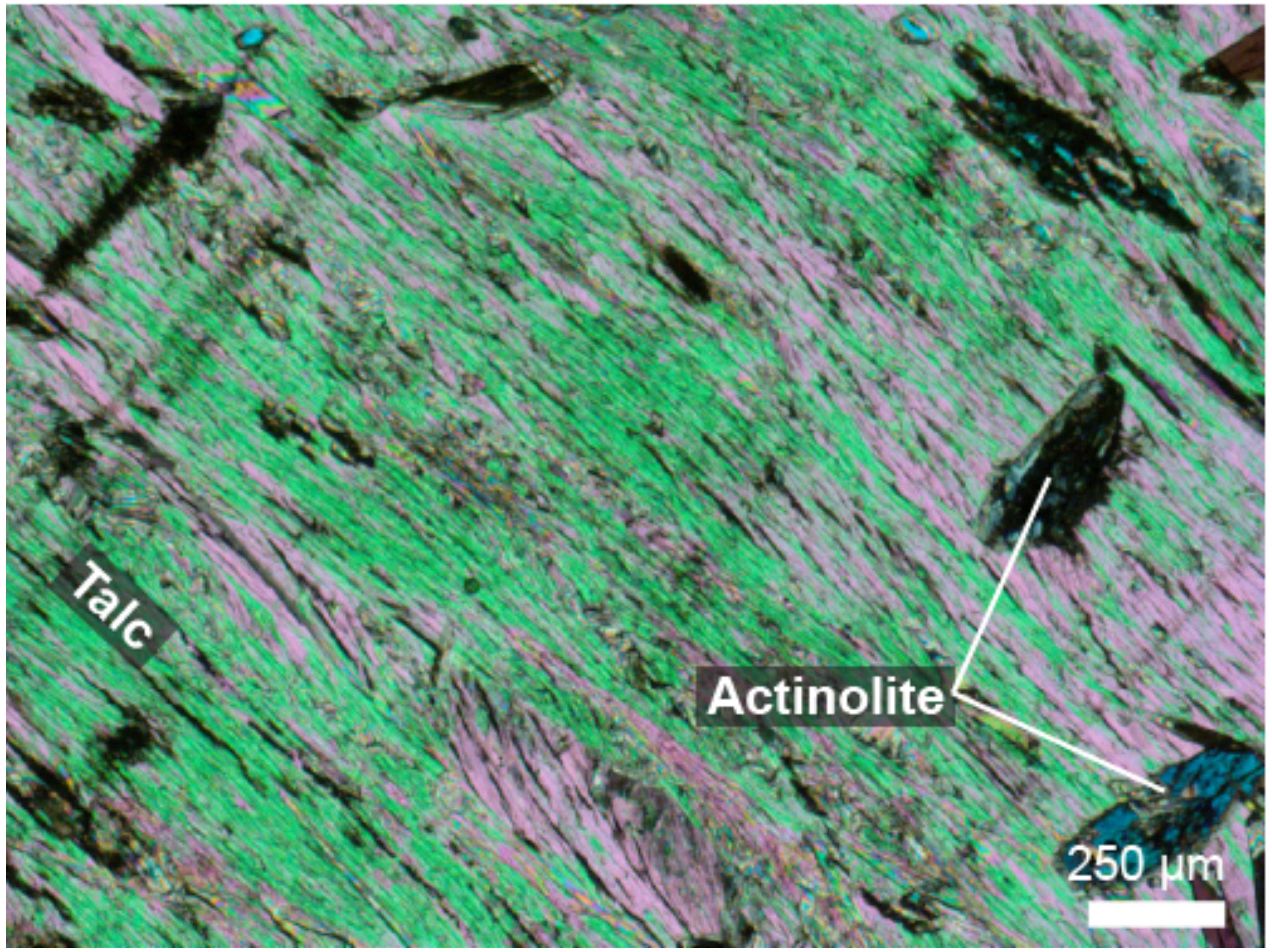

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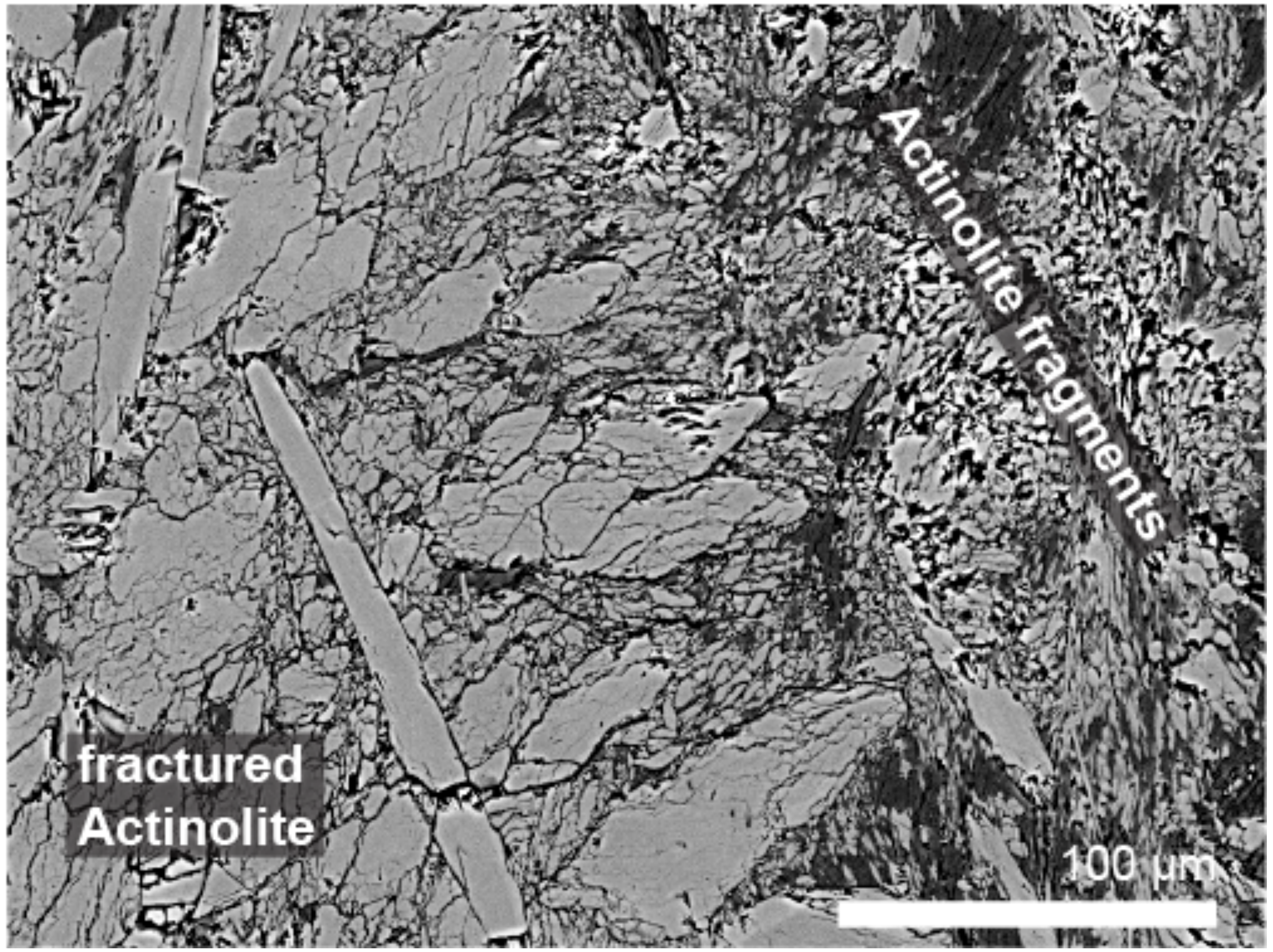
BSE



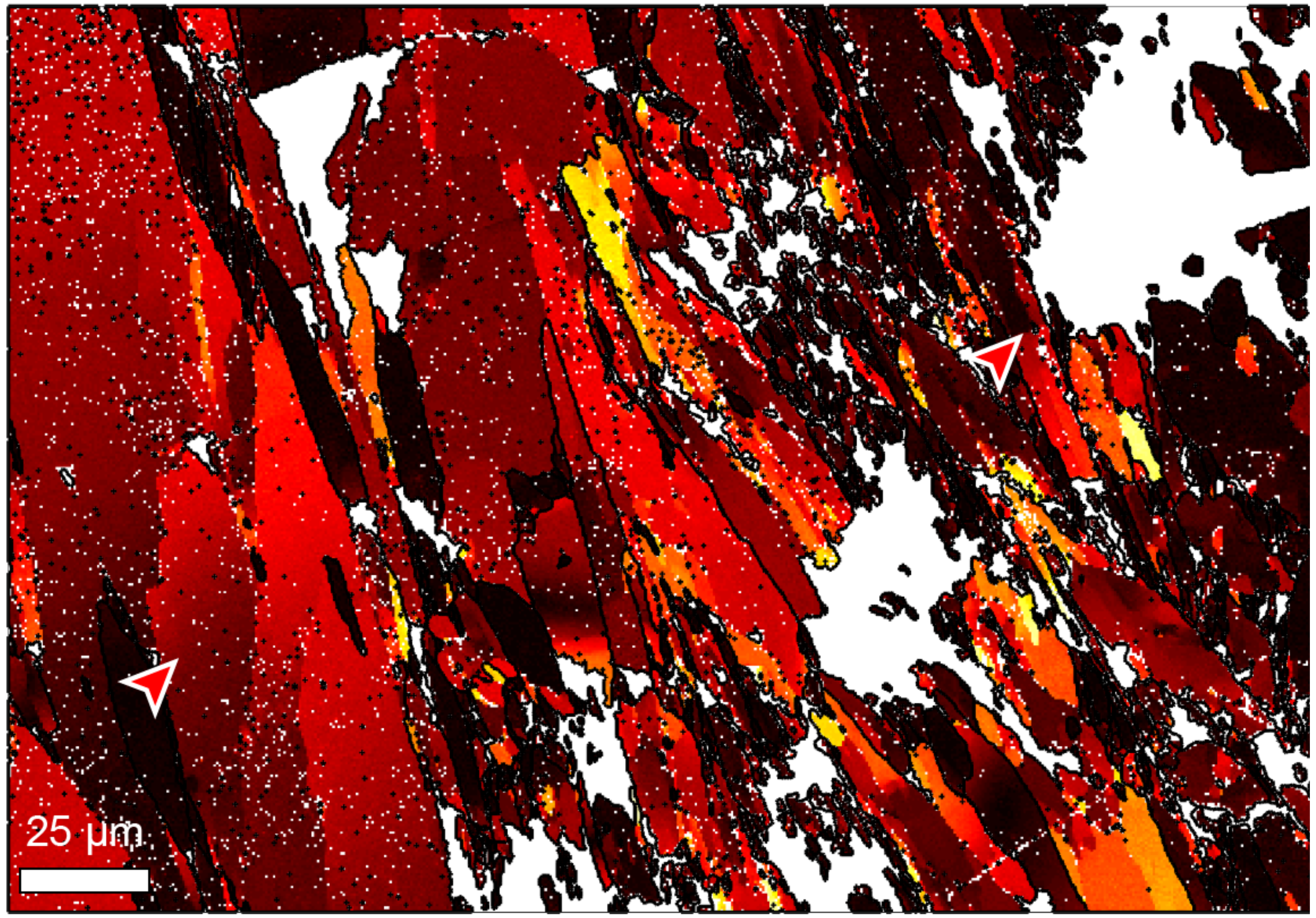
Actinolite has subgrain formation and cataclastic features

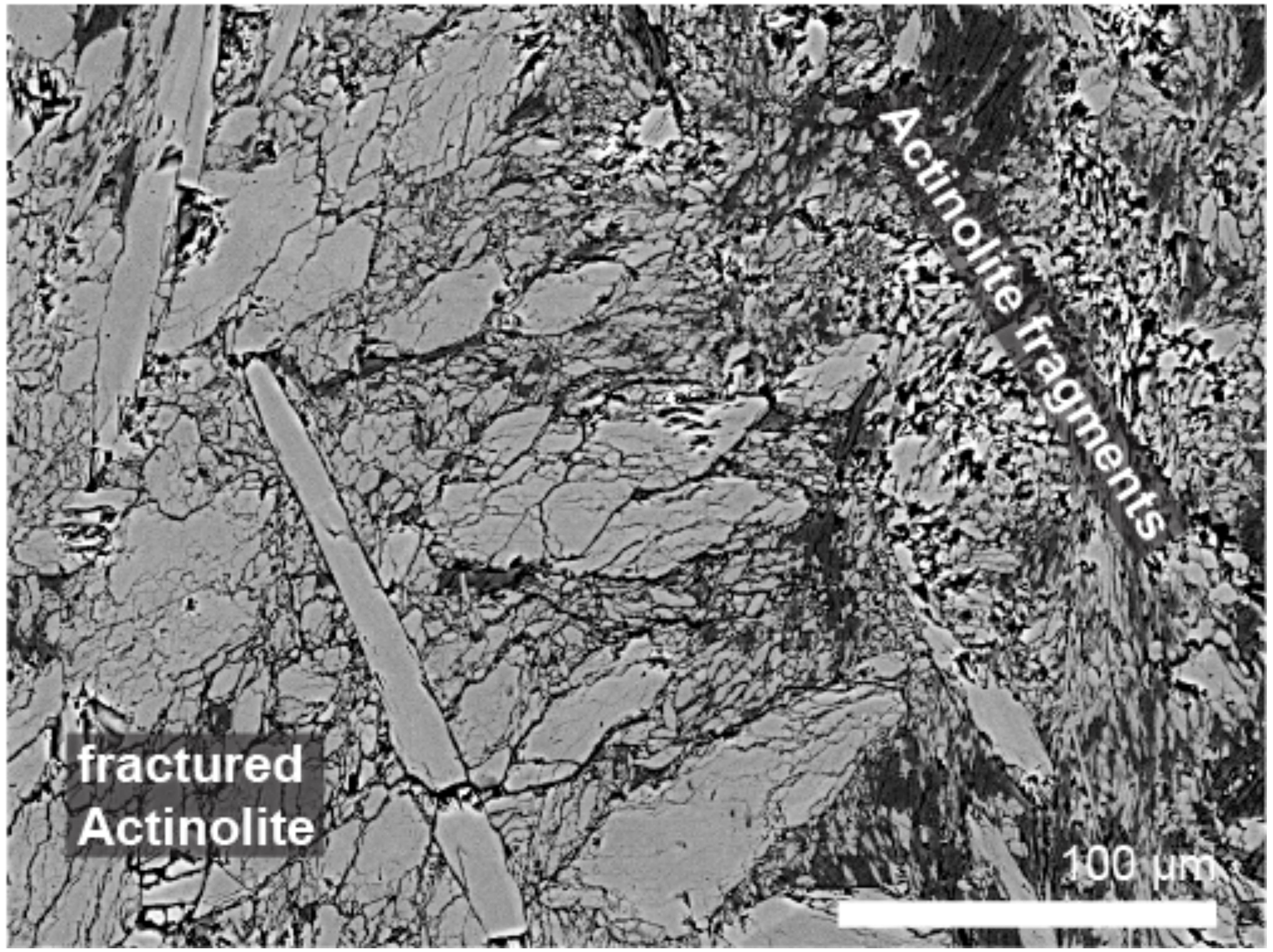
Hoover, Condit, et al; 2022 GRL

Talc-Actinolite Schist - Metasomatic with an ultramafic protolith

EBSD - how the crystal lattice is deformed BSE

Talc Schist





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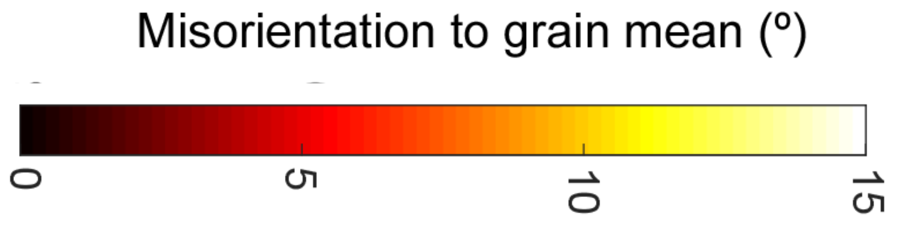
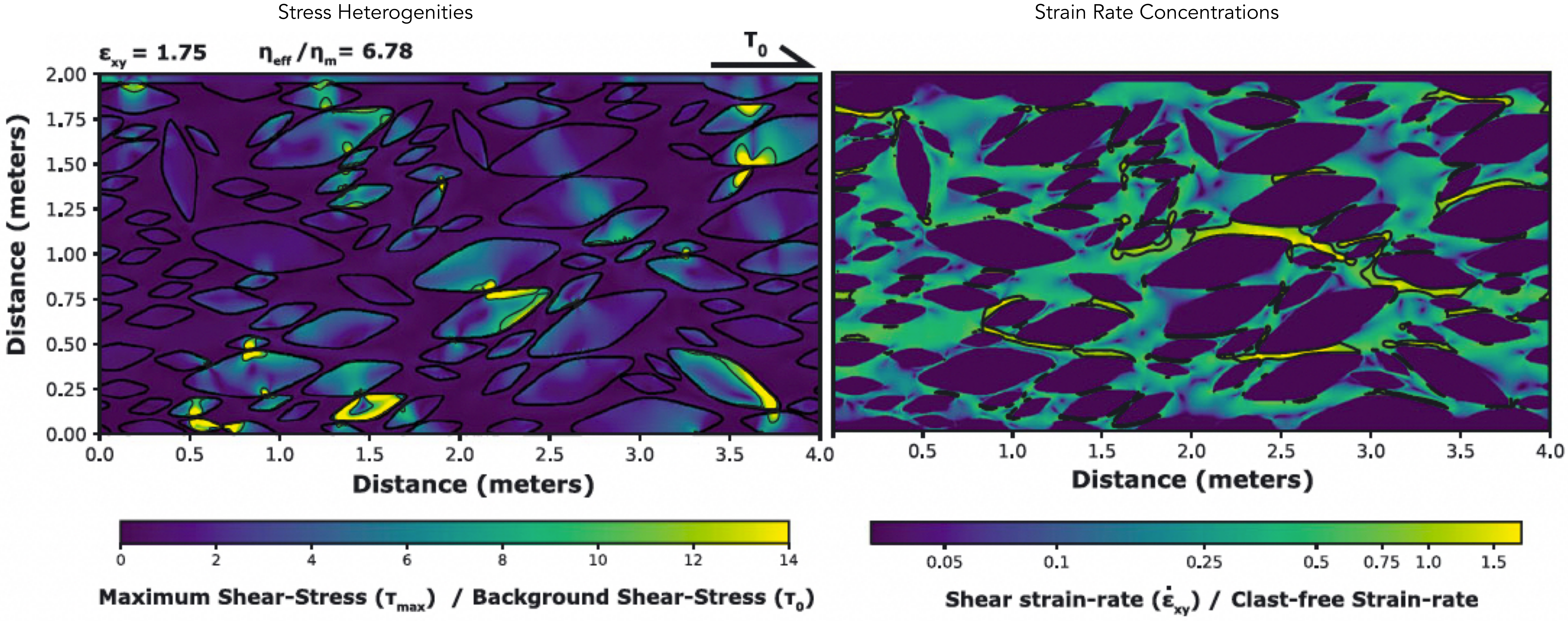


Hoover, Condit, et al; 2022 GRL

Actinolite has subgrain formation and cataclastic features

Actinolite deforming by ~higher stress mechanisms

Geodynamic models of stress amplifications in block and matrix structures

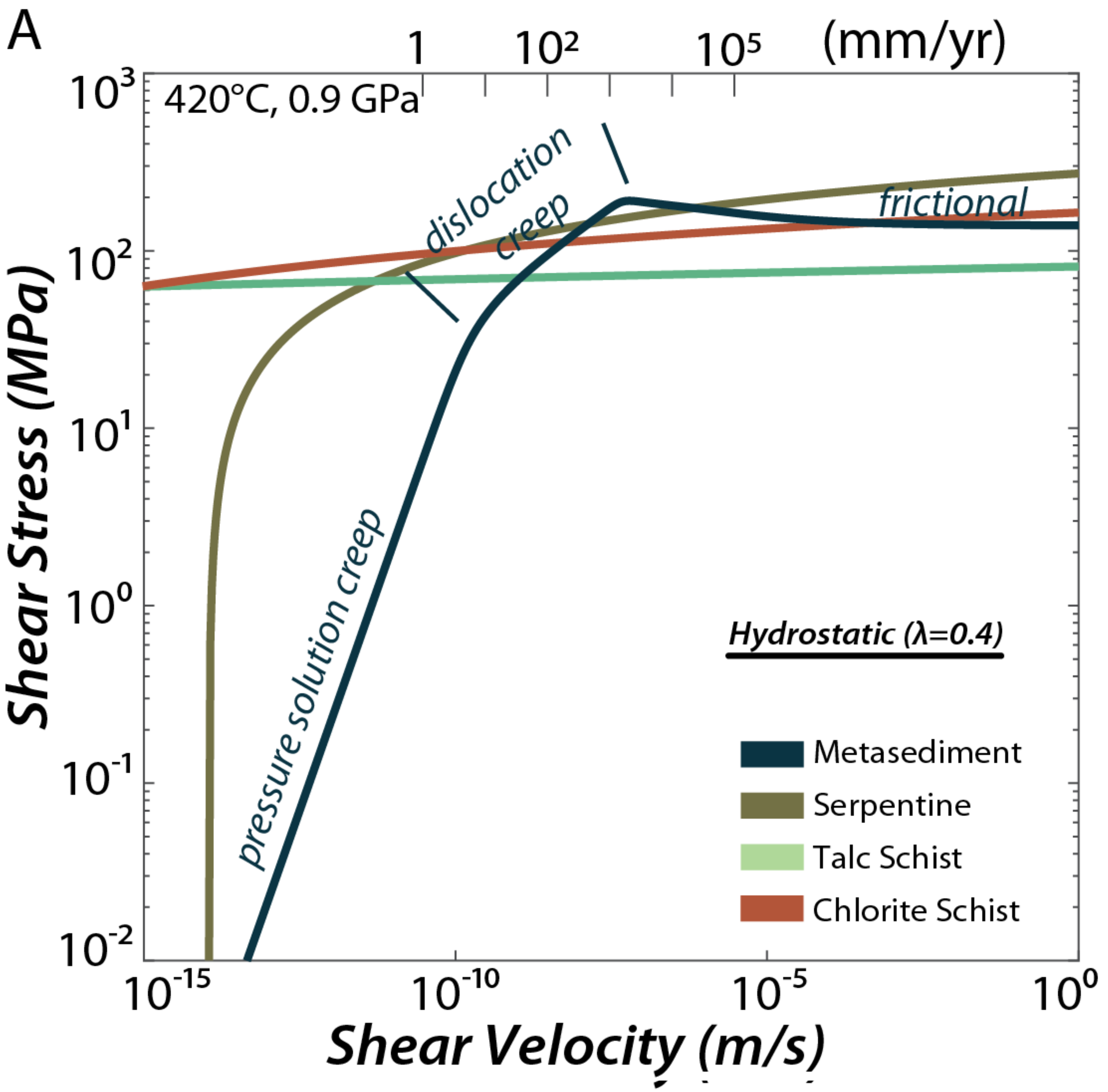


Stress amplifications in melange matrix:

Beall et al., 2019, GRL

- Weak matrix (in our case Talc) can localize strain and deform quickly
- Create force chains + high stress zones in stronger blocks (in our case actinolite)

How weak might the talc be?



Experimental studies: talc is very weak, frictional deformation is important at a range of P-T conditions

Horn & Skemer, 2023, Boneh et al., 2023

After French & Condit, 2019

Hoover, Condit, and Cross in prep

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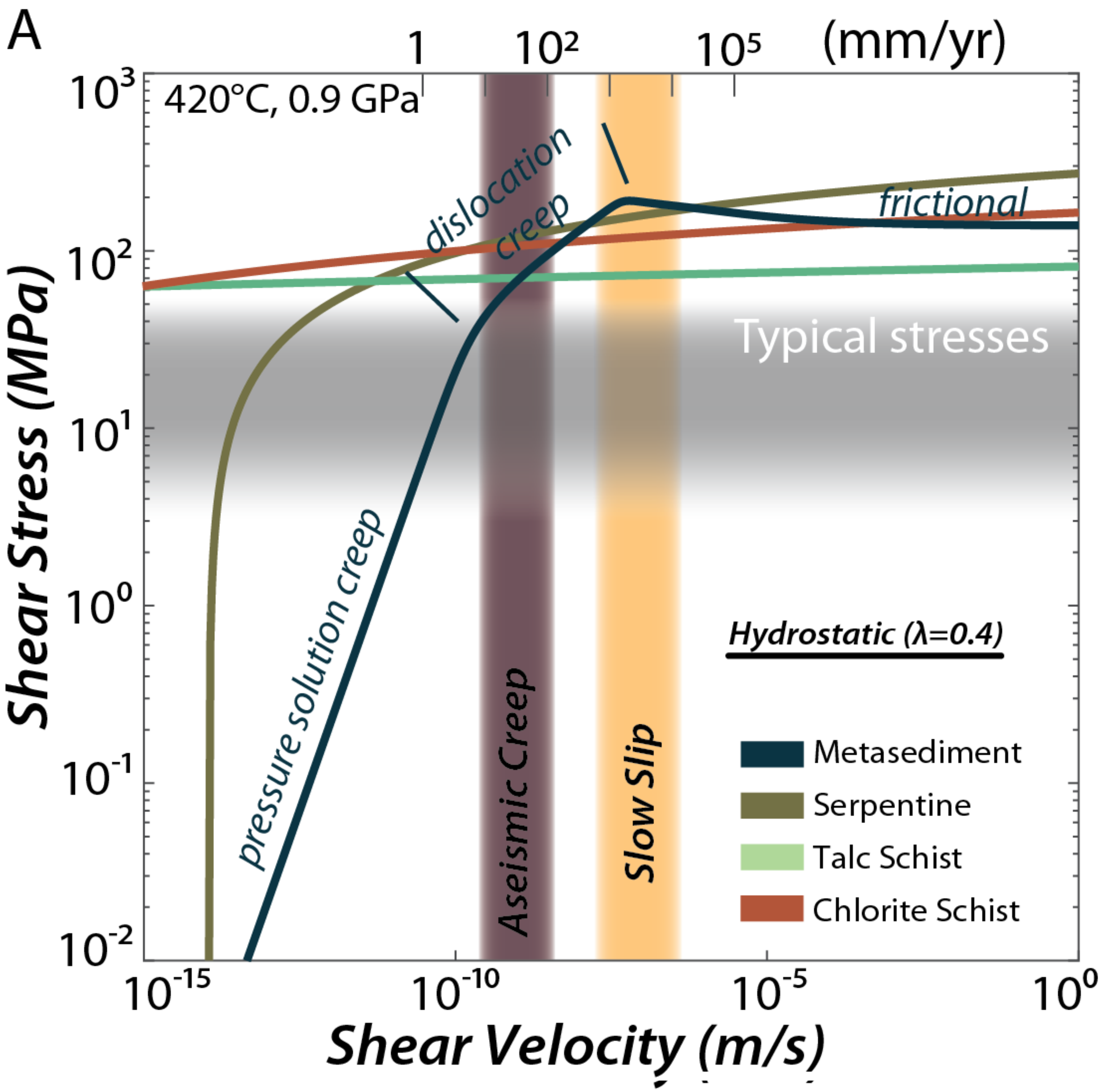

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Aseismic creep and **slow slip** velocities

Hydrostatic P_f - high stresses

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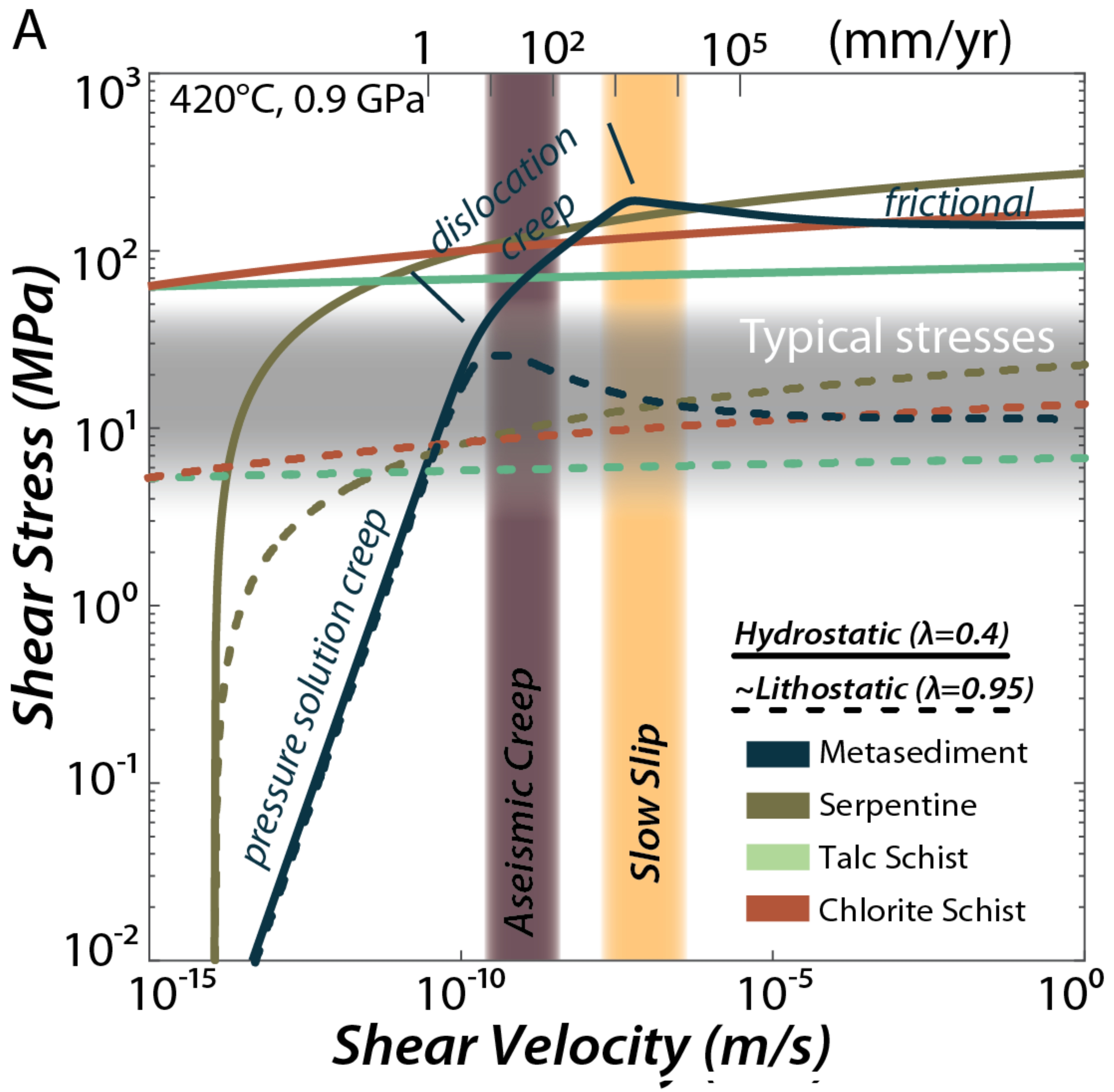
How weak might the talc be? Can it host slow earthquakes with high Pf?



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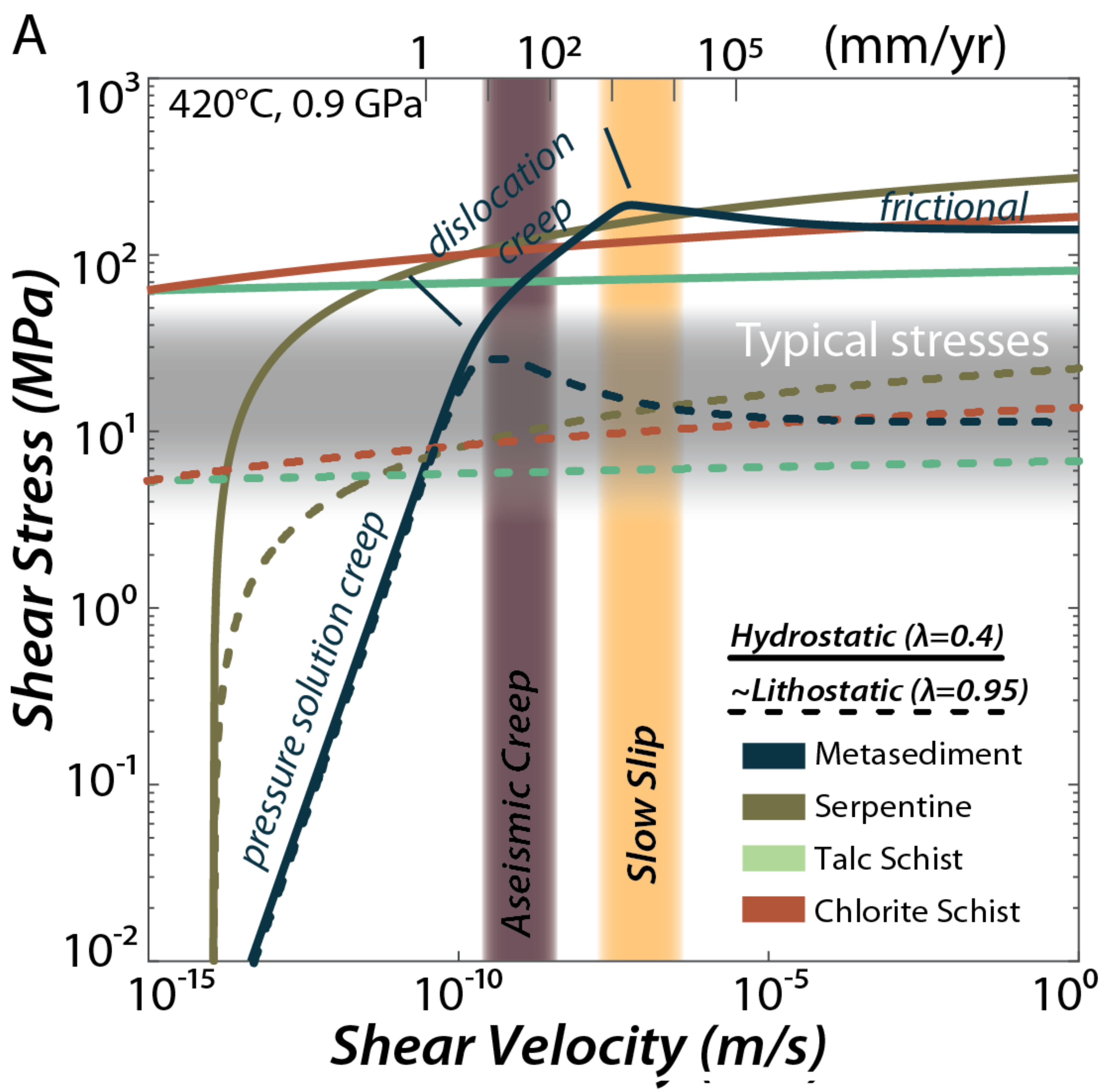

If Pf are ~lithostatic, talc-schists could host slow slip events

Near lithostatic P_f - subduction zone stresses accommodate slow slip with frictional deformation

After French & Condit, 2019

Hoover and Condit., in prep

Observations from the exhumed rock record from the base of the subduction seismogenic zone

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Evidence for brittle deformation (seismic slip?) at these deep depths intimately related to fluid process

Ios Island, Greece
Cycladic Blueschist Unit

Mutually crosscutting relationships between early exhumation subduction fabrics and quartz veins ± pseudotachylyte (?)

Fluids appear intimately related to brittle failure ± seismic slip at ~400 °C, 0.8-1.0 GPa (~25-35 km depth)

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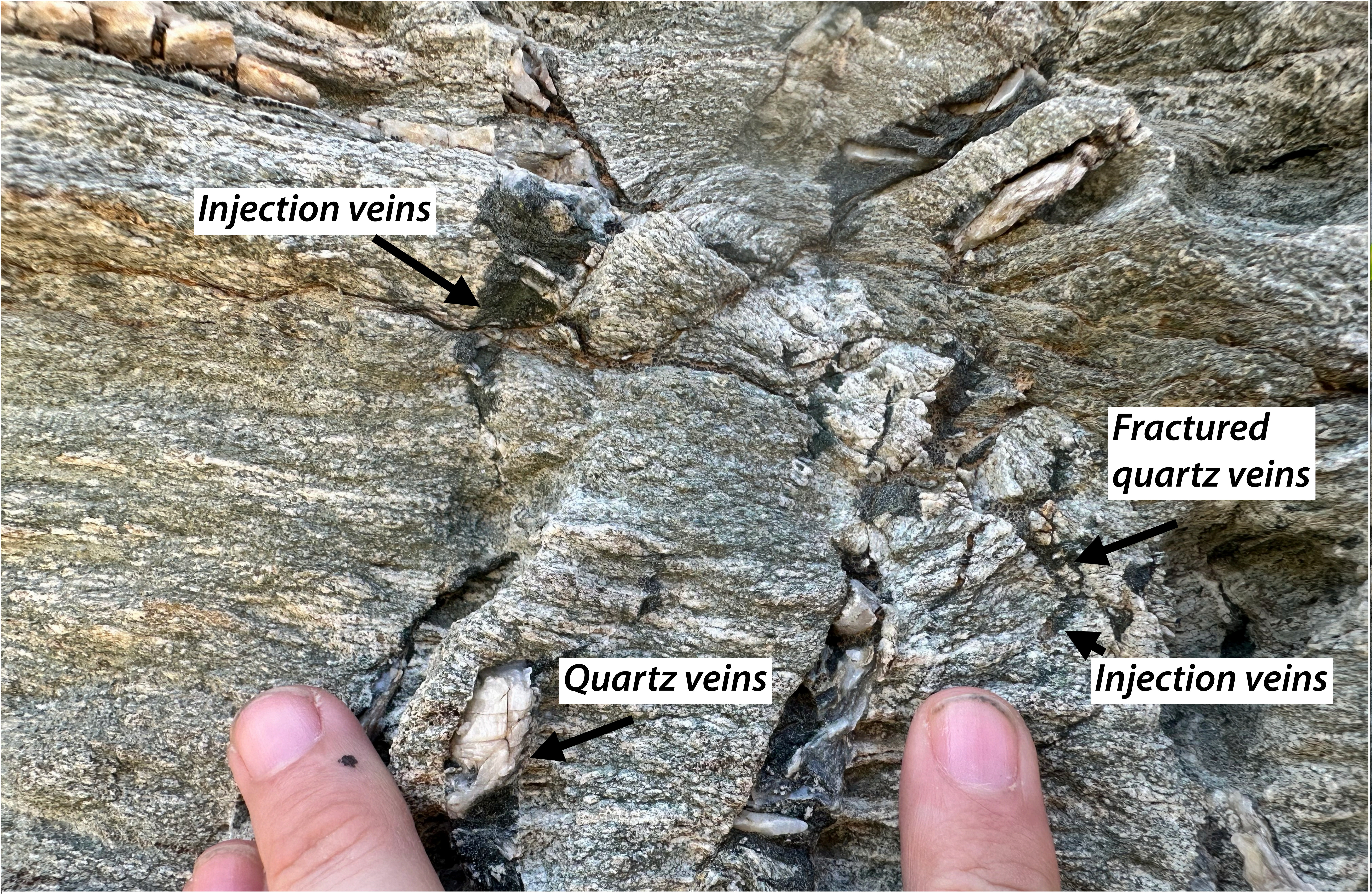

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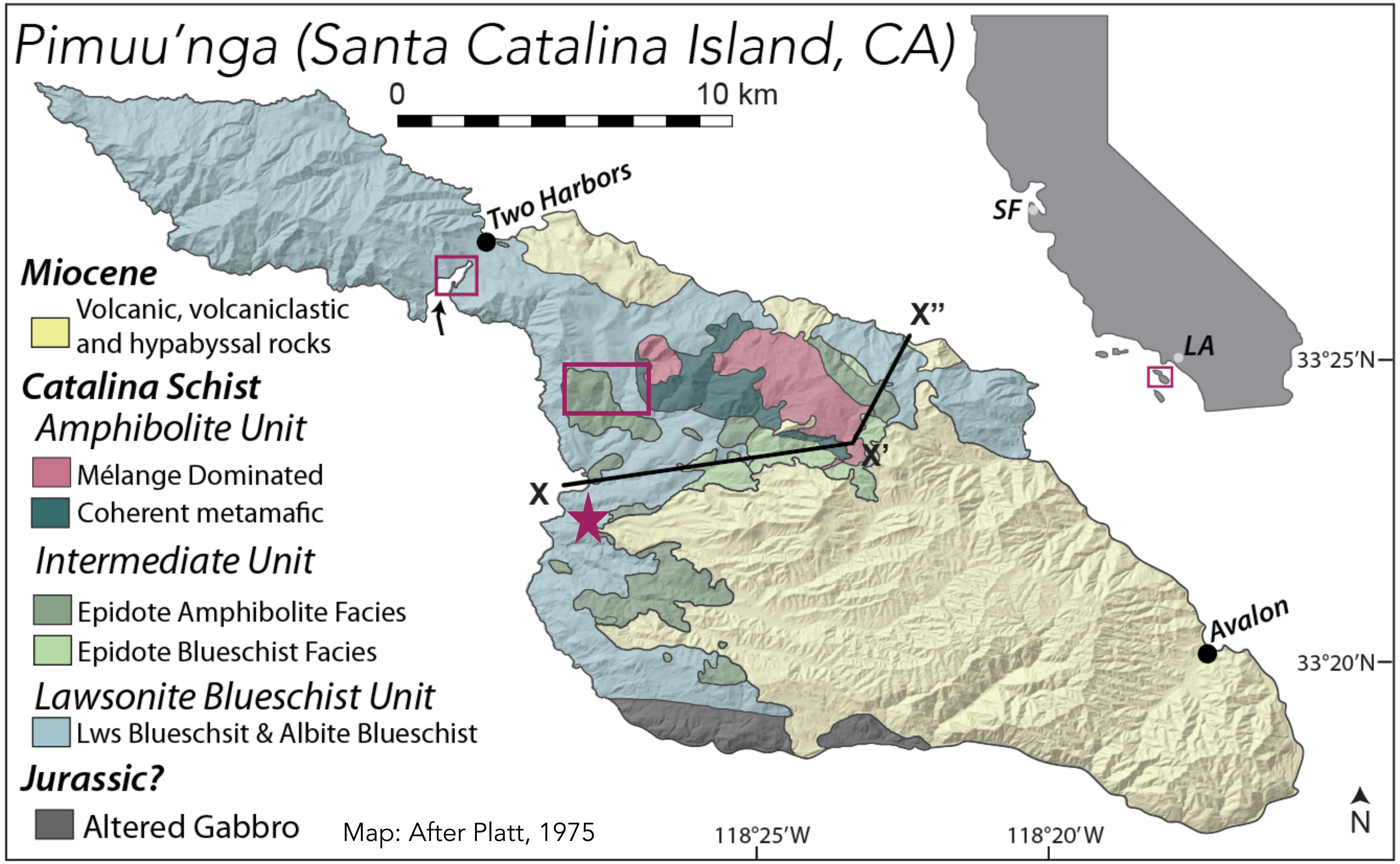
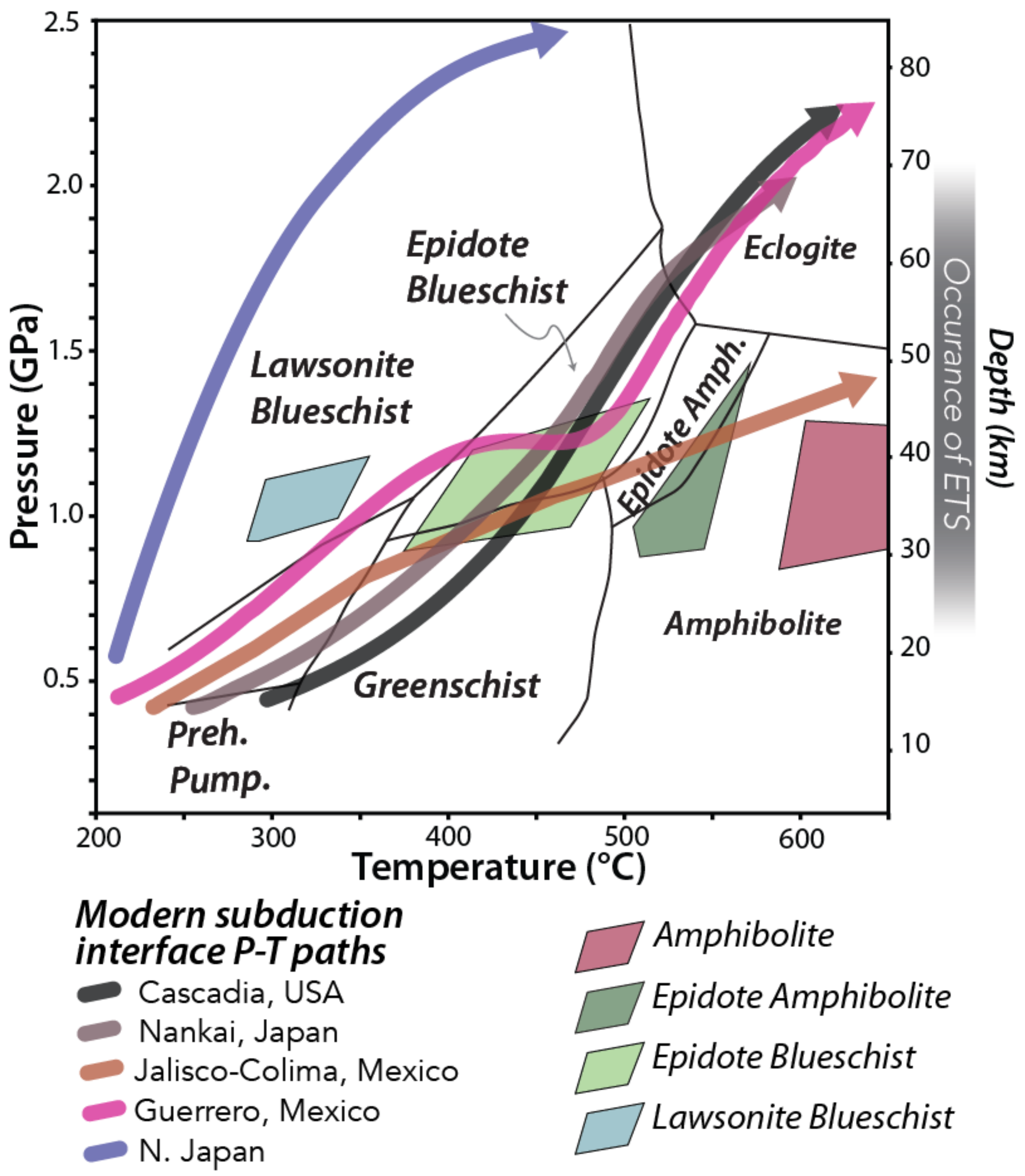
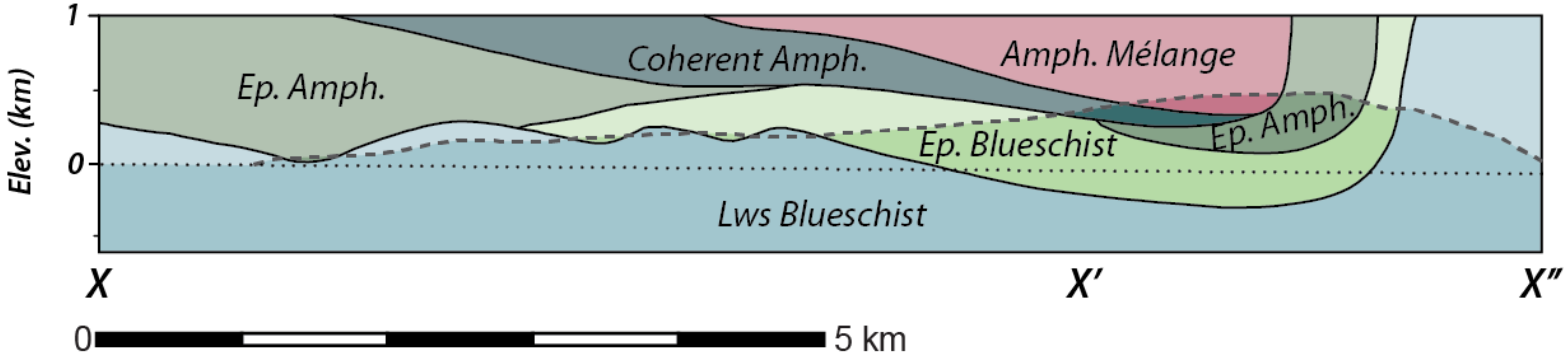


Map: After Platt, 1975





Cross-section: Platt and Schmidt, 2024

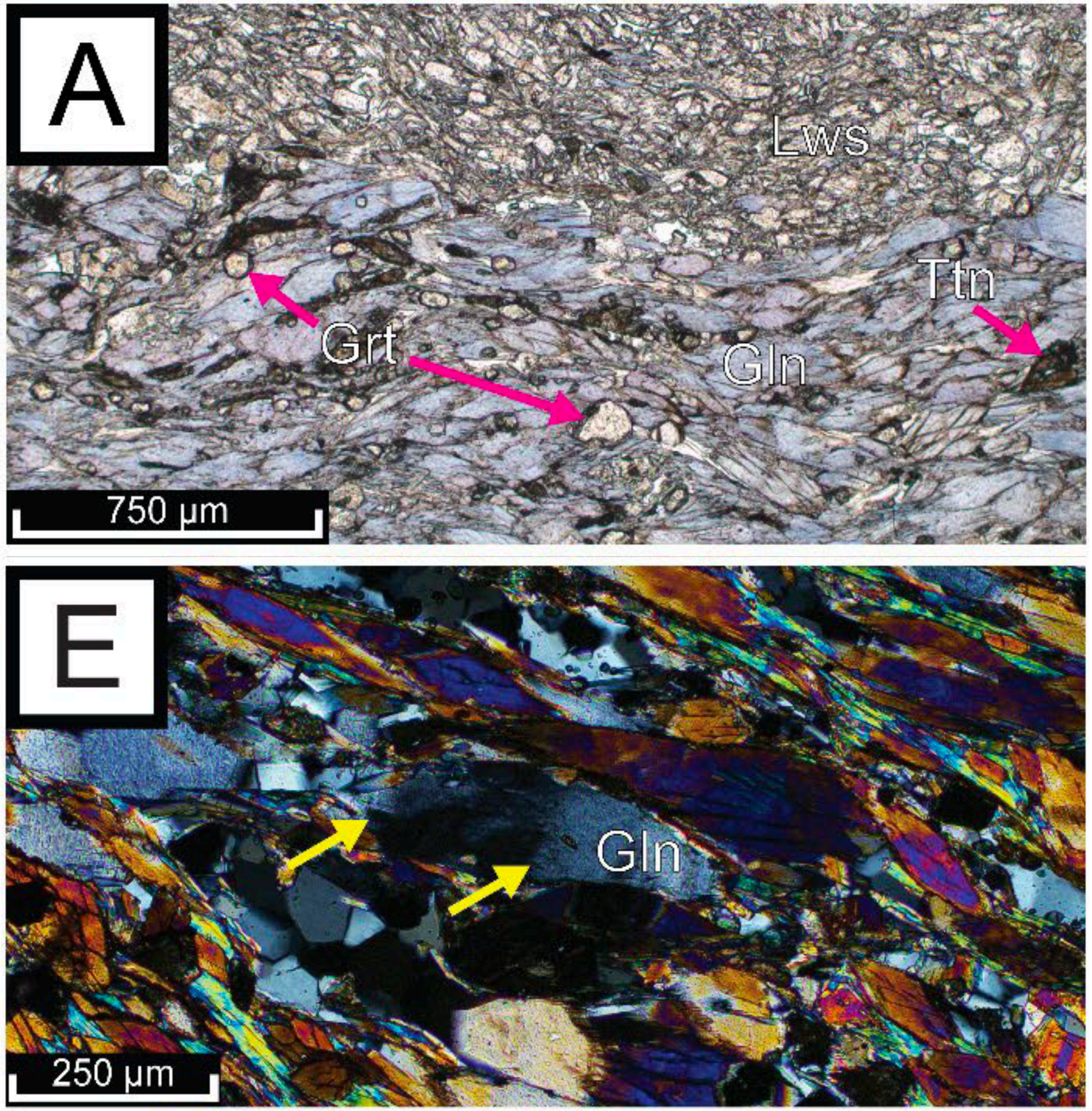
Lawsonite blueschist unit - ~1.0 GPa (30-35 km) and ~320-330 °C

Temperatures: Platt and Schmidt, 2024

Dislocation to diffusive mechanism shift in glaucophane

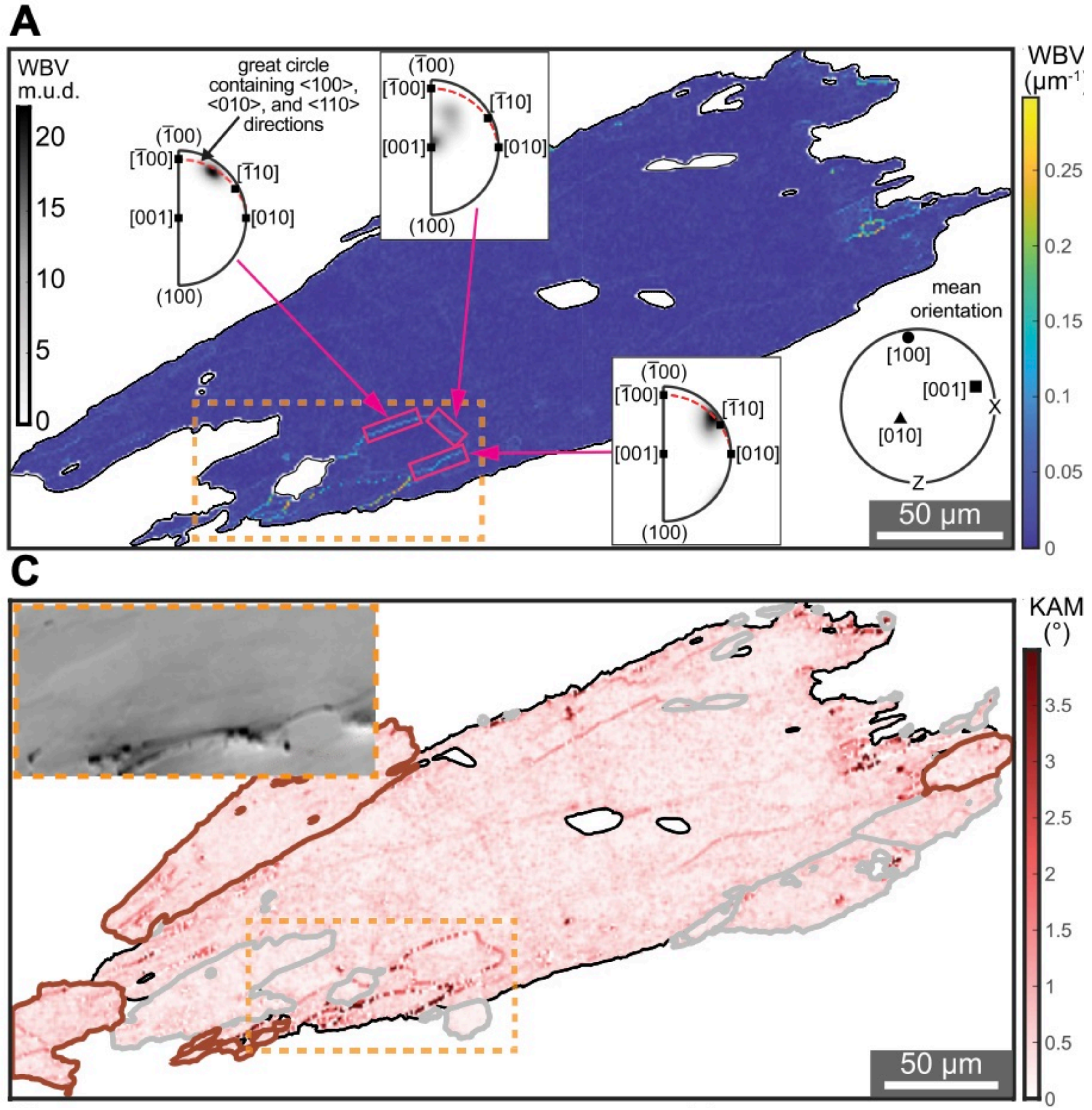
Mafic blueschists (the metamorphosed slab) accommodate a lot of deformation; Gluacophane (sodic amphibole) the main strain accommodating phase.

How does glaucophane deform?

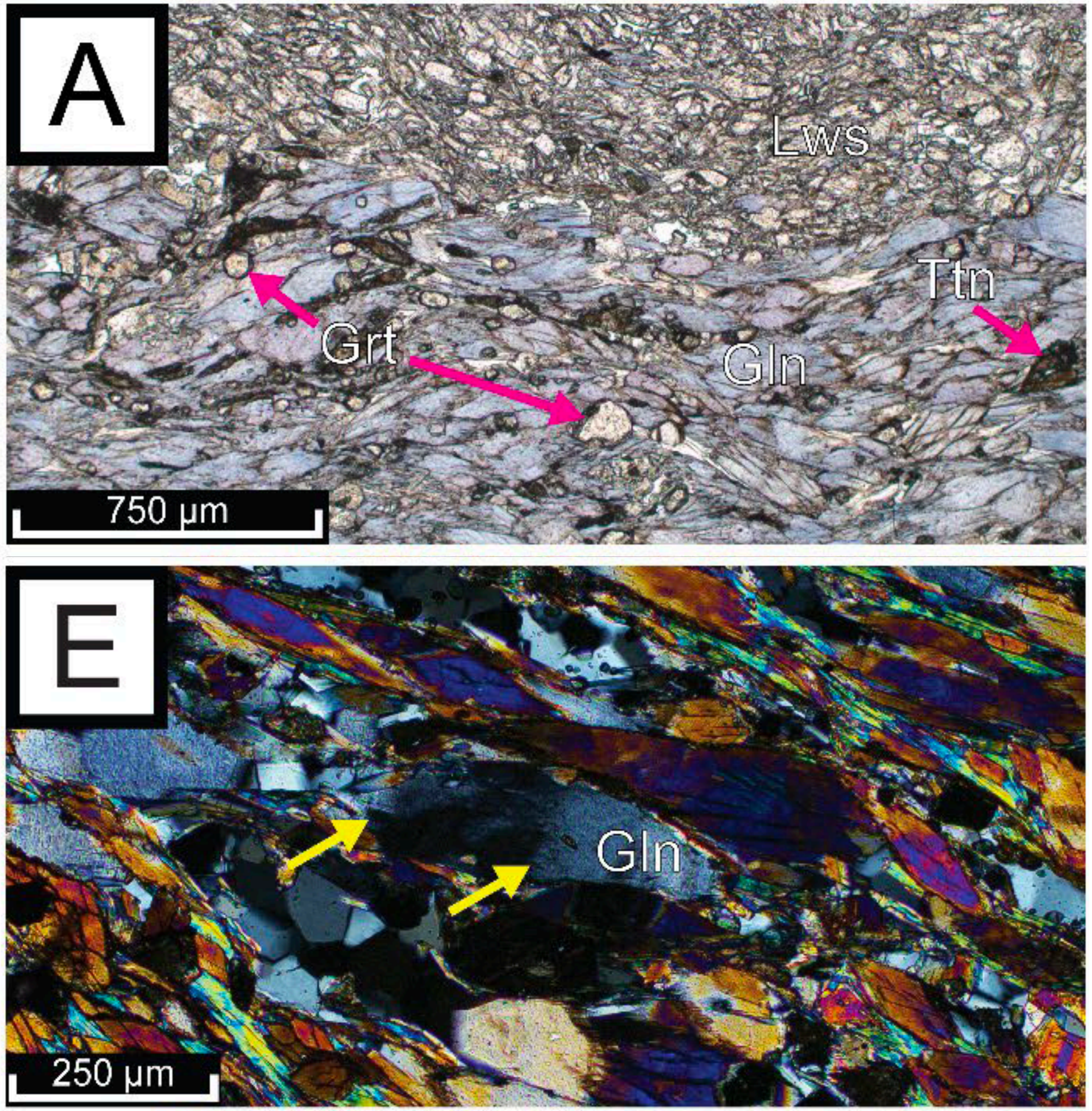


Ott, Condit et al., 2025 Geology

Dislocation to diffusive mechanism shift in glaucophane

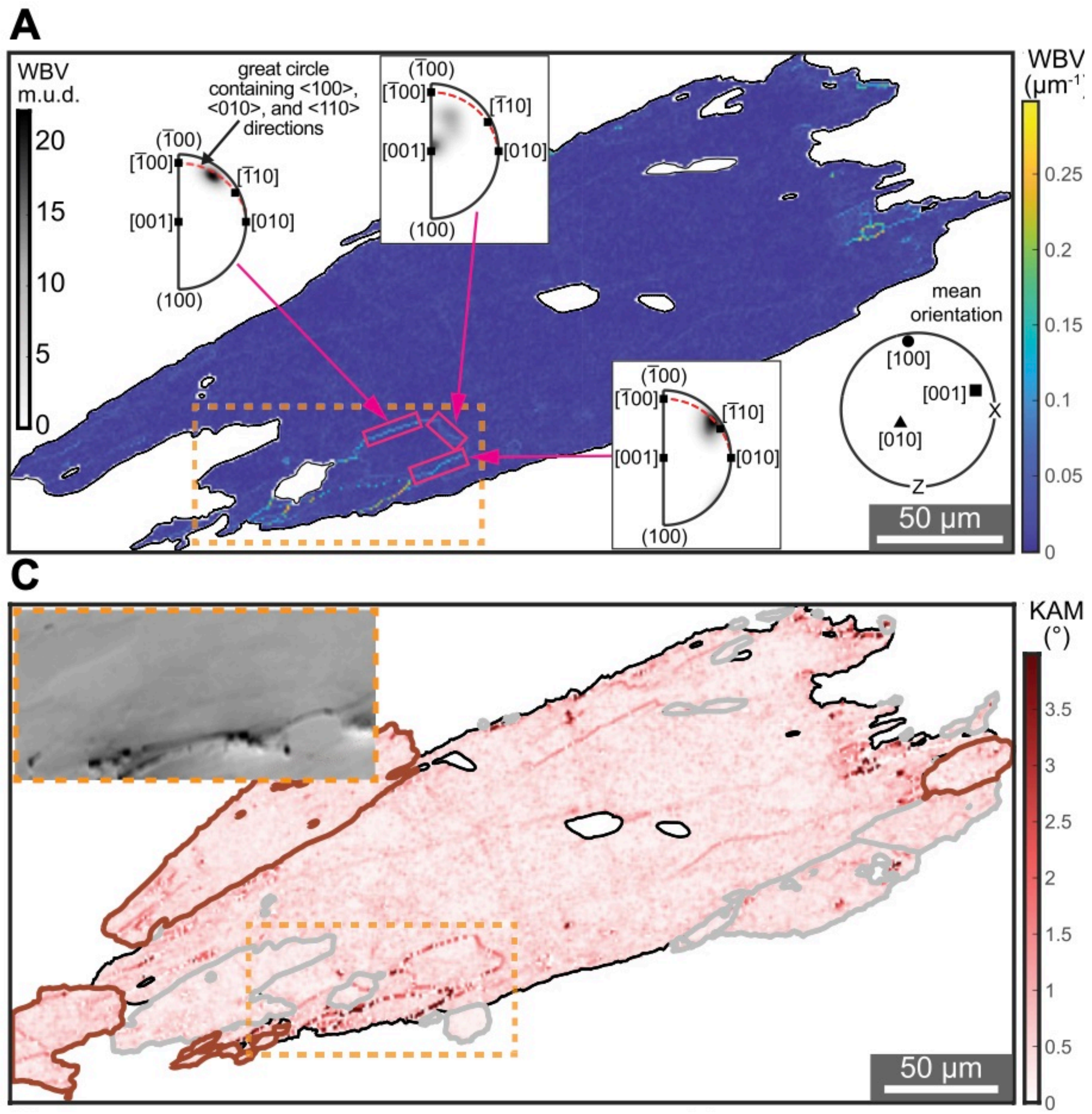


Weighted Burgers vector analysis shows multiple slip systems active - Dislocation creep



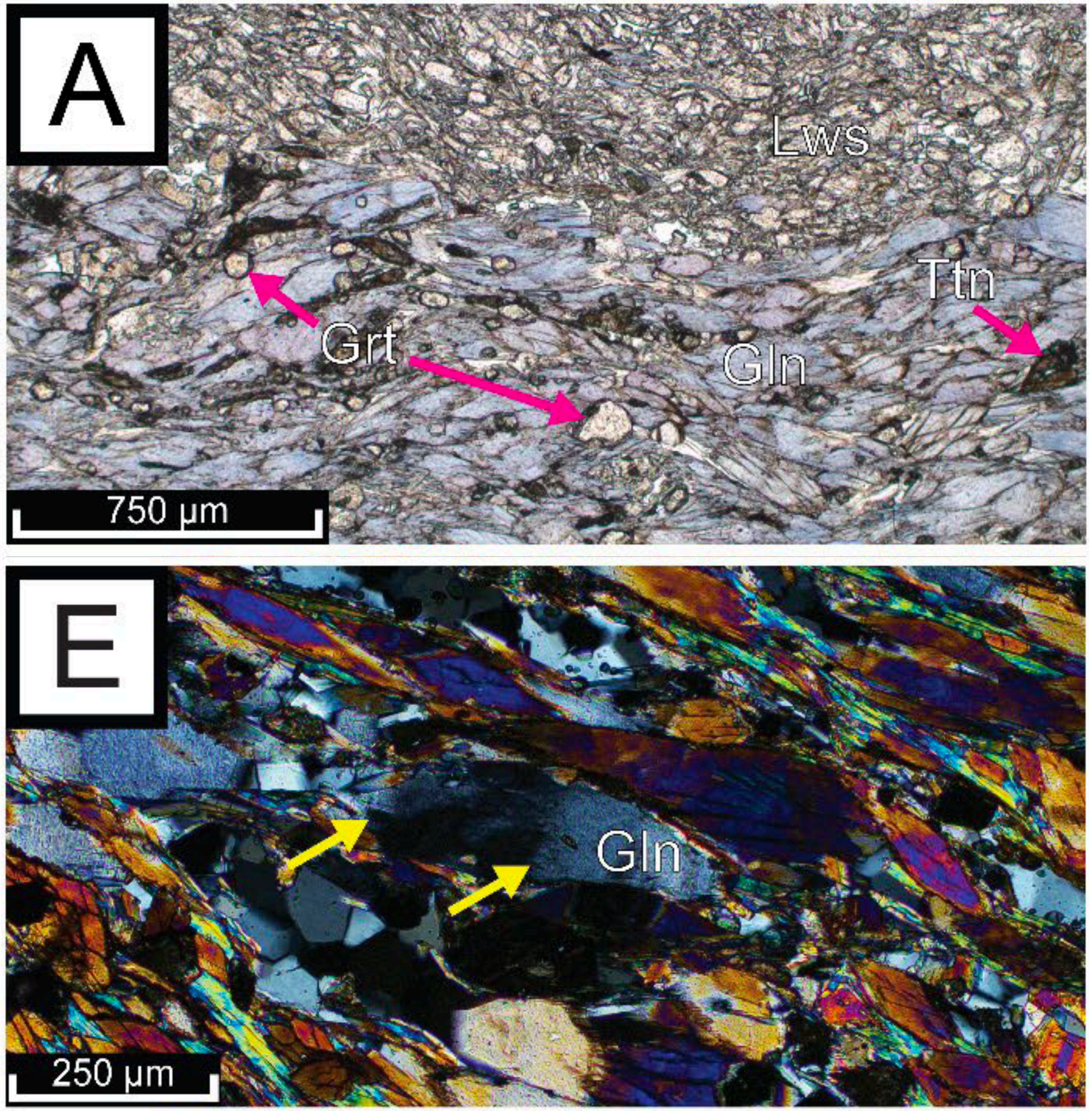
Ott, Condit et al., 2025 Geology

Dislocation to diffusive mechanism shift in glaucophane



Weighted Burgers vector analysis shows multiple slip systems active - Dislocation creep

Griggs type experiments reveal n = 5; flow law in prep.
Work of Jason Ott (Ott, Condit, & Pec, *in prep)*



Ott, Condit et al., 2025 Geology

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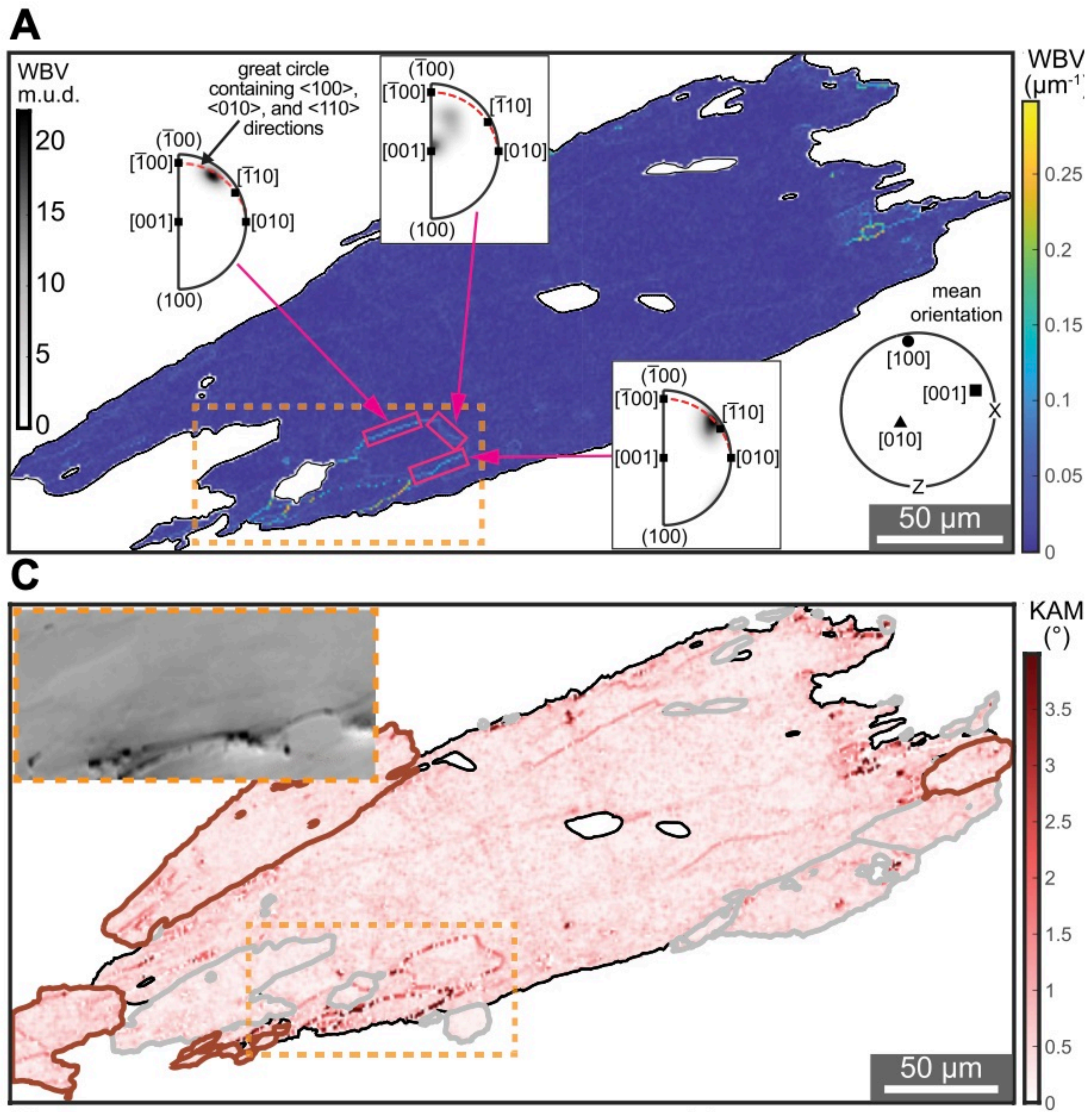
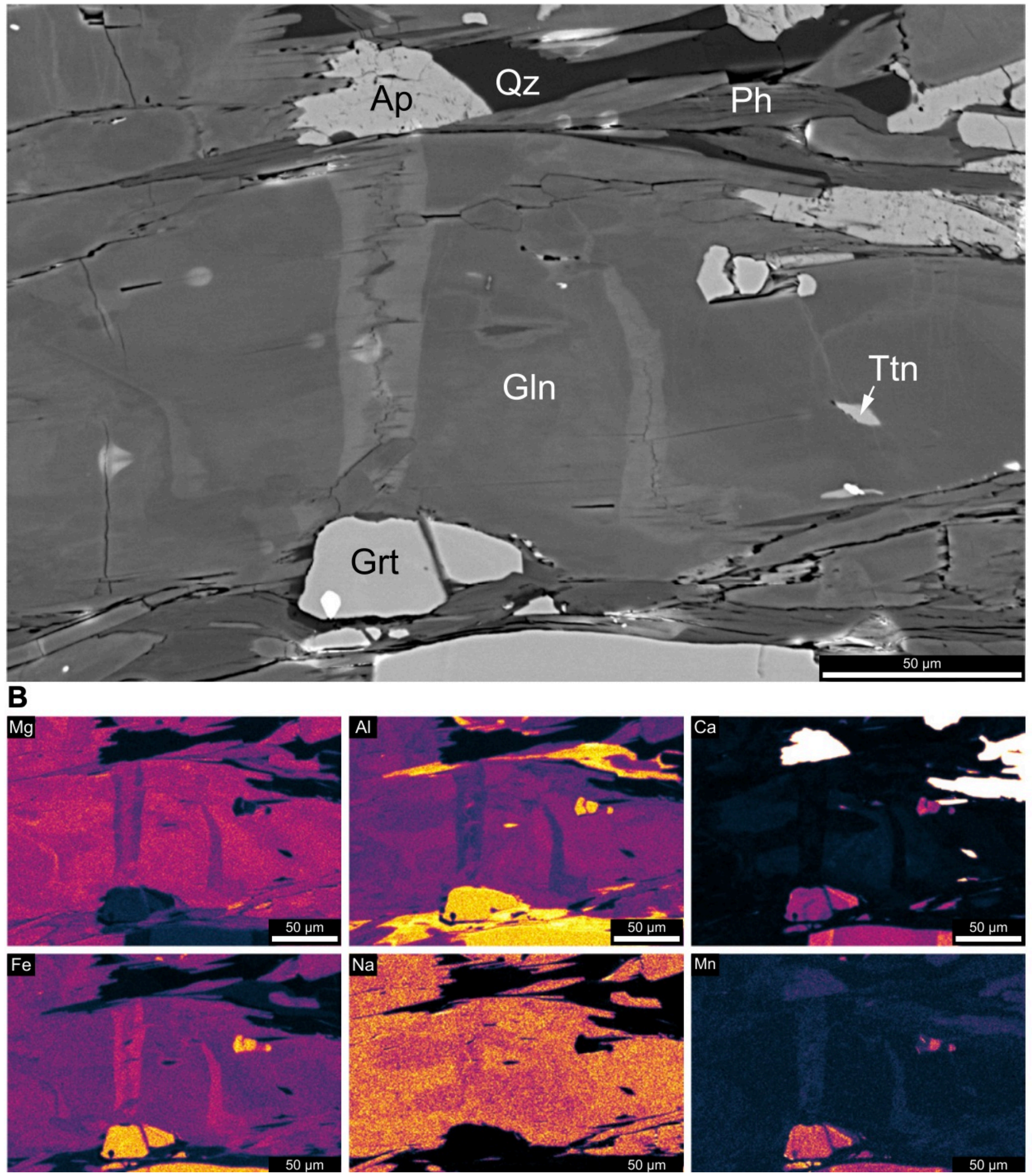


Weighted Burgers vector analysis shows multiple slip systems active - Dislocation creep



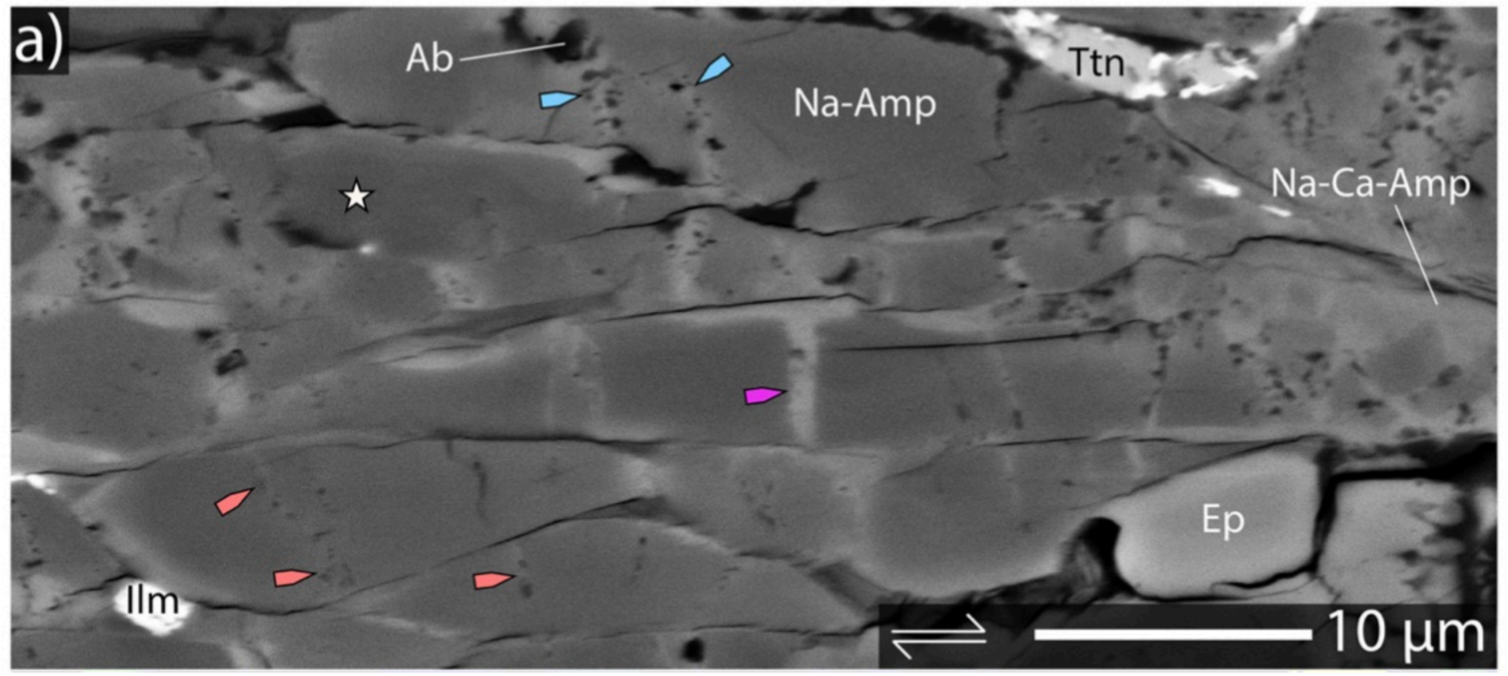
Later microboudinage; new amphibole growth with fluid infiltration and chemical potential gradients - reactive fluids and/or shift in P-T conditions

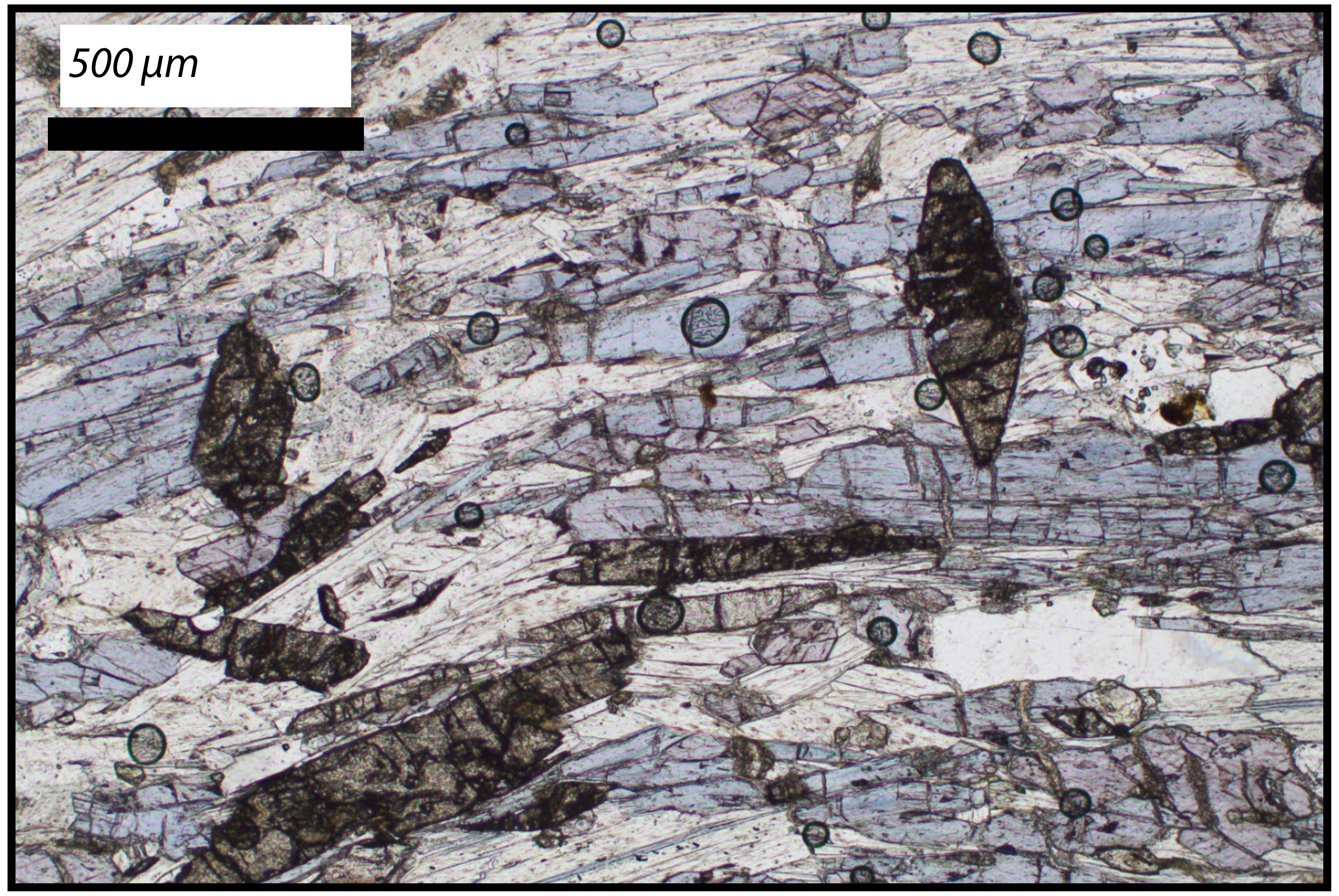
Griggs type experiments reveal n = 5; flow law in prep.
Work of Jason Ott (Ott, Condit, & Pec, *in prep)*

Ott, Condit et al., 2025 Geology

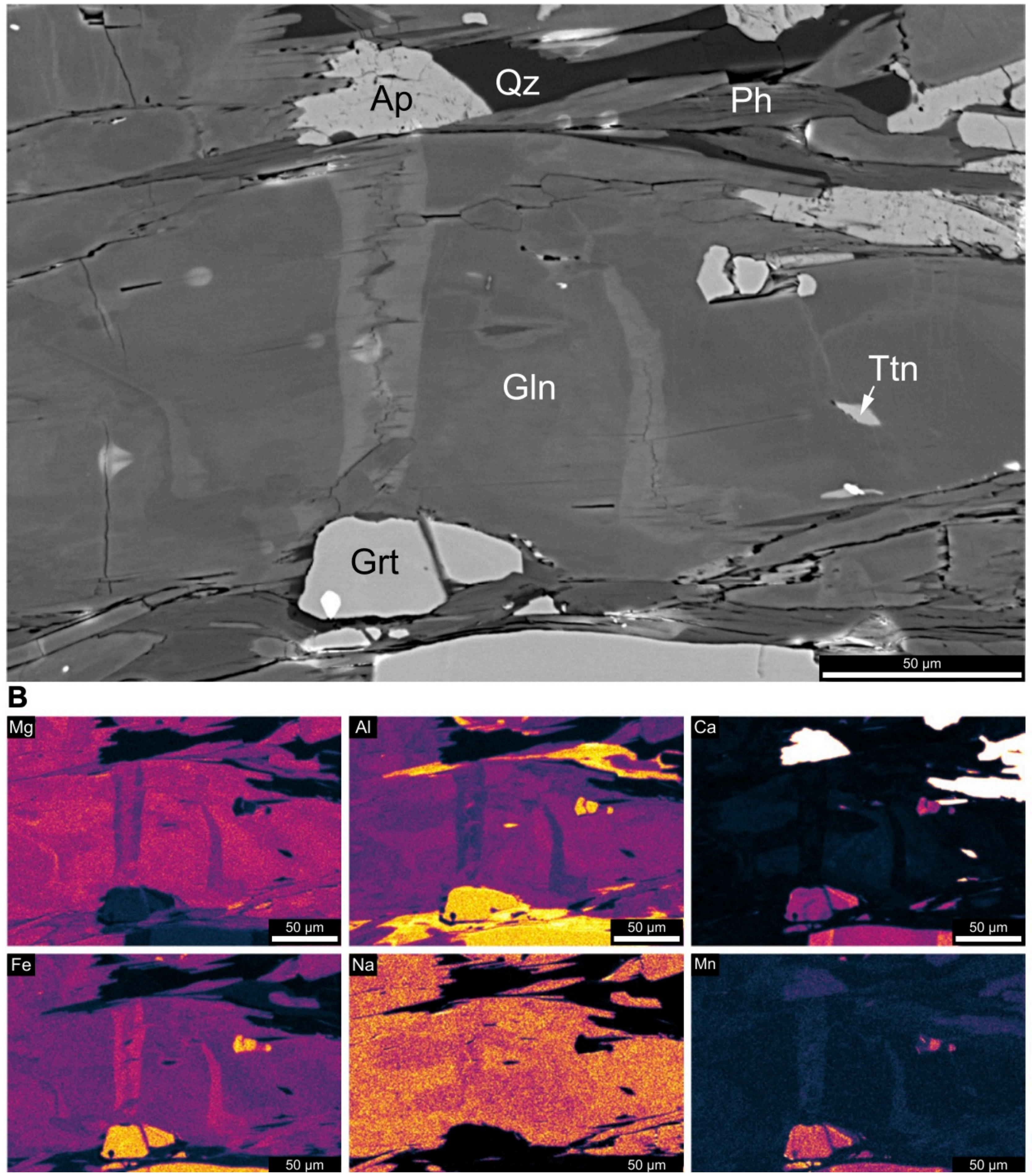
Dislocation to diffusive mechanism shift in glaucophane

Seen experimentally by Tokle et al., 2023; n = 2





Seen during early exhumation on Sifnos, Island, GR
(~1.2 GPa; 400°C + H_2O & CO_2 fluid)



Later microboudinage; new amphibole growth with fluid infiltration and chemical potential gradients - reactive fluids and/or shift in P-T conditions

Ott, Condit et al., 2025 Geology