Microscale stress heterogeneities: Mechanical, rheological, and mineralogical impact

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1 Introduction

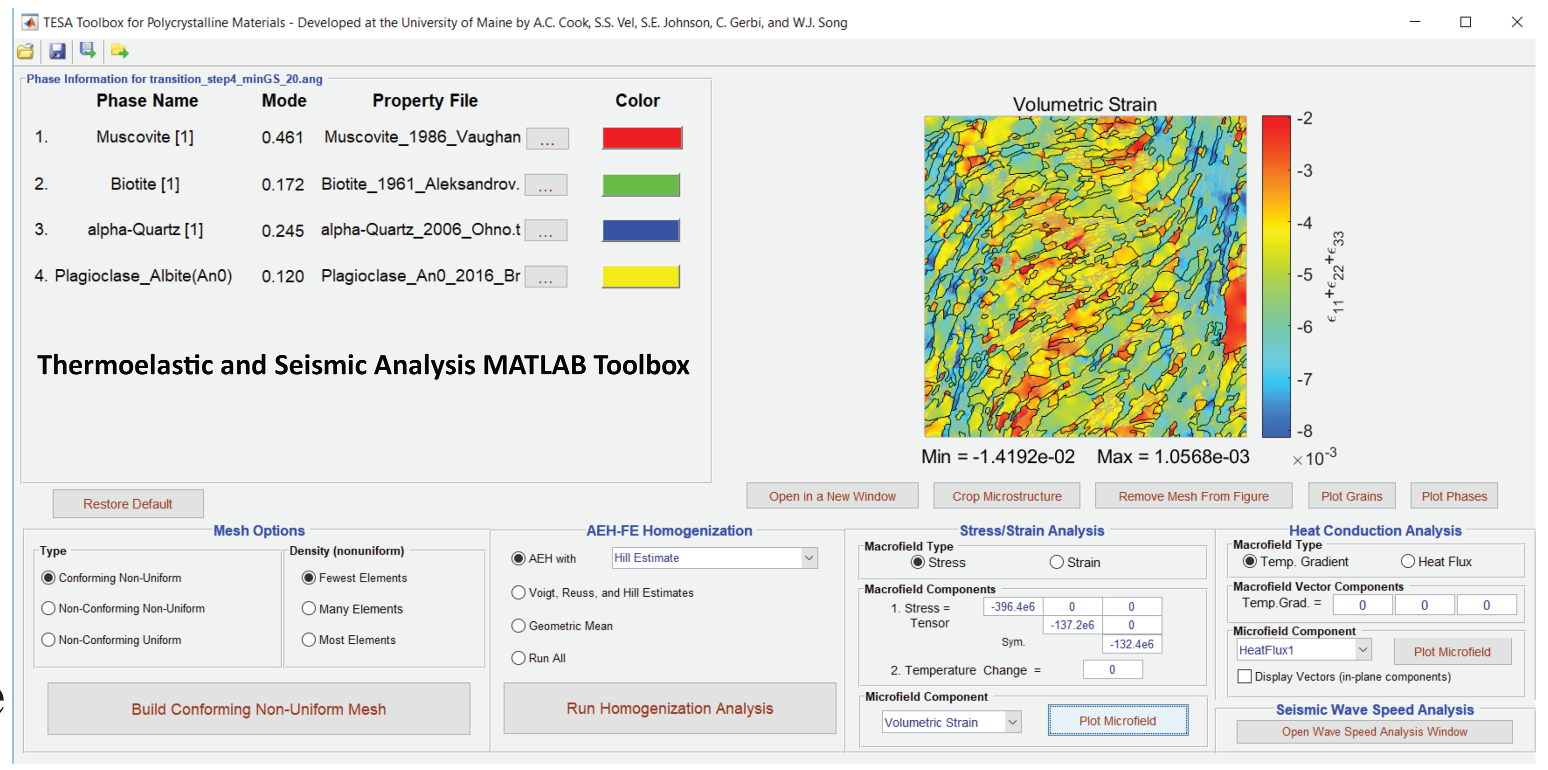
The roots of lithospheric rheology lie at the grain scale, where mineral assemblages and microstructure respond to their environment. Phase shapes, distributions, and orientations transform macroscale loading into microscale stress and strain(-rate) fields, which in turn feed back to the macroscale response. Because of the heterogeneity induced by the inherent anisotropy of rock microstructure, these microscale fields can vary significantly from the bulk conditions. We present some examples of how microscale stresses influence microstructural evolution and rock rheology.

SOFTWARE TOOLS
https://umaine.edu/mecheng/vel/software/

ThermoElastic and Seismic Analysis Toolbox (TESA)
- Grain-scale distribution of elastic properties (Vel et al., 2016).
- Input: EBSD file and macroscale load or gradient,
- Process: Solves the 3-D anisotropic elastic equilibrium and thermal equations.

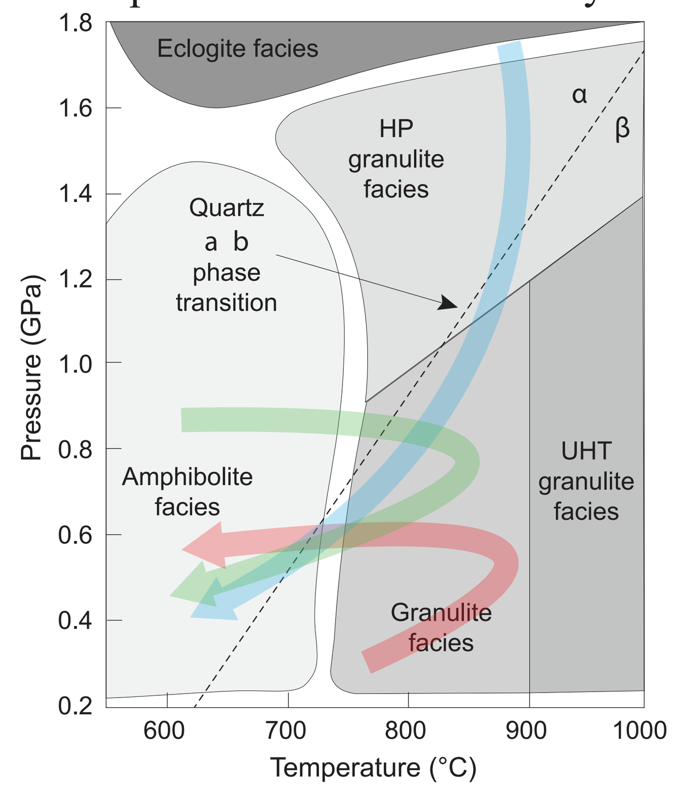
Power-law Creep Toolbox (PLC)
- Phase-scale distribution of viscous properties(Cook et al., 2014).
- Input: Image file and macroscale load
- Process: Iteratively solves the 3-D viscous equilibrium equations.

TESA interface



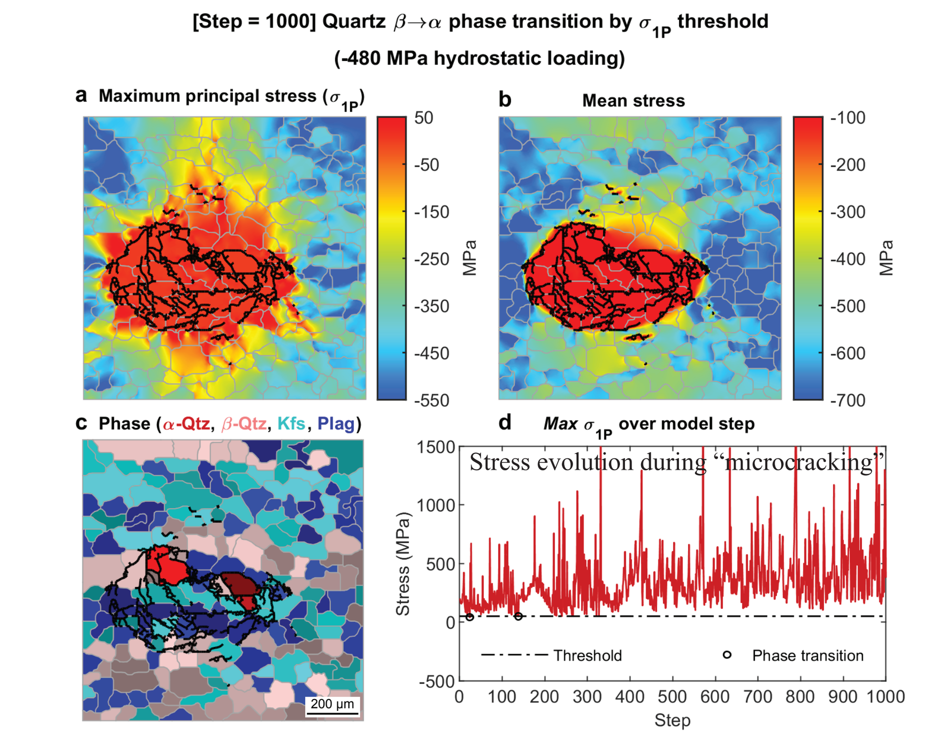
2 The Quartz α↔β Phase Transition and Crustal Damage

Experimental work has focussed on expansion during the up-temperature α→β transition. However, contraction during the down-temperature β→α transition can produce large tensile stresses due to the differences in elastic anisotropy and volume between the two phases. These stresses may lead to extensive microcracking, **changing the bulk mechanical and transport properties**.

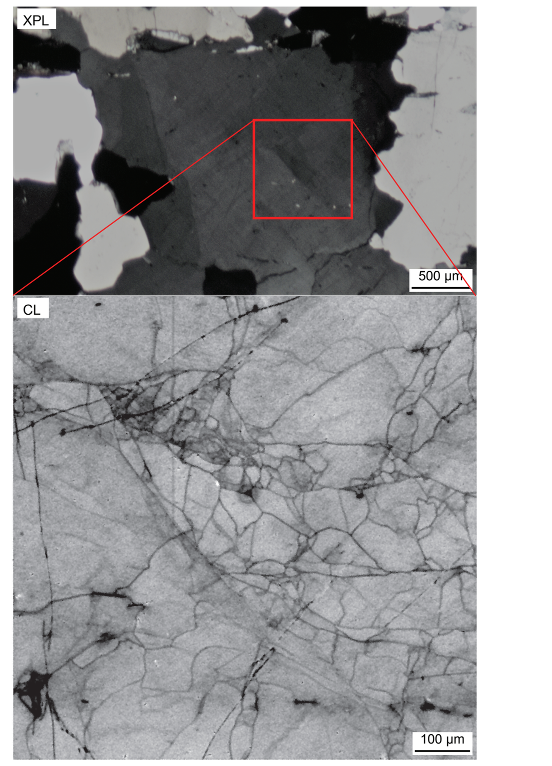


Several paths from the literature crossing the transition near the Granulite/Amphibolite boundary.

Johnson et al., in review.



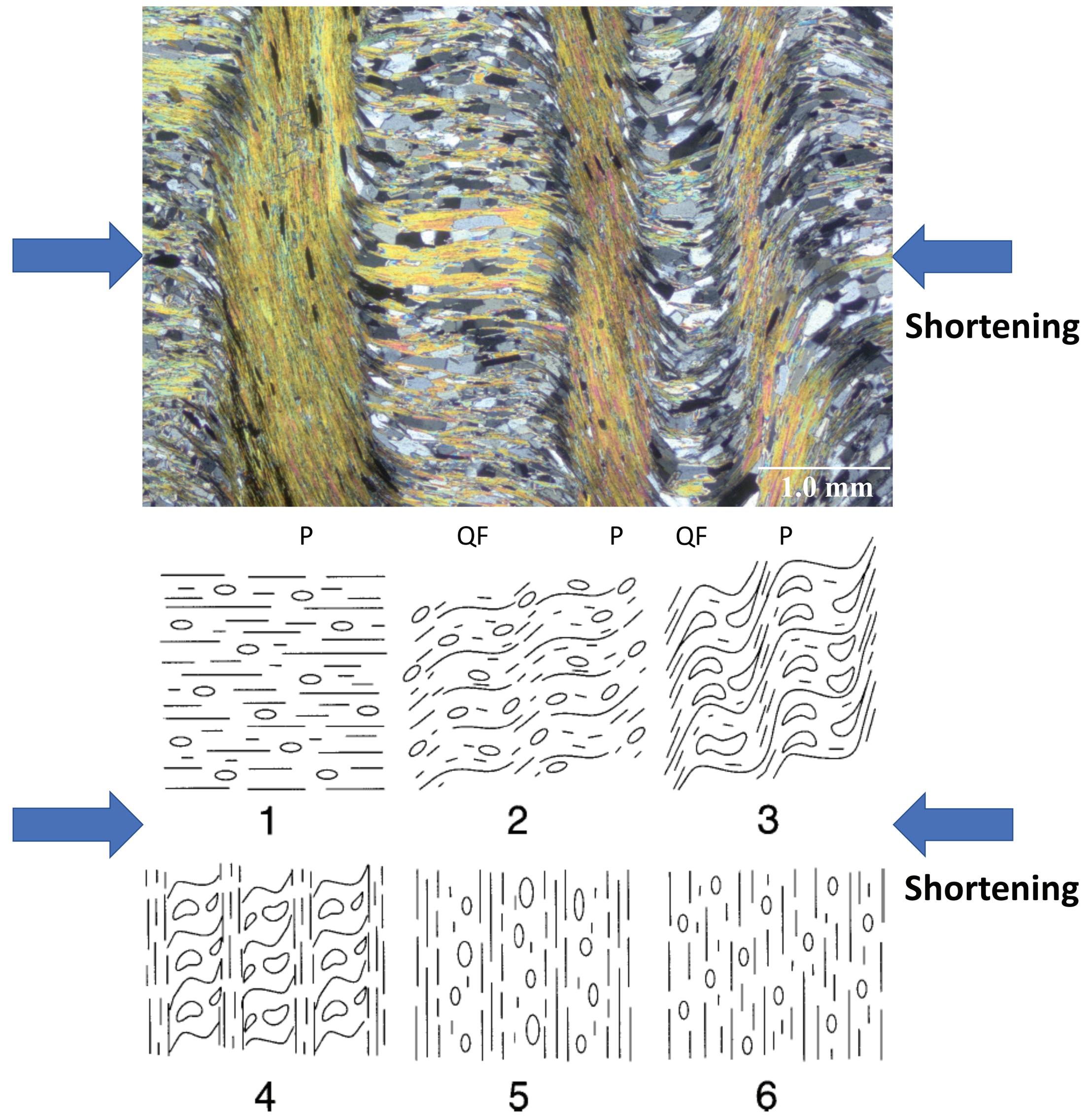
TESA simulation of the β→α transition and associated damage caused by local tensile failure under hydrostatic macroscale compression of -480 MPa. All quartz grains begin as β-quartz and all phases have a tensile strength of 50 MPa. The transformation of only 3 grains causes cascading failure in all phases.

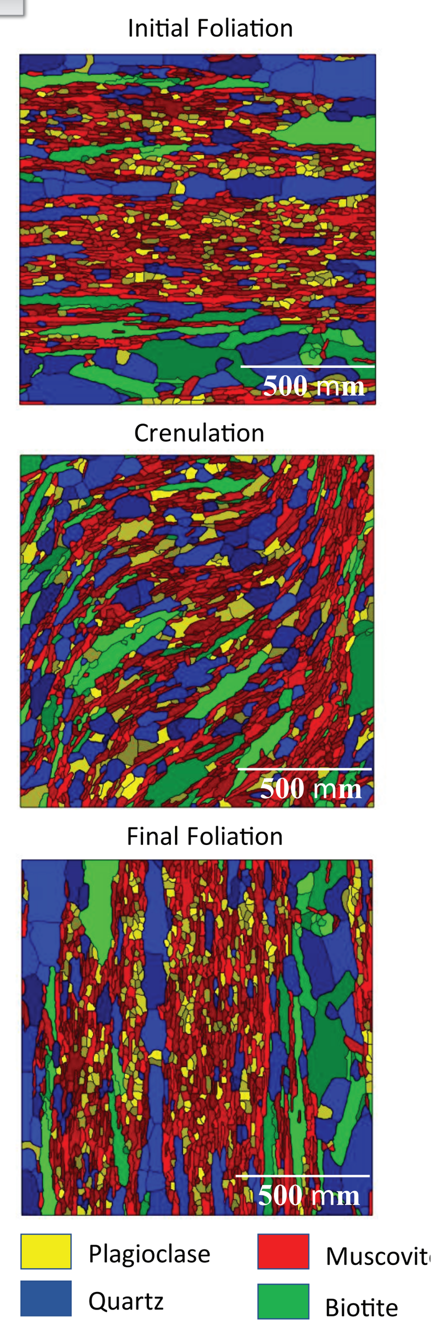


Quartz grains from felsic granulite/amphibolite rocks from the Grenville Orogen, Ontario, Canada. Cathodoluminescence (CL) image shows many interconnected healed microcracks that may have formed when crossing the β→α transition.

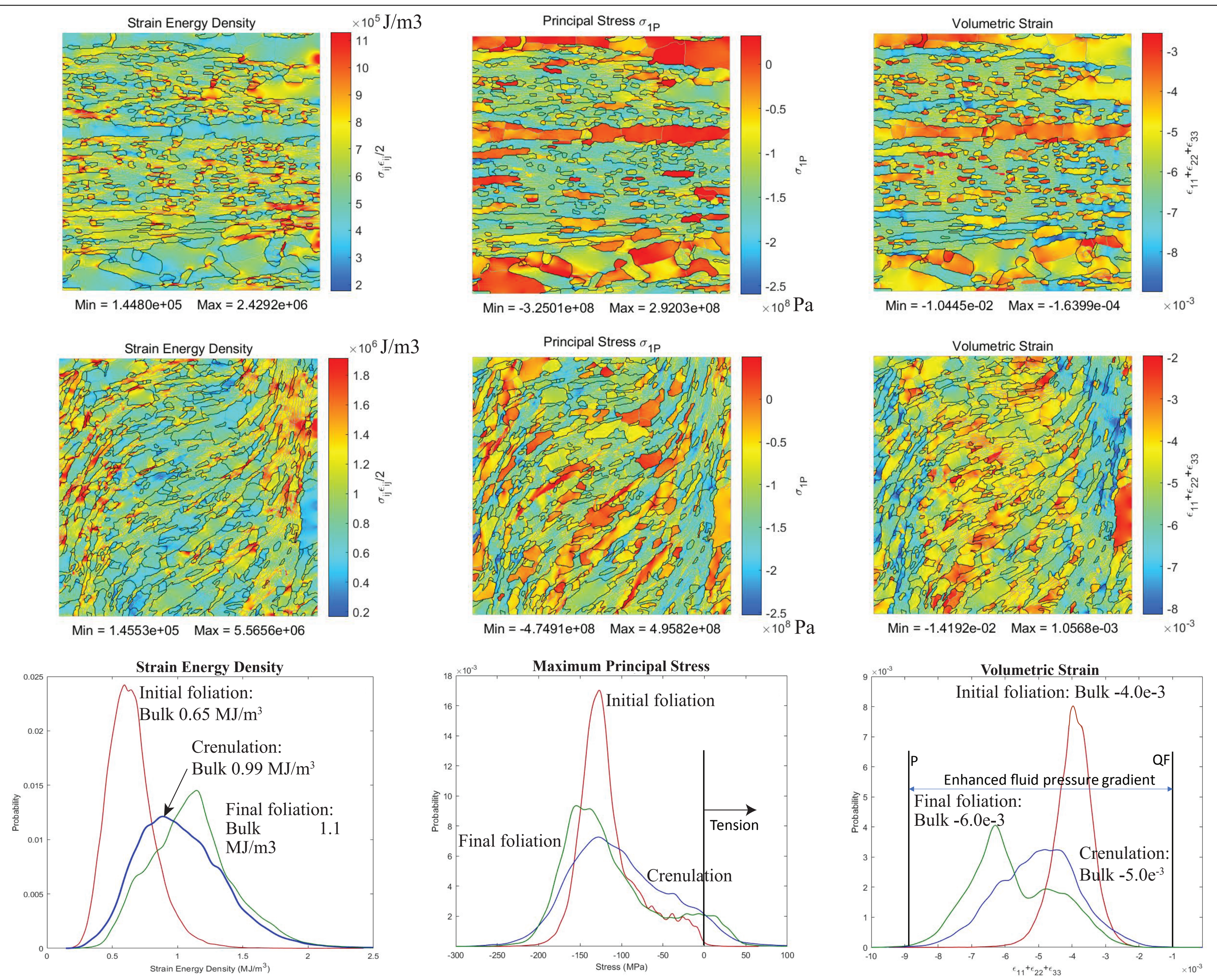
3 Mechanics of Crenulation Cleavage Development

Crenulation cleavage, which forms mineralogically segregated layering perpendicular to the shortening direction, is one form of chemical transport that affects bulk rheology and localization. Quartz (and feldspar) are dissolved in the evolving P-Domains and transported to the dilational QF-Domains.





Phase maps from rocks of the Moretown Formation in Massachusetts. Williams et al. (2001) and Naus-Thijssen et al. (2011).



3D macroscopic loading was applied as shown in the TESA image in Section 1.

Important points:

1) More elastic strain energy is stored in the crenulated and final foliation owing to the orientations of elastically compliant mica c-axes irelative to the shortening direction. What is the thermodynamic significance of this?

2) Tensile (positive) principal stresses are concentrated in the QF-domains of the developing crenulations, which facilitates precipitation of quartz and feldspar transported from the P-domains.

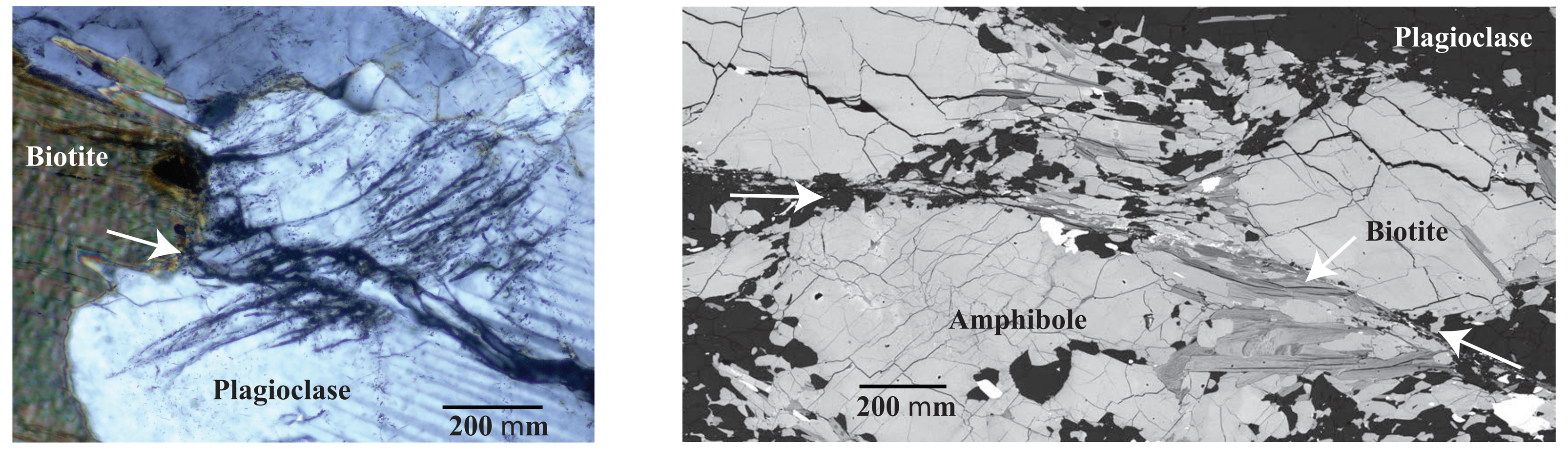
3) Volumetric strain gradients are strongly enhanced in the crenulated rock, which would enhance fluid pressure gradients and drive fluid advection from the P-domains to the QF-domains, facilitating transport of quartz and feldspar from P- to QF-domains.

4) Chemical transport can drive localization in many situations, highlighting the value of understanding dissolution, precipitation, and transport relative to microscale stress fields.

Johnson et al., in preparation.

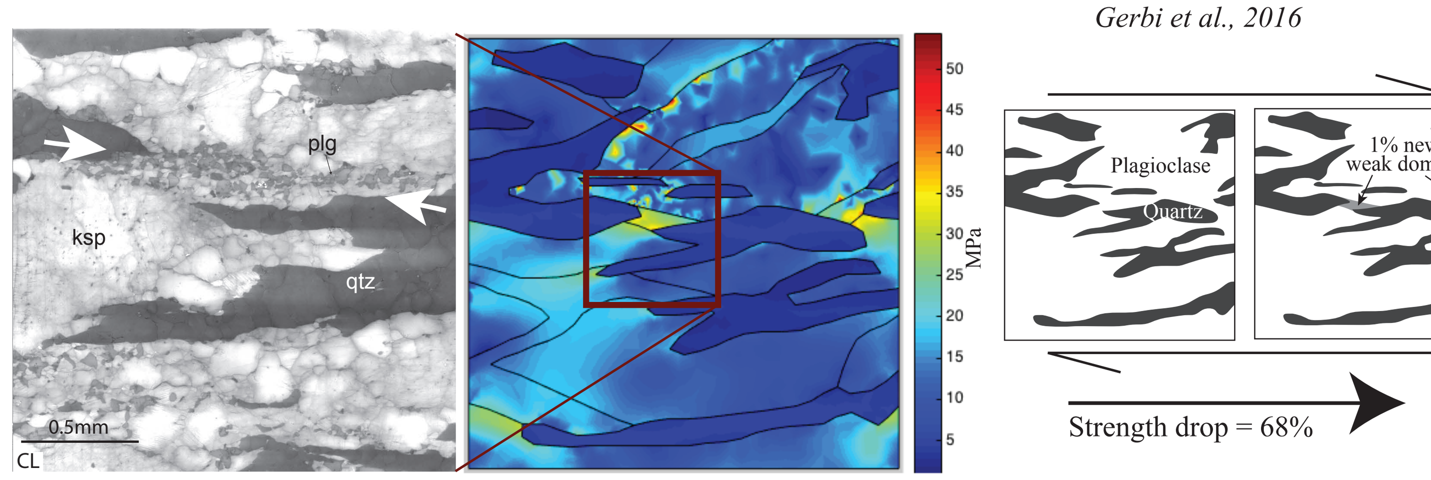
4 Stress and Development of Weak Domains

Development and interconnection of weak domains in the viscous regime drives rheologic change and localization. Only small modal percentages of new weak domains, **which appear to form at sites of high stress**, can weaken a rock by nearly an order of magnitude.

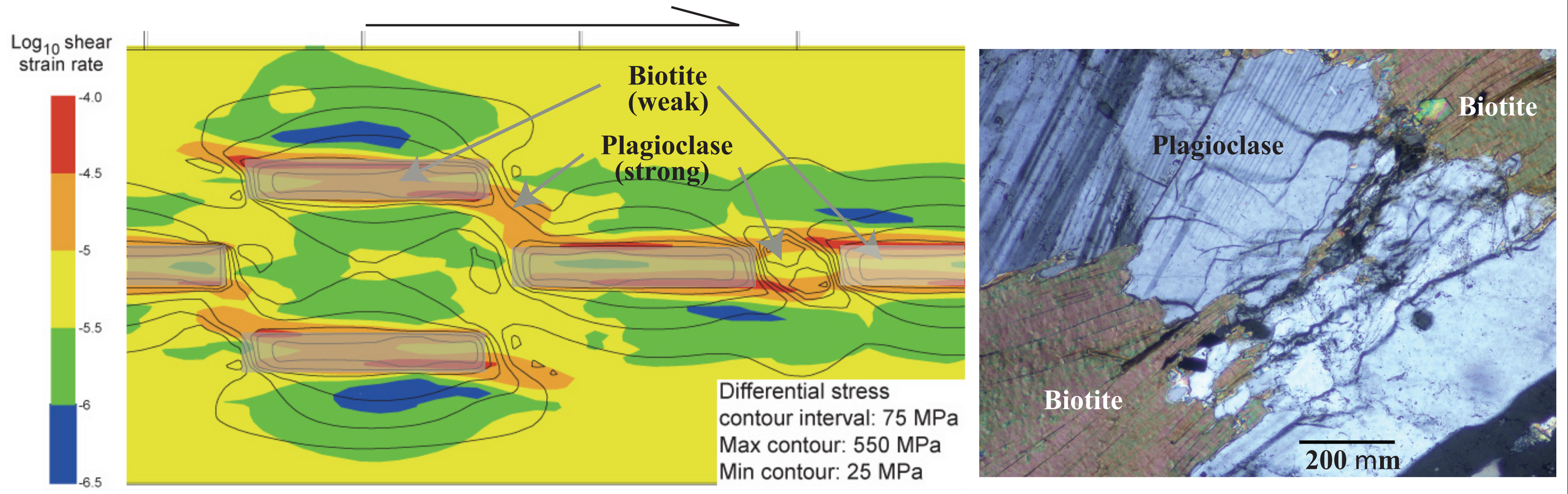


Left: curved fractures trending to upper right and lower left, emanating from biotite grain and from east–west-trending fracture in plagioclase. Right: BSE map showing biotite-lined fractures (white arrows) in amphibole extending between two plagioclase grains.

Gerbi et al., 2016



Left: recrystallized feldspar grains in a bridge zone linking two quartz grains. Center: numerical model using the Power Law Creep Toolbox showing second invariant of the deviatoric stress using plagioclase and quartz flow laws. Red box shows area at left. Right: adding 1% modal weak domain reduces strength by 68%.



Johnson et al., 2004

Left: numerical model (FLAC3D) showing strain rate and differential stress distributions using flow laws for biotite (transparent grey) in a plagioclase framework. Instantaneous strain rate in biotite drives large differential stresses in plagioclase that separates the biotite grains. Right: example of plagioclase brittly damaged between two biotite grains.

Important point: Stress concentrations in strong minerals that bridge weak minerals causes them to undergo grain-size reduction through both brittle and viscous processes leading to interconnected weak zone that strongly impact rheology through weakening and localization.

5 References

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