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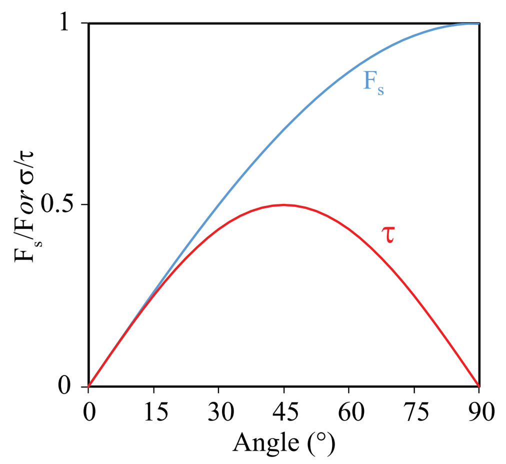
Foliation Intensity and Orientation and Their Effect on Feldspathic Rock Strength

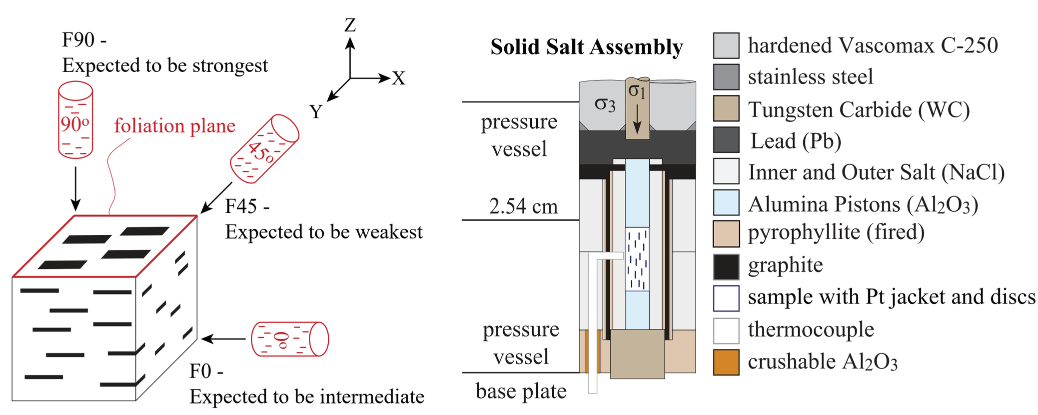
Jake Waller (jaw279@uakron.edu) and Caleb W. Holyoke, III

Introduction

Seismic events in the upper crust induce redistribution of stresses into the lower crust which causes crystal-plastic deformation at depth. Current models of the rheology of the mid to lower crust are based on experiments on homogeneous quartzites, but the mid to lower crust is composed of heterogeneous rocks that are foliated and also contain feldspars and micas. The effect of heterogeneities such as variations in composition, grain size, lineations, and foliations on rheology need to be determined to accurately model crustal deformation. Viscous anisotropy in foliated rocks may be caused by shear stresses being minimized and maximized along biotite grains in different orientations. In order to determine how foliations affect the strength of the mid to lower crust, we deformed two foliated granitic rocks with similar biotite contents, but different foliation intensities using a Griggs-type apparatus and solid-salt sample assembly as the confining medium. These experiments were performed at temperature (T) of 800°C, confining pressure (P_c) of 1.5 GPa and a strain rate ($\dot{\varepsilon}$) of 1.6 x 10^{-6}/s, which promotes crystal-plastic deformation in all phases in these rocks.

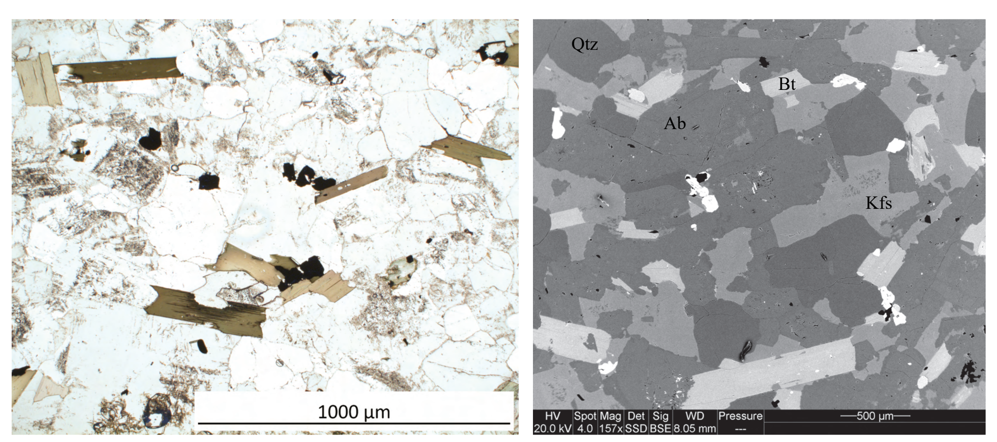


Methods



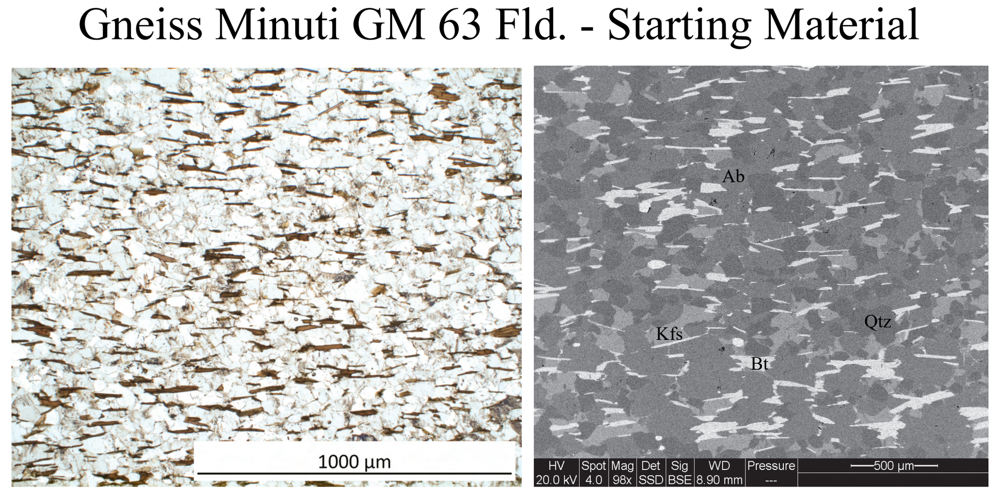
Cores were collected perpendicular, at 45° or parallel to the preexisting foliation in each rock (*above left*). If the rocks were viscously anisotropic, cores with foliation perpendicular or parallel to their lengths should be stronger than cores with the foliation at 45° to the length. The cores were dried >4 hours at 300°C prior to installation in the assembly and taken to experimental conditions (*above right*).

Westerly Granite - Starting Material



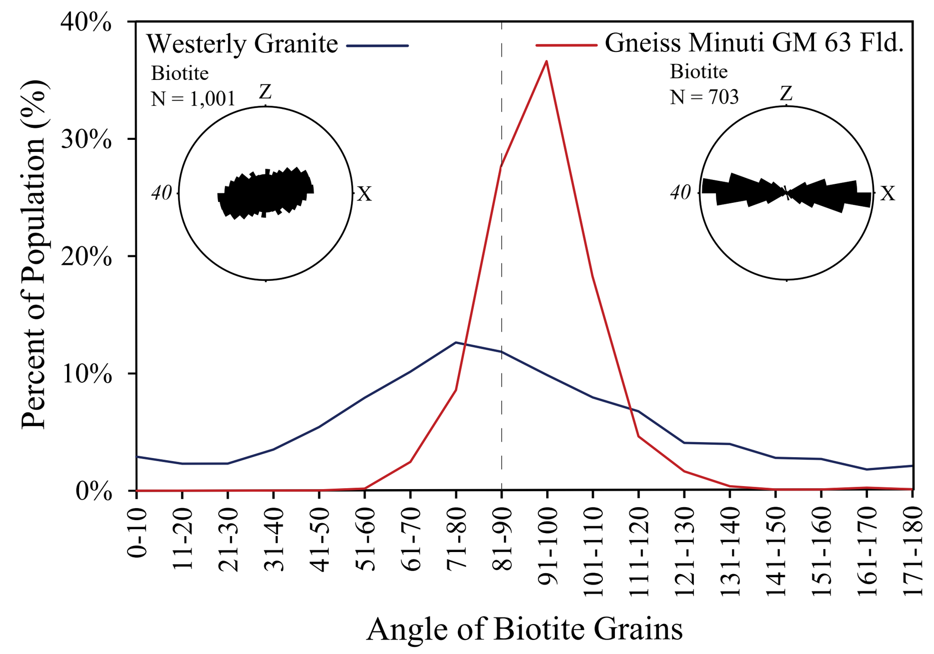
Westerly Granite is a weakly-foliated Permian granite from Rhode Island, USA, and is composed of 22 vol% quartz (Qtz), 26 vol% K-feldspar (Kfs), 45 vol% albite (Ab), and 7 vol% biotite (Bt). Feldspar grains contain a significant amount of sericite (white mica, *above left*). The average grain size (d) is ≈ 500 microns.

Gneiss Minuti GM 63 Fld. - Starting Material

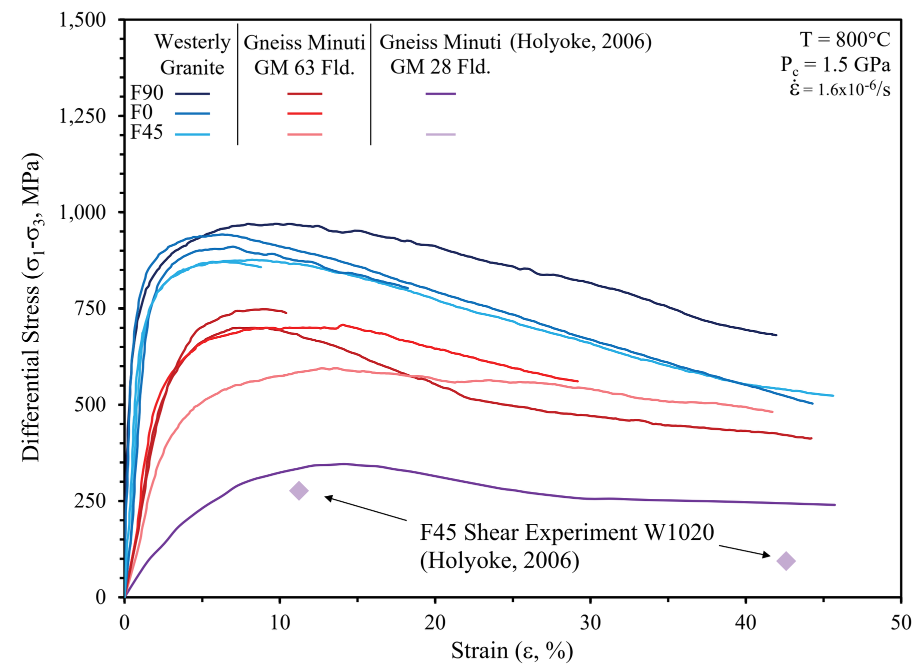


Gneiss Minuti is an Ordovician paragneiss from Nivetta, Italy with layers that have variable compositions. The layer used in this study is composed of 29 vol% quartz, 10 vol% K-feldspar, 53 vol% albite and 7 vol% biotite. Feldspar grains contain sericite (white mica, *above left*). The average grain size (d) is ≈ 150 microns.

Foliations, Mechanical Data, and Reactions

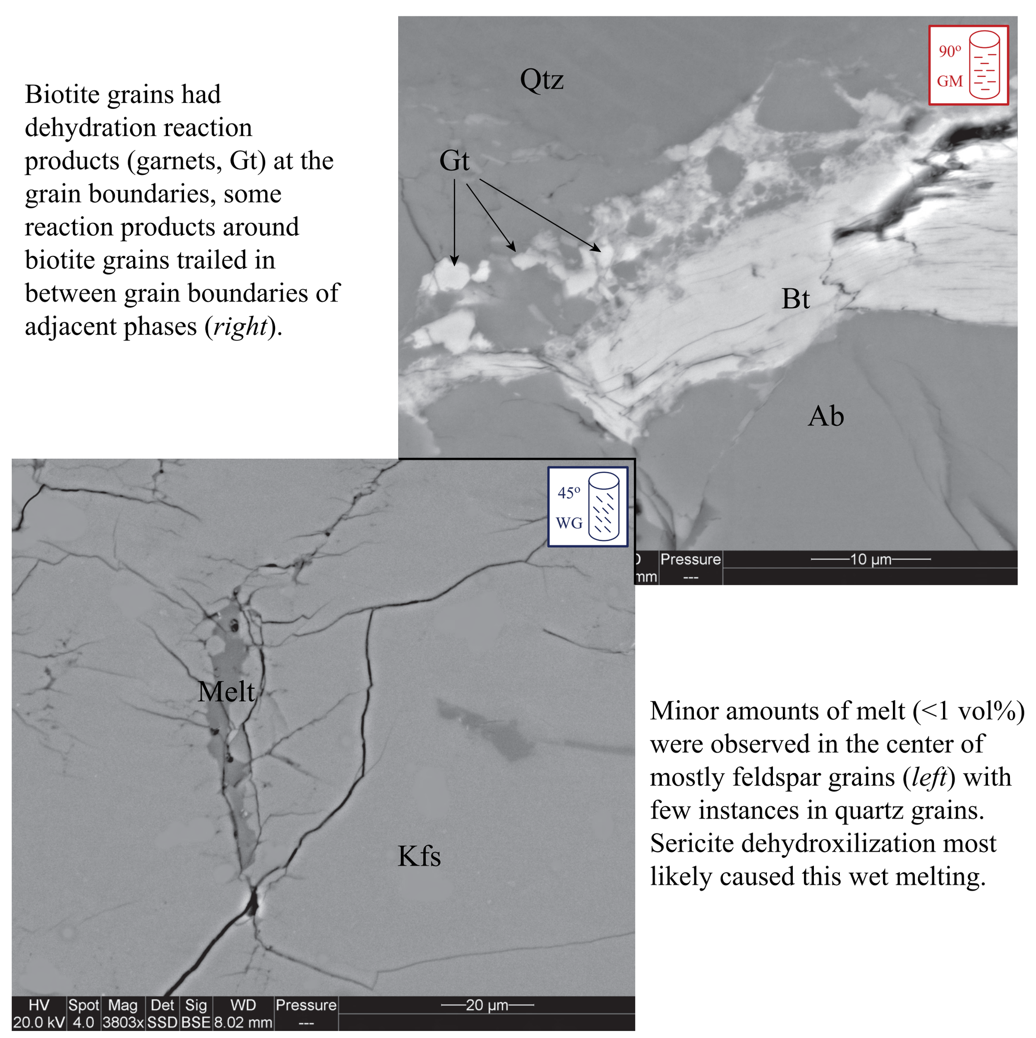


Grain orientation data from traced biotite grains in both rocks show a distinct difference in foliation intensity and bulk biotite orientation. Biotite orientation distribution is very broad in the Westerly Granite (*above blue line and left rose diagram*), whereas biotite orientation distribution is very narrow in the Gneiss Minuti (*above red line and right rose diagram*).



Peak differential stresses of Westerly Granite cores (850-950 MPa) are greater than those of Gneiss Minuti cores (550-700 MPa) and all cores strain weaken after reaching peak stress. Peak differential stresses of cores with foliation oriented at 45° to the compression direction are weakest of the three orientations, but not by a significant amount. Cores of a quartz-rich layer of the Gneiss Minuti (58 vol% Qtz, 28 vol% plagioclase (Pl), and 13 vol% Bt; Holyoke, 2006; unpublished data) deformed at the same conditions are significantly weaker and show the same small variation in strength with changes in foliation orientation.

Biotite grains had dehydration reaction products (garnets, Gt) at the grain boundaries, some reaction products around biotite grains trailed in between grain boundaries of adjacent phases (*right*).

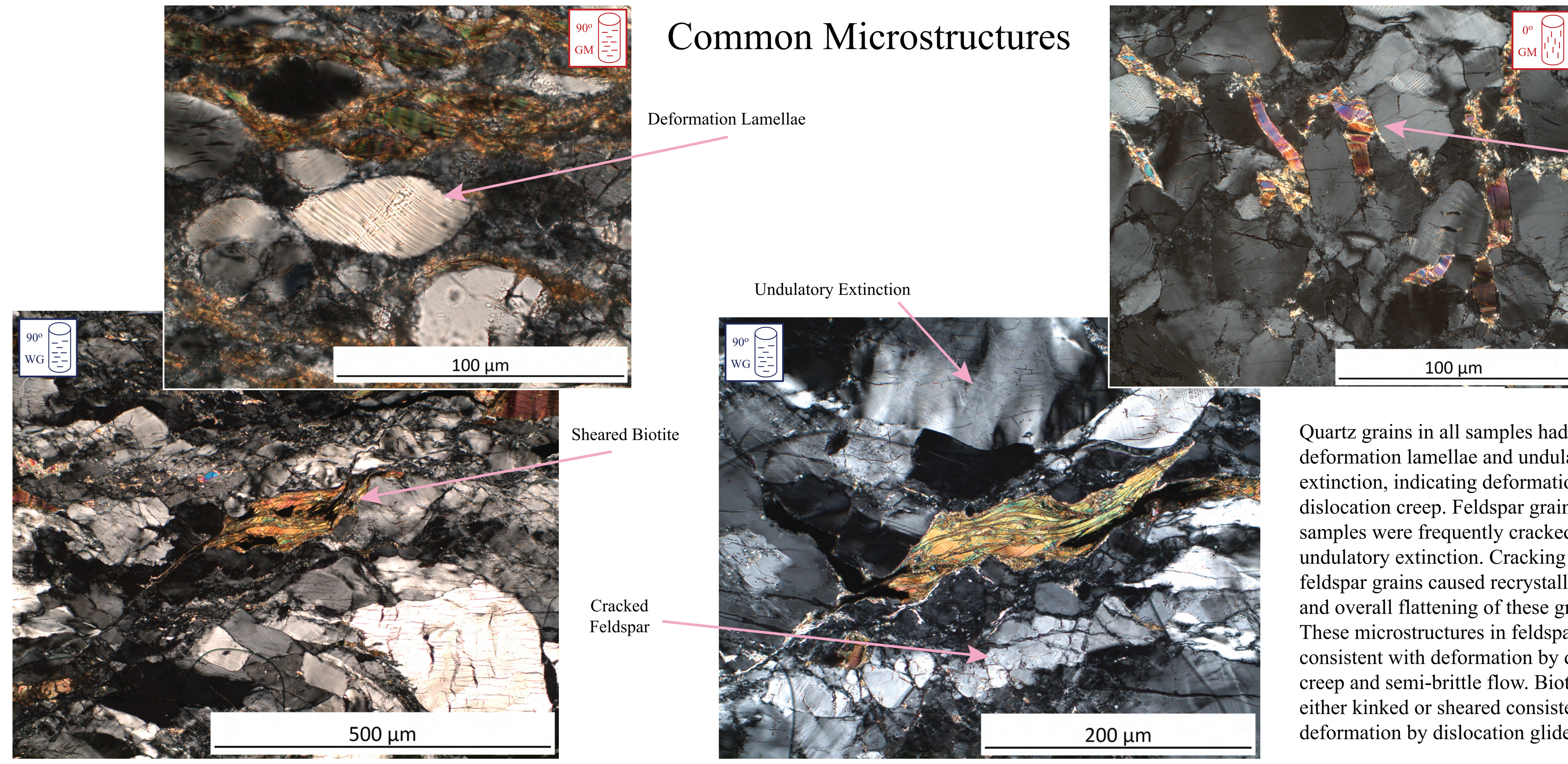


Minor amounts of melt (<1 vol%) were observed in the center of mostly feldspar grains (*left*) with few instances in quartz grains. Sericite dehydroxilization most likely caused this wet melting.

Microstructural Data

All images σ_1

Common Microstructures



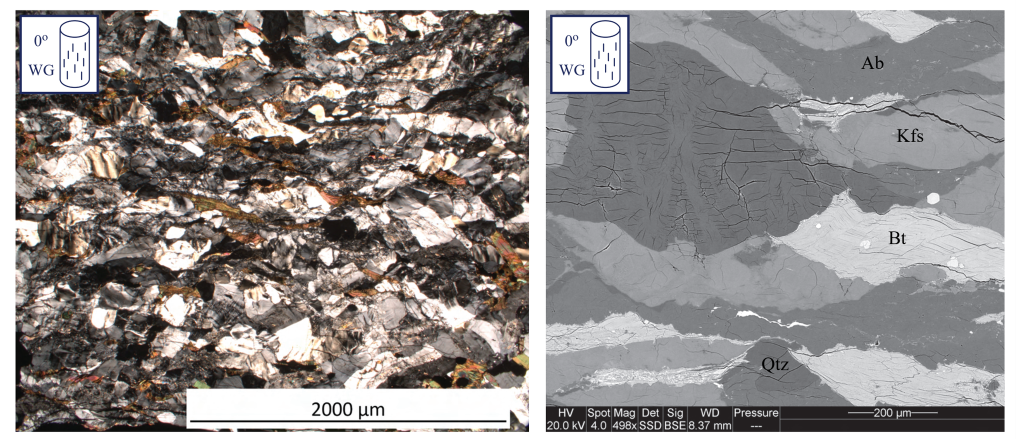
Quartz grains in all samples had deformation lamellae and undulatory extinction, indicating deformation by dislocation creep. Feldspar grains in all samples were frequently cracked and had undulatory extinction. Cracking of feldspar grains caused recrystallization and overall flattening of these grains. These microstructures in feldspar are consistent with deformation by dislocation creep and semi-brittle flow. Biotite grains either kinked or sheared consistent with deformation by dislocation glide.

Orientation-Specific Microstructures

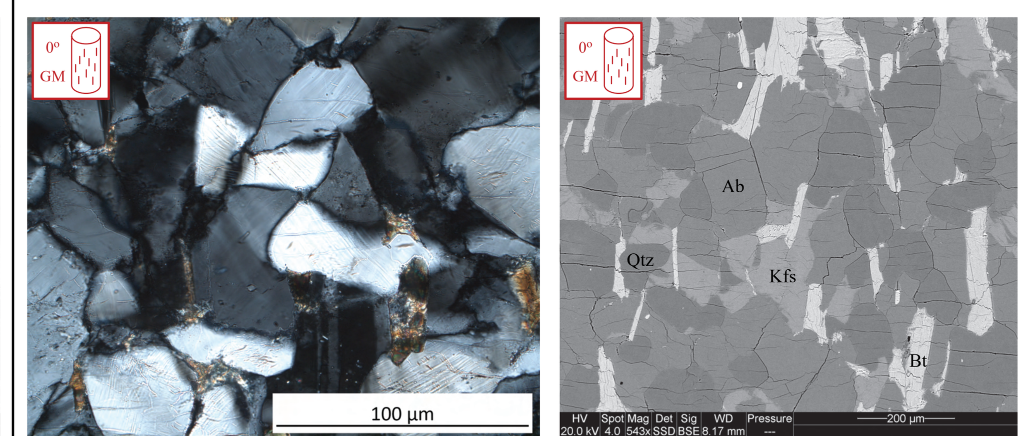
Westerly Granite

Gneiss Minuti GM 63 Fld.

Foliation Parallel F0

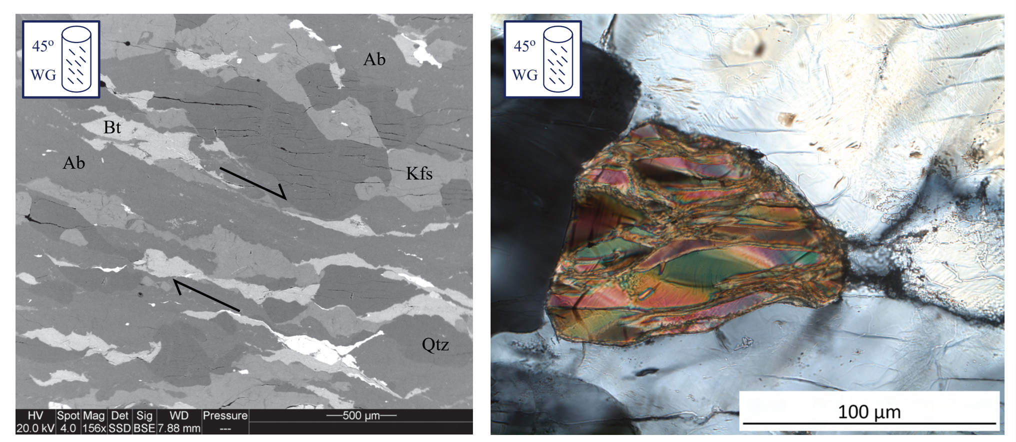


In the core with foliation parallel to σ_1, deformation was homogeneous and the long axes of almost all feldspar and biotite grains are nearly perpendicular to the compression direction (*above*). Quartz grains are not significantly flattened, indicating that deformation was primarily accommodated by feldspars and biotite.

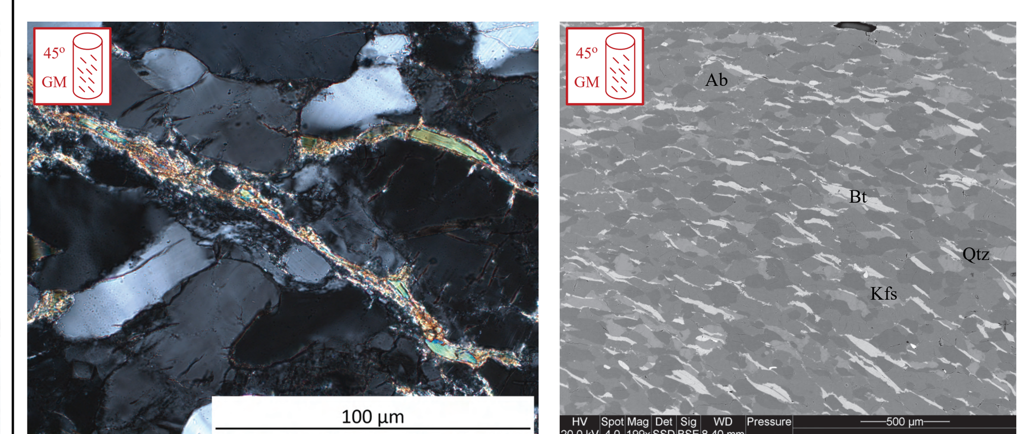


In the core with foliation parallel to σ_1, deformation was homogeneous. None of the constituent phases are rotated significantly from their original orientations (*above*).

Foliation at 45° F45

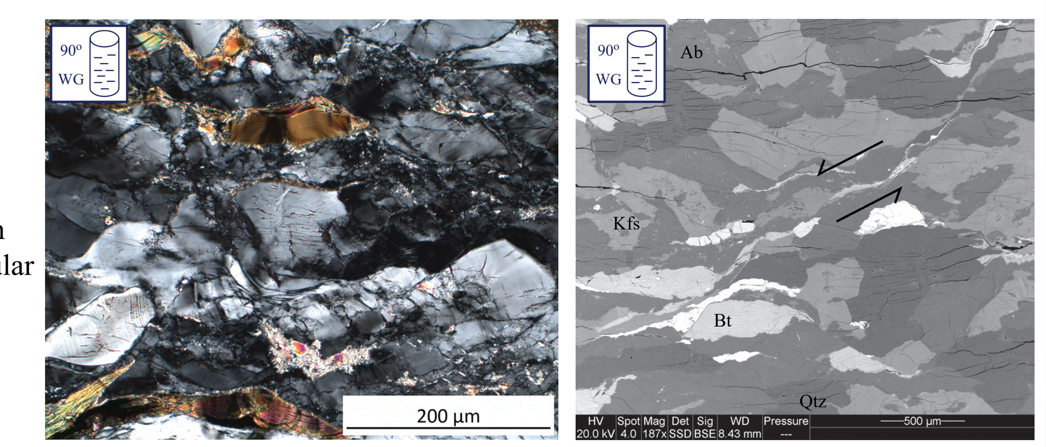


In the core with foliation at 45° to σ_1, a shear zone developed that was dominantly composed of albite with biotite and K-felsdpar at the edges of the shear zone (*above left*). Outside of the shear zone, biotite grains have kinked, sheared, and recrystallized (*above*) and are generally perpendicular to the compression direction along with feldspar grains. Quartz grains are not significantly flattened.

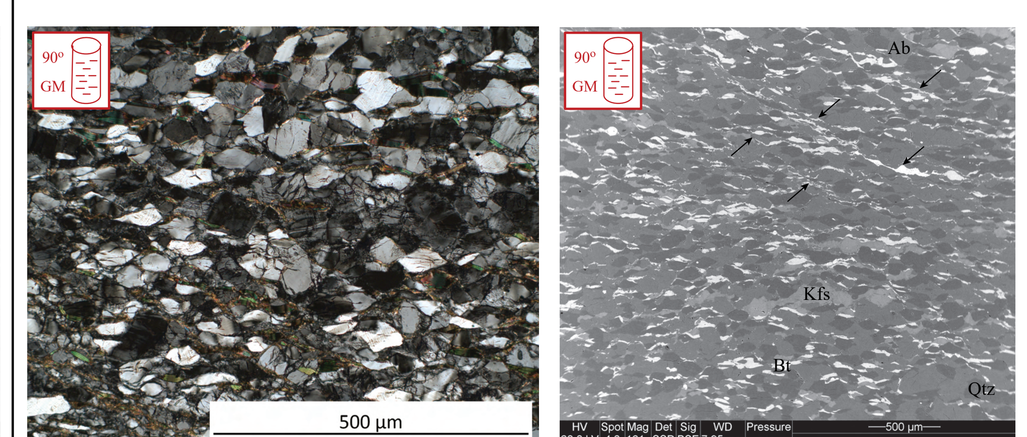


In the core with foliation at 45° to σ_1, deformation was homogeneous with minor rotation of the foliation (*above right*). Weaker biotite and quartz grains remain isolated in the feldspar framework, despite shearing of these phases (*above left*).

Foliation Perpendicular F90

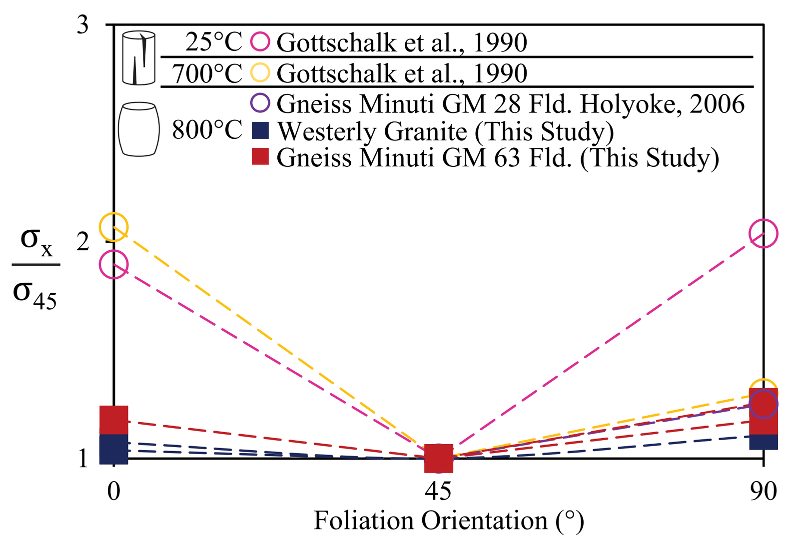


In the core with foliation perpendicular to σ_1, a small shear zone developed (*above right*), but outside of this shear zone strain is evenly distributed between quartz, feldspar, and biotite grains (*above*).



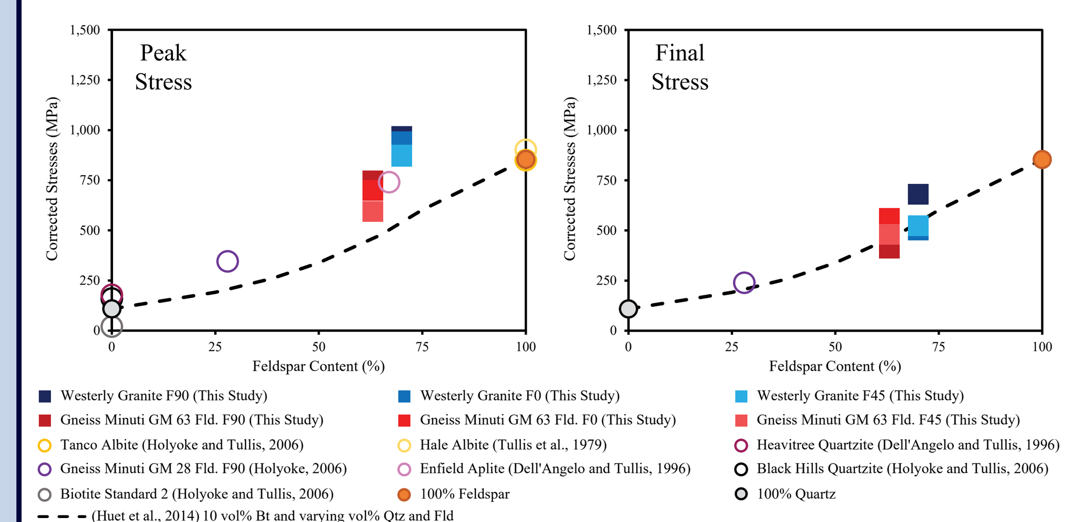
In the core with foliation perpendicular to σ_1, several bands of interconnected and highly sheared biotite developed which crosscut the foliation and formed a different 650 micron wide shear zone (*arrows, above right*). Grains outside of this diffuse shear zone are homogeneously flattened (*above*).

Implications



Foliation orientation causes significant strength anisotropy in low-mica content rocks that deform by brittle mechanisms (*above*, Gottschalk et al., 1990). However, our data indicate foliation orientation and intensity only cause mild viscous anisotropy when the constituent phases deform predominantly by crystal-plastic mechanisms (WG = 1.1x; GM 63 Fld. = 1.2x). A Gneiss Minuti layer with similar biotite content (13 vol%), but quartz dominated (59 vol%) framework has a similarly low anisotropy (1.3x; Holyoke, 2006; unpublished data).

Feldspar Content

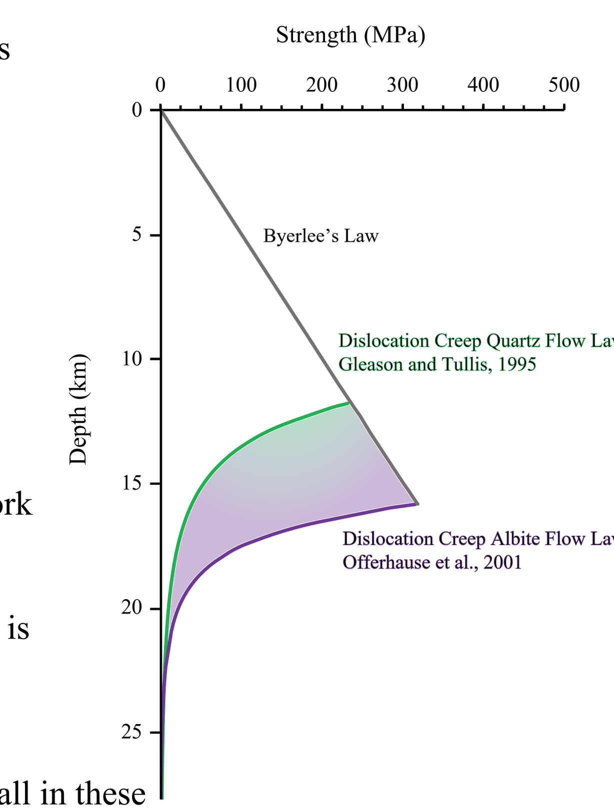


Stresses of feldspar-bearing rocks increase as a function of feldspar content (*above*) and do not appear to be affected significantly by secondary weaker phases until feldspar contents are <65 vol%. Framework phase content appears to have a greater affect on strength than the variations in strength caused by the foliation orientation.

Final stresses in our experiments match the Huet et al. (2014) mixed phase model prediction better than the peak stresses which are considerably higher. These results indicate that the prediction of the Huet model is reasonably accurate for steady state processes, but may not reflect the stresses during initial yielding at plate boundaries.

Conclusions

We deformed cores of Westerly Granite and Gneiss Minuti with foliations at different orientations to the compression direction at conditions which promote crystal-plastic deformation. Our results indicate:



1) Deformation of coarse-grained Westerly Granite is dominated by deformation of the framework feldspar grains and weak biotite grains, whereas in Gneiss Minuti, deformation is homogeneously distributed within all phases.

2) Viscous anisotropy is small in these foliated rocks at low strain and decreases with increasing strain and microstructural evolution.

3) Strength of feldspathic rocks with weaker secondary phases appears to be more dependent on the feldspar content than on foliation orientation, which indicates that modeling of the strength of feldspar-rich continental crust based on feldspar flow laws may be accurate.