Effects of heterogeneities on the flow of the ductile continental crust and upper mantle

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During the seismic cycle, stresses are transferred from the brittle upper crust to the ductile lower crust and upper mantle, causing crystal plastic deformations of these rocks (Handy and Brun, 2004; Montesi, 2004; Burgmann and Dresen, 2008). Modeling of the seismic cycle based on geodetic observations indicates the rheology of the lower crust and upper mantle affects the duration and intensity of aftershock events (Owen et al., 2002; Kenner and Segall, 2003; Ryder et al., 2014). Models of post-seismic deformation incorporate rheologies of isotropic materials in the lower crust and upper mantle [Pollitz et al., 2000; Freed and Burgmann, 2004; Hetland and Hager, 2005; Burgmann and Dresen, 2008, Barbot and Fialko, 2010; Ryder et al., 2014; Zhang and Shcherbakov, 2016]. These rheologies are based on flow laws derived from laboratory deformation experiments performed on homogeneous, monophase materials such as Black Hills quartzite (Gleason and Tullis, 1995; Hirth et al. 2001) and hot pressed olivine aggregates (i.e. synthetic dunites; Mei and Kohlstedt, 2001; Hirth and Kohlstedt, 2003). However, rocks in the continental crust and upper mantle are usually composed of multiple phases and contain other heterogeneities caused by deformations such as foliations, lineations and lattice preferred orientations (LPOs), which can cause deviations from the rheologies predicted by homogeneous monophase materials (Fig. 1; Jaeger, 1960; Donath, 1961; 1972; Borg and Handin, 1966; Gottschalk et al., 1990; Shea and Kronenberg, 1992; 1993; Rawling et al., 2002; Holyoke and Tullis, 2006a; Hansen et al., 2012; Qi et al. 2015).

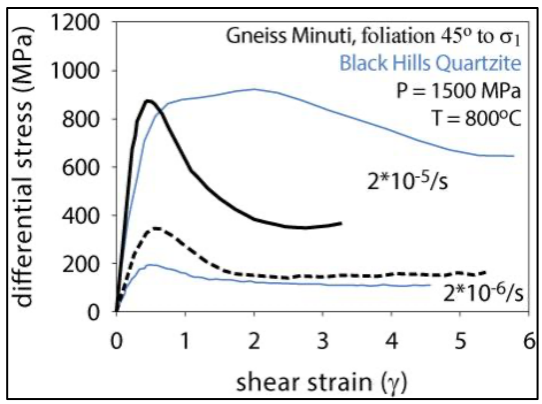


Figure 1 – Strengths of a foliated gneiss with a quartz framework can be significantly weaker, stronger or essentially the same strength as a homogeneous quartzite deformed at the same conditions (Holyoke and Tullis, 2006a).

Elastic anisotropy, which has been extensively studied [e.g., Zhang and Karato, 1995; Jung et al., 2006; Bollinger et al., 2013], affects seismic wave velocity and allows imaging of mantle flow patterns [Savage, 1999] and crustal shear zones [Lloyd et al., 2009; Ward et al., 2012; Shao et al. 2016]. Viscous anisotropy can likewise produce materials that are weak in some orientations relative to the ambient stress state and strong in others [Hansen et al., 2012], which can affect large-scale mantle flow [Lev and Hager, 2011], among other applications [Owen et al., 2002; Kenner and Segall, 2003; Ryder et al., 2014]. Strength anisotropy has been widely studied in rocks deformed by brittle mechanisms (Jaeger, 1960; Donath, 1961; 1972; Borg and Handin, 1966; Gottschalk et al., 1990; Shea and Kronenberg, 1992; 1993; Rawling et al., 2002), but few studies have identified processes that lead to strength anisotropies in viscously deforming polycrystalline mantle and lower crustal rocks [Hansen et al., 2012; Qi et al. 2015].

In order to increase the accuracy of models of deformation of Earth's crust and mantle throughout the seismic cycle, the following questions need to be addressed:

1. How does the inclusion of second and third phases affect the rheology and deformation mechanisms operating rocks relative to monophase rocks?

2. How do foliations, lineations and lattice preferred orientations affect the strength of common rocks deforming by crystal plastic mechanisms in the crust and upper mantle? Do all macroscopically heterogeneous rocks behave anisotropically?

3. How do the strengths and deformation mechanisms operating in these complex rocks evolve with strain?

4. How do metamorphic reactions affect these complex rocks' strengths and the dominant deformation mechanisms operating during these reactions?

These questions are consistent with solving problems related to two of the Grand Challenges described in the recent white paper, Challenges and Opportunities for Research in Tectonics (Huntington and Klepeis, 2018) (GC2 Understanding Variations in Rheology Throughout the Lithosphere and GC3 Understanding Fault Behavior from Earth's Surface to the Base of the Lithosphere). Using deformation apparatus at synchrotron light sources to investigate these questions is uniquely advantageous. Progress towards obtaining the data necessary to answer these questions can be obtained using current technologies at beamlines, but some will likely need new apparatus and in-situ analytical techniques that are under development. The data that modelers and structural geologists need may also change as we develop a deeper understanding of how complex rocks deform.

1. Effects of additional phases on bulk rheology

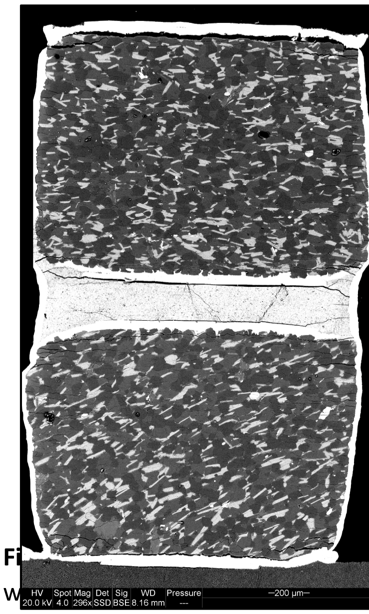
Comparison of the strengths of a foliated gneiss with isolated biotite and plagioclase in an interconnected quartz framework and a homogeneous quartzite deformed at high and low stresses demonstrate the complexity of trying to relate monophase flow laws to complex rocks. At higher stresses, the peak stress of the gneiss is similar to the quartzite, but as the weak biotite in the gneiss becomes interconnected forming a shear zone, the strength of the gneiss decreases to half of that of the quartzite. At lower stresses, the gneiss is initially almost twice as strong as the quartzite, but with increasing strain and dynamic recrystallization, the strength becomes comparable to the quartzite. These differences are due to heterogeneous stresses in the polyphase rock (Holyoke and Tullis, 2006a). At high stresses, stress concentrations about biotite grains cause locally high dislocation densities in quartz that induce semi-brittle strain in quartz leading to a localized zone of interconnected biotite. At low stresses, stress concentrations cause higher dislocation densities, leading to work hardening of the quartz framework which is recovered by distributed recrystallization of quartz during strain weakening and widespread interconnection of biotite.

Evidence of heterogeneous distribution of stresses in polyphase rocks is also commonly observed in natural rocks, for example causing local variations in recrystallized grain size (Handy, 1994). Observational studies such as those mentioned above identify the complexity, but these offer little quantification of the degree of variation in stresses about phases in polyphase rocks that cause heterogeneous behavior. However, using X-ray spectra to determine bulk stresses in different phases in complex rocks during deformation is possible at the moment if the diffraction peaks of the phases do not overlap significantly. However, not all grains in the complex rock are experiencing the same stress state, which can cause operation of different deformation mechanisms. Techniques to interrogate grain-scale stresses in-operando along with bulk stress measurements would provide data necessary for modelers to start to construct more accurate models of the stress states and bulk rheology of these rocks.

2. Foliations, lineations and lattice preferred orientations

It is not uncommon for rocks to experience multiple deformation events in major orogenic zones, such as the Appalachian mountains (Thigpen and Hatcher, 2017; Hatcher et al. 2017; Piette-Lauzière et al., 2020). These deformations produce foliations, lineations and lattice preferred orientations in rocks, which can cause viscous and elastic anisotropy. Hansen et al. (2012) observed that strengths of olivine aggregates became more anisotropic as a lattice preferred orientation developed in the aggregates, a phenomenon not accounted for in current flow laws. Beyond this study, very little has been done to quantify the effects of foliations, lineations or lattice preferred orientations on the strength of rocks deforming by crystal plastic mechanisms in the crust or upper mantle. However, deformation of foliated rocks at conditions where the quartz-plagioclase framework is brittle indicates that the strength of foliated rocks with low mica contents (<35%) will be anisotropic and at greater mica contents strengths will be isotropic (Gottschalk et al. 1990; Shea and Kronenberg, 1992).

Synchrotron-based investigations are well suited to provide the basic data necessary to start to investigate this problem. For example, simple axial compression experiments using stacked cores of foliated rocks with the foliations in different orientations can be performed using the D-DIAs at the Advanced Photon Source at Argonne National Laboratory (Fig. 2). X-radiographs of the samples can be used to measure strain and strain rates providing immediate measures of viscosity contrasts between the different materials deformed under the same load, temperature and pressure during the experiment. Many simple experiments could yield a significant amount of rheological data useful to modelers and structural geologists, especially when combined with detailed post-mortem analyses of microstructural evolution.



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(top) and at 45° to (bottom) the compression direction (vertical).

3. Evolution of complex rock rheology with strain

Development of technologies to perform saw-cut shear experiments (Dell'Angelo and Tullis, 1989; and subsequent studies) and torsion experiments (Paterson and Olgaard, 2000; and subsequent studies) at high pressures and temperatures which crystal plastic deformation mechanisms operate in rocks led to significant advances in studies of strain localization (Barnhoorn et al., 2005; Holyoke and Tullis, 2006a, among others), melt segregation (Holtzman et al. 2003; King et al. 2011, among others), phase mixing (Sundberg and Cooper, 2008; Cross and Skemer 2017, among others) and lattice preferred orientation development (Zhang and Karato, 1995; Heilbronner and Tullis, 2006; Jung et al. 2006, among others). Many of these processes involve strain weakening that diverges from predicted strengths of common flow laws. However, these techniques also have limitations: 1) saw cut shear experiments have an upper strain limit due to decreasing overlap between the pistons, which causes complications with stress determination (Heilbronner and Kilian, 2017), 2) torsion experiments in the gas apparatus are limited to upper pressures of 300 MPa (Paterson and Olgaard, 2000), which limits the materials that can be deformed in these apparatus and 3) no direct measurements of bulk stress are collected by the high pressure torsion apparatus used by Cross and Skemer (2017).

Development of rotary shear devices such as the Rotary Drickamer apparatus (Yamazaki and Karato, 2001) and Paris Edinberg cell (Shen and Wang, 2014) for use at synchrotron facilities enables high strain deformation at high pressures and temperatures with in-operando stress and strain measurement. Future development of in-operando, high resolution X-ray tomographic analyses will be useful for grain-scale imaging of shear zone formation, phase mixing, melt segregation and lattice preferred orientation formation. If high pressure experimentalists are able to image many stages of texture evolution with strain, they will be able to perform fewer experiments to get the same microstructural information that currently takes several experiments to collect. This increased experimental efficiency will also allow high pressure experimentalists to perform more experiments on different materials or to increase the number of experiments on a single material creating more robust microstructural and mechanical data sets. These data showing the grain-scale evolution of common structures formed by processes acting at plate boundaries in conjunction with mechanical and environmental data will also be invaluable to modelers and structural geologists.

4. Effects of syndeformational reactions on rheology and microstructures

Many studies of naturally deformed rocks in the crust and mantle have documented strain localization concomitant with localized metamorphic reactions (Mitra, 1978; Austrheim and Boundy, 1994; Wintsch et al., 1995; Newman et al. 1999; Keller et al. 2004). Experiments on similar materials have documented the transitions in deformation mechanisms and strain weakening at the onset of metamorphic reactions (Rutter and Brodie, 1988; Stunitz and Tullis, 2001; Holyoke and Rushmer, 2002; de Ronde et al. 2004, Holyoke and Tullis, 2006b; Chernak and Hirth, 2011). These results indicate that reactions cause strain weakening in rocks and will cause deviations from the simple rheologies used to predict the strength of the crust and upper mantle (Figs. 1 and 3).

Deformation at synchrotron beam facilities using both low and high strain deformation apparatus will allow experimentalists to better characterize the onset of reaction by changes in the phases observed in X-ray spectra. Increasing resolution of X-ray tomography of samples during deformation will also allow high pressure experimentalists to determine the specific locations where reaction products nucleate and relate these locations to deformation of the host rock. X-ray tomography will also allow experimentalists to determine how these reaction products begin to mix with the phases in the host rock at the same time as stress measurements are being collected, providing a more robust view of the processes operating during syndeformational metamorphic reactions.

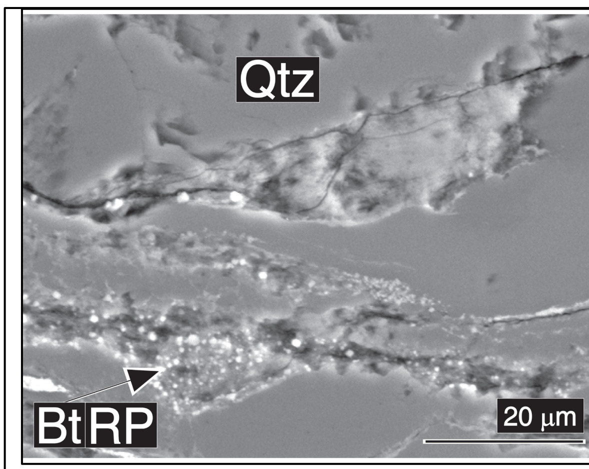

Figure 3 – Reaction products are thoroughly mixed with biotite inside the shear zone (Bt/RP) where reaction progress is greatest, but outside of the shear zone, reaction products are only observed in areas of locally high strain, such as in the biotite grain at the boundary of the shear zone (Holyoke

Summary

In summary, high pressure experimentalists can make significant contributions to determining how heterogeneities in complex rocks will affect the strength of the crust with current capabilities of synchrotron beamlines 6-BMB and GSECARS at the Advanced Photon Source at Argonne National Laboratory. In-operando data such as X-ray spectra and radiographs can be used for many basic analyses to determine how strengths change. Post-mortem analyses of samples from these experiments can be analyzed by common techniques, such as electron backscatter diffraction pattern analysis and optical, transmission and scanning electron microscopy. However, new developments to analyze deforming materials in-operando, such as high resolution X-ray tomography and techniques to analyze grain scale stresses during experiments, will allow experimentalists to generate more useful data for modelers and structural geologists to explore the rheology of Earth’s lower crust and upper mantle.

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