Formation and maintenance of shear zones

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ABSTRACT

The processes that initiate and maintain prograde ductile shear zones are not well understood. We have performed shear experiments ($\gamma = 1$ to $3$) on a fine-grained (100–150 $\mu$m) gneiss (59% quartz, 28% plagioclase, 13% aligned but not interconnected biotite) to determine the evolution of deformation mechanisms that produce dramatic strain weakening and localization, at conditions (1.5 GPa, 800 °C, $\gamma = 2 \times 10^{-5}/s$) where pure quartz aggregates deform homogeneously by dislocation creep. Initial yield occurs where stress concentrations at the tips of weak biotite grains produce semibrittle deformation in intervening quartz or plagioclase, allowing local biotite interconnection by slip on (001) and initiating strain weakening. After yield, the interconnected biotites kink and thus strengthen, but the highly strained parts of grains react to a fine-grained, mixed-phase assemblage which deforms by grain-size–sensitive creep, allowing further strain weakening and localization. At $\gamma = 3.3$, the strain and strain rate in the $\sim$100-µm-thick shear zone are 100 times that of the enclosing host rock, similar to the localization observed in natural shear zones. Thus, the processes that initiate strain localization are not necessarily the same as those that preserve the weak shear zone, and once formed, a shear zone may be permanently weakened.

Keywords: shear zones, polyphase processes, biotite gneiss, strain localization, Gneiss Minuti.

INTRODUCTION

Ductile shear zones are common features in Earth’s crust. The localization of strain requires strain weakening, which means a transition from higher-stress to lower-stress deformation mechanisms at a constant strain rate. Therefore, an understanding of the strain-weakening mechanisms that operate in shear zones is critical to determine the strength of the lithosphere. However, the mechanisms that lead to the formation of ductile shear zones are not well understood because the subsequent high strain obliterates the microstructural evidence of their operation. The weakening mechanisms in a polyphase rock, such as a quartzo-feldspathic gneiss, are likely to involve either the interconnection of an initially dispersed weak phase such as mica (e.g., Berthe et al., 1979), formation of weak phases by hydration reactions (e.g., Mitra, 1978), or formation of fine-grained, mixed-phase assemblages that can deform by diffusion–accommodated grain boundary sliding (e.g., Stünitz and Tullis, 2001).

Handy (1990, 1994) has emphasized the importance of the transition from a load-bearing framework to an interconnected weak phase, but the specific processes by which polyphase aggregates accomplish such a transition at conditions where the framework minerals deform by crystal plasticity are not well understood. Similarly, the feedbacks between high strain and metamorphic reactions are not well understood, although reactions restricted to shear zones are commonly documented (e.g., Keller et al., 2004). We undertook an experimental study to determine how these two important processes act to initiate and maintain a localized ductile shear zone. Shear experiments at several different strains allowed us to observe the evolution of deformation mechanisms during the strain weakening that accompanied the transition from a load-bearing framework of quartz to throughgoing interconnection of the weak phase (biotite), at conditions where the framework phase undergoes dislocation creep. Additionally, due to the high temperatures used in this study, the interconnected, highly strained biotite grains reacted with quartz and plagioclase to form a fine-grained mixed-phase assemblage (garnet, K-feldspar, and water) that maintained the weakness of the materials in the narrow shear zone and allowed it to accommodate the majority of sample strain (Fig. 1B). Our results provide insight to the evolution of stresses and deformation mechanisms operating in a polyphase aggregate, and the factors that allow strain localization to be maintained.

EXPERIMENTAL PROCEDURES

Experiments were conducted using the Gneiss Minuti, a fine-grained (~150 ± 25 $\mu$m) quartzo-feldspathic gneiss from the southern Alps (Zurbriggen et al., 1998). All experimental samples were cored from two layers of the gneiss composed of 13 vol% biotite, 28 vol% plagioclase ($\text{An}_{27.7}\text{Ab}_{71.9}\text{Or}_{0.4}$), 58 vol% quartz, and 1 vol% garnet/Fe-Ti oxides (Fig. 1A). Quartz and plagioclase grains are relatively equant and have no optically visible deformation microstructures. Quartz grains form an interconnected framework, biotite grains are well aligned but not interconnected, and plagioclase grains are also isolated.

All experiments were conducted with no added water at 800 °C, 1.5 GPa, and a shear strain rate ($\dot{\gamma}$) = $2 \times 10^{-5}/s$. Samples 1.2 mm thick were sliced from cores with the foliation parallel to the shear plane and placed between two 45°-cut $\text{Al}_2\text{O}_3$ shear pistons (inset, Fig. 1A). Three samples of Gneiss Minuti were deformed to shear strains ($\gamma$) of 0.6 (at yield), 1.1 (during strain weakening), and 3.3 (steady state), with associated thinning of 10%, 17%, and 37%, respectively (Table 1). Experiments were conducted using an all-salt assembly; there is some error in stress (~50 MPa) due to piston friction, but it is considerably less.

Figure 1. In scanning electron microscope–backscattered electron (SEM-BSE) images, quartz is always darkest gray, plagioclase is intermediate gray, and biotite is white. A: Gneiss Minuti, SEM-BSE micrograph; ~100–150 $\mu$m grain size, 55 vol% quartz, 33 vol% plagioclase ($\text{An}_{27.7}$), 13 vol% biotite. Inset shows schematic of sample and pistons. B: SEM-BSE image of W1008. Narrow shear zone (bracket) accommodates most of sample strain (schematic in inset shows geometry). Abandoned shear zone path indicated by dashed line. S—foliation surface; C—shear surface.

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W1008 3.3/37% Single through-going shear

Grains depend on their location relative to bi-
crystalline variations observed in quartz by the quartz-plagioclase framework. Most of the load is initially borne cause the biotites are in their weakest easy slip pany strain weakening and localization. Be-

Changes in deformation processes that accom-

Quartz microstructures were used to infer dislocation creep, their relation to flow stress, and recrystallization- to climb-accommodated deformation mechanisms of semibrittle flow variations at the experimental conditions. The mechanisms are the most sensitive to stress in the Gneiss Minuti, and its deformation properties, weak S-C fabric.

Table 1: Optical and TEM Microstructures of Three Samples of Gneiss Minuti

<table>
<thead>
<tr>
<th>Expt.</th>
<th>Shear Strain/ Thinning</th>
<th>Sample scale structure</th>
<th>Quartz</th>
<th>Optical and TEM Microstructures</th>
<th>Plagioclase</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1019</td>
<td>0.6/10%</td>
<td>Initial interconnection of biotite grains by grain-scale faults in quartz and plagioclase</td>
<td>High density of tangled dislocations away from tips of biotite grains, microcracks and parallel arrays of tangled dislocations near tips of biotite grains. Grain-scale faults through some grains (Fig. 3).</td>
<td>Kinks and some shearing into grain-scale faults through framework grains. (Fig. 3)</td>
<td>Fracturing of grains, few dislocations</td>
</tr>
<tr>
<td>W1009</td>
<td>1.1/17%</td>
<td>Strands of multiply interconnected biotite grains, first reaction products, weak S-C' fabric</td>
<td>High density of tangled dislocations in porphyroclasts and some fine (~1 μm) recrystallized grains at the boundaries. In shear zone, very fine-grained and highly recrystallized, outside of shear zone, undulatory extinction, low dislocation density, dislocation arrays, and some fine recrystallized grains (~1-2 μm, Fig. 5)</td>
<td>Kinking, shearing, and a few initial dehydration reaction products (&lt;1 vol%) in highly strained biotites (Fig. 4)</td>
<td>Fracturing of grains, few dislocations</td>
</tr>
<tr>
<td>W1008</td>
<td>3.3/37%</td>
<td>Single through-going shear zone, weak S-C' fabric outside of shear zone (Fig. 1b)</td>
<td>Fracturing of grains, few dislocations</td>
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</table>

The stress-strain curves for the Gneiss Minuti samples (Fig. 2) show pronounced strain weakening, with an average peak strength of 1.3 GPa followed by weakening to 40% of the yield strength by γ = 3. The sample-scale and grain-scale microstructures in each sample are listed in Table 1; representative microstructures are illustrated in Figures 1B, 3, 4, and 5. Quartz forms the interconnected framework in the Gneiss Minuti, and its deformation mechanisms are the most sensitive to stress variations at the experimental conditions. The deformation mechanisms of semibrittle flow and recrystallization- and climb-accommodated dislocation creep, their relation to flow stress, and their microstructures are documented in Hirth and Tullis (1992, 1994). Therefore, quartz microstructures were used to infer changes in deformation processes that accompany strain weakening and localization. Because the biotites are in their weakest easy slip orientation, most of the load is initially borne by the quartz-plagioclase framework. The microstructural variations observed in quartz grains depend on their location relative to bi-

Table 2: Experiments and Shear Strain

<table>
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Figure 2. Differential stress versus bulk shear strain.

Figure 3. Low-strain sample (W1019) optical micrographs. A: Quartz grain between two biotite grains developed zone of localized strain (area “a,” with deformation lamellae). B: Same as A, but polarizers rotated 45°. C: Biotite lining grain-scale shear zone in quartz formed in response to local stress concentrations between two biotite grains.
However, very little reaction occurred in biotite grains outside the shear zone (Fig. 5). The reaction forming the mixed-phase assemblage in the shear zone is

$$2\text{Bi} + 3\text{An} + 3\text{Qtz} \rightarrow 3\text{almandine/pyrope} + \text{grossular} + 2\text{K-feldspar} + 2\text{H}_2\text{O}.$$  

The details of the reaction and stability field are not pertinent to this study; they are discussed in more detail in a separate study.

**DISCUSSION**

**Shear Zone Formation: Weak Phase Interconnection**

The initial biotite interconnection occurred by (001) slip in a few locations where intervening quartz underwent grain-scale faulting. The localized semibrittle flow microstructures observed in quartz at the tips of biotite grains indicate that the stresses there are significantly higher than elsewhere; Hirth and Tullis (1994) found that stresses of 1.6–2.3 GPa were required for semibrittle flow of quartzites at the $P$, $T$, and $\gamma$ of our experiments. These values are consistent with models of the stress distribution in an elastic sheet containing weak ellipsoidal inclusions with an aspect ratio of 5:1 (similar to the biotite grains in the Gneiss Minuti and oriented at 45° to $\sigma_1$, which predict stress concentrations 1.5 times the remote stress, or ~2 GPa for our samples at yield (Jaeger and Cook, 1969). These results are also similar to those of Johnson et al. (2004), who modeled the stress concentrations in a hard matrix at the tips of weak zones with an aspect ratio similar to that of our micas, and found them to be ~1.3–2 times the confining pressure. Similar localized deformation resulting from stress concentrations near biotite grains was observed in quartz-feldspathic gneiss samples deformed at lower P-T conditions where the matrix quartz and feldspar grains are entirely brittle (e.g., Gottschalk et al., 1990).

**Evolution of Strain and Strain Rate During Strain Localization**

We have estimated the difference in strain and strain rate between the shear zone and the material outside the shear zone (“host rock”) using quartz microstructures in the intermediate- and high-strain samples. The orientations of the long axes of quartz porphyroclasts relative to the shear plane were measured in the intermediate-strain sample and in the host rock portion of the high-strain sample. The difference in flattening (pure shear) between the two samples was removed, and the shear strain between the two samples was calculated to be $\gamma = 0.3$. The strain rate of the host rock portion of the high-strain sample was then calculated from the time difference between the two experiments. The samples followed the same stress-strain path, and the thickness of the host rock in the high-strain sample is known, so its shear strain rate $(3.0 \times 10^{-6}/s)$ could be calculated. The strain rate of the shear zone $(2.8 \times 10^{-4}/s)$ could then be calculated because the sum of the host rock and shear zone strain rates times their respective volume fractions must equal the bulk shear strain rate $(2.3 \times 10^{-5}/s)$. This relationship also allowed us to calculate the shear strain in the shear zone ($\gamma = 30$). A schematic diagram of the evolution of quartz deformation mechanisms and strain rates prior to and after localization is presented in Figure 6.

We can check the calculated strain rates for the host rock and the shear zone in the high-strain sample by comparing the quartz microstructures in the two regions with those observed by Hirth and Tullis (1992) in pure quartzites deformed at the same $P$ and $T$. In quartz grains within the host rock, with a calculated strain rate of $3.0 \times 10^{-4}/s$, we observe some dislocation arrays and some very small dislocation-free recrystallized grains, consistent with dislocation creep that is transitional between recrystallization- and climb-accommodated. For a strain rate of $3.0 \times 10^{-5}/s$ at 800°C, Hirth and Tullis (1992) observed that “as-is” quartzites deform by dislocation creep that is transitional between re-

Figure 4. Scanning electron microscope–secondary electron image of mid-strain sample (W1009). Quartz and plagioclase are similar medium gray; biotite is light gray. Sheared biotite grains and dehydration reaction products (RP, enlarged in inset) observed only in highly strained biotite; no reaction occurred in undeformed portion of biotite grain.

![Figure 4](image)

Figure 5. Scanning electron microscope–secondary electron image of high-strain sample (W1008). Quartz and plagioclase are similar medium gray; biotite is lightest gray. Image shows shear zone (lower half of image); biotite grain (Bi) adjacent to shear zone is partially reacted (Bi/RP) where highly strained.

![Figure 5](image)
crystallization- and climb-accommodated. Quartz grains within the shear zone, with a calculated strain rate of $2.8 \times 10^{-4}/s$, include porphyroclasts with a high dislocation density but no cracks and small dislocation-free recrystallized grains, consistent with recrystallization-accommodated dislocation creep. However, the results of Hirth and Tullis (1992, 1994) indicate that water-added quartzite at this strain rate should deform by semibrittle flow. This apparent contradiction indicates that even within the exceedingly narrow ductile shear zone, strain and strain rate are partitioned away from the quartz grains and into the mixed-phase reaction products.

Comparison to Natural Shear Zones

In our gneiss samples that develop strain localization and weakening, we observe a sequence of quartz microstructures indicative of decreasing stress. The same sequence of stress-dependent microstructures is observed in natural quartzites (e.g., Dunlap et al., 1997; Stipp et al., 2002). Strain weakening indicates a transition from higher- to lower-stress deformation mechanisms during constant strain rate deformation. The high-stress deformation mechanisms that initiate ductile shear zones are not the same as the lower-stress deformation mechanisms operating after localization and are not preserved after small strains.

The restriction of reaction products to high-strain zones indicates that high strain enhances reaction progress. In order to maintain strain localization, additional processes may be required to preserve the weakness of the material in the shear zone.

Once formed, the localized weak zone will remain weaker than the adjacent host rock, and in subsequent deformation events, strain will tend to relocalize in the weak zone, even if it is not in the optimal orientation.

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