

# Influence of water fugacity and activation volume on the flow properties of fine-grained anorthite aggregates

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Received 1 February 2005; revised 16 November 2005; accepted 27 December 2005; published 30 March 2006.

[1] To specify quantitatively the effect of pressure and water weakening on the flow strength of feldspar we performed triaxial creep experiments in a gas deformation apparatus at temperatures of 1000–1150°C, confining pressures of 100–450 MPa, and axial stresses of 10–400 MPa, resulting in strain rates of  $\sim 6 \times 10^{-7}$  to  $3 \times 10^{-3} \text{ s}^{-1}$ . Dense samples with a grain size of  $\sim 3 \text{ }\mu\text{m}$  were prepared by hot-isostatic pressing of anorthite glass powder. Hydrous samples contain about  $0.33 \pm 0.14 \text{ wt } \% \text{ H}_2\text{O}$  and dry specimens  $0.0005\text{--}0.02 \text{ wt } \% \text{ H}_2\text{O}$ . The estimated residual glass content of wet samples is  $<2 \text{ vol } \%$ . Samples deformed by grain boundary diffusion-controlled creep at low stresses and dislocation creep at stresses  $\geq 150 \text{ MPa}$ . We estimate an activation volume of  $V \approx 24 \text{ cm}^3 \text{ mol}^{-1}$  for anhydrous samples deforming in diffusion creep. For wet samples, deformed in hydrous conditions with varying buffers fixing oxygen fugacity, the activation volume is about  $38 \text{ cm}^3 \text{ mol}^{-1}$ . Creep rate of hydrous anorthite aggregates depends on water fugacity raised to a power of  $r = 1.0 \pm 0.3$ , suggesting hydrolysis of oxygen bonds. Considering the effect of activation volume and water fugacity on extrapolation of constitutive laws to conditions prevailing in the continental lower crust, viscosities of hydrous feldspar aggregates increase by a factor of  $<3$ .

**Citation:** Rybacki, E., M. Gottschalk, R. Wirth, and G. Dresen (2006), Influence of water fugacity and activation volume on the flow properties of fine-grained anorthite aggregates, *J. Geophys. Res.*, 111, B03203, doi:10.1029/2005JB003663.

## 1. Introduction

[2] Quantitative estimates of the viscosity of the Earth's lower crust and upper mantle are based on modeling of postseismic surface deformation [Freed and Burgmann, 2004; Hetland and Hager, 2003; Hu et al., 2004; Kenner, 2004; Nishimura and Thatcher, 2003; Vergnolle et al., 2003] and extrapolation of laboratory measurements to natural conditions [e.g., Kohlstedt et al., 1995; Montesi and Hirth, 2003]. Early experimental investigations on natural samples revealed that so-called “dry” or anhydrous rocks are much stronger than “wet” or hydrous aggregates, see reviews by Evans and Dresen [1991] and Evans and Kohlstedt [1995]. The terms “dry” and “wet” indicate mainly the heat treatment of samples before deformation, e.g., water-added, as-is or untreated, oven-dried, or vacuum-dried, but usually without specification of water content or the type of hydrogen incorporation, e.g., as fluid inclusions or structurally bonded hydrogen.

[3] Almost 40 years ago, Griggs and Blacic [1965] and Griggs [1967] in their pioneering studies observed that flow strength of quartz decreases significantly in the presence of trace amounts of water, which they attributed to hydrolysis of O-Si-O bonds. Hydrolytic weakening was subsequently observed in a plethora of experimental stud-

ies on quartz [Hobbs et al., 1972; Koch et al., 1989; Kronenberg et al., 1986; Kronenberg and Tullis, 1984; Ord and Hobbs, 1986; Post et al., 1996], although the physics of the process and solid state reactions involved still remain enigmatic [Paterson, 1989]. A significant reduction of high-temperature flow strength has been discovered for the dominant mineral constituents of the crust and upper mantle such as feldspar [Dimanov et al., 1999; Rybacki and Dresen, 2000, 2004; Tullis and Yund, 1980; Tullis et al., 1996], pyroxene [Hier-Majumder et al., 2005; McDonnell, 1998; McDonnell et al., 2000; Mei et al., 2001], and olivine [Chopra and Paterson, 1984; Karato et al., 1986; Karato and Jung, 2003; Mei and Kohlstedt, 2000a, 2000b].

[4] Concentration of water-related point defects in rocks depends on thermodynamic conditions if transport kinetics are fast enough to allow for equilibration. For water-saturated rocks in thermodynamic equilibrium, solubility of water-related defects in silicates and high-temperature creep rate  $\dot{\epsilon}$  were found to increase with water fugacity  $f_{\text{H}_2\text{O}}$  raised to the power of  $r$ , i.e.,  $\dot{\epsilon} \propto f_{\text{H}_2\text{O}}^r$  [Karato et al., 1986; Paterson, 1989]. When rocks are undersaturated with respect to water or thermodynamic equilibrium was not achieved, the constitutive behavior may be differently affected by water content. For example, creep activation energy may depend on water concentration, or the rate-limiting creep mechanism may change with water content [Rybacki and Dresen, 2000].

[5] Estimates of the water fugacity exponent  $r$  for high-temperature creep of silicates are still scarce. For quartzite,

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exponents  $r$  range between 1 and 2, suggesting the replacement of oxygen by  $\text{OH}^-$  or silicon by  $\text{H}^+$ , respectively [Gleason and Tullis, 1995; Hirth et al., 2001; Kohlstedt et al., 1995; Post et al., 1996; Rutter and Brodie, 2004]. For creep of Fe-bearing olivine aggregates, Mei and Kohlstedt [2000a, 2000b] estimated a water fugacity exponent between 0.69 and 1.25 assuming activation volumes  $V$  of 0 and  $38 \text{ cm}^3 \text{ mol}^{-1}$ , respectively, and Karato and Jung [2003] obtained  $r = 1.20$  with  $V = 24 \text{ cm}^3 \text{ mol}^{-1}$ . Hier-Majumder et al. [2005] measured an exponent of 1.4 for diffusion creep of wet clinopyroxenite. For diffusion creep of hydrous feldspar aggregates the fugacity exponent was estimated  $r \approx 0.5$  [Rybacki and Dresen, 2000]. In this study, we investigate the effect of water fugacity on the constitutive behavior of water-saturated synthetic anorthite aggregates. In this context, the creep activation volume was estimated from deformation experiments performed on dry and wet specimens.

## 2. Experimental Methods

### 2.1. Starting Material and Sample Preparation

[6] Synthetic specimens were fabricated from crushed  $\text{CaAl}_2\text{Si}_2\text{O}_8$  glass powder with a particle size of either  $<11 \mu\text{m}$  or  $<60 \mu\text{m}$  (Schott Glaswerke, An<sub>99</sub> composition). Initially, powders were cold pressed into iron cans of 0.5 mm wall thickness at an axial pressure of about 200 MPa in a vacuum chamber at about 1.5 kPa pressure. A few small anorthite single crystals ( $\sim 2 \text{ mm}$  in size) were added to the powder used to produce some wet specimens (P114–P117). The single crystals allowed estimating the amount of intracrystalline water incorporated at test conditions. Hot pressing was performed in a Paterson-type gas deformation apparatus at 300 MPa pressure. To enhance compaction, samples were kept initially at  $877^\circ\text{C}$  temperature for 0.5 hour, which is slightly above the glass transition temperature of  $871^\circ\text{C}$  [Dresen et al., 1996]. To crystallize the glass, samples were subsequently annealed at  $1100^\circ\text{C}$  for 22 hours, exceeding the nucleation temperature by about  $80^\circ\text{C}$  [Dresen et al., 1996]. After hot-pressing iron jackets were removed by dissolving in acid and cylindrical samples were precision ground to dimensions of  $10 \times 20$  and  $6.9 \times 14 \text{ mm}$  (diameter times length) for dry and wet samples, respectively. One hot-pressed sample (P106) was cut into parts of  $10 \times 10 \text{ mm}$  in size. To produce dry samples hot-pressed aggregates were dried in an oven at  $860\text{--}970^\circ\text{C}$  for 260–480 hours duration. Final porosity of samples is less than about 0.5% as determined by Archimedes' method and submersion of samples in ethanol.

### 2.2. Water Content

[7] A Fourier-transformed infrared spectrometer (FTIR, Bruker IFS-66v) was used to measure the water content on  $\sim 150 \mu\text{m}$  thick doubly polished sections. Spectra were recorded at room temperature in the wave number range 2500 to  $4000 \text{ cm}^{-1}$ . The shape of measured spectra is generally broad without distinct peaks, representative of molecular water. Measurements performed on polycrystalline sections represent the bulk water content since the spot size of the spectrometer (minimum  $\sim 20 \mu\text{m}$ ) spans several grains including grain boundaries. We calculated the water concentration from the peak height of absorbance spectra

using Beer-Lambert's law with a molar extinction coefficient of  $32 \text{ L}_{(\text{H}_2\text{O})} \text{ mol}^{-1}$  [Beran, 1987]. Reported values (Table 1) are about half as high compared to calculations using the integrated absorbance [Johnson and Rossman, 2003; Libowitzky and Rossman, 1997; Paterson, 1982].

[8] Undeformed wet samples contained  $0.22 \pm 0.08 \text{ wt } \%$   $\text{H}_2\text{O}$  ( $33400 \pm 12400 \text{ ppm H/Si}$ ) which is similar to the average water content measured for "typical" plutonic feldspars [Johnson and Rossman, 2004]. Measurements of the embedded (optically clear) single crystals yielded  $0.04 \pm 0.01 \text{ wt } \%$   $\text{H}_2\text{O}$  ( $6800 \pm 1700 \text{ ppm H/Si}$ ), which is about 4.5 times higher than their water content prior to hot-isostatic pressing ( $1500 \pm 490 \text{ ppm H/Si}$ ). If equilibrated under experimental (hot press) conditions, this value may represent the intracrystalline water solubility. For comparison, Johnson and Rossman [2003] measured about 3100 ppm H/Si on natural anorthite crystals from tholeiitic origin. Since the bulk hydroxyl content is about 5 times higher than for single crystals most of the water is expected to be located on grain boundaries. The most significant difference between spectra of single crystals and polycrystalline feldspar is a shift of the absorbance peak from  $3200\text{--}3400 \text{ cm}^{-1}$  to slightly above  $3500 \text{ cm}^{-1}$ , probably indicating the presence of water-bearing melt inclusions on grain boundaries [Johnson and Rossman, 2004].

[9] The water content of dry samples was determined only after deformation. It is about  $0.0025 \pm 0.0005 \text{ wt } \%$   $\text{H}_2\text{O}$  ( $380 \pm 80 \text{ ppm H/Si}$ ) for specimens obtained from fine-grained powder ( $<11 \mu\text{m}$ , samples P106-1, P106-2, P123, P130, P131) and  $0.020 \pm 0.003 \text{ wt } \%$   $\text{H}_2\text{O}$  ( $3100 \pm 500 \text{ ppm H/Si}$ ) for anhydrous samples fabricated from coarse-grained glass powder ( $<60 \mu\text{m}$ , samples P107, P108, P124) (Table 1). Predrying of some powder batches, as well as drying of some cold-pressed aggregates at  $850^\circ\text{C}$  for several days under reducing atmosphere, has no influence on the final water content.

### 2.3. Microstructure

[10] Grain shape and size was analyzed by scanning electron microscopy (SEM, Zeiss DSM 962) of thermally etched sections. Grains are often prismatic and twinned. The average grain size was determined with the line intercept method [Underwood, 1970]. To correct for stereological truncation effects mean intercept lengths are multiplied by a factor of 1.9, assuming a grain aspect ratio of 2.5. The mean grain size is  $2.7 \pm 0.6 \mu\text{m}$  for deformed dry samples and  $3.5 \pm 0.4 \mu\text{m}$  for deformed wet samples, respectively. For some samples we estimated grain size before and after deformation and found no significant grain growth during testing. These observations agree with findings of [Rybacki and Dresen, 2000] on a similar starting material.

[11] Microstructures were investigated using a Philips CM200 transmission electron microscope (TEM). Samples with large electron-transparent areas were prepared using a focused ion beam instrument (Fei FIB200) [Wirth, 2004]. Dislocations are rarely found in the undeformed starting material irrespective of water content. Some grains contain finely spaced twins and antiphase domains that are likely due to phase transformations during crystallization and annealing of the starting anorthite glass [Carpenter, 1991]. In general, with increasing water content we observed fewer submicron-sized grains, less twins, and more antiphase

**Table 1.** Material Properties and Test Conditions of Synthetic Anorthite Aggregates

| Sample <sup>a</sup> | T, °C | Deformation Conditions |                                          | Deformed  |                                          | Undeformed               |           | Comment                             |
|---------------------|-------|------------------------|------------------------------------------|-----------|------------------------------------------|--------------------------|-----------|-------------------------------------|
|                     |       | P, MPa                 | C <sub>H2O</sub> , <sup>b</sup> ppm H/Si | d, μm     | C <sub>H2O</sub> , <sup>b</sup> ppm H/Si | d <sub>powder</sub> , μm | Jacketing |                                     |
| Dry Samples         |       |                        |                                          |           |                                          |                          |           |                                     |
| P123                | 1125  | 400, 300, 200, 100     | 470                                      | 2.9 ± 0.4 |                                          | <11 (predried)           | Fe        | extension                           |
| P130                | 1140  | 400, 300, 200, 100     | 410                                      | 3.5 ± 1.2 |                                          | <11                      | Fe        | extension                           |
| P107                | 1150  | 400, 300, 200, 100     | 3000                                     | 2.4 ± 0.4 |                                          | <60                      | Fe        |                                     |
| P124                | 1160  | 400, 300,200, 100      | 3700                                     | 3.2 ± 0.8 |                                          | <60                      | Fe        | extension, second run               |
| P106_1              | 1175  | 300, 200               | 250                                      | 1.9 ± 0.4 |                                          | <11 (predried)           | Fe        | extension, preloaded                |
| P106_2              | 1175  | 400                    | 400                                      | 1.9 ± 0.3 |                                          | <11 (predried)           | Fe        |                                     |
| P131                | 1185  | 400, 300, 200          | 380                                      | 3.1 ± 0.9 |                                          | <11                      | Fe        | extension, much CO <sub>2</sub>     |
| P108                | 1200  | 400, 300, 200          | 2700                                     | 2.3 ± 0.3 |                                          | <60                      | Fe        |                                     |
| Wet Samples         |       |                        |                                          |           |                                          |                          |           |                                     |
| P113                | 1000  | 100                    | 57000                                    | 3.9 ± 0.9 | 20100                                    | <11 (predried)           | Ni-Fe-Fe  | second run                          |
| P125                | 1000  | 300                    | 54300                                    | 4.0 ± 1.0 |                                          | <11                      | Ni-Fe-Fe  |                                     |
| P121                | 1000  | 400                    | 60100                                    | 3.3 ± 0.9 | 16300                                    | <11 (predried)           | Ni-Fe-Fe  | fracture                            |
| P119                | 1050  | 100                    |                                          |           | 34600                                    | <11 (predried)           | Ni-Fe-Fe  |                                     |
| P126                | 1050  | 300                    | 33100                                    | 3.3 ± 0.8 |                                          | <11                      | Ni-Fe-Fe  |                                     |
| P118                | 1050  | 400                    | 63800                                    | 3.8 ± 0.7 | 32300                                    | <11 (predried)           | Ni-Fe-Fe  |                                     |
| P133                | 1050  | 450, 300, 150          | 77600                                    | 3.9 ± 1.0 |                                          | <11                      | Fe-Fe-Fe  |                                     |
| P134                | 1050  | 450, 300, 150          | 60100                                    | 3.7 ± 0.8 |                                          | <11                      | Fe-Fe-Fe  |                                     |
| P132                | 1050  | 450, 300               | 39600                                    | 3.8 ± 0.9 |                                          | <11                      | Ni-Ni-Ni  | second run, fracture                |
| P135                | 1050  | 450, 300               | 12600                                    | 4.2 ± 1.0 |                                          | <11                      | Ni-Ni-Ni  |                                     |
| P136                | 1050  | 450, 300, 150          | 64500                                    | 3.8 ± 0.7 |                                          | <11                      | Cu-Cu-Cu  |                                     |
| P137                | 1050  | 450, 300, 150          | 74800                                    | 3.7 ± 0.9 |                                          | <11                      | Cu-Cu-Cu  |                                     |
| P117                | 1100  | 100                    | 39500 ± 17100 (sc:5900 ± 700)            | 3.6 ± 1.1 | 59300                                    | <11                      | Ni-Fe-Fe  | second run embedded single crystals |
| P114                | 1100  | 200                    | 21400 ± 14200 (sc:4400 ± 2300)           | 2.8 ± 0.7 | 43400 ± 17700 (sc:5100 ± 1100)           | <11                      | Ni-Fe-Fe  | embedded single crystals            |
| P115                | 1100  | 300                    | 29500 ± 18900 (sc:3300 ± 1400)           | 3.0 ± 0.4 | 28500 (sc:8500 ± 2200)                   | <11                      | Ni-Fe-Fe  | embedded single crystals            |
| P116                | 1100  | 400                    | 35800 ± 15300 (sc:6300 ± 900)            | 3.2 ± 0.8 | 38500 ± 7200 (sc:6900 ± 2100)            | <11                      | Ni-Fe-Fe  | embedded single crystals            |
| P120                | 1150  | 100                    | 42100                                    | 2.7 ± 0.4 | 42500                                    | <11                      | Ni-Fe-Fe  |                                     |
| P127                | 1150  | 200                    | 77900                                    | 3.7 ± 0.9 |                                          | <11                      | Ni-Fe-Fe  |                                     |
| P122                | 1150  | 300                    | 37300                                    | 2.9 ± 0.6 | 28900                                    | <11                      | Ni-Fe-Fe  |                                     |
| P129                | 1150  | 400                    | 88100                                    | 4.1 ± 1.2 |                                          | <11                      | Fe-Fe-Fe  |                                     |

<sup>a</sup>T is temperature, P is pressure, C<sub>H2O</sub> is water content, d is grain size.<sup>b</sup>The sc denotes water content of single crystals.

**Table 2.** Creep Data of Wet Samples

| $P$ , MPa   | $T$ , °C | $\log(\sigma)$ , MPa | $\log \dot{\epsilon}$ , s <sup>-1</sup> |
|-------------|----------|----------------------|-----------------------------------------|
| <i>PL13</i> |          |                      |                                         |
| 100         | 1000     | 1.62                 | -6.25                                   |
| 100         | 1000     | 1.82                 | -5.91                                   |
| 100         | 1000     | 1.98                 | -5.61                                   |
| 100         | 1000     | 2.09                 | -5.38                                   |
| 100         | 1000     | 2.24                 | -5.08                                   |
| 100         | 1000     | 2.33                 | -4.88                                   |
| 100         | 1000     | 2.40                 | -4.75                                   |
| 100         | 1000     | 2.44                 | -4.64                                   |
| 100         | 1000     | 2.48                 | -4.50                                   |
| <i>PL25</i> |          |                      |                                         |
| 300         | 1000     | 1.15                 | -5.32                                   |
| 300         | 1000     | 1.39                 | -5.09                                   |
| 300         | 1000     | 1.54                 | -4.94                                   |
| 300         | 1000     | 1.66                 | -4.82                                   |
| 300         | 1000     | 1.74                 | -4.72                                   |
| 300         | 1000     | 1.89                 | -4.59                                   |
| 300         | 1000     | 1.99                 | -4.48                                   |
| 300         | 1000     | 2.14                 | -4.31                                   |
| 300         | 1000     | 2.25                 | -4.16                                   |
| 300         | 1000     | 2.37                 | -3.93                                   |
| 300         | 1000     | 2.42                 | -3.79                                   |
| 300         | 1000     | 2.46                 | -3.66                                   |
| <i>PL21</i> |          |                      |                                         |
| 400         | 1000     | 1.38                 | -4.73                                   |
| 400         | 1000     | 1.68                 | -4.42                                   |
| 400         | 1000     | 1.87                 | -4.23                                   |
| 400         | 1000     | 2.00                 | -4.13                                   |
| 400         | 1000     | 2.27                 | -3.79                                   |
| 400         | 1000     | 2.33                 | -3.66                                   |
| 400         | 1000     | 2.38                 | -3.57                                   |
| 400         | 1000     | 2.42                 | -3.46                                   |
| 400         | 1000     | 2.46                 | -3.31                                   |
| <i>PL19</i> |          |                      |                                         |
| 100         | 1050     | 1.45                 | -5.38                                   |
| 100         | 1050     | 1.51                 | -5.31                                   |
| 100         | 1050     | 1.70                 | -4.99                                   |
| 100         | 1050     | 1.83                 | -4.77                                   |
| <i>PL26</i> |          |                      |                                         |
| 300         | 1050     | 1.63                 | -5.06                                   |
| 300         | 1050     | 1.73                 | -4.90                                   |
| 300         | 1050     | 1.81                 | -4.79                                   |
| 300         | 1050     | 1.93                 | -4.60                                   |
| 300         | 1050     | 2.03                 | -4.49                                   |
| 300         | 1050     | 1.45                 | -5.29                                   |
| 300         | 1050     | 2.01                 | -4.50                                   |
| 300         | 1050     | 2.16                 | -4.30                                   |
| 300         | 1050     | 2.26                 | -4.11                                   |
| 300         | 1050     | 2.34                 | -3.95                                   |
| 300         | 1050     | 2.40                 | -3.79                                   |
| 300         | 1050     | 2.45                 | -3.65                                   |
| <i>PL18</i> |          |                      |                                         |
| 400         | 1050     | 1.44                 | -4.61                                   |
| 400         | 1050     | 1.64                 | -4.35                                   |
| 400         | 1050     | 1.79                 | -4.19                                   |
| 400         | 1050     | 1.90                 | -4.10                                   |
| 400         | 1050     | 2.02                 | -3.97                                   |
| 400         | 1050     | 2.25                 | -3.65                                   |
| 400         | 1050     | 2.33                 | -3.51                                   |
| 400         | 1050     | 2.39                 | -3.36                                   |
| 400         | 1050     | 2.43                 | -3.23                                   |
| 400         | 1050     | 2.47                 | -3.06                                   |
| <i>PL37</i> |          |                      |                                         |
| 150         | 1050     | 1.59                 | -3.74                                   |
| 150         | 1050     | 1.72                 | -3.65                                   |
| 150         | 1050     | 1.81                 | -3.55                                   |
| 150         | 1050     | 1.91                 | -3.40                                   |

**Table 2.** (continued)

| $P$ , MPa   | $T$ , °C | $\log(\sigma)$ , MPa | $\log \dot{\epsilon}$ , s <sup>-1</sup> |
|-------------|----------|----------------------|-----------------------------------------|
| 300         | 1050     | 1.58                 | -3.64                                   |
| 300         | 1050     | 1.75                 | -3.52                                   |
| 300         | 1050     | 1.83                 | -3.44                                   |
| 300         | 1050     | 1.92                 | -3.33                                   |
| 450         | 1050     | 1.43                 | -3.55                                   |
| 450         | 1050     | 1.66                 | -3.34                                   |
| 450         | 1050     | 1.80                 | -3.18                                   |
| 450         | 1050     | 1.91                 | -3.07                                   |
| <i>PL36</i> |          |                      |                                         |
| 150         | 1050     | 1.66                 | -3.71                                   |
| 150         | 1050     | 1.81                 | -3.60                                   |
| 150         | 1050     | 1.92                 | -3.47                                   |
| 300         | 1050     | 1.75                 | -3.67                                   |
| 300         | 1050     | 1.86                 | -3.61                                   |
| 300         | 1050     | 1.95                 | -3.51                                   |
| 300         | 1050     | 2.39                 | -2.55                                   |
| 300         | 1050     | 2.40                 | -2.50                                   |
| 450         | 1050     | 1.50                 | -3.68                                   |
| 450         | 1050     | 1.61                 | -3.58                                   |
| 450         | 1050     | 1.73                 | -3.49                                   |
| 450         | 1050     | 1.85                 | -3.37                                   |
| 450         | 1050     | 1.95                 | -3.31                                   |
| <i>PL34</i> |          |                      |                                         |
| 150         | 1050     | 1.99                 | -4.30                                   |
| 150         | 1050     | 2.26                 | -4.01                                   |
| 150         | 1050     | 2.31                 | -3.96                                   |
| 150         | 1050     | 2.35                 | -3.85                                   |
| 150         | 1050     | 2.41                 | -3.69                                   |
| 300         | 1050     | 2.02                 | -4.30                                   |
| 300         | 1050     | 2.28                 | -3.98                                   |
| 300         | 1050     | 2.33                 | -3.91                                   |
| 300         | 1050     | 2.38                 | -3.83                                   |
| 300         | 1050     | 2.43                 | -3.72                                   |
| 450         | 1050     | 2.05                 | -4.37                                   |
| 450         | 1050     | 2.30                 | -3.99                                   |
| 450         | 1050     | 2.36                 | -3.92                                   |
| 450         | 1050     | 2.41                 | -3.89                                   |
| 450         | 1050     | 2.46                 | -3.73                                   |
| <i>PL33</i> |          |                      |                                         |
| 150         | 1050     | 1.66                 | -4.90                                   |
| 150         | 1050     | 1.81                 | -4.80                                   |
| 150         | 1050     | 1.92                 | -4.71                                   |
| 150         | 1050     | 2.01                 | -4.60                                   |
| 300         | 1050     | 1.68                 | -4.92                                   |
| 300         | 1050     | 1.83                 | -4.76                                   |
| 300         | 1050     | 1.94                 | -4.65                                   |
| 300         | 1050     | 2.02                 | -4.56                                   |
| 450         | 1050     | 1.68                 | -4.96                                   |
| 450         | 1050     | 1.82                 | -4.77                                   |
| 450         | 1050     | 1.93                 | -4.64                                   |
| 450         | 1050     | 2.03                 | -4.50                                   |
| <i>PL35</i> |          |                      |                                         |
| 300         | 1050     | 1.73                 | -5.22                                   |
| 300         | 1050     | 1.85                 | -5.13                                   |
| 300         | 1050     | 1.96                 | -4.94                                   |
| 300         | 1050     | 2.04                 | -4.85                                   |
| 450         | 1050     | 1.71                 | -5.21                                   |
| 450         | 1050     | 1.85                 | -5.10                                   |
| 450         | 1050     | 1.95                 | -4.94                                   |
| 450         | 1050     | 2.05                 | -4.80                                   |
| <i>PL32</i> |          |                      |                                         |
| 300         | 1050     | 1.96                 | -4.00                                   |
| 300         | 1050     | 2.39                 | -3.22                                   |
| 300         | 1050     | 2.44                 | -3.10                                   |
| 300         | 1050     | 2.46                 | -3.01                                   |
| 450         | 1050     | 2.01                 | -4.34                                   |
| 450         | 1050     | 2.46                 | -3.51                                   |
| 450         | 1050     | 2.51                 | -3.33                                   |

Table 2. (continued)

| $P$ , MPa | $T$ , °C | $\log(\sigma)$ , MPa | $\log \dot{\epsilon}$ , s <sup>-1</sup> |
|-----------|----------|----------------------|-----------------------------------------|
| 450       | 1050     | 2.54                 | -3.16                                   |
|           |          | <i>PL17</i>          |                                         |
| 100       | 1100     | 1.74                 | -4.88                                   |
| 100       | 1100     | 1.87                 | -4.72                                   |
| 100       | 1100     | 1.97                 | -4.60                                   |
| 100       | 1100     | 2.09                 | -4.45                                   |
| 100       | 1100     | 2.25                 | -4.19                                   |
| 100       | 1100     | 2.34                 | -4.00                                   |
| 100       | 1100     | 2.41                 | -3.79                                   |
| 100       | 1100     | 2.46                 | -3.60                                   |
| 100       | 1100     | 2.53                 | -3.24                                   |
|           |          | <i>PL14</i>          |                                         |
| 200       | 1100     | 1.72                 | -4.50                                   |
| 200       | 1100     | 1.77                 | -4.44                                   |
| 200       | 1100     | 1.84                 | -4.35                                   |
| 200       | 1100     | 1.95                 | -4.24                                   |
| 200       | 1100     | 2.07                 | -4.10                                   |
| 200       | 1100     | 2.29                 | -3.74                                   |
| 200       | 1100     | 2.36                 | -3.57                                   |
| 200       | 1100     | 2.42                 | -3.38                                   |
| 200       | 1100     | 2.47                 | -3.21                                   |
| 200       | 1100     | 2.51                 | -3.00                                   |
|           |          | <i>PL15</i>          |                                         |
| 300       | 1100     | 1.70                 | -4.47                                   |
| 300       | 1100     | 1.83                 | -4.30                                   |
| 300       | 1100     | 1.93                 | -4.21                                   |
| 300       | 1100     | 2.05                 | -4.07                                   |
| 300       | 1100     | 2.26                 | -3.72                                   |
| 300       | 1100     | 2.34                 | -3.55                                   |
| 300       | 1100     | 2.40                 | -3.38                                   |
| 300       | 1100     | 2.44                 | -3.24                                   |
| 300       | 1100     | 2.50                 | -3.05                                   |
|           |          | <i>PL16</i>          |                                         |
| 400       | 1100     | 1.70                 | -4.66                                   |
| 400       | 1100     | 1.83                 | -4.49                                   |
| 400       | 1100     | 1.94                 | -4.40                                   |
| 400       | 1100     | 2.06                 | -4.27                                   |
| 400       | 1100     | 2.28                 | -3.97                                   |
| 400       | 1100     | 2.35                 | -3.83                                   |
| 400       | 1100     | 2.42                 | -3.69                                   |
| 400       | 1100     | 2.46                 | -3.58                                   |
| 400       | 1100     | 2.51                 | -3.45                                   |
|           |          | <i>PL20</i>          |                                         |
| 100       | 1150     | 1.58                 | -4.01                                   |
| 100       | 1150     | 1.74                 | -3.82                                   |
| 100       | 1150     | 1.87                 | -3.67                                   |
| 100       | 1150     | 1.96                 | -3.54                                   |
| 100       | 1150     | 2.19                 | -2.98                                   |
| 100       | 1150     | 2.25                 | -2.69                                   |
|           |          | <i>PL27</i>          |                                         |
| 200       | 1150     | 0.92                 | -5.05                                   |
| 200       | 1150     | 1.13                 | -4.84                                   |
| 200       | 1150     | 1.27                 | -4.69                                   |
| 200       | 1150     | 1.39                 | -4.58                                   |
| 200       | 1150     | 1.47                 | -4.49                                   |
| 200       | 1150     | 1.54                 | -4.41                                   |
| 200       | 1150     | 1.60                 | -4.34                                   |
| 200       | 1150     | 1.70                 | -4.22                                   |
| 200       | 1150     | 1.78                 | -4.12                                   |
| 200       | 1150     | 1.90                 | -3.94                                   |
| 200       | 1150     | 2.04                 | -3.73                                   |
| 200       | 1150     | 2.14                 | -3.54                                   |
| 200       | 1150     | 2.24                 | -3.29                                   |
| 200       | 1150     | 2.32                 | -3.05                                   |
| 200       | 1150     | 2.38                 | -2.81                                   |

Table 2. (continued)

| $P$ , MPa | $T$ , °C | $\log(\sigma)$ , MPa | $\log \dot{\epsilon}$ , s <sup>-1</sup> |
|-----------|----------|----------------------|-----------------------------------------|
|           |          | <i>PL22</i>          |                                         |
| 300       | 1150     | 1.48                 | -4.20                                   |
| 300       | 1150     | 1.59                 | -4.07                                   |
| 300       | 1150     | 1.75                 | -3.87                                   |
| 300       | 1150     | 1.87                 | -3.70                                   |
| 300       | 1150     | 1.96                 | -3.60                                   |
| 300       | 1150     | 2.21                 | -3.25                                   |
| 300       | 1150     | 2.33                 | -2.98                                   |
| 300       | 1150     | 2.35                 | -2.89                                   |
| 300       | 1150     | 2.40                 | -2.73                                   |
|           |          | <i>PL29</i>          |                                         |
| 400       | 1150     | 0.89                 | -5.01                                   |
| 400       | 1150     | 1.25                 | -4.62                                   |
| 400       | 1150     | 1.46                 | -4.39                                   |
| 400       | 1150     | 1.08                 | -4.79                                   |
| 400       | 1150     | 1.35                 | -4.52                                   |
| 400       | 1150     | 1.43                 | -4.43                                   |
| 400       | 1150     | 1.50                 | -4.35                                   |
| 400       | 1150     | 1.56                 | -4.29                                   |
| 400       | 1150     | 1.66                 | -4.19                                   |
| 400       | 1150     | 1.74                 | -4.09                                   |
| 400       | 1150     | 1.87                 | -3.94                                   |
| 400       | 1150     | 1.97                 | -3.81                                   |
| 400       | 1150     | 2.12                 | -3.60                                   |
| 400       | 1150     | 2.23                 | -3.40                                   |
| 400       | 1150     | 2.31                 | -3.21                                   |
| 400       | 1150     | 2.43                 | -2.84                                   |

domains. Hydrous samples contain more residual glass and Si-enriched melt located in triple junctions. Wetting of grain boundaries was not observed. Intracrystalline fluid inclusions are frequently surrounded by glass. The total melt content is estimated to be  $\leq 1$  vol %. Interestingly, intracrystalline fluid inclusions are also frequently found in dry samples. This suggests that solubility of water-related point defects in the synthetic anorthite may be lower than that of embedded single crystals at experimental conditions. Similarly, *Dresen et al.* [1996] found that anorthite crystallized from a glass containing about 200 ppm H/Si displayed numerous fluid inclusions. The authors suggested that fluid inclusions containing H<sub>2</sub>O likely exsolved during crystallization at 0.1 MPa pressure and  $>1000^\circ\text{C}$ .

#### 2.4. Experimental Deformation and Data Analysis

[12] We performed deformation experiments in a Paterson-type gas deformation apparatus on both dry and wet feldspar specimens to investigate the effect of activation volume and water fugacity on sample strength. Dry samples were jacketed using a  $\sim 0.35$  mm thick iron sleeve and deformed in a standard gas deformation apparatus assembly [Paterson, 1990]. For deformation tests at hydrous conditions the standard sample assembly inside the iron sleeve consisted of a thin nickel foil wrapped around the sample, surrounded by a 0.85 mm thick pyrophyllite sleeve, and enclosed in a sealed steel capsule [Mei and Kohlstedt, 2000a], referred to in the following as NFF assembly (abbreviation for Ni foil–Fe capsule–Fe jacket). Gas-tight sealing of the capsule was ensured by careful laser welding. Pyrophyllite dehydrates above a temperature of about  $400^\circ\text{C}$  at 300 MPa pressure, releasing  $\sim 5$  wt % H<sub>2</sub>O. If the anorthite aggregates would incorporate the released water completely they would contain about 2.9 wt %. The

**Table 3.** Creep Data of Dry Samples

| $P$ , MPa   | $T$ , °C | $\log(\sigma)$ , MPa | $\log \dot{\epsilon}$ , s <sup>-1</sup> |
|-------------|----------|----------------------|-----------------------------------------|
| <i>PL23</i> |          |                      |                                         |
| 100         | 1125     | 1.57                 | -5.99                                   |
| 100         | 1125     | 1.69                 | -5.90                                   |
| 100         | 1125     | 2.00                 | -5.63                                   |
| 100         | 1125     | 2.09                 | -5.57                                   |
| 100         | 1125     | 2.20                 | -5.44                                   |
| 100         | 1125     | 2.34                 | -5.24                                   |
| 100         | 1125     | 2.48                 | -5.09                                   |
| 100         | 1125     | 2.51                 | -5.04                                   |
| 200         | 1125     | 1.58                 | -6.06                                   |
| 200         | 1125     | 1.78                 | -5.89                                   |
| 200         | 1125     | 1.88                 | -5.82                                   |
| 200         | 1125     | 1.98                 | -5.74                                   |
| 200         | 1125     | 2.17                 | -5.56                                   |
| 200         | 1125     | 2.46                 | -5.28                                   |
| 200         | 1125     | 2.48                 | -5.27                                   |
| 200         | 1125     | 2.51                 | -5.25                                   |
| 300         | 1125     | 1.87                 | -5.89                                   |
| 300         | 1125     | 2.01                 | -5.80                                   |
| 300         | 1125     | 2.09                 | -5.76                                   |
| 300         | 1125     | 2.22                 | -5.67                                   |
| 300         | 1125     | 2.35                 | -5.52                                   |
| 300         | 1125     | 2.45                 | -5.41                                   |
| 300         | 1125     | 2.48                 | -5.39                                   |
| 300         | 1125     | 2.51                 | -5.36                                   |
| 300         | 1125     | 2.54                 | -5.31                                   |
| 300         | 1125     | 2.56                 | -5.27                                   |
| 400         | 1125     | 1.70                 | -6.13                                   |
| 400         | 1125     | 1.79                 | -6.09                                   |
| 400         | 1125     | 1.92                 | -5.98                                   |
| 400         | 1125     | 2.06                 | -5.80                                   |
| 400         | 1125     | 2.19                 | -5.63                                   |
| 400         | 1125     | 2.39                 | -5.38                                   |
| 400         | 1125     | 2.45                 | -5.31                                   |
| 400         | 1125     | 2.50                 | -5.21                                   |
| 400         | 1125     | 2.55                 | -5.12                                   |
| 400         | 1125     | 2.59                 | -5.07                                   |
| <i>PL30</i> |          |                      |                                         |
| 100         | 1140     | 1.56                 | -5.29                                   |
| 100         | 1140     | 1.78                 | -5.13                                   |
| 100         | 1140     | 1.92                 | -5.03                                   |
| 100         | 1140     | 2.03                 | -4.96                                   |
| 100         | 1140     | 2.15                 | -4.89                                   |
| 100         | 1140     | 2.24                 | -4.82                                   |
| 100         | 1140     | 2.32                 | -4.74                                   |
| 100         | 1140     | 2.38                 | -4.61                                   |
| 100         | 1140     | 2.43                 | -4.47                                   |
| 200         | 1140     | 1.55                 | -5.35                                   |
| 200         | 1140     | 1.77                 | -5.19                                   |
| 200         | 1140     | 1.92                 | -5.10                                   |
| 200         | 1140     | 2.02                 | -5.03                                   |
| 200         | 1140     | 2.14                 | -4.93                                   |
| 200         | 1140     | 2.24                 | -4.86                                   |
| 200         | 1140     | 2.31                 | -4.80                                   |
| 200         | 1140     | 2.38                 | -4.73                                   |
| 200         | 1140     | 2.43                 | -4.68                                   |
| 300         | 1140     | 1.56                 | -5.27                                   |
| 300         | 1140     | 1.77                 | -5.18                                   |
| 300         | 1140     | 2.02                 | -5.04                                   |
| 300         | 1140     | 2.14                 | -4.97                                   |
| 300         | 1140     | 2.23                 | -4.91                                   |
| 300         | 1140     | 2.35                 | -4.80                                   |
| 300         | 1140     | 2.43                 | -4.72                                   |
| 300         | 1140     | 2.47                 | -4.65                                   |
| 400         | 1140     | 1.78                 | -5.41                                   |
| 400         | 1140     | 1.93                 | -5.32                                   |
| 400         | 1140     | 2.03                 | -5.25                                   |
| 400         | 1140     | 2.15                 | -5.13                                   |
| 400         | 1140     | 2.25                 | -5.05                                   |
| 400         | 1140     | 2.37                 | -4.90                                   |
| 400         | 1140     | 2.44                 | -4.79                                   |
| 400         | 1140     | 2.49                 | -4.71                                   |

**Table 3.** (continued)

| $P$ , MPa     | $T$ , °C | $\log(\sigma)$ , MPa | $\log \dot{\epsilon}$ , s <sup>-1</sup> |
|---------------|----------|----------------------|-----------------------------------------|
| 400           | 1140     | 2.53                 | -4.64                                   |
| <i>PL07</i>   |          |                      |                                         |
| 100           | 1150     | 1.90                 | -4.69                                   |
| 100           | 1150     | 2.00                 | -4.63                                   |
| 200           | 1150     | 1.93                 | -4.76                                   |
| 200           | 1150     | 2.11                 | -4.66                                   |
| 200           | 1150     | 2.25                 | -4.53                                   |
| 200           | 1150     | 2.47                 | -3.77                                   |
| 200           | 1150     | 2.50                 | -3.75                                   |
| 200           | 1150     | 2.52                 | -3.70                                   |
| 300           | 1150     | 1.93                 | -4.80                                   |
| 300           | 1150     | 2.10                 | -4.69                                   |
| 300           | 1150     | 2.24                 | -4.56                                   |
| 300           | 1150     | 2.49                 | -3.87                                   |
| 300           | 1150     | 2.52                 | -3.85                                   |
| 300           | 1150     | 2.55                 | -3.80                                   |
| 400           | 1150     | 1.94                 | -4.78                                   |
| 400           | 1150     | 2.11                 | -4.64                                   |
| 400           | 1150     | 2.25                 | -4.49                                   |
| 400           | 1150     | 2.46                 | -4.23                                   |
| 400           | 1150     | 2.49                 | -4.19                                   |
| 400           | 1150     | 2.52                 | -4.10                                   |
| 400           | 1150     | 2.56                 | -4.01                                   |
| <i>PL24</i>   |          |                      |                                         |
| 100           | 1160     | 1.90                 | -4.77                                   |
| 100           | 1160     | 2.04                 | -4.66                                   |
| 100           | 1160     | 2.15                 | -4.55                                   |
| 100           | 1160     | 2.26                 | -4.40                                   |
| 100           | 1160     | 2.42                 | -3.93                                   |
| 100           | 1160     | 2.45                 | -3.74                                   |
| 100           | 1160     | 2.48                 | -3.56                                   |
| 100           | 1160     | 2.50                 | -3.35                                   |
| 200           | 1160     | 1.90                 | -4.79                                   |
| 200           | 1160     | 2.04                 | -4.70                                   |
| 200           | 1160     | 2.15                 | -4.62                                   |
| 200           | 1160     | 2.26                 | -4.50                                   |
| 200           | 1160     | 2.42                 | -4.26                                   |
| 200           | 1160     | 2.45                 | -4.22                                   |
| 200           | 1160     | 2.48                 | -4.18                                   |
| 200           | 1160     | 2.51                 | -4.12                                   |
| 200           | 1160     | 2.53                 | -4.09                                   |
| 300           | 1160     | 2.03                 | -4.77                                   |
| 300           | 1160     | 2.13                 | -4.69                                   |
| 300           | 1160     | 2.24                 | -4.59                                   |
| 300           | 1160     | 2.40                 | -4.40                                   |
| 300           | 1160     | 2.43                 | -4.37                                   |
| 300           | 1160     | 2.46                 | -4.33                                   |
| 300           | 1160     | 2.49                 | -4.29                                   |
| 300           | 1160     | 2.51                 | -4.25                                   |
| 400           | 1160     | 1.92                 | -5.16                                   |
| 400           | 1160     | 2.01                 | -5.04                                   |
| 400           | 1160     | 2.12                 | -4.92                                   |
| 400           | 1160     | 2.21                 | -4.83                                   |
| 400           | 1160     | 2.31                 | -4.72                                   |
| 400           | 1160     | 2.45                 | -4.51                                   |
| 400           | 1160     | 2.50                 | -4.43                                   |
| 400           | 1160     | 2.54                 | -4.35                                   |
| 400           | 1160     | 2.57                 | -4.26                                   |
| 400           | 1160     | 2.60                 | -4.18                                   |
| <i>PL06_1</i> |          |                      |                                         |
| 200           | 1175     | 1.84                 | -4.42                                   |
| 200           | 1175     | 1.95                 | -4.36                                   |
| 200           | 1175     | 2.08                 | -4.26                                   |
| 200           | 1175     | 2.30                 | -4.02                                   |
| 200           | 1175     | 2.44                 | -3.80                                   |
| 200           | 1175     | 2.50                 | -3.64                                   |
| 200           | 1175     | 2.52                 | -3.55                                   |
| 200           | 1175     | 2.54                 | -3.46                                   |
| 300           | 1175     | 1.95                 | -4.44                                   |
| 300           | 1175     | 2.08                 | -4.36                                   |

**Table 3.** (continued)

| $P$ , MPa     | $T$ , °C | $\log(\sigma)$ , MPa | $\log \dot{\epsilon}$ , s <sup>-1</sup> |
|---------------|----------|----------------------|-----------------------------------------|
| 300           | 1175     | 2.30                 | -4.12                                   |
| 300           | 1175     | 2.44                 | -3.88                                   |
| 300           | 1175     | 2.50                 | -3.71                                   |
| 300           | 1175     | 2.52                 | -3.61                                   |
| 300           | 1175     | 2.54                 | -3.51                                   |
| <i>PL06_2</i> |          |                      |                                         |
| 400           | 1175     | 1.82                 | -4.56                                   |
| 400           | 1175     | 1.93                 | -4.48                                   |
| 400           | 1175     | 2.06                 | -4.37                                   |
| 400           | 1175     | 2.28                 | -4.12                                   |
| 400           | 1175     | 2.42                 | -3.88                                   |
| 400           | 1175     | 2.47                 | -3.72                                   |
| 400           | 1175     | 2.51                 | -3.58                                   |
| 400           | 1175     | 2.54                 | -3.45                                   |
| <i>PL31</i>   |          |                      |                                         |
| 200           | 1185     | 1.53                 | -4.93                                   |
| 200           | 1185     | 1.66                 | -4.88                                   |
| 200           | 1185     | 1.75                 | -4.83                                   |
| 200           | 1185     | 1.90                 | -4.71                                   |
| 200           | 1185     | 2.00                 | -4.64                                   |
| 200           | 1185     | 2.13                 | -4.49                                   |
| 200           | 1185     | 2.22                 | -4.36                                   |
| 200           | 1185     | 2.30                 | -4.25                                   |
| 200           | 1185     | 2.36                 | -4.14                                   |
| 300           | 1185     | 1.55                 | -5.07                                   |
| 300           | 1185     | 1.76                 | -4.92                                   |
| 300           | 1185     | 1.91                 | -4.83                                   |
| 300           | 1185     | 2.01                 | -4.77                                   |
| 300           | 1185     | 2.13                 | -4.67                                   |
| 300           | 1185     | 2.23                 | -4.59                                   |
| 300           | 1185     | 2.30                 | -4.51                                   |
| 300           | 1185     | 2.37                 | -4.40                                   |
| 300           | 1185     | 2.42                 | -4.32                                   |
| 400           | 1185     | 1.63                 | -5.36                                   |
| 400           | 1185     | 1.78                 | -5.26                                   |
| 400           | 1185     | 1.92                 | -5.16                                   |
| 400           | 1185     | 2.03                 | -5.09                                   |
| 400           | 1185     | 2.15                 | -4.97                                   |
| 400           | 1185     | 2.24                 | -4.87                                   |
| 400           | 1185     | 2.32                 | -4.77                                   |
| 400           | 1185     | 2.38                 | -4.68                                   |
| 400           | 1185     | 2.47                 | -4.53                                   |
| 400           | 1185     | 2.51                 | -4.44                                   |
| 400           | 1185     | 2.55                 | -4.35                                   |
| <i>PL08</i>   |          |                      |                                         |
| 200           | 1200     | 1.87                 | -4.35                                   |
| 200           | 1200     | 2.01                 | -4.27                                   |
| 200           | 1200     | 2.11                 | -4.20                                   |
| 200           | 1200     | 2.22                 | -4.08                                   |
| 200           | 1200     | 2.36                 | -3.50                                   |
| 200           | 1200     | 2.41                 | -3.45                                   |
| 200           | 1200     | 2.45                 | -3.39                                   |
| 200           | 1200     | 2.49                 | -3.30                                   |
| 300           | 1200     | 1.87                 | -4.35                                   |
| 300           | 1200     | 2.01                 | -4.27                                   |
| 300           | 1200     | 2.12                 | -4.18                                   |
| 300           | 1200     | 2.35                 | -3.49                                   |
| 300           | 1200     | 2.39                 | -3.45                                   |
| 300           | 1200     | 2.44                 | -3.39                                   |
| 300           | 1200     | 2.47                 | -3.30                                   |
| 400           | 1200     | 1.88                 | -4.40                                   |
| 400           | 1200     | 2.02                 | -4.27                                   |
| 400           | 1200     | 2.15                 | -4.14                                   |
| 400           | 1200     | 2.36                 | -3.80                                   |
| 400           | 1200     | 2.41                 | -3.73                                   |
| 400           | 1200     | 2.45                 | -3.63                                   |
| 400           | 1200     | 2.49                 | -3.53                                   |

jacketing materials served as solid buffers setting oxygen fugacity during deformation of wet (Ni-NiO) and dry (Fe-FeO) samples [Mei and Kohlstedt, 2000a]. A few samples were buffered using metal sleeves prepared entirely from nickel, iron or copper, respectively (Table 1).

[13] To correct load for the strength of metal and pyrophyllite sleeves, we ran calibration experiments on dummy samples from similar material or used published flow laws [Frost and Ashby, 1982]. The deformation apparatus is equipped with an internal furnace, load cell, and LVDT. Temperature uncertainty is less than 0.5%. Stress was calculated assuming constant volume deformation. We give true (natural) strain determined from the measurement of axial displacement and corrected for system compliance. Sensor-related accuracy of axial stress is 0.6% and of strain rate 0.3%. During the course of an experiment uncertainty of calculated stress increases by 0.6% due to uncertainty of applied jacket correction, 0.8% due to the pressure sensitivity of the load cell for small confining pressure fluctuations, and ~2% due to sample bulging. Precision of measured initial sample diameter yields another 1% uncertainty. In total, accuracy of stress is 3% and in few cases 5%.

[14] Specimens were usually annealed for 17 h at test conditions before starting deformation runs to allow for equilibration with thermodynamic conditions and chemical environment. All samples were deformed at constant load with a stepwise increase of the axial load for a single sample at constant temperature (creep testing). Strain per step was between 1.3 and 2.1% and secondary creep at constant rate was usually achieved after straining for about 0.5%. Increase of sample diameter during axial shortening results in about 2% uncertainty of reported “constant” stress values and “steady state” creep rates. No correction for grain growth was required as grain size of deformed samples is comparable to undeformed specimens.

[15] A total of 20 hydrous samples were deformed at  $T = 1000\text{--}1150^\circ\text{C}$ , pressures between 100 and 450 MPa, and stresses of ~10–340 MPa, yielding steady state strain rates of  $\sim 6 \times 10^{-7}$  to  $3 \times 10^{-3} \text{ s}^{-1}$  (Table 2). For 14 samples, confining pressure was maintained constant and 6 samples were deformed at a stepwise reduced pressure.

[16] Eight dry samples were coaxially deformed at temperatures of  $1125^\circ\text{--}1200^\circ\text{C}$ , confining pressures stepwise reduced from 400 to 100 MPa, and axial stresses between ~30 and 400 MPa, resulting in axial strain rates of about  $7 \times 10^{-7}$  to  $5 \times 10^{-4} \text{ s}^{-1}$  (Table 3). Two dry specimens (P107 and P108) were first deformed at low stresses (200 MPa) and stepwise reduced confining pressure. Samples were then loaded to higher stresses and deformed with similar pressure steps. After deformation at each pressure step the remaining dry samples were elongated to the original length over night by low stress extension. This procedure allowed performing several tests at different conditions on a single specimen. Sample P106 was cut in two parts that were tested at different pressures. For all samples, annealing time after pressure stepping was at least 2 hours to allow for reequilibration.

### 3. Results

#### 3.1. Mechanical Data

[17] Specimens deformed at hydrous conditions are weaker than dry samples. Stress-strain rate data of the

deformed wet and dry rock samples reveal lower viscosities with increasing temperature (Tables 2 and 3). However, small variations in microstructure, grain size and water content significantly affect the deformation

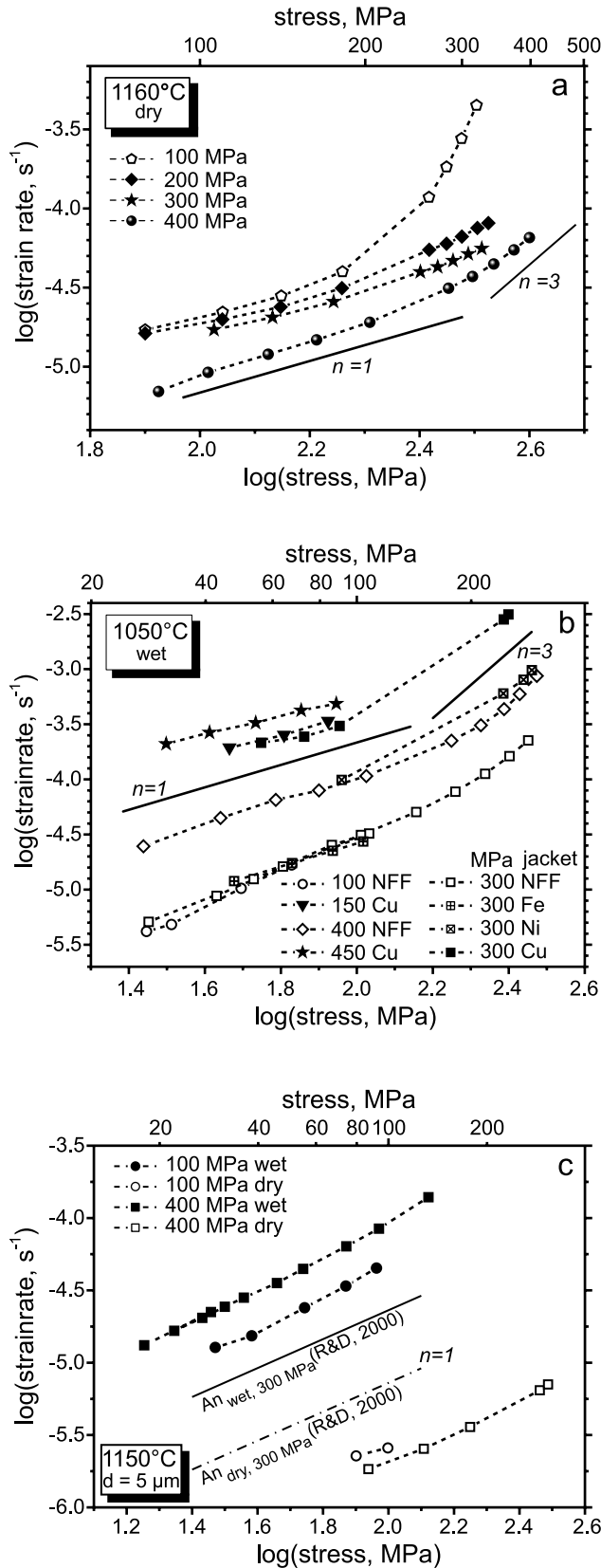
behavior. The experimental data are fit to a power law of the form

$$\dot{\epsilon} = A\sigma^n \exp\left[-\frac{Q+pV}{RT}\right] d^{-m} f_{\text{H}_2\text{O}}^r f_{\text{H}/\text{O}_2}^w \quad (1)$$

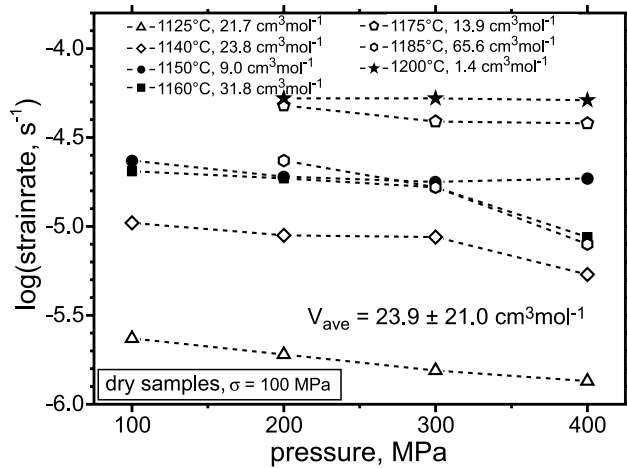
where  $\dot{\epsilon}$  is strain rate,  $A$  is a material constant,  $\sigma$  is stress,  $n$  is stress exponent,  $Q$  is activation energy,  $p$  is pressure,  $V$  is activation volume,  $T$  is absolute temperature,  $R$  is the molar gas constant,  $d$  is grain size,  $m$  is grain size exponent,  $f_{\text{H}_2\text{O}}$  is water fugacity,  $f_{\text{H}/\text{O}_2}$  is fugacity of hydrogen/oxygen, and  $r, w$  are fugacity exponents [Evans and Kohlstedt, 1995; Mei and Kohlstedt, 2000a; Paterson, 1989]. Theoretical models of grain boundary and lattice diffusion - controlled creep predict  $m = 3$  and  $m = 2$ , respectively with a stress exponent of  $n = 1$ . For climb-controlled dislocation creep, deformation is commonly assumed to be grain size insensitive ( $m = 0$ ) with a stress exponent of  $n = 3-5$  [Chokshi and Langdon, 1991]. If individual deformation mechanisms operate independently and in parallel, strain rates add at given stress and the fastest mechanism is expected to dominate the bulk creep behavior.

[18] At stresses  $\lesssim 200$  MPa for anhydrous samples and stresses  $\lesssim 100$  MPa for wet specimens, deformation was linear viscous with  $n \approx 1$  suggesting diffusion-controlled creep. At higher stresses we observed a gradual transition to dislocation creep with  $n > 2$  (Figure 1). When stresses are significantly higher than the confining pressure, creep rates accelerated due to microfracturing of the samples. In this paper we only discuss mechanical data obtained in the low stress region.

[19] At anhydrous conditions the viscosity of anorthite aggregates increases with increasing confining pressure although the data shows some scatter (Figure 1a and Table 3). To estimate flow law parameters, we assumed  $n = 1$  and  $m = 3$  as suggested by previous studies on grain boundary diffusion-controlled creep of fine-grained feldspar aggregates [see Rybacki and Dresen, 2000, and references therein]. At dry



**Figure 1.** Representative stress-strain curves for high-temperature creep of fine-grained anorthite aggregates. In log-log scale the curves reveal a gradual transition from Newtonian flow (stress exponent  $n = 1$ ) at low stresses to power law creep ( $n \approx 3$ ) at high stresses, indicating a transition from diffusion-accommodated creep to dislocation creep. (a) Dry samples are stronger with increasing pressure. Note the accelerated creep at high stress and 100 MPa confining pressure, indicating the onset of tertiary creep (sample PI24,  $T = 1160^\circ\text{C}$ ). (b) Wet samples usually show enhanced creep rate with increasing pressure. At given pressure and temperature (e.g., 300 MPa,  $1050^\circ\text{C}$ ), samples buffered by Cu-CuO (solid symbols, sample PI36) are considerably weaker than those buffered by Ni-NiO and Fe-FeO (crossed squares, samples PI32 and PI33, respectively) and specimens buffered by Ni-Fe-Fe (NFF, open symbols, samples PI19, PI26, and PI18). (c) At  $1150^\circ\text{C}$ , dry samples (PI07) are about 1.5 orders of magnitude stronger than wet samples (PI20, PI29). For comparison, the creep curves for grain boundary diffusion of synthetic anorthite obtained at 300 MPa pressure [Rybacki and Dresen, 2000] are shown. Data are normalized to  $5 \mu\text{m}$  grain size.



**Figure 2.** The log (strain rate) versus confining pressure for dry samples at 100 MPa axial stress (diffusion creep regime). For each temperature the slope of curve determines the activation volume  $V$  under dry conditions. Solid symbols denote samples with about 10 times higher bulk water content than those indicated by open symbols (compare Table 1). The average activation volume is  $24 \pm 21 \text{ cm}^3 \text{ mol}^{-1}$ .

conditions fugacity exponents are assumed  $r$ ,  $w = 0$ . A multilinear regression fit to the data at stresses  $< 210 \text{ MPa}$  yields an activation energy of  $Q = 482 \pm 41 \text{ kJ mol}^{-1}$  and a preexponential factor of  $\log(A) = 12.4 \pm 1.5 \text{ MPa}^{-1} \mu\text{m}^3 \text{ s}^{-1}$ . This is in good agreement with results of Rybacki and Dresen [2000] for dry synthetic anorthite aggregates ( $Q = 467 \pm 16 \text{ kJ mol}^{-1}$  and  $\log(A) = 12.1 \pm 0.6 \text{ MPa}^{-1} \mu\text{m}^3 \text{ s}^{-1}$ ).

[20] At hydrous conditions strain rates generally increase with increasing confining pressure (Figure 1b and Table 2). Interestingly, samples buffered by Cu-CuO are about 1 order of magnitude weaker than specimens buffered by Ni-NiO or Fe-FeO at a pressure of 300 MPa and 1050°C. The creep strength of samples buffered in the NFF assembly is very similar to that of Fe-buffered samples. Two samples were buffered by Ni-NiO. Their data show a large scatter and samples failed at low confining pressure (150 MPa, Table 2). At 1150°C temperature dry samples are more than 1 order of magnitude stronger than wet specimens (Figure 1c).

### 3.2. Activation Volume of Anhydrous Samples

[21] Determination of the activation volume  $V$  from diffusion creep data of individual specimens for a single temperature shows considerable scatter of  $V$  between  $1.4 \text{ cm}^3 \text{ mol}^{-1}$  and  $65.6 \text{ cm}^3 \text{ mol}^{-1}$  (Figure 2). Averaging over the entire data set yields  $V = 23.9 \pm 21.0 \text{ cm}^3 \text{ mol}^{-1}$ , corresponding to a pressure-dependent change of the apparent activation energy  $Q_{\text{app}} = Q + pV$  of  $2.4 \text{ kJ mol}^{-1}$  per 100 MPa. In comparison, using a multilinear regression fit to the data yields an activation volume  $V$  of  $32.4 \pm 6.6 \text{ cm}^3 \text{ mol}^{-1}$ . However, we believe that the averaging approach better reflects the large uncertainty involved in our estimates of the activation volume due to the relatively small pressure range accessible in the gas apparatus. For example, uncertainty in grain size of about 10% results in an uncertainty of  $10 \text{ cm}^3 \text{ mol}^{-1}$  for the activation volume

at the experimental conditions commonly used in the gas apparatus.

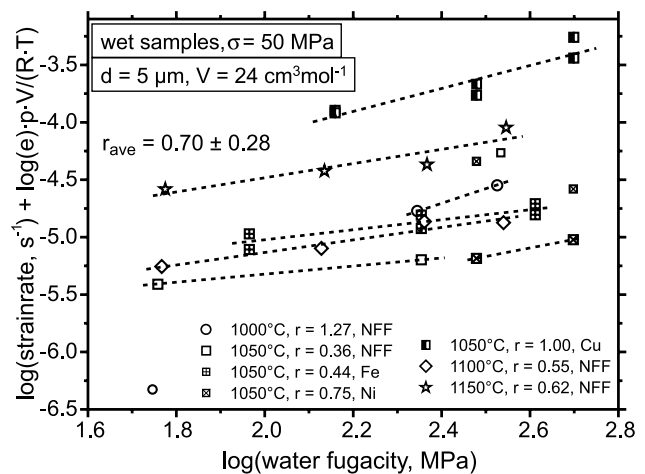
[22] No significant difference in activation volume is found for samples fabricated from coarse-grained starting powders (solid symbols in Figure 2) and specimens produced from fine-grained powder containing about 10 times less water.

### 3.3. Activation Volume and Water Fugacity Exponent of Hydrous Samples

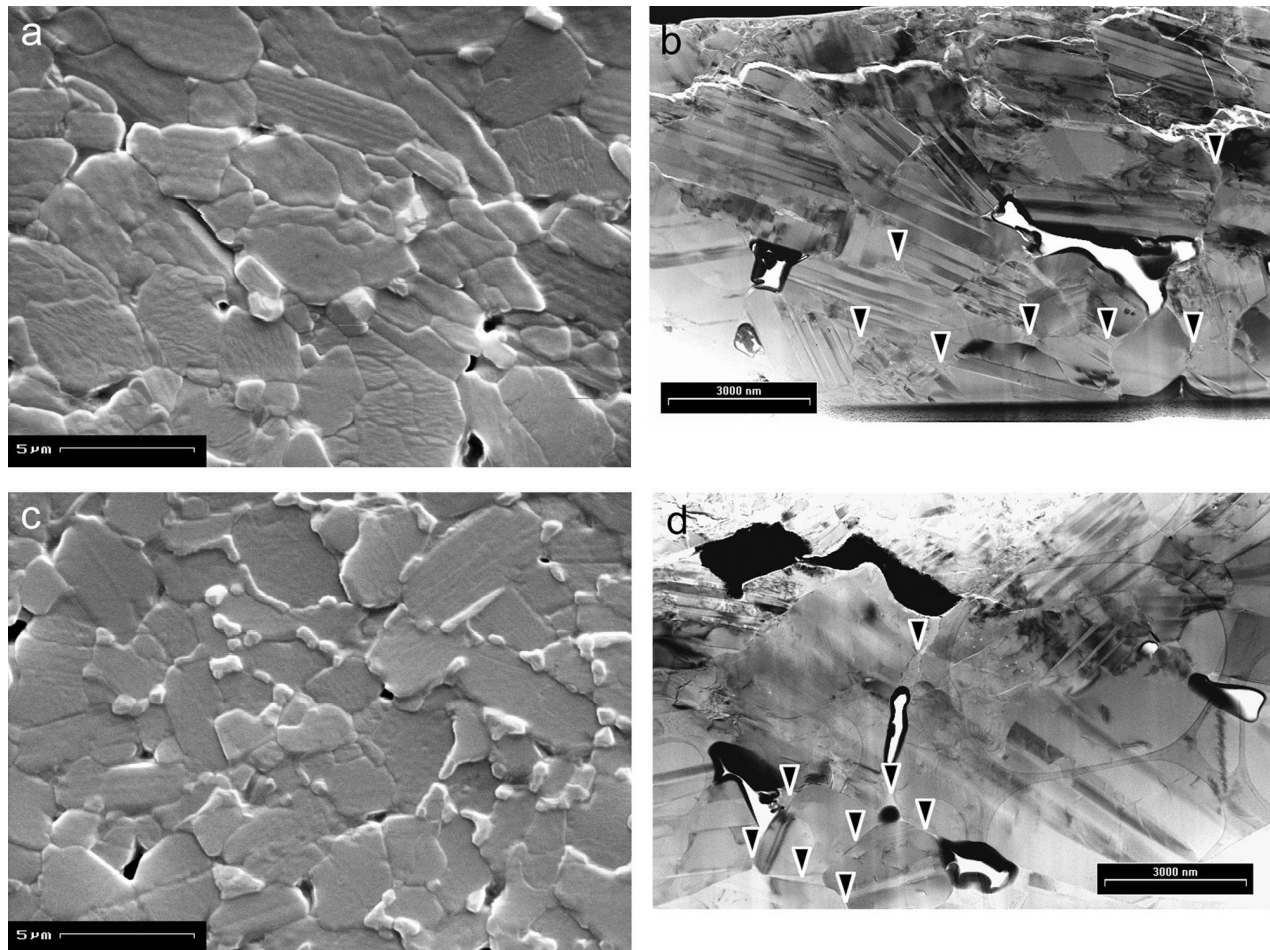
[23] Water fugacity values were calculated following Churakow and Gottschalk [2003a, 2003b] and Gottschalk [1997]. For the standard NFF assembly we expect that the fugacity is buffered near Fe-FeO. Mei and Kohlstedt [2000a] used a similar assembly to buffer deformation experiments on olivine at Ni-NiO. However, using X-ray diffraction analysis and optical inspection we never found clear evidence for the formation of NiO after deformation.

[24] We used two different approaches to obtain the water fugacity exponent for creep of hydrous feldspar aggregates. On the basis of the results of Rybacki and Dresen [2000] for diffusion creep of similar wet anorthite aggregates we set the stress exponent to  $n = 1$ , the grain size exponent to  $m = 3$ , and the activation energy to  $Q = 170 \text{ kJ mol}^{-1}$ . Using a three-dimensional (3-D) fit program (Table Curve 3D, SPSS Inc.) allows determining water fugacity exponent and activation energy simultaneously. We ignored 4 data points from a failed run of sample PL13. A fit of 101 data yields a water fugacity exponent of  $r = 0.98$  and an activation volume of  $V = 36.4 \text{ cm}^3 \text{ mol}^{-1}$ . However, the fit also depends on the preexponential constant  $A$  and shows several local minima of the residuals.

[25] In an additional approach to constrain the water fugacity exponent we assume that the activation volume determined for dry rocks provides a lower bound for the activation volume of diffusion creep at hydrous conditions. Taking  $V = 24 \text{ cm}^3 \text{ mol}^{-1}$ , the water fugacity exponent



**Figure 3.** The log (strain rate) plotted versus log (water fugacity) for wet samples at 50 MPa axial stress (diffusion creep regime) for an assumed activation volume of  $24 \text{ cm}^3 \text{ mol}^{-1}$ . The average water fugacity exponent  $r$  is  $0.70 \pm 0.28$ . Small symbols were not considered for fitting. Abbreviations denote jacketing materials (NFF = Ni-Fe-Fe). Data are corrected for  $5 \mu\text{m}$  grain size.



**Figure 4.** Micrographs of deformed samples. (a) and (b) SEM and (FIB-)TEM sections of Fe-jacketed sample P134 are shown, and (c) and (d) SEM and (FIB-)TEM sections of Cu-jacketed sample P136 are shown, both deformed at 1050°C. Pores appear as black holes in SEM and white areas, surrounded by Ga deposits from ion beaming, in TEM, respectively. The small fractures visible at the top of TEM micrographs result from saw cutting. SEM sections were thermally etched to separate grain boundaries. The two large black areas in the upper left quarter of Figure 4d are Cu deposits. Note grain boundaries and triple junctions containing glass in Cu-jacketed sample.

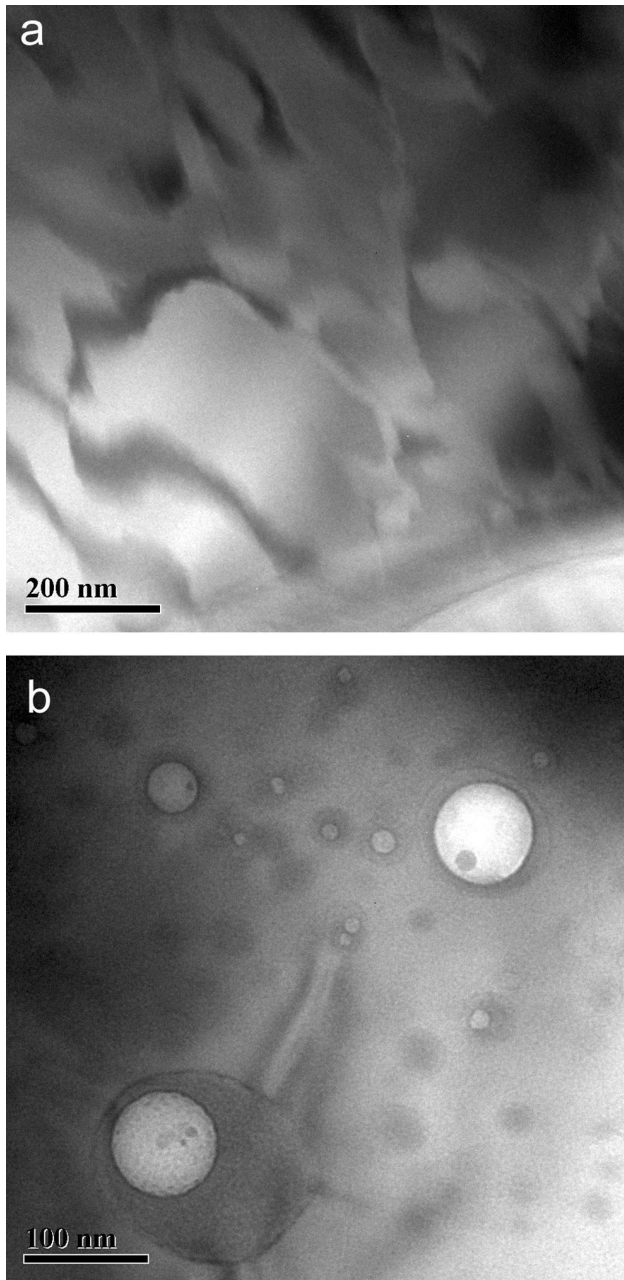
estimated for the low-stress diffusion creep regime is  $r = 0.7 \pm 0.3$  (Figure 3). Assuming the NNF assemblies were buffered by Ni-NiO instead of Fe-FeO changes the average water fugacity exponent by  $<\pm 0.1$ .

[26] The calculated water fugacities may have been affected by the presence of dissolved carbon from the steel jackets, decreasing the reported values by  $\sim 40\text{--}60\%$  in the investigated P-T range [Connolly and Cesare, 1993]. However, the grayish coloration of sample rims and X-ray analysis of the samples using Rietveld refinement show that only the outermost rims are contaminated.

### 3.4. Water Content

[27] After deformation the hydroxyl content of samples deformed at hydrous conditions remained similar to the starting material or increased only slightly. The average water content was  $0.33 \pm 0.14$  wt %  $\text{H}_2\text{O}$ , or  $51000 \pm 21000$  ppm H/Si (Table 1). For one sample a water content of  $\sim 0.3$  wt % was also estimated by Raman spectroscopy in the wave number range of  $3100\text{--}3750\text{ cm}^{-1}$ . FTIR spot

measurements along profiles with  $20\text{ }\mu\text{m}$  spacing show a sixfold increase in water content from embedded anorthite single crystals toward the fine-grained matrix. This indicates that a significant amount of hydroxyl is stored in grain boundaries. A similar finding was reported by Mei and Kohlstedt [2000a] in a study on olivine, where these authors found a 15–20 times higher bulk water concentration than in olivine single crystals. Notably, Mei and Kohlstedt [2000a] also reported an increase of bulk water content with increasing confining pressure, which we did not observe in our samples. This observation and the abundance of fluid inclusions in the anorthite matrix suggest that samples were possibly oversaturated even in the absence of pyrophyllite. The anorthite single crystals did not incorporate significantly higher hydroxyl content with increasing pressure. However, diffusion kinetics of water related species in anorthite are not well known. As a first estimate, Dimanov *et al.* [1999] report a diffusion coefficient  $D$  of about  $10^{-15}\text{ m}^2\text{ s}^{-1}$  for volume diffusion of water in anorthite at  $T = 1150^\circ\text{C}$ , the highest temper-



**Figure 5.** TEM micrographs showing (a) antiphase domains and (b) fluid inclusions surrounded by melt rims (sample P136).

ature attained in our experiments. With the relation  $d = \sqrt{2Dt}$  the equilibrium distance  $d$  is about 12  $\mu\text{m}$  for a typical experiment of  $t = 20$  hour duration including annealing time prior to testing. For comparison, *Paterson and Luan* [1990] estimated  $d \approx 7 \mu\text{m}$  for volume diffusion of water in quartz at similar conditions. This short distance suggests that the duration of experiments was too short for the water content of the embedded large single crystals to fully equilibrate with pressure.

### 3.5. Microstructures

[28] The grain size of deformed samples did not change significantly compared to the starting material. Grains are

often prismatic with relatively straight boundaries forming  $120^\circ$  triple junctions. Frequently grains are twinned but show few dislocations (Figure 4). Wet samples locally show antiphase domains, shells of amorphous material surrounding fluid inclusions, and Si-enriched glass in triple junctions (Figures 5 and 6). The glass present in triple junctions is commonly depleted in Ca and Al and is not found along grain boundaries. Si enrichment may result from local nonstoichiometry of the starting glass but is more likely due to partial melting at high water fugacity. The total amount of glass estimated from large, FIB-prepared TEM foils is about 1–2 vol %. Samples that were significantly weaker like the specimens deformed in copper jackets showed glass films contained in grain boundaries interconnecting separate larger glass pockets in triple junctions. The glass is enriched in Si. Interestingly, interfacial angles estimated at grain triple junctions are about  $40^\circ \pm 10^\circ$  irrespective of the wetting behavior of the glass (Figures 6 and 7).

## 4. Discussion

### 4.1. Activation Volume

[29] At anhydrous conditions we estimate an activation volume  $V$  for diffusion-controlled creep of anorthite aggregates of  $24 \pm 21 \text{ cm}^3 \text{ mol}^{-1}$ . To our knowledge, no other measurements of  $V$  for grain boundary or volume diffusion in plagioclase are available to date [e.g., *Bejina et al.*, 2003]. However, the activation volume can be estimated roughly relating  $V$  to the pressure dependence of the melting temperature  $T_m$ :

$$V = \frac{Q}{T_m} \frac{dT_m}{dP}. \quad (2)$$

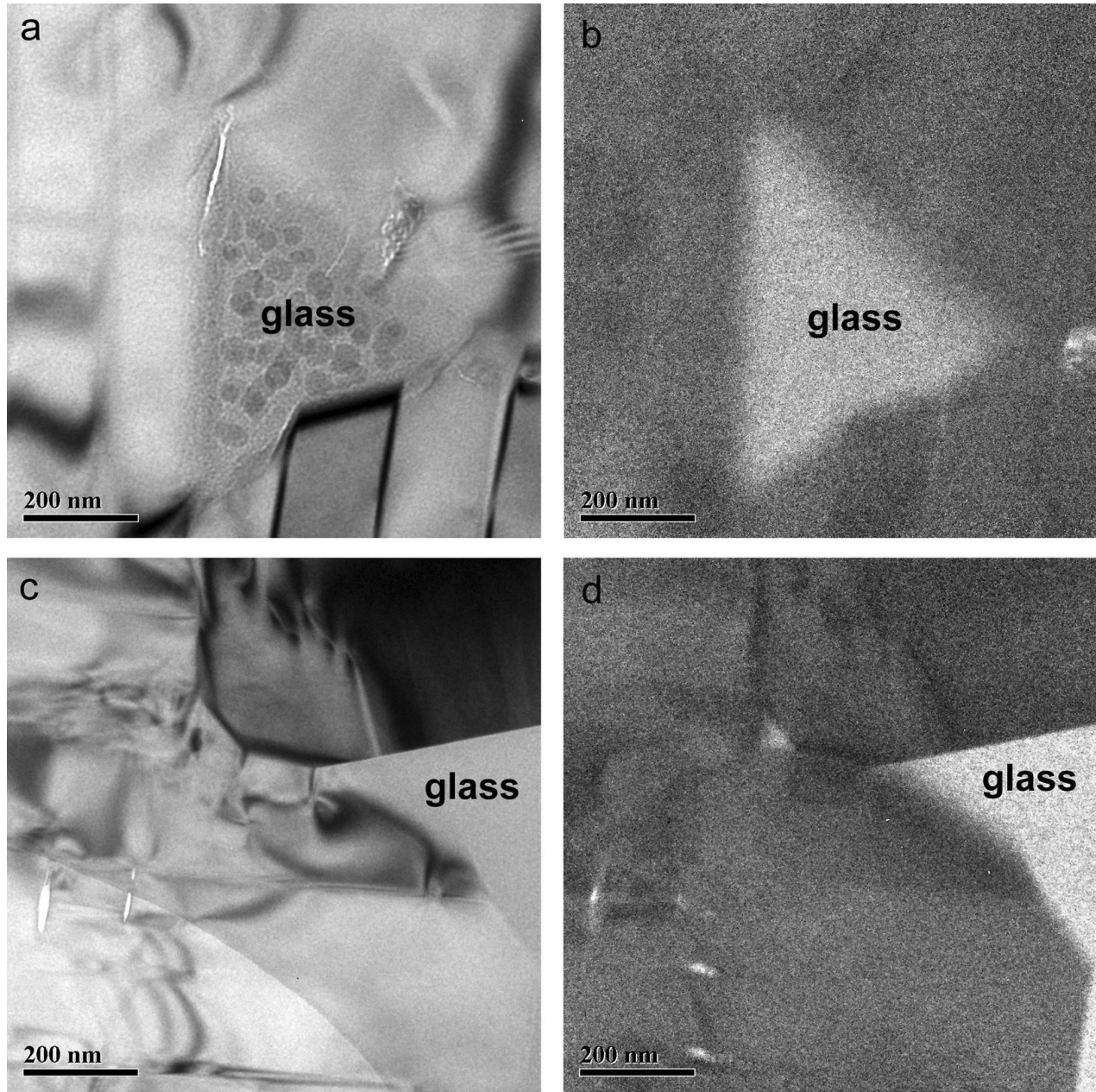
Using the pressure sensitivity of  $T_m$  for anhydrous anorthite given by *Holland and Powell* [2001] and the activation energy for diffusion creep of dry anorthite samples by *Rybacki and Dresen* [2000] results in an activation volume of  $V \approx 6 \text{ cm}^3 \text{ mol}^{-1}$ .

[30] Local elastic shear and volume distortions surrounding point defects result in pressure sensitivity of the shear modulus  $G$  and bulk modulus  $K$ , respectively. This allows estimating the activation volume for diffusion:

$$V = E \left( \frac{1}{G} \frac{dG}{dP} - \frac{1}{K} \right) \quad V = E \left( \frac{1}{K} \frac{dK}{dP} - \frac{1}{K} \right) \quad (3)$$

Using the elastic constants of anorthite and their pressure derivatives [*Sobolev and Babeyko*, 1994], we have  $V \approx 24 - 29 \text{ cm}^3 \text{ mol}^{-1}$  for dry aggregates in good agreement with our measured value of  $24 \text{ cm}^3 \text{ mol}^{-1}$ .

[31] In the intrinsic diffusion regime the activation volume is the sum of point defect formation and migration, where the first term can be approximated by equation (2) and the second by equation (3) [*Bejina et al.*, 2003; *Karato*, 1981]. Although these are only rough estimates the resulting values suggest that the migration-related term dominates. The activation volume for diffusion creep of dry feldspar is close to estimates for high-temperature creep of other silicates. For dry dunite, *Kohlstedt and Wang* [2001] obtained  $V \approx 20 \text{ cm}^3 \text{ mol}^{-1}$  and for dry olivine aggregates

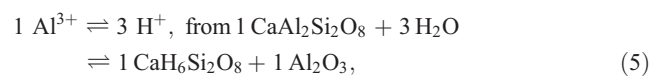
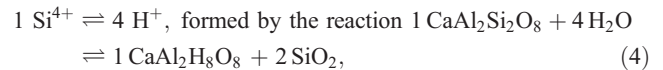


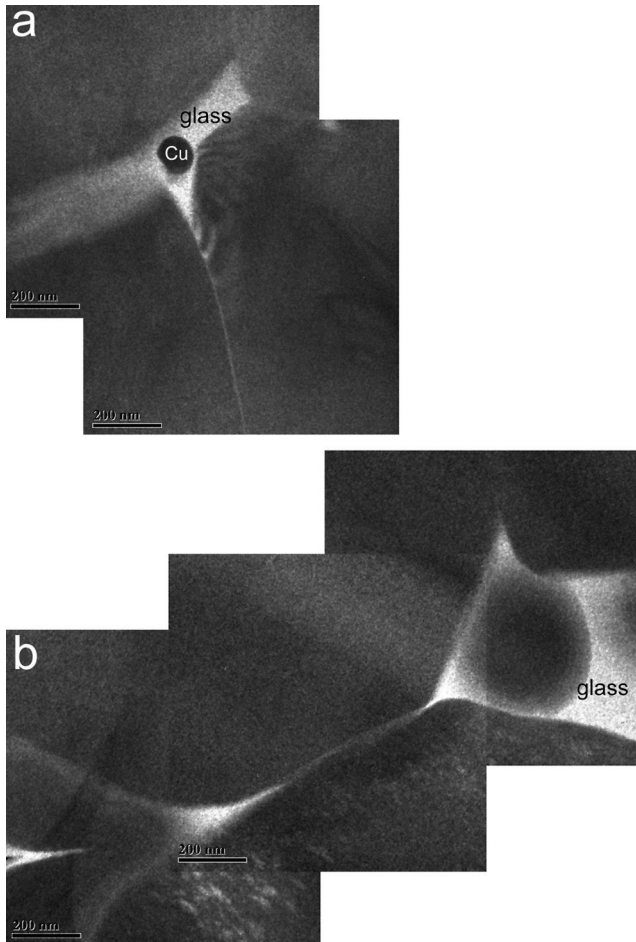
**Figure 6.** TEM micrographs of deformed samples PI34 (Figures 6a and 6b) and PI26 (Figures 6c and 6d), showing the topology of melt pockets. PI34 was Fe-jacketed and PI26 was NFF-jacketed. (a) and (c) Bright field are shown, and (b) and (d) dark field images are shown. Note the high apparent “wetting angle” of the amorphous phase. Both samples were deformed at 1050°C.

the creep activation volume is  $V = 15 \pm 5 \text{ cm}^3 \text{ mol}^{-1}$  [Karato and Rubie, 1997].

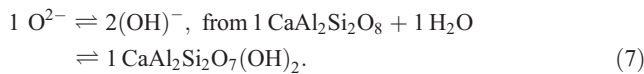
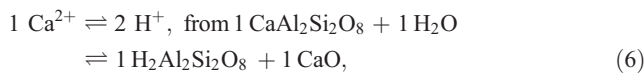
[32] Under wet conditions we obtained an activation volume of about  $36 \text{ cm}^3 \text{ mol}^{-1}$  and  $r = 0.98$  from a multiparameter fit to the data. Assuming that  $V$  estimated for dry samples forms a lower bound to  $V$  for wet feldspar this yielded a fugacity exponent of  $r = 0.7$ . We further assume that under wet conditions the relatively small ionic radius of protons incorporated in the crystal lattice and grain boundaries do not significantly affect the formation and migration volume of larger, potentially rate-controlling defects, like Si. The reaction of dry to water-bearing

anorthite requires a volume change due to incorporation of protons. This allows estimating the activation volume for (proton-related) defect formation  $V_f$ . We estimate  $V_f$  for the following four defect mechanisms that may conceivably occur in a hydrous environment:





**Figure 7.** Melt topology of Cu-jacketed sample PL36 (TEM dark-field images). (a) The dark spot in the center of the melt pocket represents exudated copper. (b) Most grain boundaries are wetted by a ~10 nm thick melt film.



For reactions (4)–(7) we find creep activation volume and fugacity exponent assuming that strain rate  $\dot{\epsilon}$  is proportional to the defect concentration  $x$ . For example, formulating the equilibrium of reaction (4) in terms of Gibb's free energy  $G^o$  and activities  $a$  of the pure phase components yields

$$0 = \Delta G_{(P,T)}^o + RT \ln \frac{a_{\text{an}(4\text{H})} a_{\text{qtz}}}{a_{\text{an}(\text{Si})} f_{\text{H}_2\text{O}}^4}. \quad (8)$$

Assuming pure quartz ( $a_{\text{qtz}} = 1$ ), a low hydrogen defect concentration  $x_{4\text{H}}$ , applying Henry's law ( $a_{\text{an}(4\text{H})} = x_{4\text{H}}^2 k_{4\text{H}}^2$ , two sites per formula unit, where  $k_{4\text{H}}$  is the Henry constant) and Raoult's law ( $a_{\text{an}(\text{Si})} = x_{\text{an}(\text{Si})}^2 \approx 1$ ), and further assuming no change in reaction entropy and heat capacity, yields

$$0 = \Delta G_{P_r}^o + \Delta V^o(P - P_r) + RT \ln \frac{x_{4\text{H}}^2 k_{4\text{H}}^2}{f_{\text{H}_2\text{O}}^4}, \quad (9)$$

where  $\Delta V^o$  is the volume change of solids and  $P_r$  a reference pressure of 0.1 MPa. Solving equation (9) for  $x_{4\text{H}}$  yields the dependence of creep rate on water fugacity and volume change for defect formation

$$\dot{\epsilon} \sim x_{4\text{H}} = k_{4\text{H}}^{-1} f_{\text{H}_2\text{O}}^2 \exp\left(-\frac{\Delta G^o + \Delta V^o(P - P_r)}{2RT}\right). \quad (10)$$

This gives a fugacity exponent  $r = 2$  and a formation volume  $V_f = \Delta V^o/2$ .  $\Delta V^o$  is not known for formation of hydroanorthite. However, the volume change associated with the replacement of  $\text{Si}^{4+}$  by  $4\text{H}^+$  is known for katoite (hydrogrossular), where 3Si in grossular ( $\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$ ) are replaced by  $4\text{H}^+$ . The resulting volume change is  $24 \text{ cm}^3 \text{ mol}^{-1}$ . Since in hydroanorthite only 2Si are exchanged, we assume a volume change of  $16 \text{ cm}^3 \text{ mol}^{-1}$ . Adding twice the molar volume of quartz or coesite ( $\sim 22 \text{ cm}^3 \text{ mol}^{-1}$ , reaction (4)) we obtain  $\Delta V^o \approx 60 \text{ cm}^3 \text{ mol}^{-1}$ , and  $V_f \approx 30 \text{ cm}^3 \text{ mol}^{-1}$ . Adding  $V_f$  and  $V = 24 \text{ cm}^3 \text{ mol}^{-1}$  adopted from dry material yields a total activation volume of  $V_{4\text{H}} = 54 \text{ cm}^3 \text{ mol}^{-1}$ . Estimates of activation volumes and fugacity sensitivities for reactions (4)–(7) are summarized in Table 4. For the reaction  $1 \text{ O}^{2-} \rightleftharpoons 2(\text{OH})^-$  the estimated activation volume is  $38 \text{ cm}^3 \text{ mol}^{-1}$  which agrees with the value of  $\sim 36 \text{ cm}^3 \text{ mol}^{-1}$  estimated from the 3-D fitting approach. However, for both estimates the error bar on  $V$  may be as large as  $20 \text{ cm}^3 \text{ mol}^{-1}$  due to the implicit assumptions and scatter of the data, respectively.

[33] For wet olivine, *Karato and Jung* [2003] determined  $V = 24 \pm 3 \text{ cm}^3 \text{ mol}^{-1}$ , which is considerably higher than for dry olivine. For wet clinopyroxenite, *Hier-Majumder et al.* [2005] calculated  $V = 14 \pm 6 \text{ cm}^3 \text{ mol}^{-1}$ . In comparison, the activation volume for Si volume diffusion in quartz and olivine is between about  $-2$  to  $2 \text{ cm}^3 \text{ mol}^{-1}$  [Bejina et al., 2003], which is substantially smaller than the values reported above that are estimated from creep tests. It is conceivable that grain boundary diffusion and the formation and migration of jogs and kinks in dislocation creep display higher pressure sensitivity than volume diffusion of point defects.

## 4.2. Fugacity Sensitivity

[34] From FTIR spectra and TEM observations it is evident that molecular  $\text{H}_2\text{O}$  and water-related point defects

**Table 4.** Activation Volume and Water Fugacity Dependence of Water-related Defects in Anorthite

| Defect <sup>a</sup>                 | $\Delta V^o$ ,<br>$\text{cm}^3 \text{ mol}^{-1}$ | $V$ ,<br>$\text{cm}^3 \text{ mol}^{-1}$ | $r_{\text{nom}}$ | $r_{\text{det}}$ |
|-------------------------------------|--------------------------------------------------|-----------------------------------------|------------------|------------------|
| 1 $\text{Si}^{4+}$ 4 $\text{H}^+$   | 60 <sup>b</sup>                                  | 54                                      | 2                | $1.3 \pm 0.4$    |
| 1 $\text{Al}^{3+}$ 3 $\text{H}^+$   | 38 <sup>c</sup>                                  | 43                                      | 1.5              | $1.1 \pm 0.3$    |
| 1 $\text{Ca}^{2+}$ 2 $\text{H}^+$   | 17 <sup>d</sup>                                  | 41                                      | 1                | $1.0 \pm 0.3$    |
| 1 $\text{O}^{2-}$ 2 $(\text{OH})^-$ | 14 <sup>e</sup>                                  | 38                                      | 1                | $1.0 \pm 0.3$    |

<sup>a</sup> $\Delta V^o$  is molar volume of defect formation,  $V$  is total activation volume for creep,  $r_{\text{nom}}$  is predicted water fugacity exponent,  $r_{\text{det}}$  is fitted fugacity exponent using  $V$ .

<sup>b</sup>Estimated from replacement of Si by H in hydrogrossular (see text).

<sup>c</sup>Estimated from molar volume of corundum ( $\sim 26 \text{ cm}^3 \text{ mol}^{-1}$ ) and volume change of  $\sim 12 \text{ cm}^3 \text{ mol}^{-1}$  (assuming  $3/4$  of the volume change for hydrogrossular since only 3 protons are replaced).

<sup>d</sup>Estimated from molar volume of lime ( $\sim 17 \text{ cm}^3 \text{ mol}^{-1}$ ) and formation volume of  $0 \text{ cm}^3 \text{ mol}^{-1}$  since  $\text{Ca}^{2+}$  ions are much larger than  $\text{H}^+$  ions.

<sup>e</sup>Estimated from the average molar volume of minerals that differ by 1  $\text{H}_2\text{O}$  in composition, e.g., diaspore or boehmite versus corundum ( $\sim 11 \text{ cm}^3 \text{ mol}^{-1}$ ), brucite versus periclase ( $\sim 13 \text{ cm}^3 \text{ mol}^{-1}$ ), portlandite versus lime ( $\sim 16 \text{ cm}^3 \text{ mol}^{-1}$ ) and ice ( $18 \text{ cm}^3 \text{ mol}^{-1}$ ).

**Table 5.** Flow Law Parameters for Dry and Wet Anorthite Aggregates

| Regime <sup>a</sup> | $\log A$ , $\text{MPa}^{-n-r}$<br>$\mu\text{m}^m \text{s}^{-1}$ | $n$ | $Q$ , $\text{kJ mol}^{-1}$ | $V$ , $\text{cm}^3$<br>$\text{mol}^{-1}$ | $r$ | $m$ |
|---------------------|-----------------------------------------------------------------|-----|----------------------------|------------------------------------------|-----|-----|
| Diffusion creep     |                                                                 |     |                            |                                          |     |     |
| Wet                 | -0.7                                                            | 1   | 159                        | 38                                       | 1   | 3   |
| Dry                 | 12.1                                                            | 1   | 460                        | 24                                       | 0   | 3   |
| Dislocation creep   |                                                                 |     |                            |                                          |     |     |
| Wet                 | 0.2                                                             | 3   | 345                        | 38                                       | 1   | 0   |
| Dry                 | 12.7                                                            | 3   | 641                        | 24                                       | 0   | 0   |

<sup>a</sup> $A$  is a constant,  $n$  is stress exponent,  $Q$  is activation energy,  $V$  is activation volume,  $r$  is water fugacity exponent, and  $m$  is grain size exponent.

are incorporated in feldspar at elevated confining pressure. Water solubility in anorthite is not well constrained, but FTIR measurements suggest that significant amounts of  $\text{H}_2\text{O}$  are stored in the grain boundary region, and possibly in antiphase domain boundaries. Therefore we assume that both, water content and water fugacity affect the mechanism controlling grain size-sensitive creep of anorthite aggregates at hydrous conditions.

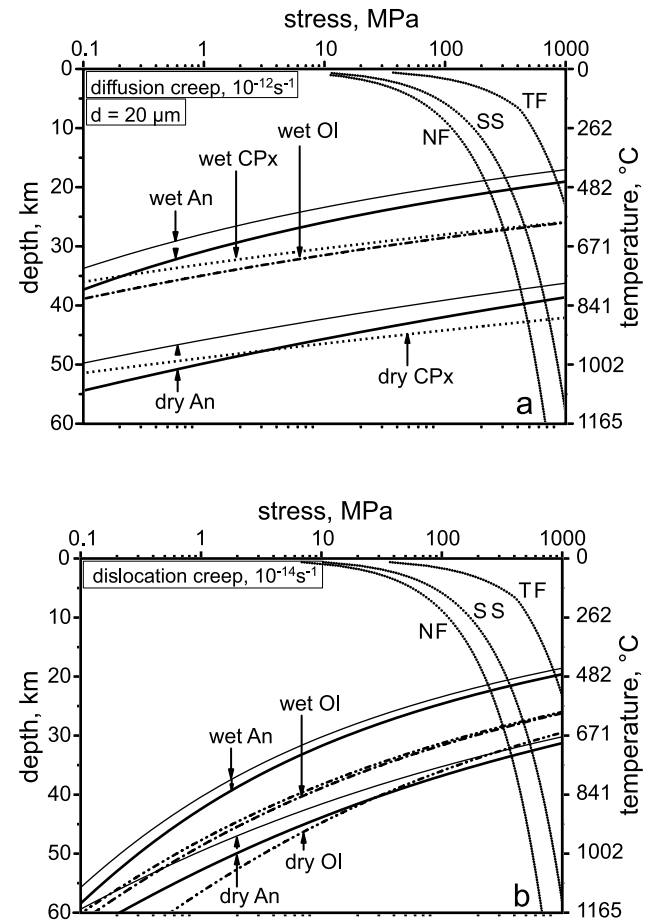
[35] For some silicates like olivine a particular point defect mechanism could be inferred using fugacity sensitivity [Kohlstedt and Mackwell, 1998; Nakamura and Schmalzried, 1983]. In the feldspar lattice interstitials (Frenkel defects) are more likely to occur than vacancies (Schottky defects) [Behrens *et al.*, 1990]. However, under wet conditions, Behrens [1994] suggested that for plagioclase the incorporation of water is linked to vacancies with hydrolysis of Al-O-Si bonds. Simple substitution mechanisms predict water fugacity exponents  $r = 1-2$  (Table 4). We refitted the creep data shown in Figure 3 taking into account the activation volume estimated for defect formation under hydrous conditions as discussed above. The resulting fugacity exponents vary between  $r = 1.0$  and  $1.3$  (Table 4) which agrees well to  $r \approx 1$  obtained by the 3-D fitting routine. At present, a particular defect mechanism rate-limiting diffusion-controlled creep cannot be determined unequivocally. However, the observed fugacity sensitivity of  $1.0 \pm 0.3$  suggests the replacement of  $\text{O}^{2-}$  by  $2(\text{OH})^-$  (Griggs defect).

[36] The water fugacity sensitivity  $r$  of the strain rate was also determined from creep tests on other major silicate rocks. For olivine aggregates,  $r$  is in the range of  $0.7-1.25 \pm 0.05$  [Karato and Jung, 2003; Mei and Kohlstedt, 2000a, 2000b] and for clinopyroxene  $r = 1.4 \pm 0.2$  [Hier-Majumder *et al.*, 2005]. For quartz,  $r \approx 1$  [Gleason and Tullis, 1995; Hirth *et al.*, 2001; Kohlstedt *et al.*, 1995], but values of  $r \geq 2$  [Post *et al.*, 1996] and  $r = 0.25-0.41$  [Wang *et al.*, 1994] were also reported.

### 4.3. Effect of Melt Topology in Cu-CuO Buffered Specimens

[37] The samples contained in copper jackets (P136, P137) are about 1 order of magnitude less viscous than specimens buffered in nickel or iron sleeves (Figure 1b and Table 2). We do not expect that the strength of anorthite aggregates depends on oxygen fugacity as no multivalent ionic species are present in the synthetic aggregates. Wang *et al.* [1996] deformed anorthite aggregates from a similar starting material at anhydrous conditions and oxygen fugacities between  $f_{\text{O}_2} = 10^{-19}-10^{-4}$  MPa and found no effect on

strength. However, the Cu-CuO buffered specimens show abundant melt films along grain boundaries that were not observed in other samples (Figure 7). Dimanov *et al.* [2000] report that  $\sim 1\%$  melt wetting grain boundaries reduced the



**Figure 8.** Stress-depth profiles for the continental crust from extrapolated flow laws of synthetic feldspar (An), pyroxene (Cpx), and olivine (Ol) rocks. (a) Grain boundary diffusion creep data are plotted for  $20 \mu\text{m}$  grain size and  $10^{-12} \text{s}^{-1}$  strain rate, and (b) dislocation creep data are plotted for a strain rate of  $10^{-14} \text{s}^{-1}$ . The extrapolation indicates the effect of activation volume and water fugacity on strength. Thick solid lines are based on flow laws for anorthite aggregates from this study, assuming that the activation volume and water fugacity exponent are similar for diffusion creep and dislocation creep (Table 5). Thin solid lines represent flow laws for anorthite from a previous study [Rybacki and Dresen, 2000] that do not include  $V$  and  $r$  estimates. Short dashed lines represent (Sleaford Bay) clinopyroxene [Hier-Majumder *et al.*, 2005]. Data for olivine are taken from Mei and Kohlstedt [2000a, 2000b] (dash-dotted lines) and Karato and Jung [2003] (dash-dot-dotted lines). Temperature calculation corresponds to surface heat flow of  $80 \text{ mW m}^{-2}$  [Chapman and Furlong, 1992]. Fugacities were determined assuming quartz-fayalite-magnetite (QFM)-buffered conditions in the continental crust. NF, SS, and TF denote frictional strength of normal faults, strike-slip faults, and thrust faults, respectively, using Byerlee's law [Byerlee, 1978] for a mean crustal density of  $2.7 \text{ g cm}^{-3}$  and assuming hydrostatic pore pressure.

strength of labradorite aggregates by about 1 order of magnitude compared to specimens where grain boundaries were not wetted. We suggest that the reduced viscosities of the copper-jacketed samples are due to the abundance of melt films along grain boundaries. However, it remains unclear why only the Cu-CuO-buffered samples exhibit melt films. In TEM, metallic Cu was found in glass contained in grain triple junctions (Figures 4d and 7a). It is possible that anorthite and copper form a eutectic with a melting point significantly below that of pure copper ( $\sim 1100^\circ\text{C}$ ).

#### 4.4. Constitutive Laws and Geological Applications

[38] To determine constitutive equations for high-temperature creep of anorthite aggregates we use the extensive data set of Rybacki and Dresen [2000], for which oxygen fugacity was buffered by Fe-FeO, since for all experiments iron jackets were used. For the recalculation of flow law parameters we assume that the activation volume and fugacity sensitivities determined for diffusion creep also hold for dislocation creep. The resulting flow law parameters are given in Table 5, where the water fugacity exponent is set to  $r = 1$  and the activation volume is  $V = 38$  and  $24 \text{ cm}^3 \text{ mol}^{-1}$  for wet and dry anorthite, respectively.

[39] In extrapolating the data to pressure and temperature conditions relevant for the continental crust we use a strain rate of  $10^{-12} \text{ s}^{-1}$  and  $20 \text{ }\mu\text{m}$  grain size for diffusion-controlled creep (Figure 8a). These may be typical values for localized deformation of ultramylonites in high-temperature shear zones [Kenkmann and Dresen, 2002]. For rocks deforming in dislocation creep, data are extrapolated to strain rates of  $10^{-14} \text{ s}^{-1}$  (Figure 8b). Stresses predicted from extrapolation of experiments performed at hydrous conditions are less than a factor of 3 higher when the combined effects of activation volume and water fugacity sensitivity are included. However, in extrapolating dislocation creep data of dry anorthite aggregates, stresses increased by about a factor of 10.

[40] In general, feldspar aggregates deformed at hydrous conditions are considerably weaker than dry rocks (Figure 8). For dry rocks the strengths of anorthite and clinopyroxenite deforming in diffusion creep are relatively similar. Similar viscosities are also predicted for anorthite and olivine rocks deforming in dislocation creep. However, at hydrous conditions, feldspar rocks are predicted to be significantly weaker than pyroxenites and olivine rocks (Figure 8). Strikingly, extrapolation of the laboratory data for a given geothermal gradient indicates that fine-grained feldspar and olivine rocks will deform in diffusion creep at lower stresses compared to dislocation creep, suggesting that diffusion creep will dominate in fine-grained ultramylonites.

[41] **Acknowledgments.** We like to thank Michael Naumann for assisting with sample testing, Stefan Gehrmann for preparation of thin sections, Heike Steigert for X-ray analysis, and Reiner Thomas for conducting Raman spectroscopy. Greg Hirth and Shun Karato provided constructive and thoughtful reviews.

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