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Tectonophysics 446 (2008) 16–30
TECTONOPHYSICS
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A natural example of crystal-plastic deformation enhancing the incorporation of water into quartz

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Received 15 February 2007; received in revised form 6 September 2007; accepted 27 September 2007
Available online 6 October 2007

Abstract

Water content of quartz in and around a greenschist facies mylonitic shear zone located in the western Adirondacks was analyzed by micro-FTIR spectroscopy. The shear zone is within a pegmatitic dike, which cuts across a granitic gneiss. The thickness of the shear zone varies along strike from 15 cm wide and encompassing all of the pegmatite dike at its northern most exposure to 5 cm wide approximately 10 m south, along strike. Microstructures, including quartz ribbons and recrystallized grains, indicate quartz and feldspar within the mylonite underwent dislocation creep. Infrared spectral analysis was carried out using a Nicolet micro-FTIR on mylonitic quartz ribbons, pegmatitic quartz and gneissic quartz. A small aperture size (56 μm by 50 μm) for the IR beam allowed optically clear regions of the quartz grains to be analyzed without any contribution from grain boundaries. The smallest dimension of the quartz ribbons is 0.3 mm, whereas the pegmatitic quartz has a grain size of 3 to 5 cm. Results show mylonitic quartz ribbons contain the most water (320 H:10^6 Si average, range of 50 to 1120 H:10^6 Si); pegmatite quartz contains much less water (30 H:10^6 Si average, range of 20–40 H:10^6 Si) and the gneissic quartz contained an intermediate amount (200 H:10^6 Si average, range of 20 to 870 H:10^6 Si). These data indicate that water was preferentially incorporated into the deformed quartz ribbons.

Keywords: Quartz; Mylonite; Water; Micro-FTIR; Hydrolytic weakening; Dislocation creep

1. Introduction

Experimental deformation studies on quartz, on both single crystals and aggregates, have demonstrated that water has a profound effect on the dislocation creep strength, a phenomenon referred to as hydrolytic weakening (*e.g.*, Griggs and Blacic, 1964, 1965; Kekulawala et al., 1978, 1981; Kronenberg and Tullis, 1984). Infrared (IR) spectroscopy measurements of the water content of these deformed samples indicate that large concentrations of molecular water, as indicated by a broad peak in the IR spectra centered at a wave number of approximately 3400 cm^{-1}, correlate with the weakening effect (Kekulawala et al., 1978, 1981). In contrast, dry natural Brazil quartz crystals only contain hydrogen defects, display sharp peaks in their IR spectra, and mechanically are very strong (Kronenberg et al., 1986).

The water content necessary for the weakening effect appears to be above the equilibrium solubility of water in quartz, which is estimated to be less than 200 H:10^6 Si (Paterson, 1989; also see discussion by Post and Tullis, 1998). Most examples of quartz weakened by water have 100 s to 1000 s H:10^6 Si (see review by Kronenberg, 1994). For example, deformation experiments (at 800 °C, 1500 MPa confining pressure, strain rate of 10^{-6} s^{-1}) using Heavy tree quartzite demonstrated that vacuum-dried samples containing only 240+/−60 H:10^6 Si, had higher strength (1550 MPa) than as-is samples (250 MPa) containing 1750+/−420 H:10^6 Si (Post and Tullis, 1998). It is not fully understood how this “excess” water enters the quartz, but it is most likely a non-equilibrium process. Mechanisms have been identified that aid quartz in the uptake of water. For example, microfracturing has been documented to increase the content of molecular water in quartz both in nature (Kronenberg et al., 1990) and in laboratory experiments (Kronenberg et al., 1986). Water along the microfractures is trapped in fluid inclusions as the fractures

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0040-1951/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2007.09.006

heal. Grain boundary migration during dynamic recrystallization is inferred to have enhanced oxygen isotope exchange in natural quartz mylonites (Kirschner et al., 1995). Since molecular water is thought to be the dominant oxygen-bearing species for hydrothermal oxygen diffusion in quartz (Farver and Yund, 1991) and in rhyolitic glasses (Zhang et al., 1991), the movement of oxygen may reflect the movement of molecular water in quartz. Post and Tullis (1998) demonstrated that water penetrates experimentally deformed quartz with a moderate to high dislocation density ($\sim 10^{13}$ to $10^{16}/\mathrm{m}^2$) an order of magnitude faster than the rate of hydrothermal oxygen diffusion. Thus it appears that deformation of quartz is an important factor in the uptake of the excess water required for hydrolytic weakening, creating a positive feedback between the two processes.

This study contains an example of quartz grains deformed by dislocation creep that contain more water than the corresponding starting material, apparently without the aid of microfracturing or grain-boundary migration. The quartz grains are ribbons in a mylonite that was deformed at mid-greenschist facies conditions. The mylonite is within a pegmatite dike, which cuts across a Grenville age gneiss in the southern Adirondacks. It seems clear that the quartz ribbons were derived from the pegmatitic quartz. Micro-FTIR analysis was used to determine the intracrystalline water content of three populations of quartz: mylonitic quartz ribbons, undeformed pegmatitic quartz and gneissic quartz. Few IR studies on the intragranular water content of naturally deformed quartz have been done and even fewer have measured the water content of the interior of the grains without contribution from grain boundaries (Kronenberg et al., 1990; Nakashima et al., 1995; Muto et al., 2005). In this study, the thickness of the rock sections was less than most of the grain diameters so that clear grain interiors could be sampled by IR spectroscopy. The FTIR results indicate the deformed mylonitic quartz ribbons contain more water than the surrounding pegmatitic quartz.

2. Geologic setting and rock descriptions

2.1. Regional geology

The mylonitic shear zone examined in this study is located along the south bank of the Moose River in the western Adirondack Mountains of New York State (Fig. 1). It is within a pegmatitic dike that cuts across the foliation of the granitic gneiss of unit CG (charnockite-granite gneiss) of Whitney et al. (2002). According to Whitney et al. (2002), the igneous protolith of the gneiss may have been intruded 1160 Ma to 1090 Ma, then deformed during a collisional event approximately 1050 Ma. Peak pressures and temperatures have been estimated as high as 800 MPa and 800 °C, respectively (Whitney et al., 2002; Storm and Spear, 2005). Whitney et al. (2002) estimate that deformation was over by about 1030 Ma, but temperatures remained elevated resulting in the intrusion of pegmatite dikes. Zircon from one such dike, located about 10 km west long the Moose River, produced a concordia intercept date of 1034 +/− 10 Ma (McLelland et al., 2001). The mylonitic shear zone described

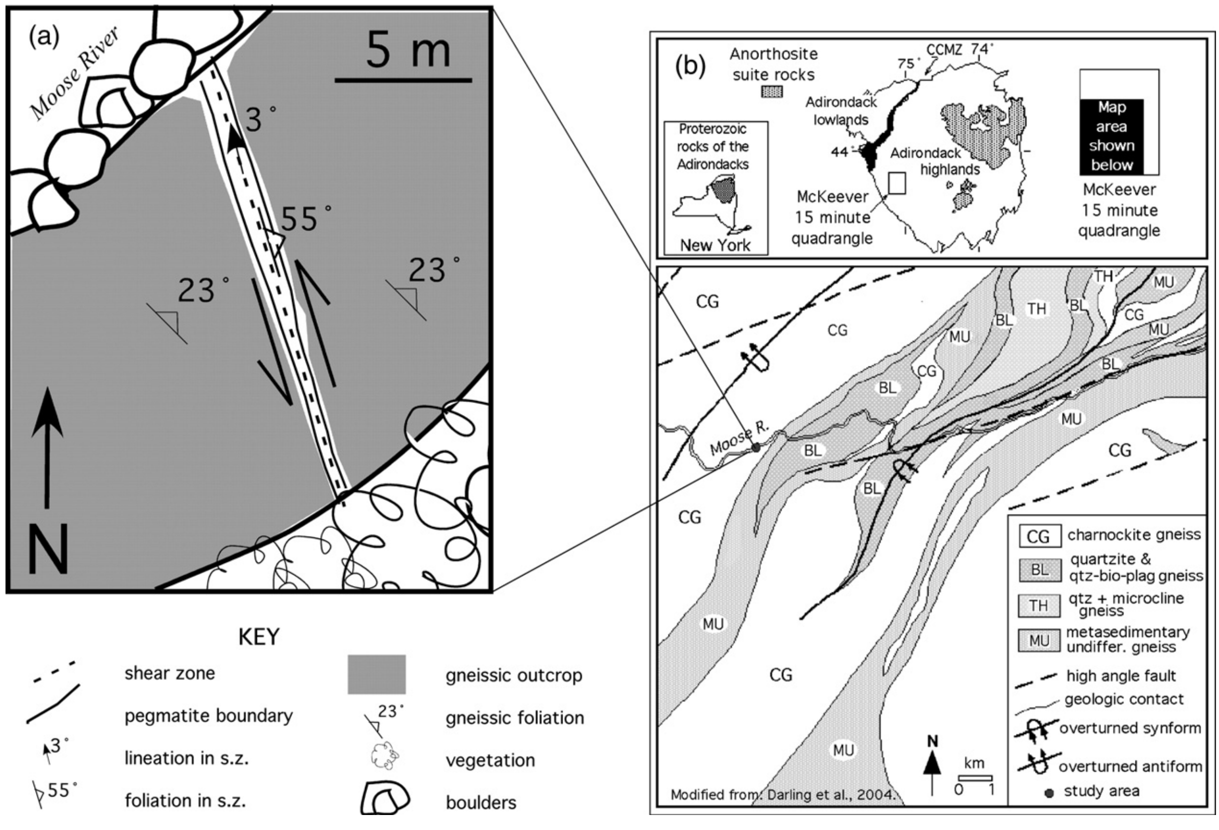

Fig. 1. Index map showing shear zone location. (a) Sketch map of shear zone and pegmatite in outcrop of gneiss. Orientations of foliations and lineation are indicated. Pegmatite thickness is exaggerated. (b) General geology of the region (modified from Darling et al., 2004).