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Strength variation and deformational behavior in anisotropic granitic mylonites under high-temperature and -pressure conditions – An experimental study

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ABSTRACT

We performed deformation experiments on foliated granitic mylonites under high-temperature and -pressure conditions. To investigate the effects of pre-existing fabric properties on the rheology of the rocks, these experiments were carried out at different compression directions 30°, 45°, and 60° relative to the foliation, at temperatures of 600–850 °C, under confining pressures of 800–1200 MPa, within a strain rate range of $1 \times 10^{-4}/S - 2.5 \times 10^{-6}/S$. The results of the experiments show that the deformation of three group samples is in the semi-brittle region at temperatures between 600 and 700 °C, and that the deformation of the samples transforms to plastic deformation by power-law creep with the stress exponent $n = 3 \pm 0.3$ at temperatures between 800 and 850 °C. In the semi-brittle region, the mechanical data show that strength reaches its minimum value at an angle of 30° between the compression direction and the original foliation. In the plastic deformation regime, strength reaches its minimum value at an angle of 45° between the foliation and the orientation of the maximum principal stress. The strength with angles between 30° and 60° is lower than that of the compression direction perpendicular to foliation and the compression direction parallel to foliation. Microstructure analysis based on optical and electron microscopy of the deformation microstructures showed plastic deformation of aggregates of biotite and quartz at 800–850 °C. This deformation was extensive and formed new foliation. Quartz c-axis fabrics analysis by EBSD show that at temperatures of 600–700 °C, the c-axis fabric patterns could have been formed by the dominant activity of basal<a> slip, similar with the starting granitic mylonite samples, but the dominant slip systems have been changed and transformed from basal <a> slip to rhomb <a> slip and prism<a> slip at temperature of 800 °C and 850 °C. Microfractures were developed in hornblende and feldspar grains with local plastic deformation. Dehydration reaction was observed in grain rims of hornblende and biotite, where new fine-grained hornblende and biotite crystals grew, accompanied by partial melting. This was followed by experimental deformation and replacement of the original foliation of the samples. The mechanical microstructure data show that there is a significant effect of fabric on the strength of rock, but almost no effect on brittle-plastic transition and deformation mechanism.

1. Introduction

It is common for crustal rocks to exhibit layered structures (e.g., Gottschalk et al., 1990; Shea and Kronenberg, 1992, 1993; Ji et al., 2000; Holyoke and Tullis, 2006), especially metamorphic crustal rocks in which pre-existing fabrics coexist with mechanically newly-formed layers, e.g. schist, gneiss and mylonite. However, investigating the effects of pre-existing fabrics on current rheologies is difficult due to a lack of available experimental data. Early studies on the shear failure and folding of slates and phyllites (e.g., Jaeger, 1960; Donath, 1961, 1964, 1972; Borg and Handin, 1966; Paterson and Weiss, 1966; McLamore and Gray, 1967; McCabe

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and Koerner, 1975), and on the brittle to semi-brittle deformation of mica-bearing foliated schists and gneisses (e.g., Shea and Kronenberg, 1992, 1993) demonstrated that compressive strength is a function of the angle between the foliation plane and the compression axis. In these experiments, mica-rich schist samples loaded at an angle of 45° to the foliation plane were often several (1.5–4) times weaker than those loaded parallel or perpendicular to the foliation plane (e.g., Shea and Kronenberg, 1992, 1993), whose strengths were similar (e.g., Gottschalk et al., 1990; Shea and Kronenberg, 1992, 1993). Experiments by Ji et al. (2000) on quartz-feldspar inter-layered samples indicated that thin-layered rocks compressed normal to their foliation planes were, in fact, stronger than homogeneous isotropic mixtures under equivalent temperature-pressure conditions.

Recently, the deformation of rocks with pre-existing fabrics has attracted renewed attention (e.g., Druiventak et al., 2011; Liu et al., 2013b, 2016; Rabinowitz et al., 2012). Druiventak et al. (2011) conducted deformation experiments using natural peridotite which was loaded parallel to and normal to the foliation plane, respectively. Results revealed that the strength of the peridotite under those two experimental conditions was similar. However, the experiments by Rabinowitz et al. (2012) in which a granitic mylonite sample were loaded at an angle of 45° to the foliation plane revealed that pre-existing fabric properties had a significant influence on the strength and deformation of granitic mylonites. Liu et al. (2013b, 2016) conducted experiments on granite gneisses and granitic mylonite samples under high-temperature and -pressure conditions. Results showed that the strength of PER samples (where the loading was normal to the foliation plane) was much higher than that of PAR samples (where the loading was parallel to the foliation plane) under similar temperature and strain rate conditions. All of these results imply that the pre-existing fabric properties of the samples significantly influenced the strengths of these anisotropic samples.

The current study complements a previous study by Liu et al. (2016) where samples were compressed parallel and perpendicular to the foliation. In this study, we deformed well-foliated natural granitic mylonite samples under high-temperature and -pressure conditions in a molten-salt Griggs-type apparatus, applying compression at angles of 30°, 45°, and 60° to the foliation plane, respectively. Here, we investigate the mechanical behavior and microstructures of the samples under these different conditions to assess the effects of pre-existing fabric properties on the rheologies of the granitic mylonite samples.

2. Experimental samples and methods

2.1. Properties of experimental starting materials

The fresh, fine-grained granitic mylonite samples used as the experimental material in this study were collected from the Jinzhou detachment fault in eastern Liaoning, on the margin of the North China Craton. Initially, this material was foliated with well-developed lineation. Microstructures of the material were examined using a polarizing optical microscope and a scanning electron microscope. Quartz grains displayed irregular undulatory extinction, implying sub-grain and dynamic recrystallization. Kinked and elongated biotite grains were distributed along the quartz and plagioclase grains (Fig. 1a–d), whereas the plagioclase, K-feldspar and hornblende grains appeared less deformed (Fig. 1b–c). Biotite, quartz and hornblende grains formed the original foliation (Fig. 1a).

To measure the grain size distribution of the starting material, we used the line intercept method proposed by Underwood (1970). Mineral grain sizes in the starting samples were categorized into two groups: the large grains (mainly plagioclase, K-feldspar and hornblende) with sizes of 100–400 μm (and a mean of roughly 250 μm), and the small grains comprising a mixture of quartz grains (10–50 μm), biotite grains (20–100 μm).

The chemical composition of the starting material was measured by X-ray fluorescence spectroscopy (DMAX-IIIB). The main oxides detected were SiO_2 (64.6 wt%), TiO_2 (0.73 wt%), Al_2O_3 (15.1 wt%), Fe_2O_3 (2.85 wt%), MnO (0.14 wt%), MgO (3.68 wt%), CaO (6.42 wt%), Na_2O (3.89 wt%), K_2O (2.16 wt %), and P_2O_5 (0.39 wt %).

Three groups of samples should be drilled to cylindrical cores from the natural granitic mylonite material with the angle between the compression direction of experiments and the original foliation S of samples of 30°,45° and 60° and compression direction perpendicular to lineation L, respectively. The cylindrical cores were polished to diameter of 3 mm and height of 6 mm. The prepared cylindrical samples were dried in a vacuum oven at 150 °C for about 48 h and then jacketed in a mechanically sealed nickel capsule before the compressive deformation process commenced.

2.2. Experimental apparatus, temperature, confining pressure and axial friction calibration

Griggs-type solid-medium triaxial rock deformation apparatus has been used in this study containing 3 GPa molten salt medium pressure vessel (e.g., Liu et al., 2016). The confining pressure and axial load are generated by servo-controlled hydraulic rams driving an outer confining pressure piston and an inner load piston into the pressure vessel. Confining pressure and axial load are measured externally by pressure transducer of the hydraulic Pc system and load cell of the load column, respectively. Displacements of the loading rams for confining pressure and axial stress are measured by two external displacement transducers. Experimental data are digitally recorded with a 16-bit analog/digital converter at a 1 s interval. Changes in displacement control/load control can be made without perturbing the load or displacement signals during an experimental run at any time. Temperature is controlled with a proportional-integral-derivative (PID) controller (Yamatake-Honeywell DCP30, 0.1% FS accuracy).

The sample assembly used in the experiment is shown in Fig. 2. The mixed salt with 50% sodium chloride (NaCl) and 50% potassium chloride (KCl) were used as confining medium. Two NiCr–NiSi thermocouples of sheath type are placed parallel to the sample in the wall of a pyrophyllite tube inside the graphite furnace, and one at the upper one-third positions of the sample was used to control the temperature, and another at the lower one-third positions of the sample was used to measure the temperature.

The temperature and confining pressure calibration were performed (e.g., Han et al., 2009, 2011) before the deformation experiments, and temperature and confining pressure in this study were corrected based on those calibrations. The temperature calibration results show that temperatures were measured by thermocouples at the upper and lower positions of the sample in the pyrophyllite tube where temperatures are the same. The temperatures are about 4% and 9% lower in the centre and bottom of the sample respectively than the temperature monitored in the pyrophyllite tube. The results indicate a relative temperature gradient of 5% from the centre to the top and bottom ends of the sample. We used the phase relations for solid–liquid LiCl/KCl salt mixtures to calibrate the confining pressure (e.g., Han et al., 2011). Based on the temperature of partial melt of LiCl/KCl mixture salt, the true confining pressure can be obtained. The calibration results show that the friction is about 10–13% of digitally measured values of pressure when the LiCl/KCl mixture salt began to melt at 600 °C.

To determine the hit-point and estimate the axial dynamic friction contribution of the top mitre ring with displacement, deformation cycles were made with piston run-in and run-out at a