Experimental evaluation of grain-size-sensitive creep and grain-size-insensitive creep of quartz

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Plastic deformation of polycrystalline materials is categorized into two main mechanisms; one controlled by grain boundary process which depends on grain size (grain-size-sensitive creep; GSS creep) and the other controlled by intragrain dislocation process which does not depend on grain size (grain-size-intensive creep; GSI creep). Studies of experimentally deformed and naturally deformed rocks suggest that in general, the transition between GSS and GSI creep can occur in the grain size of the micrometer order.

Quartz controls the ductile strength of continental rocks because of its abundant existence and weakness. Therefore, a lot of experimental studies have been done to construct the flow laws of quartz ductile deformation. Most experiments used large grain aggregates such as a few hundred μm of each grain, which promote GSI (dislocation) creep. The stress exponents were 3~4 and the microstructures exhibit elongated grains and/or recrystallized grains with host large grains. The host grains still constitute the large volume of the aggregates, leading to GSI creep. The mechanical properties of GSS creep are not well known. In this study, we use fine-grained quartz to experimentally demonstrate GSS creep and its transition to GSI creep.

We hot pressed fine-grained quartz powder of ~2 μm in a solid-pressure-medium deformation (Griggs-type) apparatus at 1.5 GPa and 900°C. We observed systematic grain growth from 2 μm to 25 μm with increasing annealing times from 1 hour to 240 hours. The hot-pressed samples show polygonal grain shapes, tight grain boundaries, and no lattice preferred crystallographic orientations (LPOs). Next, strain-rate stepping experiments were performed under 1.5 GPa, 900-600°C, and the strain rates of $10^{-3.5}$-$10^{-6.0}$/sec. At 900 and 800°C, the stress exponents determined were n=1.5~2.0 (av. 1.7) regardless of the different hot press durations. At temperatures down to 600°C, the stress exponents increased up to 5. The microstructure of the samples shows undulatory extinction and recrystallized fine grains of 1 μm. The crystallographic orientations have weak LPOs that reflect some crystal plasticity and recrystallization. The later stage of deformation appears to be controlled mostly by GSS creep of finely recrystallized grains, as indicated by low stress exponents. Temperature stepping experiments show corresponding two trends; one at 900-750°C and the other at 700-550°C. The activation energies for the high temperature data were 160-200 *kJ/mol* (av. 180 *kJ/mol*) with the stress exponents of 1.7. The strength changes by pressure stepping corresponded to the water fugacity changes. The obtained water exponent is r=1 with n=1.7.

We extrapolate our GSS creep data to natural conditions together with previous flow laws for quartz dislocation creep. Under mid-crustal conditions where the temperature and strain rate conditions are around 400°C and 10^{-14}/sec, respectively, the transition from dislocation creep to GSS creep is predicted at a grain size of ~10 μm. This result is consistent with observations for natural quartz deformed by GSS creep. Our data indicate that the transition from dislocation creep to GSS creep occurs at crustal conditions for fine-grained quartz-rich rocks.

Keywords: Quartz rheology, Flow law, Crustal strength, Griggs-type deformation apparatus