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Deformation of quartz aggregates : interplay between plasticity and grain boundary processes, and the role of water

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The interplay between H₂O and quartz deformation is a long-standing question since the discovery of the H₂O-weakening effect by Griggs and others in the 60's. Some of the early works focused on single crystal experiments and on intra-crystalline processes, but a complete understanding of the phenomenon requires to consider quartz aggregates, where both intra- and intercrystalline processes contribute to bulk strain and strength.

We have carried out a series of deformation experiments on quartz polycrystals at high pressure (0.6 to 2 GPa) and high temperature (800°C), at strain rates of $\sim 1 \cdot 10^{-6}$ to $2 \cdot 10^{-5} \text{ s}^{-1}$, in a Griggs-type apparatus. The main set of experiments used a natural quartzite with a large starting grain size ($\sim 150\text{-}200\mu\text{m}$) in coaxial geometry ($\sim 30\%$ strain). A second series used synthetic mixtures of large ($\sim 100\text{-}200\mu\text{m}$) and dry quartz clasts embedded in a matrix of fine-grained ($\sim 6\text{-}10\mu\text{m}$) powder of natural quartz in a shear geometry, up to large strains ($\epsilon \approx 3\text{-}4$). In both sets of experiments, 0.1 to 0.15 wt% H₂O was added to the assemblage. The H₂O content was measured by FTIR on thick ($\sim 100\text{-}200\mu\text{m}$) plates after deformation, either as spot analyses on grain interiors or on regions containing grain boundaries.

Nearly all strain in the coarse grained quartzite was acquired by crystal-plastic deformation of quartz grains, determined by the shape change of original sand grains that constitute the quartzite (revealed by cathodoluminescence) before and after deformation. Crystal plastic deformation is accompanied by minor recrystallization along grain boundaries, where a mantle of small-sized ($\sim 3\text{-}5\mu\text{m}$) grains developed around some porphyroclasts. While crystallographic fabrics remained weak because of the low strain, low-angle grain boundaries are abundant and indicate incipient recrystallization by subgrain rotation and dominant prism $\langle a \rangle$ slip. In addition to this classic pattern of intracrystalline plasticity and dynamic recrystallization, there is evidence for fracturing and dissolution-precipitation that have produced small grains around the original large grains.

In the starting material, H₂O was mostly contained in fluid inclusions and aggregates, characterized in FTIR by broad-band molecular H₂O, (typically ≈ 4500 H/10⁶Si). The H₂O content in quartz grains was strongly diminished by (i) the application of pressure and temperature and (ii) deformation, down to ≈ 1000 H/10⁶Si. Irrespective of the conditions of deformation, the H₂O content systematically remains higher in grain boundary regions compared to grain interiors. The H₂O expelled during deformation concentrated in domains of fine recrystallized grains of euhedral shapes with large intergranular porosity. These domains are interpreted as pockets of excess H₂O (sometimes with partial melt) where the storage capacity of the grain boundary regions of the quartz aggregate is exceeded. The FTIR spectra show no significant variation with the pressure conditions of the experiments, except for the peak at 3585cm⁻¹, which increased with pressure. As the strength of the aggregates decreased with pressure, we tentatively correlate this peak with point defects in quartz responsible for the pressure-dependent weakening.