A theory on the grain size piezometer of quartz

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The average grain size in dynamically recrystallization (DRX) is often used as an indicator of flow stress, but theoretical basis for the scaling relation between grain size and stress has not well been established. In this paper, theories on recrystallized grain size are reviewed and their applicability is examined. Special attention is paid for the dependence of the grain size-sress relation on DRX mechanisms.

Steady-state DRX is classified into discontinuous DRX with bulge (BLG) nucleation+grain boundary migration (GBM) and continuous DRX with subgrain rotation (SGR) nucleation+GBM. Both belong to 'migration' recrystallization, whereas 'rotation' recrystallization is considered as a transient state of continuous DRX. Continuous DRX with SGR nucleation is common in minerals at relatively high-T/low-strain rate conditions, whereas discontinuous DRX with BLG nucleation takes place at low-T/high-strain rate conditions. The nucleation-and-growth model of the Derby-Ashby theory (Derby and Ashby, 1987, *Scripta Metall.*; Derby, 1991, *Acta Metall. Mater.*) describes the processes of BLG+GBM, whereas that of the Shimizu theory (Shimizu, 1998, *GRL*) applies to the SGR+GBM case. Althought the Twiss theory (Twiss, 1977, *PAGEOPH*) is meaningful for subgrain size, its extension to recrystallized grain size is questionable. The lower limit of grain size is possibly constrained by the change of deformation mechanisms from dislocation creep to diffusion creep (De Bresser et al., 1998, *GRL*). Appreciable theories all predict weak negative temperature dependence of the steady-state grain size.

Laboratory data on minerals and metals suggest that there are almost no correlation between stress exponent p of recrystallized grain size and n of dislocation creep flow laws. The exponent p of minerals resulting from SGR+GBM recrystallization are well explained by the theory of Shimizu (1998).

The grain size piezometer of quartz was calibrated by the intracrystalline SGR+GBM model. The steady-state grain size d[microns] of beta-quartz is written as a function of stress s [MPa] and temperature T [K] as (Fig. a):

$$s = 3.33\text{x}10^{2}\ d^{-0.8} \exp(698/T)$$

The theoretical equation is in good agreement with recent experimental results (Stipp and Tullis, 2003, *GRL*; Stipp et al., 2006, *JGR*). The piezometric relation of alpha-quartz is obtained as (Fig. b):

$$s = 2.06\text{x}10^{2}\ d^{-0.8} \exp(1194/T)$$

The theoretical piezometer calibrated for quartz suggests significant temperature effects at low-temperature metamorphic conditions. Direct application of the empirical relation to nature may lead to serious errors.