Deformation Mechanisms and Rheology of the Crust

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Tectonophysicists studying the deformation of the crust, whether from the perspective of structural geologists examining surface rock exposures or geophysicists using seismic techniques to remotely query the deeper portions of the crust, have a number of common questions. These include the strength of the crust, especially a compared to the sub-crustal lithosphere, and the processes of strain localization within the crust. This paper will present an experimentalist's perspective on these questions, with a focus on ductile deformation.

Deformation of the crust is complex in several ways. First it involves the deformation of polyphase aggregates, and the constituent phases may have quite different strengths and even deform by different mechanisms. The flow strength of the aggregate will depend on the strength of the constituent phases, their volume fractions, and geometric arrangement; appropriately summing the behavior of the constituents to model the behavior of the aggregate is a non-trivial problem.

Second, the flow strength of crustal rocks may change with progressive deformation. The geometric arrangement of the phases may change; the stronger phase may become increasingly dispersed and the weaker phase increasingly interconnected with progressive strain, and this is especially effective in simple shear. As a related factor, aggregates tend to develop a strong crystallographic preferred orientation when highly strained, and this may cause strain hardening or weakening. In addition, the grain size of one or more of the phases may be reduced by cataclasis or dynamic recrystallization, perhaps sufficiently to allow a significant component of grain boundary sliding or diffusion creep. Another complexity is the common occurrence of phase changes (metamorphism) accompanying the deformation. Dehydration reactions tend to produce harder phases, and hydration (retrograde) reactions to produce softer phases. Fluids involved in such reactions or derived from other sources may affect the rock strength mechanically or chemically. In addition, the simultaneous nucleation of two or more phases, even if hard phases, may produce strain weakening because the different phases pin one another's grain boundaries, maintaining a very fine grain size that allows a switch to grain boundary sliding and/or diffusion creep.

Experimental studies of ductile crustal deformation seek primarily to duplicate the processes that operate in nature; in order for those processes to produce measurable strain in lab times it is necessary to use high temperatures, fine grain sizes, and/or high water fugacities. Experimentalists face the problem of choosing systems that are simplified enough to allow unambiguous conclusions but not oversimplified to the point where no meaningful geological conclusions can be drawn. Generally one begins by investigating the deformation behavior of pure mono-phase aggregates over a range of P,T, strain rate, water fugacity etc conditions, including natural and synthetic aggregates (the latter are usually necessary in order to control the grain size), and then progresses on to polyphase aggregates, again both natural and synthetic (the latter allow better control of grain size and volume proportions). In order to interpret the deformation experiments, it is obviously important to have information from experimental mineralogists and petrologists on such things as phase stability, reaction kinetics, and volume and grain boundary diffusion rates.

tentative outline

Experimental Deformation of Quartzo-Feldspathic Rocks

Feldspars

Brittle-ductile transition: faulting to cataclastic flow

Tullis, J. and Yund, R., 1992, The brittle-ductile transition in feldspar aggregates: An ex- perimental study. *in* Fault Mechanics and Transport Properties of Rocks, Academic Press, 89-117.

Transition to crystal plasticity (recrystallization-accommodated dislocation creep)

Tullis, J. and Yund, R., 1987, Transition from cataclastic flow to dislocation creep of feld- spar: Mechanisms and microstructures. *Geology, 15,* 606-609.

Implications of recrystallization-accommodated dislocation creep for strain localization

Tullis, J., Dell Angelo, L.N. and Yund, R.,1990, Ductile shear zones from brittle precur- sors in feldspathic rocks: the role of dynamic recrystallization. *in* Geophys. Monograph 56, AGU, 67-81.

Pressure-solution creep in fine-grained albite aggregates with adsorbed water

Tullis, J., Yund, R., and Farver, J.,1996, Deformation-enhanced fluid distribution in feld- spar aggregates and implications for ductile shear zones. *Geology, 24,* 63-66.

Quartz

Brittle-plastic transition

Hirth, G. and Tullis, J., 1994. The brittle-plastic transition in experimentally deformed

Dislocation creep of quartz: 3 different regimes, with mechanical implications

→Hirth, G. and Tullis, J., 1992. Dislocation creep regimes in quartz aggregates. *J. Struc. Geol., 14*, 145-159.

Effect of water on dislocation creep of quartz: importance of water fugacity (thus P)

Post, A., Tullis, J., and Yund, R., 1996. Effects of chemical environment on dislocation creep of quartzite. *J. Geophys. Res., 101*, 22143-22155.

Granitic aggregates

Quartz-mica aggregates: effects of volume fraction mica, with no reaction

Tullis, J. and Wenk, H.-R., 1994. Effect of muscovite on the strength and lattice pre-

Progressive strain of a fine-grained granite when quartz and feldspar deform by different regimes of dislocation creep, with no phase changes.

→Dell Angelo, L.N. and Tullis, J. 1996. Textural and mechanical evolution with pro-

Simultaneous deformation and reaction

Deformation of plagioclase accompanied by reaction to zoisite + ky + qtz: switch from dislocation creep to diffusion creep and grain boundary sliding.

Stunitz, H. and Tullis, J., Weakening and strain localization produced by syndeforma-

Note

The above list of references is more than anyone can or would want to read on this general topic prior to the conference, but may allow people to choose references for the particular topics that interest them most. I suggest that the two references highlighted with → would be good ones to look at. In addition, an overview is given in the following two references;

Tullis, J., 1990. Experimental studies of deformation mechanisms and microstructures in quartzo-feldspathic rocks. *in* Deformation Processes in Minerals, Ceramics and Rocks, eds. Barber & Meredith, *Mineralogical Society Series 1*, 190-227.

Snoke, A. and Tullis, J., 1998, An overview of fault rocks. *in* Fault-Related Rocks: A