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Microstructures and rheology in laboratory experiments and what it all means for interpreting and modelling natural deformation

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Deformation experiments are the principal source of information that we have at our disposal to enable us to attach mechanistic and rheological meaning to the deformation microstructures that we observe in naturally deformed rock systems. However, we are inevitably faced with the challenge of how do we extrapolate behaviour observed in laboratory experiments to describe rock deformation behaviour on the usually much longer time and length scales associated with tectonic processes.

This problem has long been recognised by the deformation, rheology and tectonics (DRT) research community. Indeed, it is well established that to extrapolate laboratory data and flow laws to nature we must activate, in the lab, the same deformation processes that operate in the natural situation of interest – for example in a pervasively ductile rock mass or in a brittle or ductile fault zone. Typically, we achieve this by speeding-up the natural deformation process, inferred from microstructural study of a natural tectonite, by conducting experiments at higher than natural temperatures or by using artificially fine grained samples. Thermally activated and grain size sensitive flow processes are thus accelerated. To verify that the laboratory data obtained are relevant to nature, we must also confirm that the microstructures produced in the lab are the same as we see in our natural target. Armed with lab data obtained in this way, and with theoretical relations describing the observed deformation mechanism so as to constrain extrapolation of rheological data, we have a means by which we can quantify the mechanical behaviour of rock materials under both crustal and upper mantle conditions – and by which we can attach quantitative meaning to tectonite microstructures, such as recrystallized grain size.

In this contribution, I will review these basic concepts in an attempt to help bridge the still-present gap between the activities of experimentalists, modellers and microstructural specialists within the DRT community. I will provide examples of the best (and worst) ways to approach applying laboratory data on rock and fault rheology to model the mechanics of the crust and to interpret microstructures in a quantitative way. Examples will be taken from both well-established and more recent studies, confirming some long-accepted ideas but also casting serious doubt on others and raising new ideas and quations.

An indispensable example in such a review is the case of experimental work on rocksalt and the question of how best to extrapolate data on its deformation behaviour, obtained in the lab, to understand and model flow during salt tectonics. Viewed as a rock analogue material, experiments on granular salt-phyllosilicate mixtures also provide extremely useful insight into how brittle, crystal plastic and solution-transfer processes can interact to control the rheology and microstructural evolution of both creeping and seismogenic fault rocks.

To answer the question of whether the same processes actually occur in quartz-phyllosilicate fault and shear zone rocks, at high pressure and temperature conditions simulating environments such as the mid crust or subduction megathrust environments, I will review the latest experimental results produced at Utrecht on such materials. These lab data compare well with micromechanical models for fault shear involving combined frictional and fluid-assisted deformation mechanisms, and they provide a new basis for modelling both aseismic creep and the transition to velocity-weakening, seismogenic slip in quartz-phyllosilicate fault rocks.

Last but not least, I will consider the currently controversial issue of the micro- and nanostructural features observed within mirror-like slip surfaces within active faults and exhumed shear zones in carbonate terraines. Recent fault slip experiments conducted at both high (1 m/s, i.e. co-seismic) and low (1 μm/s) sliding velocities have reproduced similar features, raising the question of whether, or under what circumstances, these features may provide evidence of seismogenic slip, and whether the rheological behaviour that accompanies their development in the laboratory can be extrapolated to model the mechanics of motion on such faults. Amazingly, samples sheared in the lab across the full range of velocities investigated show evidence of diffusion-accommodated nano-granular flow in extremely thin principal slip zones, alongside cataclastic grain size reduction, crystal plastic deformation and the development of strong lattice preferred orientations. Frictional behaviour accompanying localised nano-granular flow results from only partial accommodation by diffusion at rapid slip rates, resulting in intergranular cavitation or dilatation and hence the observed normal stress dependence of strength. The rheological behaviour seen in such fault shearing experiments at low velocity varies from velocity strengthening frictional behaviour at 20 to 80°C, to velocity weakening friction with stick slip at 80 to 550°C, to more or less classical ductile flow at higher temperature. Interestingly, samples showing frictional behaviour with stick slip often show a microstructure dominated by classical evidence of crystal plastic flow, with frictional slip having occurred in such a localized zone that it is barely detectable in the microstructure.

The concluding point emerging from this, of course, is that the dominant or most noticeable microstructures seen in deformed rocks do not necessarily tell us what the strength controlling process and rheology was. The upshot is that, while we have increasingly sophisticated and accurate rheological laws available from experiments, it remains essential to choose the flow laws that we use in modelling work on the basis of the careful microstructural studies that correctly identify the main strength controlling process. Collaboration between experimentalists, microstructural specialists and modellers, based on an understanding of the physics of deformation, is accordingly a must for future progress.

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