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Ductile shear zone rheology: the viewpoint of experimentally crept lower crustal rocks and analogues

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With respect to lithosphere rheology, we are especially interested in the mechanical behavior and evolution of ductile shear zones at depth, which present polyphase and heterogeneous character and multi-scale strain localization patterns. According to structural geology, most strain concentrates in ultramylonitic layers, which exhibit along with metamorphism overprinted or concomitant microstructural signatures from several deformation mechanisms. The latter are either active in volume (crystal slip plasticity and dislocation recovery processes), or in the vicinity and along interfaces (grain sliding, phase transformations and solution mass transfer). Because all of these contribute to the drastic evolution of microstructures with respect to the wall rock and the protomylonite, and because the chronology of their activation and their interactions are unclear, inference of the overall rheology from these microstructural records seems illusory. Therefore, since more than a decade we investigate experimentally and numerically the rheology of synthetic rocks representative of lower crustal mineralogy (namely plagioclases and clinopyroxenes). Samples are elaborated with different microstructures and with variable phases, fluid and melt contents for the purpose of being representative of diverse geodynamical contexts. Experiments were performed either at constant stress or strain rate, in co-axial compression or in torsion.
For macroscopic non-Newtonian flow we clearly identified dislocation glide and creep mechanisms. That is to say that power law rheology relates to dominant crystal slip plasticity accommodated by recovery processes, including dislocation climb and pile-up, sub-grain rotation and marginal recrystallization. We further refer to this regime as RCSP (recovery crystal slip plasticity). Conversely, Newtonian (linear viscous) behavior mostly involves grain boundary sliding (GBS) accommodated by diffusional mass transfer and grain boundary dislocation mechanisms, but local RCSP can still be active as well. We realized finite element (FE) modelling of a representative elementary volume (REV) constituted of volumetrically dominant fine-grained matrix and strong inclusions subjected to simple shear. The results confirmed that the microstructural heterogeneity and the contrasting rheology of the constituent phases induce very strong local stress and strain partitioning. On the one hand, GBS mechanisms dominate the overall response, which indicates Newtonian rheology as most appropriate for modelling the steady state mechanical behavior of deep crustal shear zones. On the other hand, the local stress heterogeneities trigger combined RCSP and GBS, which intimate interactions remain unclear.
To clarify the respective roles of CSP and GBS we realized a multi-scale full field measurement investigation during deformation of rock analog synthetic halite. Uniaxial compression tests were performed in-situ a scanning electron microscope (SEM) and under X-ray contrast tomography (MCT). Full in-plane and volume strain fields were computed thanks to Digital Image Correlation (DIC) analysis performed at consecutive loading steps. Cooperative CSP and GBS were identified within early localized shear bands. When CSP dominates, GBS contributes as an accommodation mechanism for the local incompatibilities of plastic strain across some grain boundaries. Conversely, when GBS is pronounced strongly localized CSP allows for sliding accommodation at triple junctions. In opposition to the common assumption, our results indicate that GBS and CSP cannot be really dissociated as competing and independent strain mechanisms. They both and cooperatively ensure macroscopically homogeneous flow.