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Localization of ductile deformation in lithosphere and rocks: the role of grain boundary sliding

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Ductile strain of the lithosphere localizes in multi-scale shear zones, ranging from km to mm scales. The resulting mylonites/ultramylonites present microstructural signatures of several concomitant deformation mechanisms. Besides cataclastic features, crystal plasticity dominates in volume, but grain boundary sliding and diffusive/solution mass transport act along interfaces. Considering solely the inherited natural microstructures does not make clear the chronology of appearance and the interactions between these mechanisms. Therefore, inference of the overall mylonitic rheology seems illusory. We have therefore realized over the last decade a systematic rheological characterization of the high temperature flow of various synthetic anorthite - diopside mixtures. The data clearly suggest Newtonian type of rheology as best adapted to the materials representative of the lower crust mylonites. However, the post mortem microstructures undoubtedly evidenced the coexistence of both crystal plasticity and grain boundary sliding processes. Yet, the specific roles of each mechanism in the localization process remained unclear. In order to clarify these aspects we realized a multi-scale micromechanical in situ investigation of the ductile deformation of synthetic rock-salt. The mechanical tests were combined with in-situ optical microscopy, scanning electron microscopy and X-ray tomography (MCT). Digital image correlation (DIC) techniques allowed for measurements and characterization of the multi-scale organization of 2D and 3D full strain fields. Macroscopic and mesoscopic shear bands appear at the sample and microstructure scales, respectively. DIC evidenced the development of discrete slip bands within individual grains, and hence of dominant crystal plasticity. Combination of DIC and EBSD allowed for identification of active slip systems. Conversely, DIC allowed for the identification and the precise quantification of minor activity ($< 5\%$ contribution) of grain boundary sliding (GBS). Most importantly, GBS is continuously operating along with crystal slip plasticity, which indicates that in spite of being a secondary mechanism it is a necessary one. GBS seems to accommodate very efficiently for plastic strain incompatibilities between neighboring grains. Our finding is strengthened by finite element (FE) modeling of the viscoplastic behavior of rock-salt, which appears inadequate in detail if solely based on crystal plasticity. Moreover, the local GBS appears to i) trigger the formation of localized shear bands at the microstructure scale, and ii) allow for homogenization of ductile strain throughout the whole specimen. Our major conclusions are that crystal plasticity and GBS are not really dissociable. They are co-operative mechanisms that accommodate each other depending on microstructure and loading conditions. Minor GBS is always necessary in order to accommodate for the pronounced plastic anisotropy of minerals. Conversely, localized minor crystal plasticity is necessary to accommodate dominant GBS. Finally, GBS is directly involved in the initial development of localized ductile strain at the aggregate scale. But, GBS might take over as the dominant mechanism within fine grained mylonites and contribute to the large scale shear zone localization.