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Self-consistent grain size evolution controls lithospheric shear zone formation during continental rifting

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In geodynamic numerical models, grain-size-independent dislocation creep often solely defines the governing crystal-plastic flow law in the upper mantle. However, grain-size-dependent diffusion creep may become the dominant deformation mechanism if grain size is sufficiently small. Previous studies implying composite diffusion-dislocation creep rheologies and fixed grain size suggest that the upper mantle is stratified with the dominant mechanism being dislocation creep at shallow depths and diffusion creep further down. Studies with variable grain size in the upper mantle depending on common grain-size evolution models demonstrate that the contrary might be the case, where diffusion creep is acting within the mantle lithosphere and dislocation creep in the asthenosphere below. Diffusion creep as a dominant mechanism has important implications for the overall strength of the lithosphere and therefore for the dynamic evolution of lithospheric-scale extension and orogeny.

To investigate the importance of grain size and the effects of resulting crystal-plastic creep within the upper mantle, we developed a two-dimensional thermo-mechanical numerical code based on the finite difference method with a fully staggered Eularian grid and freely advecting Lagrangian markers. The model implies a composite diffusion-dislocation creep rheology and a dynamic grain-size evolution model based on the paleowattmeter including recently published olivine grain growth laws.

Results of upper mantle extension indicate olivine grain sizes of ~7 cm for large parts of the upper mantle below the LAB, while in the lithosphere grain size ranges from ~1 mm at the Moho to ~5 cm at the LAB. This grain size distribution indicates that dislocation creep dominates deformation in the entire upper mantle. However, diffusion creep activates along lithospheric-scale shear zones during rifting where intense grain size reduction occurs to local stress increase. We furthermore test the implications of wet and dry olivine rheology and respective crystal growth laws and interpret their effects on large-scale tectonic processes. Our results help explain strain localization during extension by strength loss related to grain size reduction and consequent diffusion creep activation.