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Microstructural evolution and rheology of ductile shear zones: implications for lithospheric strength

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Deformation in the ductile crust and lithospheric mantle is localized as a result of a variety of strain-related weakening processes. The degree of localization depends on rock composition, water content, temperature, and strain rate, and in general decreases with increasing temperature and depth in the lithosphere. Lithospheric-scale ductile shear zones are therefore likely to become wider with depth, and the strain-rate will decrease correspondingly. Application of constitutive flow laws to lithospheric rheology therefore requires knowledge of the volume fraction of shear zone material.

In pristine lithosphere, ductile shear zones will widen until the flow stress required to accommodate the imposed strain-rate is equal to the plastic yield stress of the surrounding rocks. This means that the bulk rheology of the deforming lithosphere at any given depth is controlled by the yield stress of the undeformed rock under the prevailing conditions. As long as the boundary conditions remain unchanged, the microstructural and rheological evolution of the shear zones can therefore be regarded as a constant stress experiment. If the imposed rate of deformation decreases, or if the lithosphere contains pre-existing shear zones formed under a higher bulk imposed strain-rate, this will not be true, and the bulk rheology of the deforming lithosphere will then depend on the rheology of the shear zones and the volume fraction they form of the lithosphere.

One of the most important weakening mechanisms in shear zones, particularly at low temperature, is dynamic recrystallization. In addition to increasing the contribution of grain-boundary sliding to the strain-rate, dynamic recrystallization acts as a powerful recovery mechanism during low-temperature dislocation creep. If the recrystallized grainsize follows experimentally determined stress-grainsize relationships, these processes are likely to lead to a form of grainsize-sensitive power-law creep, resulting in a substantially enhanced strain-rate relative to normal dislocation creep. At extreme stress and very low grainsize there may be a switch to grain-boundary diffusion creep, possibly accompanied by unrestricted grain-boundary sliding. In a constant-stress shear zone, the rate of strain-energy induced grain-boundary migration in the dynamically recrystallized aggregate will be much larger than the rate of surface energy-driven grain-growth, and the two processes are mutually antagonistic. Hence there is no mechanism for grain-growth, and deformation mechanism switches due to grainsize reduction will be permanent. Grainsize-sensitive creep is therefore likely to control the width of lithospheric shear zones and the bulk mechanical properties of the lithosphere.