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Localising Plate Boundaries: Importance of Serpentinisation and Grain Size Reduction on the Rheology of the Lithosphere

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The development of plate boundaries remains one of the most challenging aspects of Earth's tectonics, as rock rheologies are typically characterized by strain-rate weakening: It is energetically favourable to distribute deformation over wide distances, resulting in a low strain rate and low stress in the deformation zone. Yet, tectonic deformation on Earth is localized on relatively narrow regions that feature a relatively high strain rate. Geodetic estimates place intraplate deformation rates at 10^{-20} to 10^{-18} s^{-1} (often below detection limits). By contrast, diffuse plate boundaries in the oceans are marked by a strain rate of 10^{-16} to 10^{-15} s^{-1}, continental deformation zones deform at somewhat higher strain rate, and narrow plate boundaries, found mostly in the oceans, deform at 10^{-13} s^{-1}or faster. We develop here rheological models of the lithosphere that explain these contrasts of strain rate.

We define the effective rheology of the lithosphere as the relation between strain rate and the integral of the associate strength envelope with depth. We document how microstructural changes in the lithosphere that are associated with active deformation modify the effective rheology and show that, if the total force exerted on the lithosphere remains constant as these changes proceed, the strain rate over the lithosphere increases to reach the values seen globally. The inclusion of serpentine reduces the near-surface, mainly brittle, strength, and can increase strain rate from 10^{-18} s^{-1} to 10^{-15} s^{-1}. This change can explain the development of diffuse plate boundaries, in particular the Central Indian Basin diffuse plate boundary, where serpentinisation is ongoing. Grain size reduction can have a similar effect, but influences instead the ductile levels of the lithosphere. Grain size reduction has a somewhat higher effect on the continental lithosphere than on the oceanic lithosphere and can explain the development of continental plate boundaries, with additional weakening processes such as foliation development leading to large-scale continental shear zones. Serpentinisation combined with grain size reduction appears necessary to form narrow plate boundaries, although, once a plate tectonic system is in place, stress focusing towards mid-ocean ridges due to variations of oceanic plate thickness maintains high strain rates. The likely absence of serpentinization on Venus may explain why no long-lived plate boundary is observed on that planet.