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Continental rifts: complex dissipative patterns from simple boundary conditions

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We present numerical models that investigate the development of crustal and mantle detachments during lithospheric extension. Our models, which consider an elasto-visco-plastic lithosphere, explore the relationship between stored and dissipated energies during deformation. We apply the fundamental thermodynamic assumptions of minimization of Helmholtz free energy (i.e. stored energy) and maximization of dissipated energy, and include in the models feedback effects modulated by temperature, such as shear heating, that lead to strain localization. Our models simulate a wide range of extensional systems with varying values of crustal thickness and heat flow, showing how strain localization in the mantle interacts with localization in the upper crust and controls the evolution of extensional systems. Model results reveal a richness of structures and deformation styles as a response to a self-organized mechanism that minimizes the internal stored energy of the system by localizing deformation. Crustal detachments, here referred as low-angle normal decoupling horizons, are well developed during extension of overthickened (60 km) continental crust, even when the initial heat flow is relatively low (50 mW m−2). In contrast, localized mantle deformation is most pronounced when the extended lithosphere has a normal crustal thickness (30–40 km) and an intermediate heat flow (60–70 mW m−2). Results show a nonlinear response to subtle changes in crustal thickness or heat flow, characterized by abrupt and sometimes unexpected switches in extension modes (e.g., from diffuse extensional deformation to effective lithospheric-scale rupturing) or from mantle- to crust-dominated strain localization. We interpret this nonlinearity to result from the interference of doming wavelengths in the presence of multiple necking instabilities. Disharmonic crust and mantle doming wavelengths results in efficient communication between shear zones at different lithospheric levels, leading to rupturing of the whole lithosphere. In contrast, harmonic crust and mantle doming inhibits interaction of shear zones across the lithosphere and results in a prolonged history of extension prior to continental breakup.