Abstract

The thesis addresses selected problems related to localized deformation of the solid Earths lithosphere that stem from non-uniform strengths or emerge from non-linear rheologies. A new code has been developed to model the spontaneous localization through strain-weakening plasticity. A code coupling technique is introduced as an attempt to efficiently solve multi-material and multi-physics problems like crust-mantle interactions.

We first address a problem of localized deformation that is caused by pre-existing heterogeneities. Specifically, the effects of laterally varying viscous strength on the Cenozoic extension of the northern Basin and Range are investigated using numerical models. Three-dimensional viscous flow models with imposed plate motions and localized zones of low viscosity show that strain rates are concentrated in weak zones with adjacent blocks experiencing little deformation. This result can explain the geodetically discovered concentrated strain in the eastern part of the northern Basin and Range as the high strains are a response to far field plate motions within a locally less viscous mantle. The low viscosity of mantle is consistent with the low seismic velocities in the region.

As an instance of spontaneously emergent localized deformations, brittle deformations in oceanic lithosphere are investigated next. We developed a Lagrangian finite difference code, SNAC, to investigate this class of problems. Brittle deformations are modeled as localized plastic strain. The detailed algorithm of SNAC is presented in Appendix A.

The spacing of fracture zones in oceanic lithosphere is numerically explored. Numerical models represent a ridge-parallel cross-section of young oceanic lithosphere.

An elasto-visco-plastic rheology can induce brittle deformation or creep according to the local temperature. The spacing of localized plastic zones, corresponding to fracture zones, decreases as crustal thickness increases. The stronger creep strength raises the threshold value of crustal thickness: If the crust is thinner than the threshold, the brittle deformation can evolve into primary cracks. Plastic flow rules are parametrized by the dilation angle. If the dilatational deformation is allowed in the plastic flow rules (dilation angle>0°), the primary cracks tend to be vertical; otherwise, a pair of primary cracks form a graben. The modeling results are compatible with the correlation between crustal thickness and the spacing of fracture zones found in different regions such as the Reykjanes ridge and the Australian Antarctic Discordance.

Three-dimensional (3D) numerical models are used to find the mechanics responsible for the various patterns made by the segments of the mid-ocean ridges and the structures connecting them. The models are initially loaded with thermal stresses due to the cooling of oceanic lithosphere and prescribed plate motions. The two driving forces are comparable in magnitude and the thermal stresses can exert ridge-parallel forces when selectively released by ridges and ridge-parallel structure. Represented by localized plastic strain, ridge segments interact in two different modes as they propagate towards each other: An overlapping mode where ridge segments overlap and bend toward each other and a connecting mode where two ridge segments are connected by a transform-like fault. As the ratio of thermal stress to spreading-induced stress (γ) increases, the patterns of localized plastic strain change from the overlapping to connecting mode. Rate effects are taken into account by the spreading rate normalized by a reference-cooling rate (Pe') and the ratio of thermal stress to the reference spreading-induced stresses (γ'). The stability fields of the two modes are unambiguously defined by Pe' paired with γ'.

Crust and mantle are distinct in terms of composition and rheology. To study the combined response of crust and mantle, it is necessary to solve multi-material and multi-physics problems that are numerically challenging. As an efficient way of solving such a problem, we introduce a code coupling technique. We adapt Pyre, a framework allowing distinct codes to exchange variables through shared interfaces, to the coupling of SNAC, a Lagrangian code for lithospheric dynamics, and CitcomS, an Eulerian code for mantle convection. The continuity of velocities and tractions and no-slip conditions are imposed on the interfaces. The benchmarks against analytic solutions to the bending of a thin plate verifies that SNAC gives an accurate solution for the given traction boundary condition. It is also shown that Pyre can correctly handle the data exchanges at the interfaces. In a preliminary high-resolution model, an elasto-visco-plastic lithosphere is coupled to a Newtonian viscous mantle. This coupled model shows a steady growth of dome in the lithosphere directly above a hot sphere placed in the mantle. However, the two coupled codes incur unnecessarily high numerical costs because they use different methods for time integration.