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Thick plate and finite element analysis of lithospheric scale folding

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We study folding instability due to lateral shortening in multilayered plate comparable to a continental lithosphere. Although buckling of the lithosphere has been reported by numerous studies there is still an open question if lithospheric-scale folds do really exist in an intracontinental setting. Accessible deep seismic data are not accurate enough to register folds of one or a few kilometers of amplitude at a depth of several tens of kilometers. Ancient folds, if present, might be obliterated by multiphase tectonic evolution of continents. Moreover, several hundred kilometers wavelength of expected lithosphere-scale folds and lateral mechanical heterogeneity of continental plates make the periodicity of folding hard to observe. In turn, undulations of structural surfaces shown by shallow geological data can be created by various deep processes. The way to verify lithosphere-scale folding hypothesis is comparison of observations with results of numerical modeling. We model effects of minor shortening, realistic for intraplate deformations, to examine most effective folding scenarios under accessible tectonic loads.

The model lithosphere is idealized as a stratified plate floating on a low-viscosity substratum representing the asthenosphere. The top surface is traction-free and the shortening is driven by applying a constant with depth horizontal velocity at the lateral boundaries. The magnitude of the velocity is adjusted during deformation to maintain a constant rate of shear. The model is subject to a body force due to gravity.

The lithospheric plate comprises four layers that correspond to the lower, middle, and upper crust underlain by the upper mantle. The rheological behavior of the layers is that of a power-law viscous fluid with a viscosity prefactor that decays exponentially with depth. The characteristic decay length is determined by the thermal state of the plate. In an attempt to incorporate a brittle deformation mechanism that may potentially operate at the upper portions of all four layers, we mimic a pressure-sensitive plastic behavior by introducing auxiliary layers, where the power-law exponent is set at a high value and the viscosity prefactor is prescribed as a function of depth. In some cases, we introduce a number of alternating layers that represent sedimentary strata at the top of the model.

We employ a thick plate analysis to quantify the fold characteristics at the nucleation stage. The analysis is based on matching an exact analytical solution for individual layers at the interfaces that are corrugated. We study the growth rates as a function of the wavelength of the infinitesimal perturbations at the layer interfaces. The analysis allows us to identify the wavelength of the most active mode of the instability. In several cases, a secondary maximum in the growth-rate vs. wavelength curve appears. During the analysis we explore the parameter space (geometric dimensions, thermal state, mechanical properties of layers) with a focus on finding a maximum growth rate that is sufficiently high to explain a prominent folding already at low strain, i.e. less than 10% of shortening. The analysis is constrained by comparing the dominant wavelengths to the ones that are observed in nature.

Finite element simulations are performed to validate the thick-plate analysis which is only an approximation to the cases when non-linear materials are present in the system or the fold amplitudes cannot be considered small with respect to the wavelength.