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Comparing thin-sheet to fully 3D models with application to the India-Asia collision

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Various models have been proposed to explain tectonic deformation during continent collision. A frequently applied model is the thin viscous sheet model which is however not fully three-dimensional (3D) and assumes a priori diffuse thickening as the dominant deformation style.
We compare a fully 3D multilayer numerical model with a corresponding thin viscous sheet numerical model for the scenario of continent indentation. In our comparison we focus on the three basic viscous deformation styles thickening, buckling (folding) and lateral crustal flow. Both numerical models are based on the finite element method (FEM) and employ either a linear or power-law viscous rheology. The 3D model consists of four layers representing a simplified continental lithosphere: strong upper crust, weak lower crust, strong lithospheric mantle and weak asthenospheric mantle. The effective viscosity depth-profile in the 3D model is used to calculate the depth-averaged effective viscosity applied in the thin-sheet model allowing a direct comparison of the models.
We quantify the differences in the strain rate and velocity fields, and investigate the evolution of crustal thickening, buckling and crustal flow resulting from the two models for two different phases of deformation: (1) indentation with a constant velocity and (2) gravitational collapse after a decrease of the indenting velocity by a factor 5. The results indicate that thin-sheet models approximate well the overall large-scale lithospheric deformation, especially during indentation and for a linear viscous rheology. However, in the 3D model, additional processes such as multilayer buckling and lower crustal flow emerge. These are ignored in the thin-sheet model but dominate the deformation style in the 3D model within a range of a few hundred kilometers around the collision zone and indenter corner. Differences between the 3D and thin-sheet model are considerably larger for a power-law viscous than for a linear viscous rheology and especially buckling and lower crustal flow are significant in the 3D model.
3D multilayer models provide a more complete picture of continental collision than thin-sheet models as they enable studying the timing, location and relative importance of different processes simultaneously which is especially important for the 100 km scale around the collision zone and indenter corners.
In a second study we apply the 3D model to the India-Asia collision, where we distinguish between the Indian and the Asian domain, i.e. material parameters are varying both in the vertical and horizontal directions. The model geometry is set up using available geophysical data. From the CRUST2.0 dataset topography and depths of the lithospheric layers are used to set up the vertical layering, and measured Bouguer anomalies are applied to constrain the density structure. The viscosity distribution is controlled by comparing viscous and gravitational stresses. Viscosities must be large enough to counteract or equilibrate gravitationally induced stresses, so that the model does not to flow under its own weight (i.e. collapse). We then perform instantaneous indentation of India into Asia to represent the present day state of the continent-continent collision. The impact of various rheological profiles on the velocity, stress and strain rate fields is studied and compared to geophysical observations, such as GPS velocities and anisotropy directions.