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Viscous overthrusting versus folding: 2-D quantitative modeling and its application to the Helvetic and Jura fold and thrust belts

Yoann Jaquet, Arthur Bauville, and Stefan M. Schmalholz
University of Lausanne, Institut of Earth Sciences, Lausanne, Switzerland (yoann.jaquet@unil.ch)

We apply a viscous model to study the tectonic evolution of the Jura and Helvetic fold-and-thrust belts of the European Alps. We present two-dimensional (2-D) numerical simulations of the shortening of a stiff viscous layer, with a pre-existing weak zone, that is embedded in a weaker viscous matrix. The model bottom remains straight during shortening and represents a detachment surface. Four deformation styles are observed that depend on the ratio of the layer and matrix viscosities, μ_L/μ_M; the thickness ratio of the bottom matrix and the overlying stiff layer, H_M/H_L; and the power-law stress exponent of the matrix, n_M. The numerical results are used to quantify the conditions for which each deformation style occurs: (1) pure shear-dominated deformation occurs for μ_L/μ_M $<\sim$50 and n_M=1 (i.e., linear viscous); (2) overthrusting-dominated deformation occurs for a power-law viscous matrix (n_M=5), μ_L/μ_M $>\sim$50 and H_M/H_L $<\sim$0.5; (3) folding-dominated deformation occurs for n_M=1, μ_L/μ_M $>\sim$50, and H_M/H_L $>\sim$1; and (4) folding and overthrusting occur for a power-law viscous matrix and $\sim$0.5$<$ H_M/H_L $<\sim$2. The power-law stress exponent of the stiff layer has a minor effect on the deformation style. Simulations with layers that contain two weak zones show the formation of a nappe stack. The simulations also show that multi-layers can overthrust like a single layer. The change in deformation style as a function of H_M/H_L corroborates field observations from the Helvetic nappe system. The agreement of the numerical results with first-order observations from the Helvetic nappe system suggests that ductile deformation dominated this fold-and-thrust belt. The results further suggest that overthrusting on an effectively viscous weak layer only occurs if the rheology of the weak layer is power-law viscous. Consequently, we argue that a mechanical model that employs a viscous (creep) rheology and layers of different viscosity is well suited to model the first-order mechanical evolution of the Helvetic nappe system. This supposition implies that, rather than the friction coefficient, the effective viscosity, which is usually a strong function of temperature and a moderate function of strain rate, grain size, and water content, controls the mechanical development. If this is true then sandbox models and the theory of critical wedges (the one based on frictional behavior) are not suitable to study the mechanical development of the Helvetic nappe system. The quantitative results have also been applied to a cross section in the Jura fold-and-thrust belt.