GSA DATA REPOSITORY 2011240

Yamato et al., "Dynamic constraints on the crustal-scale rheology of the Zagros Fold Belt, Iran"

ITEM DR1. NUMERICAL MODELING

Numerical code

Numerical simulations are performed using MILAMIN_VEP, a marker-in-cell Lagrangian visco-elasto-plastic finite element code which includes remeshing, admissible Q_2P_{-1} elements, and that was developed to simulate large-strain geological processes at crustal to lithospheric scale (e.g., Kaus, 2010). The code has been extensively benchmarked including versus viscous multilayer folding instabilities and plasticity. We employ a Maxwell viscoelastic rheology if stresses are below the yield stress, and non-associated Mohr-Coulomb plasticity if stresses are above the yield stress. The model is dynamic in the sense that shear-zones are not imposed by any means. However, since we use a finite element method, those shear zones are not discrete faults but rather zones of shear localization that are several elements wide.

Setup and material properties

For this study, in the finite strain simulations (up to 5.5 Myrs, Fig. 1), the viscosities of the weak layers are assumed to be linear and constant. The brittle layers have a temperature-dependent rheology of limestone (Turcotte and Schubert, 2002) with a linear geotherm of 25°C.km^{-1}. This geothermal gradient that fits with recent estimates derived from thermochronological data (Gavillot et al., 2010, Homke et al., 2010) is in agreement with tectonic modelling (Mouthereau et al., 2006) and is compatible with the presence of earthquakes down to depths of 30 km (Talebian and Jackson, 2004; Tatar et al., 2004; Roustaei et al., 2010). Yet, for the low-temperature conditions of the Zagros, stresses are such that these materials effectively deform in the brittle regime. Other material parameters are: density of salt is 2200 kg.m^{-3}, that of sediments is 2700 kg.m^{-3}, the cohesion is 20 MPa and the elastic shear module is 2.5×10^{10} Pa.

Our model domain is 200x7.225 km in size, and we use a total of 800x100 nodes with a mesh refined in the vertical direction to accurately resolve the thin detachment layers. Resolution tests reveal that the same overall patterns are obtained at significantly smaller resolution although the faults are less well pronounced. As initial model geometry, we use constraints from the Zagros corrected for the effect of 15% shortening on viscous media: the initial sedimentary thickness between the bottom of the Hormuz salt decollement and the surface is therefore 7.225 km, rather than 8.5 km. All numerical simulations presented here initially deform by pure-shear thickening. By reducing the initial model thickness, we obtain the present-day crustal thickness after 5.5. Myrs of deformation.

Boundary conditions

The current arid climate in the Zagros and other regions surrounding the Persian Gulf has been probably maintained since the Miocene as the consequence of a strong regional aridification in Central Asia in response to the closure of the Para-Tethys ocean and Tibetan plateau uplift (e.g., Ramstein et al., 1997; Fluteau et al., 1999). The limited erosion capacity is thus one of the main characteristics of the Zagros. The limited denudation rates (< 0.1 mm.yr^{-1}) estimated in the Zagros (Homke et al., 2010) led us to consider it negligible. Moreover, previous studies showed that erosion does not change the selection wavelength of detachment folding (Burg et al., 2004). The top boundary is a free surface and a constant background strain rate of 10^{-15} s^{-1} is applied at the right of the model box, which results in a shortening of 15% after 5.5 Myrs in agreement with geological constraints. Indeed, the duration of folding is suggested by magnetostratigraphic dating of syntectonic deposits which indicates that folding was achieved between ~13 Ma in the northern Zagros Fold Belt, as deduced from the age of the youngest folded conglomerates (Khadivi et al., 2010), and ~7.5 Ma, which is the age of onset of folding at the southern front of the Zagros Fold Belt (Homke et al., 2004). All other sides of the model are free slip conditions. To initiate the folding, the interface between the salt and the overburden rocks was perturbed with random noise with maximum amplitude of 100 m.

ITEM DR2. SEMI-ANALYTICAL METHOD TO PREDICT FOLD SPACING IN THE PRESENCE OF A BRITTLE OVERBURDEN

Since the brittle rheology of the crust is strongly nonlinear, classical multilayer folding theory is of limited applicability (Schmalholz et al., 2002; Schmid and Podladchikov, 2006), and does not correctly predict the wavelength in our model. The classical approach to treat a brittle overburden in analytical models is by setting the powerlaw exponent to infinity (e.g. Ismail-Zadeh et al.). It can easily be seen that this does not work in our case as it results in a fold wavelength of 0 km and an infinite growth rate. Yet, there is currently no theory predicting fold spacing for a non-associated plastic (frictional) overburden that has been verified versus finite-strain visco-elasto-plastic numerical models (although the method of Montesi and Zuber 2003a,b, based on negative powerlaw exponents could be a step in this direction).

Moreover, for cases with a multilayer sequence, deriving closed form analytical solutions is cumbersome (although Schmid and Podladchikov, 2006 show that viscous multilayer folding also results in an increase of growth rate compared to single layer folds). We have tested various possibilities, based on a multilayered analytical approach (similar to the one employed in Kaus & Becker 2007; Kaus et al. 2008), such as using depth-dependent viscosity with large n-exponents, but found them to be not capable of explaining the numerical results.

The method we used here is therefore based on using the finite element code (with a brittle rheology). Models were performed in which a single sinusoidal perturbation was prescribed with small amplitude. A few time steps were performed, after which the growth rate was computed by dividing the upward velocity of the salt/overburden interface by the amplitude of the perturbation. By varying the length of the box, we can create plots of growth rate versus wavelength for various material parameters and an arbitrary number of decollement layers with the crust. We performed convergence tests and used a resolution of 201x101 nodes for the plots presented here. The maximum of the growthrate-wavelength plot is the dominant wavelength and growthrate, and in order to create figure 4B, we have performed over 10’000 computations.

Simulations in which elasticity was taken into account started with an initial stress that is equal to the visco-plastic steady-state stress, in order to be able to compare our results with those of Schmalholz & Podladchikov, 1999.

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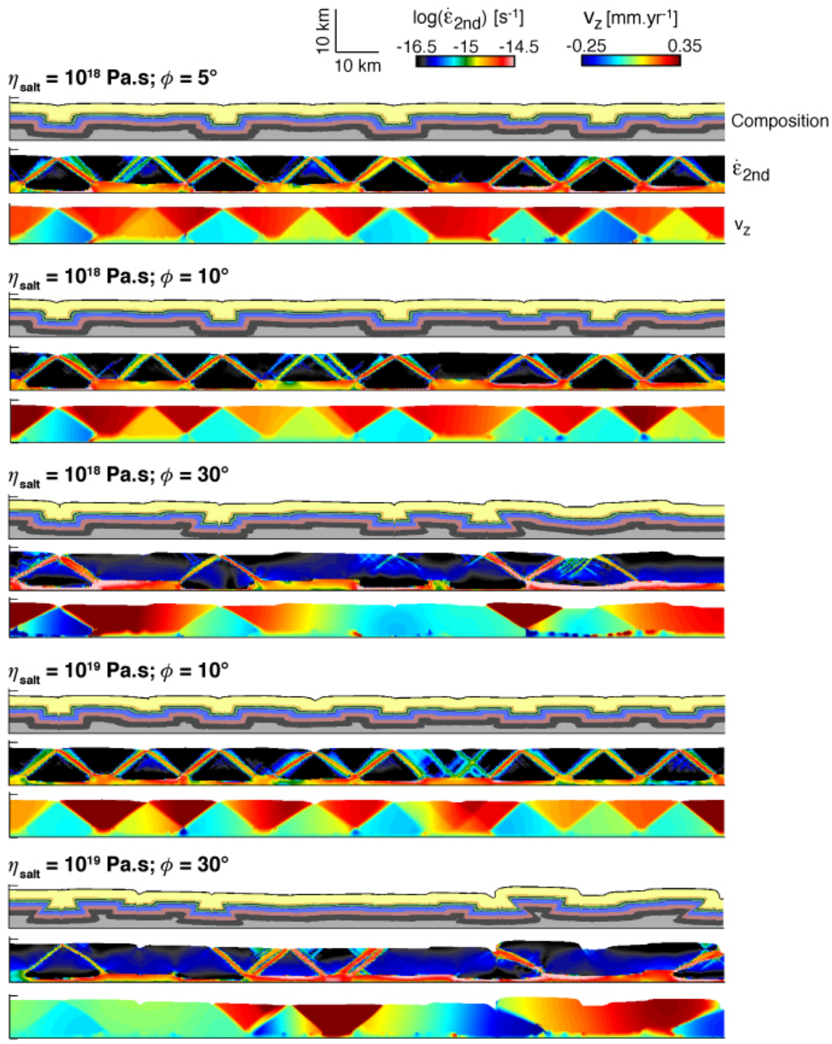

Figure DR1. Salt viscosity and overburden friction angle effects on the models implying only the salt basal decollement layer.

Results obtained in models with only a single basal (salt) decollement after 5.5 Myrs for different salt viscosities and friction angles of the overburden. All other parameters are as for Fig. 2. Results show that compared to the Zagros Fold Belt, the obtained wavelengths are too large and the deformation style, dominated by thrusting, is inconsistent with data.