Progress report for the 2007 SCEC project

A 3-D visco-plastic model of instantaneous lithospheric deformation in southern California (SMOG3D)

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Project objective

This report is for the first year of funding (second year pending) of our joint modeling project that wishes to elucidate how faults in southern California are loaded over long-term, multi-cycle timescales. We study how crustal stress arises due to plate boundary mechanics, as well as topographic and mantle flow loading in the presence of geological heterogeneity.

The project mainly provided three months of salary funding for post-doc Noah Fay who conducted the numerical experiments; some of the results are reported here. We also briefly comment on related work on the whole San Andreas from triple junction to triple junction by John Platt (USC), Boris Kaus (ETHZ/USC), and Becker. Kaus is also involved with the main SMOG3D effort through the development of a new finite element code, which we wish to compare in the future with the ABAQUS and GALE software used by Fay.

Summary of SMOG3D findings

- We constructed a simplified numerical model of San Andreas fault (SAF) geometry with realistic visco-elastic-plastic rheology to determine the effect of a Big Bend-like geometry on strain-rates and stress in the surrounding crust. A first version of the model was built to resemble Li *et al.* (2008) in order to conduct a benchmark test. Results compare favorably in their prediction of symmetric off-fault regions of high strain rates.

- We constructed more realistic, complicated models in order to include the San Jacinto fault (SJF), Elsinore fault (ELS), Eastern California Shear Zone (ECSZ), Garlock fault (GAR), and Walker Lane Belt (WLB). Using these models, we were able to explore how variable fault strength influences crustal kinematics, fault slip rates, and the distribution of stress. Some preliminary conclusions:

  - In the absence of lithospheric viscosity variations and basal drag, major faults in southern California are inferred to have variable long-term strength (defined as the time-averaged stress supported in the seismogenic portion of the crust). If only fault strength is varied to accommodate the geodetically observed distribution of slip-rates, we find that the strength of the ELS must be larger than that of the SJF, which must be larger than that of the SAF Indio by at least a factor of 3 and 2, respectively. This implies an inverse relationship between cumulative fault offset (and possibly slip rate) and fault strength, similar to what has been suggested previously based on fault morphologies.

  - Heterogeneous tectonic stress can result from relatively simple interaction of faults and non-planar fault geometry.
  - More generally, the results show that our models can in fact be used to test several suggested forces acting upon southern California faults.

- Publications and presentations
  - Initial results were presented at the 2007 SCEC Annual Meeting in Palm Springs, CA.
  - Recent results were presented (by Fay as invited speaker) at the March 6-7, 2008, LAD workshop at UCLA.

Project description

Model set up

We consider a numerical model domain of $600 \times 350 \times 60$ km oriented along a small circle about the Pacific-North America plate motion Euler pole. Therefore, the edges of the "box" are parallel and perpendicular, respectively, to the relative motion of the Pacific plate in southern California.

The model rheology is visco-elasto-plastic, as is appropriate for studying the long-term behavior of southern California under plate tectonic, convective, and topographic loading. The upper crust viscosity is 10^{25} Pas with a plastic yield strength $\sigma_y = 50$ MPa; these settings make this layer effectively elasto-plastic. The lower crust/upper mantle have a uniform viscosity of $2 \cdot 10^{20}$ Pas and $\sigma_c = 10$ MPa. "Faults" are represented as 5 km wide weak zones with same viscosity and elastic properties as surrounding crust, but with a lower plastic yield strength which is varied in the models. (We assume that the local geometric complexity, such as mapped for the present-day in the SCEC CFM, is of secondary importance to the larger scale dynamics we strive to evaluate.) Elastic parameters are 87.5 GPa for Young's modulus and 0.25 for the Poisson ratio. In the steady-state solutions we are considering, the role of elasticity is to control the level of strain build up in the surrounding medium before plastic failure.

The mechanical boundary conditions are such that the top is fixed, and the bottom has prescribed velocity boundary conditions (49 mm/yr to the left) to simulate Pacific plate motion relative to North America. The left and right sides are free. In a next step, we will implement a free-surface with topography and allow for isostatically balanced, vertical motions.

We use the finite element method to solve the force balance and continuity equations. For all results shown here, the commercial software ABAQUS was used. Our initial tests with the freely available GALE were complicated by issue with implementing relevant boundary conditions that will be addressed in the future.

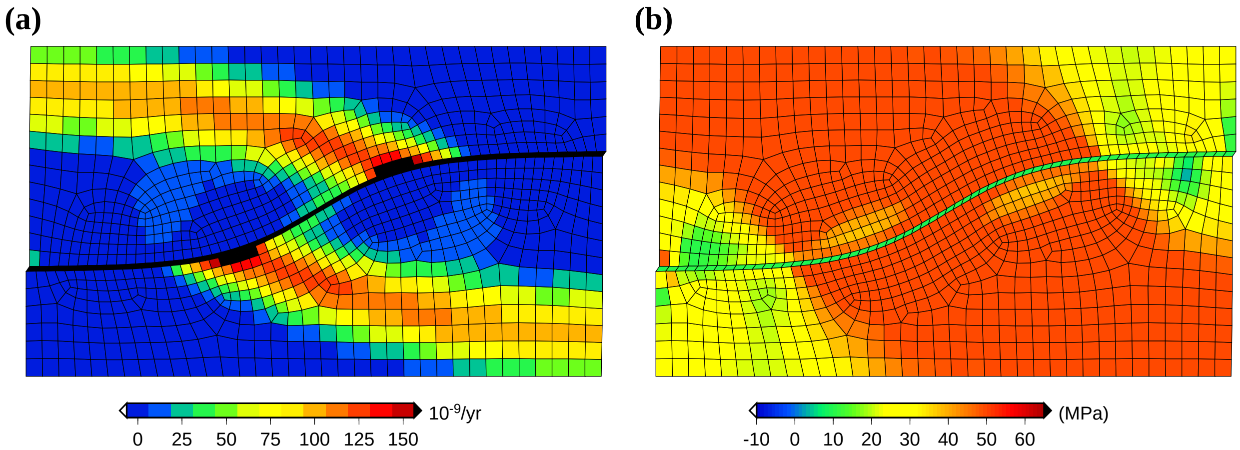

Figure 1: **(a)** Square root of the second (shear) invariant of the deviatoric strain-rate tensor at 5 km depth. Colors show off-fault strain rate (nano-strain/yr), shear strain within the fault zone is off-scale and would dominate the plot. **(b)** Square root of the second invariant of the deviatoric stress tensor at 5 km depth.

Results

Model with a single, bent San Andreas Fault The simple fault geometry in Figure 1 was chosen to be approximately the size and scale of the "Big-Bend" of the SAF in southern California, following Li & Liu (2006, 2007). This model was in part a benchmarking exercise of a relatively simple model to compare results with Li *et al.* (2008). The vast majority of plate motion in the model of Figure 1 is accommodated by the relatively weak fault with yield strength of $\sigma_y = 10$ MPa. This model illustrates the geometric consequence of a non-planar fault: two bands of off-fault strain are induced on the "outside" corners of the fault (Figure1a), which may correspond the Eastern California Shear Zone and Borderland fault systems (*cf.* Li *et al.*, 2008). The results compare favorably, with remaining discrepancies probably related to different mesh resolution employed by the different groups. We show the corresponding stress field in Figure 1b; much of the crust is at, or near, its yield strength (50 MPa), although only a small volume is appreciably straining.

Model with SAF Indio, San Jacinto, and Elsinore Figure 2 shows results for a model that incorporates a weak (relative to the bulk crust) SAF Indio (10 MPa), a stronger SJF (20 MPa), and an even stronger ELS fault (30 MPa). If strength variations of faults in an otherwise homogeneous crust are the only control on the slip rate distributions, this model illustrates the need for fault strength to decrease further inland in order for fault slip to distribute closer to observations, namely the slip rate of the SAF Indio $>$ SJF $>$ ELS.

The immediate next research steps planned for the Summer of 2008 are

- The evaluation of how much of the strain-rate partitioning can be explained by an analytical, 2-D solution given fault strength and kinematic boundary conditions, and what role the vertical rheological structure of the crust plays, and

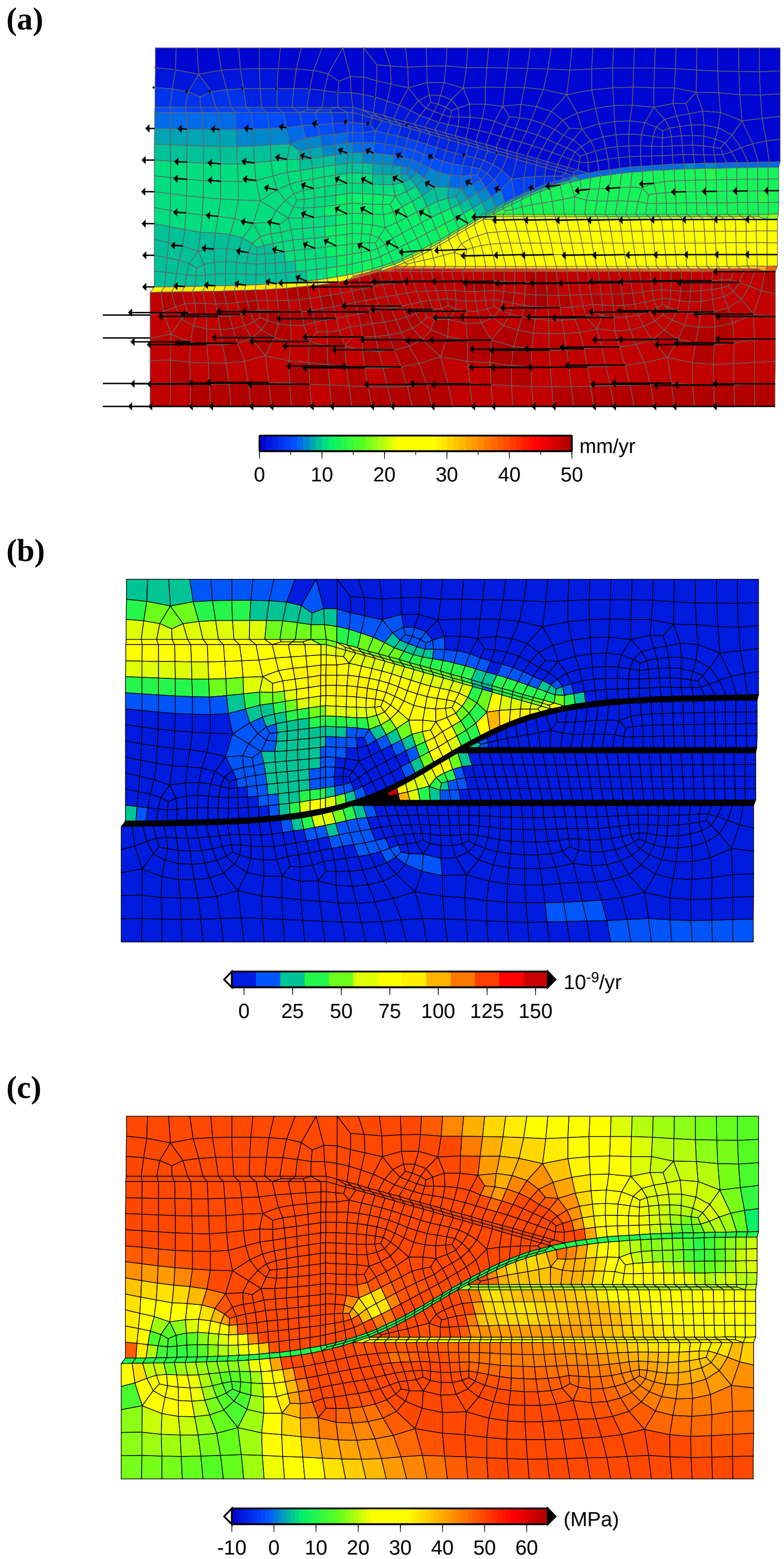

Figure 2:
(a) Velocity (in mm/yr), relative to North America, color gives magnitude, interpolated from nodes to element faces. The step in velocity across the simplified SAF Indio, SJF, and ELS faults toward the right (East) of the model indicates the slip rate of those faults.
(b) Square root of the second (shear) invariant of the deviatoric strain-rate tensor showing distributed off-fault deformation to the NE (in the Eastern California Shear Zone region, where geographic North points to the upper left corner) of the main SAF fault strand. Note how the other off-fault strain rate zone (*cf.* Figure 1a) is diminished substantially in this model that more closely resembles the southern California fault system.
(c) Square root of the second invariant of the deviatoric stress tensor. The spatially varying fault strength, geometry of the SAF, and interaction of the ELS and SJF with the SAF Indio result in a complicated stress field that can vary both across faults and along-strike (*cf.* Bailey *et al.*, 2008).

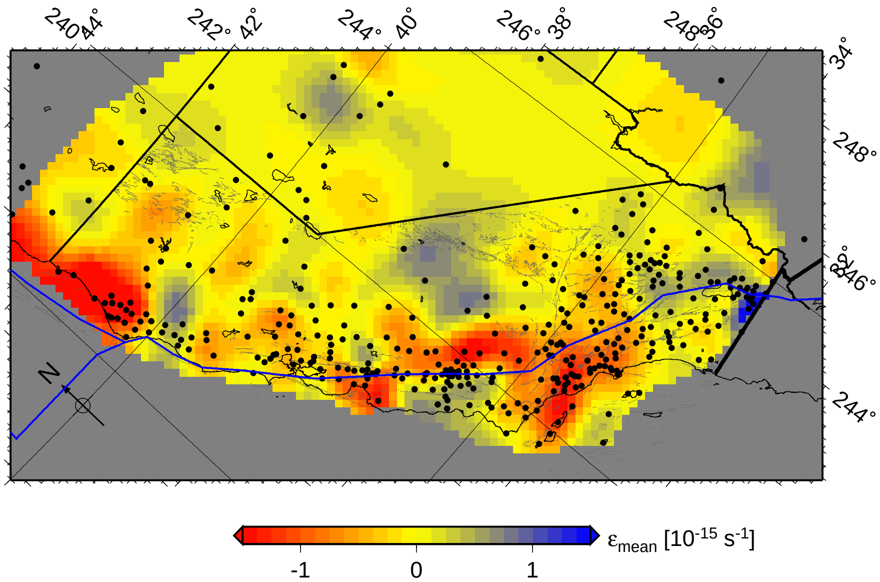

Figure 3: Mean (dilational) horizontal strain as inferred from the EarthScope PBO GPS velocity solution, selected higher quality GPS sites shown as black dots (see Platt *et al.*, 2008). Red and blue regions correspond to crustal thickening and thinning, respectively.

- the incorporation of both surface and Moho topography, basal traction loading, and introduction of rheological heterogeneity, for example a stiff Sierra Nevada/Great Valley block. We will explore how those effects modify the stress field as governed by fault strength alone.

Related work

Platt, Kaus, and Becker have developed a thin-sheet description of the San Andreas fault as a weak zone that is terminated by zero shear stress boundary conditions at its northern and southern triple junction termini (Platt *et al.*, 2008). This model predicts second-order regions of vertical motions that are directly associated with the plate boundary and, if true, will be superimposed on the overall shear strain due to the transform. In southern California, the Platt *et al.* (2008) thin sheet model predicts crustal thickening consistent with the tectonics of the Transverse Ranges and Borderland region, as well as thinning in the Salton Sea and Death Valley area. Moreover, the dilational component of the horizontal strain-rate field that may be imaged from the EarthScope PBO GPS velocities (Figure 3) is also consistent with the model predictions.

Interestingly, in an independent study by Noah Fay he was able to show that the geodetic dilation field in southern California may also be associated with the tractions that are induced by mantle flow as driven by sub-Moho density anomalies. The latter were inferred from seismic tomography, and regions of crustal thinning and thickening overly regions where extensional and compressive stresses, respectively, are exerted by mantle tractions. If the mantle density anomalies correspond to the cumulative effect of the secondary plate boundary signature discussed by Platt *et al.* (2008), then those two views of vertical tectonics along the transform are in fact complementary.

References

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