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Reconciling Geologic and Geodetic Estimates of Slip Rates in Southern California

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Objective

Estimates of fault slip rates using geodetic data are model dependent. For example, it has been demonstrated that models that assume an elastic earth with creeping faults extending to infinite depth may yield different estimates of slip rates than a model with faults in an elastic plate overlying a viscous substrate. The most comprehensive fault slip rate estimates using GPS data for southern California are derived from elastic block models. In these models, tectonic blocks bounded by faults are assumed to move as undeformed bodies over the long-term, accommodated by steady slip on the bounding faults. During the interseismic period, elastic strain accumulation due to locking of faults is modeled as a perturbation to this long-term block motion and steady fault slip with back-slip on locked portions of faults using dislocations in an elastic half-space. Some fault slip rate estimates from the block models in southern California are inconsistent with geologic estimates. The discrepancies indicate one of several possibilities: 1. the geologic estimates are wrong, 2. the elastic block model results are wrong because of deficiencies of the model assumptions, or 3. both estimates are correct but the estimates reflect different slip rates over different time periods.

In this work we are examining the possibility that the elastic block models yield incorrect slip rates because of oversimplified assumptions about long-term kinematics and lithosphere rheology. We are developing new block models for southern California in which faults are modeled in an elastic lithosphere overlying a viscoelastic asthenosphere with uniform or layered viscosity structure.

Viscoelastic Earthquake Cycle Model

We have recently developed a new 3D viscoelastic earthquake cycle model (block model) that consists of blocks bounded by faults in an elastic lithosphere overlying a viscoelastic asthenosphere. The 3D viscoelastic block model is an extension of the elastic block models developed by McCaffrey (2002) and Meade et al. (2005) which are in turn a generalization of the 2D backslip model constructed by Savage and Burford (1973). In the elastic block models, a "steady state" is imagined in which blocks bounded by faults rotate on the surface of the Earth about an Euler pole as spherical caps. In the absence of locking on the faults, the blocks translate undeformed. Elastic distortion due to locking of the faults is introduced with backslip on the faults. Sections of the fault that are completely locked are assigned backslip at the long-term rate. Sections that are creeping are assigned a backslip rate that is lower than the long-term rate. The elastic block models assume no long-term vertical motion which is problematic for areas with reverse or normal faulting.

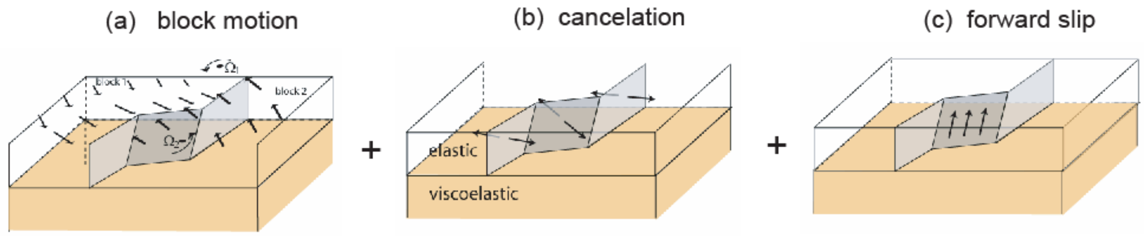


Figure 1. Illustration of the construction of the steady-state velocity field (sum of a,b,c). Euler poles for blocks 1 and 2 are Ω_1 and Ω_2. Arrows in (a) represent rigid block rotations. Arrows in (b) represent steady cancellation of fault-normal velocity discontinuities. Arrows in (c) represent imposed forward dip slip on dipping faults.

Our 3D viscoelastic cycle model also uses the concept of a “steady-state" deformation in the absence of fault locking and backslip to construct the interseismic deformation field, but the ``steady-state" does not consist of undeformed translating blocks. The “steady-sate" model incorporates long-term distortion of the blocks near the bounding faults due to dip-slip motion on thrust faults and non-planar fault geometry. The steady-state velocity field is decomposed into three components as illustrated in Figure 1. We begin with far-field motion due to relative plate velocities. This motion assumes rigid-body rotations about an Euler pole (no vertical motion). For vertical faults bounding the rigid blocks, the rigid rotations lead to strike-slip and fault-normal discontinuities in the velocity field across the faults. Rigid-body rotations of blocks bounded by dipping faults would lead in general lead to dip-slip, strike-slip, and tensile discontinuities across the faults. There are two problems with this steady-state velocity field. For one, the tensile discontinuity across faults is unphysical. Secondly, this model assumes no long-term vertical motion along dipping faults with dip-slip component - this is reasonable perhaps for subduction zones, but not for other settings. We therefore alter the rigid-body motion locally, near the faults, as illustrated in Figure 1 b,c by by a) canceling fault-normal discontinuities across all faults with tensile dislocations with sign opposite to the relative motion across the faults, and (b) imposing forward dip slip on dipping faults at the rate $\Delta v/\cos\theta$ where Δv is the fault-normal velocity discontinuity across the fault and θ is the fault dip. The cancellation and forward slip results in a long-term velocity field with only fault parallel components of velocity discontinuity across faults. The steady-state dip-slip motion on faults produces localized steady-state (long-term) vertical motions and long-term horizontal strain near dip-slip faults.

To obtain the interseismic velocity field, we perturb the steady-state velocity field with contributions from interseismic fault locking and periodic earthquakes. We follow the approach of Savage and Prescott (1983) and lock faults with steady back-slip at the long-term slip rate and sum the contribution of an infinite sequence of periodic earthquakes.

Results

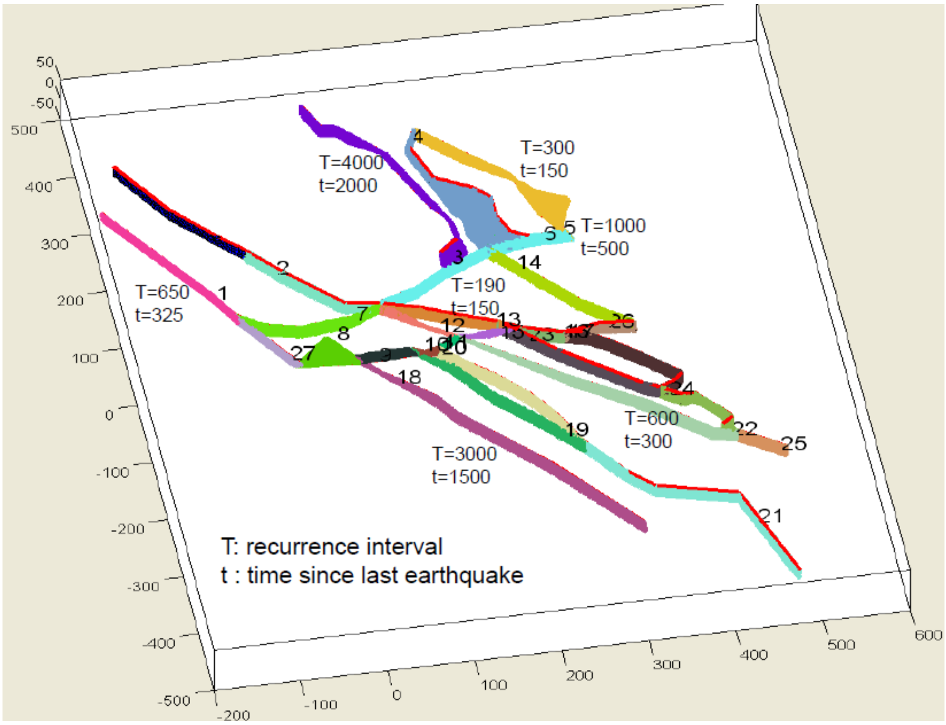


Figure 2. Rupture patches used in cycle model. Recurrence intervals are taken from literature or estimated based on slip rates and assumed rupture displacements.

In order to estimate viscosity structure and fault slip rates simultaneously, we must have data spanning multiple time periods. In Johnson et al. (2007), we modeled the Mojave region of the San Andreas Fault system using a 2D fault model, triangulation data spanning the time period of 1932-1977, post-Landers GPS time series, and the contemporary GPS velocity field. From this work we inferred a lower crustal and uppermost mantle viscosity of 10^{20}-10^{21} Pa s with mantle viscosity of about 10^{18}-$5x10^{18}$ Pa s. For this study, we assume this viscosity structure for our layered viscoelastic model.

In Figure 3 we compare the strike-slip rate estimates form the layered viscoelastic model with a “steady flow” model that assumes a uniform, high, asthenosphere viscosity. The steady flow model is similar to elastic block models.

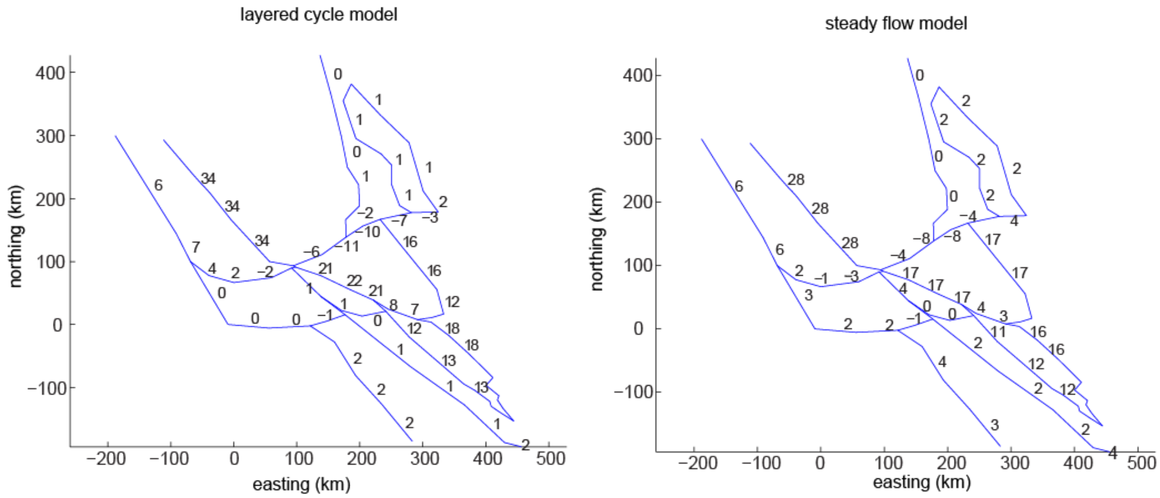
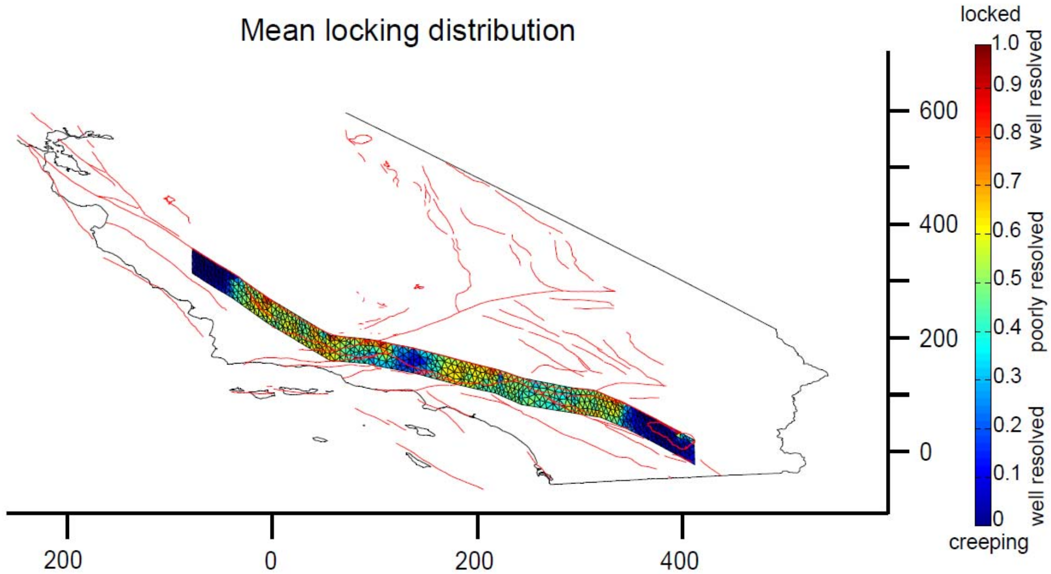


Figure 3. Strike-slip rate estimates for the layered cycle model and the steady-flow model. Right-lateral rates are positive, left-lateral rates are negative.

The slip rate estimates in the layered cycle model are systematically higher along the San Andreas fault than in the steady-flow model. The higher slip rates are a direct result of relaxing viscous asthenosphere flow (which is neglected in the steady-flow model). The San Andreas fault slip rate estimates in the layered cycle model are in better agreement with geologic slip rate estimates than the rates from the steady-flow model.

We also estimated the distribution of creep on the San Andreas fault using the steady-flow model. In this model, the San Andreas fault is subdivided into many small triangular elements. The triangular elements are assumed to be either completely locked (no slip) or creep at constant resistive shear stress. The distribution of locked and creeping patches is estimated using a Monte Carlo inversion scheme. Figure 4 shows the results of this inversion. The base of the gridded fault is at 25 km depth. The San Andreas fault creeps in the Salton trough andParkfield areas, as expected. There is also some apparent shallow creep along the northern Mojave segment of the San Andreas. Otherwise, the fault is locked down to a depth of about 20 km.

a.



b.

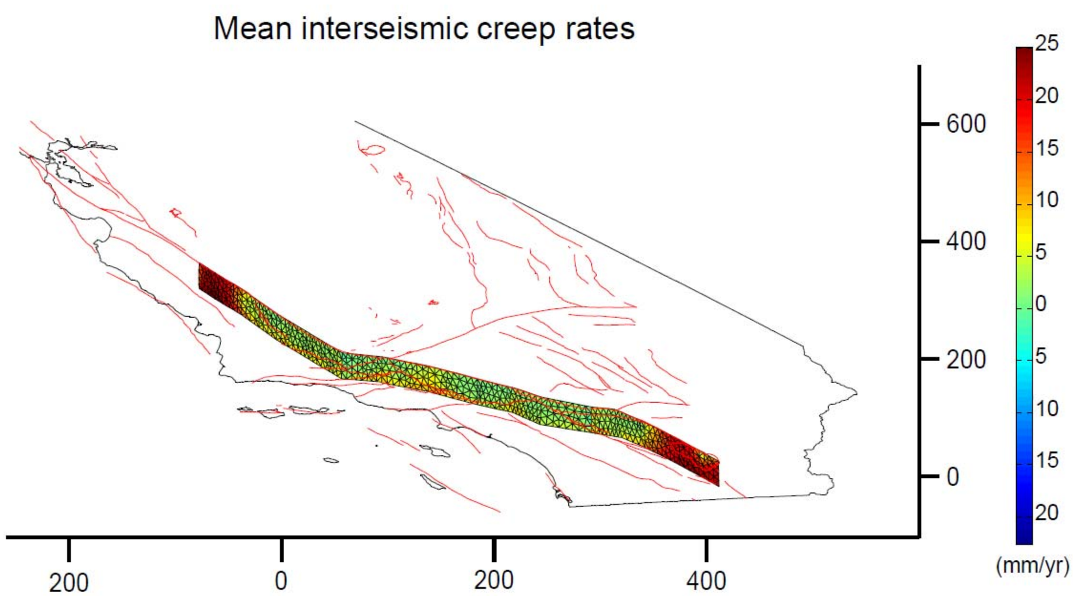


Figure 4. a. Locking on San Andreas Fault patches. 0 means fully creeping; 1 means fully locked. b. Interseismic fault-slip rates on San Andreas fault, showing two creeping sections and deep locking depth.