Fault interaction in the Los Angeles Basin and Transverse Ranges, southern California, from elastic half-space and viscoelastic finite element models

Margaret T. Glasscoe,(1,2) Louise H. Kellogg,(1) Gregory A.Lyzenga,(2,3) and Andrea Donnellan(2)

(1) Department of Geology, University of California, Davis, California, 95616, USA (e-mail: glasscoe@geology.ucdavis.edu, kellogg@geology.ucdavis.edu; phone: +1 530-752-0350). (2) Jet Propulsion Laboratory, California Institute of Technology, Pasadena California, 91109, USA (e-mail: donnellan@jpl.nasa.gov; phone: +1 818-354-4737). (3) Harvey Mudd College, Claremont, California, USA, (email: lyzenga@hmc.edu, phone +1 909-621-8378).

Abstract

We use a series of forward models of deformation in a faulted elastic half-space and a 2-D faulted, layered viscoelastic domain to model shortening across the northern Los Angeles basin. The purpose of the models is to investigate how the observed 4.5 to 6 mm/yr shortening is accommodated on known and presumed faults, and to determine whether anelastic deformation is consistent with geodetic observations. The different models incorporate a range of fault geometries; the viscoelastic models additionally incorporate a range of shortening rates across the basin and have a layered structure with variable Maxwell relaxation time. We focused on three models to address the interaction between thrust faults: (1) a model with two daylighting, steeply dipping, sub-parallel thrust faults, (2) a model with one daylighting, steeply dipping thrust and a more gently dipping blind thrust outboard of it (blind thrust model), and (3) a model with a single steeply dipping daylighting thrust. The models demonstrate how the lower-crust rheology affects the dissipation of stress imposed on the viscous layers by elastic failure of the faults. We hope to be able to identify which geometry and rheology best fits the geodetically recorded data in order to better understand how deformation in the LA basin is accommodated.

Introduction

Though significant shortening is currently being recorded in the LA Basin using continuous GPS (SCIGN), it is still unclear how exactly the shortening is accommodated. We use elastic and viscoelastic models to identify the effects that different geometries, material properties, and shortening rates have on the predicted surface deformation of the models. We then compare the model results with the observed velocities in order to determine which models best fit the data.

Geological evidence does not seem to support high slip rates on either daylighting or blind thrust faults in the LA Basin (Tom Rockwell, pers. comm.). Prior studies (e.g. Donnellan, et al., 1999) used extremely high slip rates on thrust faults in models in order to accommodate all the deformation observed in the basin on a few faults; however, this is geologically unreasonable because the slip rates on the faults are thought to be 1 mm/yr or less. This study uses several simplified models of fault geometries and rheology with "reasonable" slip rates on the modeled faults (on the order of 1 mm/yr) in order to ascertain what model of lower crustal rheology and slip distribution on faults would be consistent with geodetic observations.

Methods

The JPL SCIGN Data Center provides current shortening rates, as measured by continuous GPS across the LA Basin. A residual velocity field, obtained by removing the contribution of slip due to strike slip faults in the region, was constructed using the method of Feigl, et al., 1993 (Figure 1). We then constructed a velocity profile of the N 40 E component of the horizontal velocities in order to compare them with velocities predicted by elastic and viscoelastic forward models (see Results section).

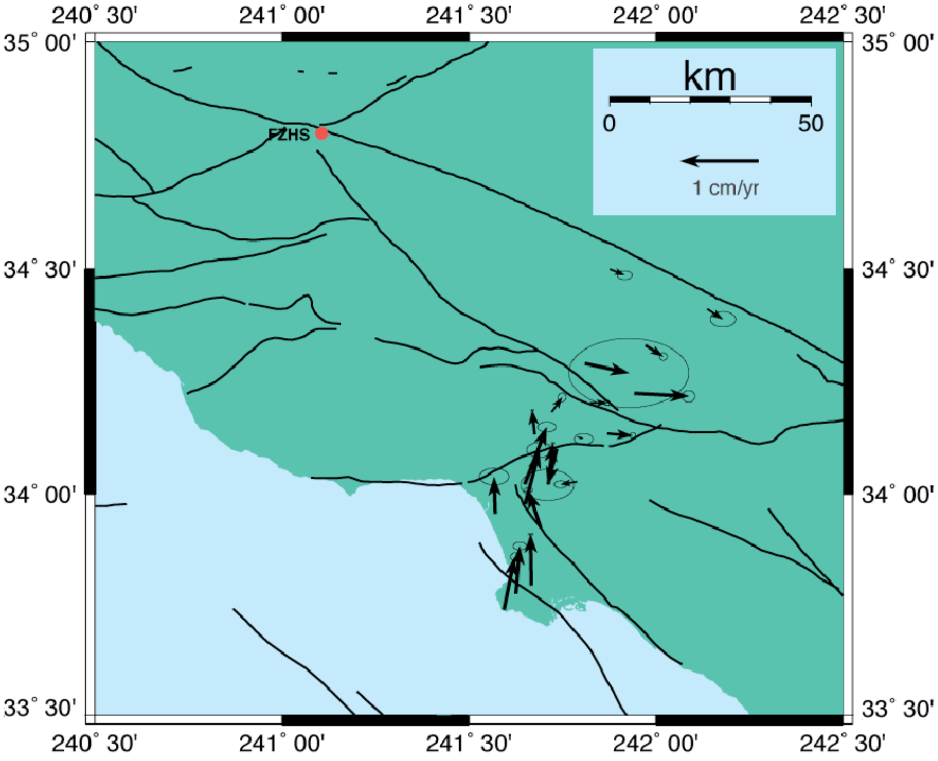
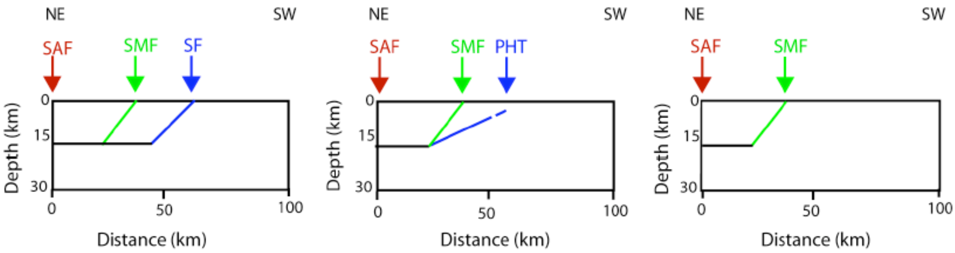


Figure 1. Residual velocity field, relative to SCIGN station FZHS, constructed using the method of Feigl, et al., 1993.

We used both elastic half-space and viscoelastic finite element forward models to determine how the models compare with geodetic data. Elastic models did not predict high enough velocities to account for all of the shortening observed geodetically. We then varied the rheology of the viscoelastic models to determine whether or not those models predicted surface deformation comparable to the GPS data. We varied the geometry of the faults to test the sensitivity of the model to differing types of fault interaction. We used a range of relaxation times comparable to those modeled by other workers (e.g. Hager, et al., 1999).

The elastic models were obtained using the elastic dislocation code DISLOC (geometry and properties are illustrated in Figure 2). Viscoelastic models were obtained by using the 2D version of JPL's GEOFEST finite element code. The viscoelastic models consisted of a model domain of 400 km x 100 km, with various faults and a layered structure, with an elastic upper crust (with a low rigidity basin between two rigid blocks to model basin sediments) and a viscoelastic middle and lower crust (Figure 3). We varied the Maxwell relaxation times of the middle crust and lower crust between 5 and 3 years, respectively, and 50 and 30 years, respectively, and 500 and 300 years, respectively.

Shortening across the LA Basin was imposed on the viscoelastic models by assigning a horizontal rate of displacement on one side of the model, while keeping the opposite side pinned horizontally. We imposed two rates: 6 mm/y (from Argus, et al., 1999) and 4.5 mm/y (from Bawden, et al., 2001). To accommodate flux from the imposed horizontal velocity, we imposed a vertical outflow along the bottom of the pinned side of the model (which mimics the tomographically imaged lithospheric structure beneath the Transverse Ranges). Slip on the faults is represented by specifying an earthquake recurrence interval and assigning a slip per earthquake event on each fault. Each model was run for multiple earthquake cycles to reach a statistical steady state.



Daylighting thrust model

Sierra Madre fault (SMF)
Dip = 52
Depth = 18 km
Slip = 1.83 mm/yr

Suggested fault (SF)
Dip = 45
Depth = 18 km
Slip = 1.03 mm/yr

Blind thrust model

Sierra Madre fault (SMF)
Dip = 52
Depth = 18 km
Slip = 1.83 mm/yr

Puente Hills thrust (PHT)
Dip = 25
Depth = 18 km
Slip = 1.23 mm/yr

SMF only model

Sierra Madre fault (SMF)
Dip = 52
Depth = 18 km
Slip = 1.83 mm/yr

Figure 2. Fault geometry and properties for elastic dislocation models.

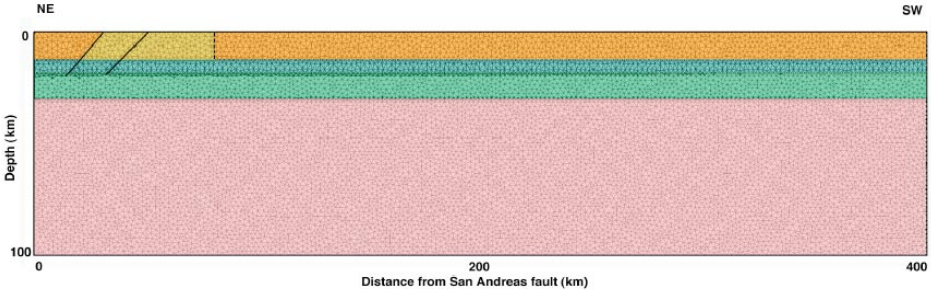


Figure 3. Geometry and properties for viscoelastic models. Geometry and slip rates are the same as listed in Figure 2. Shortening on the southwest side of the model was varied between 4.5 mm/yr and 6.0 mm/yr. Orange and yellow denote elastic crust (yellow showing a low rigidity basin), blue denotes middle crust, green denotes lower crust, and pink denotes mantle. Daylighting thrust model shown to illustrate layered structure.

Results

We plotted the N 40º E component of our constructed residual horizontal GPS velocity field against horizontal velocity profiles of the viscoelastic models at two time periods. One time period, denoted by the solid lines in Figure 4, represents a time step 10 years prior to a modeled earthquake event. The second time period, denoted by the dashed lines in Figure 4, represents a time step 10 years following a model earthquake event. We used a relaxation time of 30 years in the lower crust. This value for the relaxation time yielded velocities that were roughly comparable to the observed GPS velocity. The profiles suggest that the time period 10 years following a modeled earthquake provides a velocity profile that is the most similar to the profile we constructed from the observed data. The plots also suggest that the lower shortening rate of 4.5 mm/yr fits the GPS data better, and that the blind thrust model reasonably approximates the GPS profile.

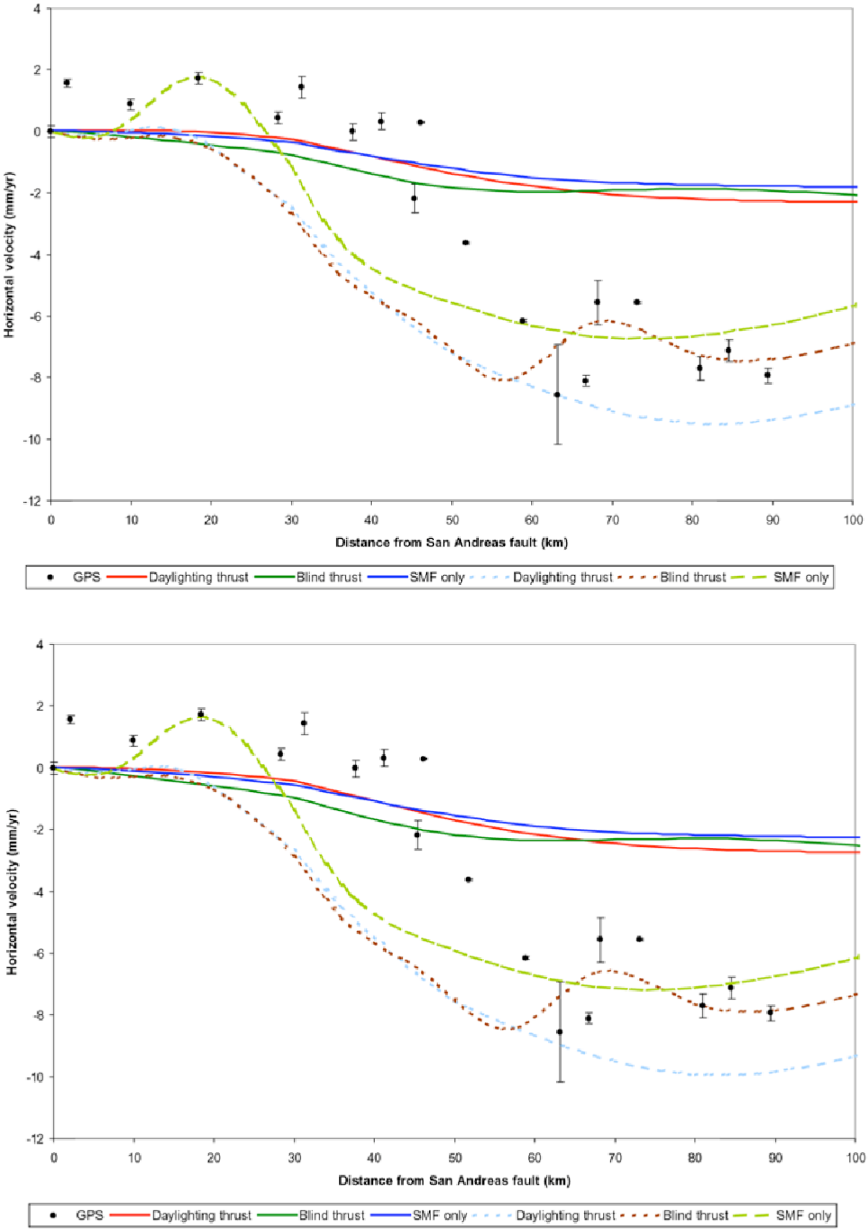


Figure 4. N 40º E component of residual horizontal GPS velocity plotted with horizontal viscoelastic model results for 4.5 mm/yr shortening rate (top) and 6 mm/yr shortening (bottom), with lower crustal relaxation time = 30 years. Solid lines are 10 years prior to a model earthquake event, dotted lines are 10 years following a model earthquake event.

Discussion

The predicted surface deformation in these models is not very sensitive to fault geometry; within the resolution of the data, it is not currently possible to distinguish between models with the same overall shortening but different fault geometries just by comparing them to geodetic rates. A weak lower crust produced unrealistically high post-seismic velocities, while higher values of relaxation time predict geologically reasonable velocities, and an extremely strong lower crust implies that the elastic portion of the crust in the model goes down to unreasonable depths (~30 km). The GPS data will be helpful in constraining the rheology of the lower crust, but integration of geologic and geophysical data is necessary in order to determine what processes are driving deformation in the LA Basin... is it accommodated on buried faults or taken up by anelastic processes? In addition, the modeled velocity profiles suggest that the GPS data best fits a velocity field 10 years following a modeled earthquake event. This could imply that the velocity field currently being recorded may be affected by a recent earthquake event and may not represent an interseismic velocity field, as has been suggested in the past.

Acknowledgments

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