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Incorporating Geodetic Surface Data into UCERF3: Estimating Slip Rates and Locking Depths

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Summary

For UCERF3, GPS-derived models are largely replacing expert opinion models of fault slip rates and off-fault seismicity rates. In this work I developed two deformation models for UCERF3 and helped coordinate the development of other models. A Deformation Model for UCERF3 consists of slip rate estimates on faults and distributed strain rates off of faults. The off-fault strain rates are used to derive moment rates for off-fault seismicity. The model slip rates drive the rate of earthquake production on the faults.

Four different kinematic models were constructed. These models are all constrained by a UCERF3-consensus GPS velocity field constructed by Thomas Herring, geologic slip rates at points on faults taken from a new UCERF3 compilation by Dawson and Weldon of slip rate estimates from the published literature, and surface creep rates compiled for UCERF 2 (Wisley et al., 2008, Appendix P).

Figure S1 summarizes the results of one new deformation model for UCERF3. This model is a kinematically-consistent average of five kinematic block models. The five block models were constructed by Kaj Johnson, Bill Hammond, Rob McCaffrey, Peter Bird, and Yuehua Zeng.

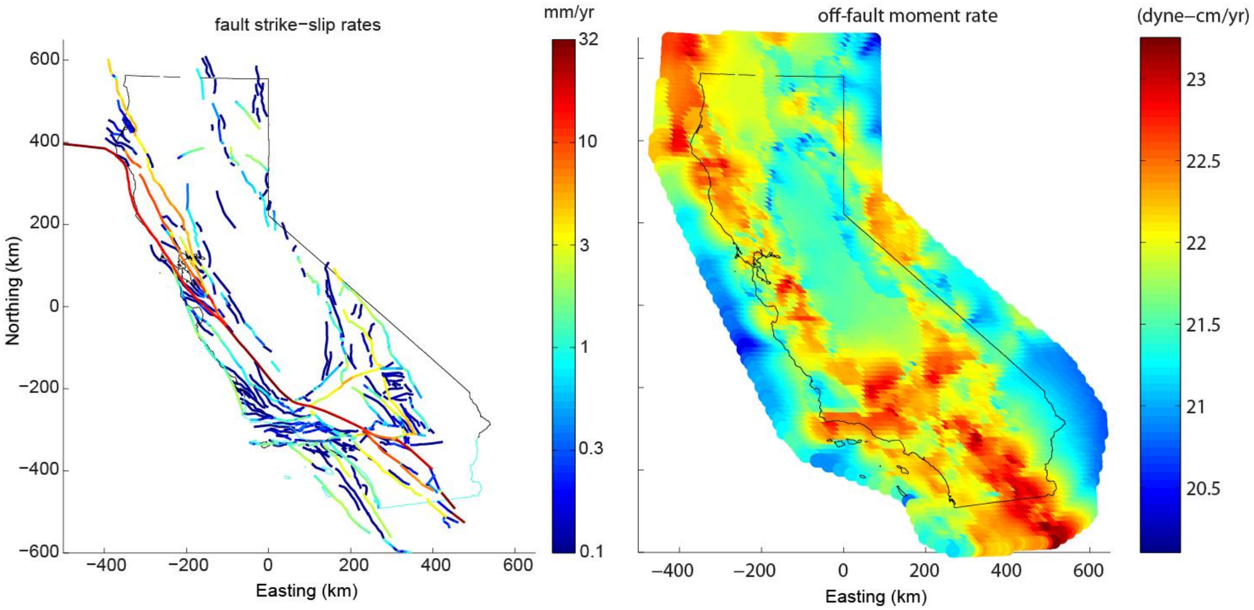

Figure S1. Kinematically-consistent average of five block model estimates of strike-slip rates and off-fault moment rates in California. This is one of four new GPS-derived deformation models for UCERF3.

Overview and objectives

UCERF2 slip-rates were assigned based on an expert-opinion evaluation of available data (mostly geologic and geodetic), together with summations across various transects to make sure the total plate tectonic rate was matched. In UCERF3, fault slip rates and off-fault strain rates estimated from inversions of GPS-derived velocities and geologic slip rates with kinematic models are largely replacing the expert opinion rates. This SCEC grant funded my effort to develop deformation models for UCERF3 and coordinate the efforts of other deformation modelers.

For UCERF3, a "deformation model" refers to the fault slip rates and off-fault strain rates. This is a somewhat confusing terminology because various kinematic models (which also might be called deformation models) and inversion schemes are used to construct the various UCEF3 Deformation Models. There are five new Deformation Models for UCERF3. Four of the models are derived from inversions of GPS and geologic data with kinematic models. The fifth deformation model is derived from geologic data only and does not formally integrate GPS data. This geologic-only model is not discussed further in this report.

In this report I briefly describe the four deformation models and the kinematic models and inversions used to derive these models.

Data

All kinematic models were constrained by a UCERF3-consensus GPS velocity field constructed by Thomas Herring (T. Herring, personal communication). The velocity field was generated by combining velocity fields submitted by 10 GPS analysis groups.

Geologic slip rates at points on faults were used as data to constrain all of the kinematic inversions. The geologic slip rates are taken from the UCERF3 compilation by Dawson and Weldon (2012, in prep). This is a compilation of slip rate estimates from the published literature along with an evaluation of the quality of the estimate.

Surface creep rates compiled for UCERF 2 (Wisley et al., 2008, Appendix P) were adopted to constrain shallow fault creep rates.

Description of Kinematic Models

This section gives an overview of each of the models and inversions. The models are categorized as either a block model or a fault-based (non-block) model. NeoKinema and the Zeng models are fault-based models.

NeoKinema

The kinematic finite-element code NeoKinema.f90 has been tested in a number of previous modeling studies, including *Bird & Liu* [2007], *Liu & Bird* [2008], *Rucker* [2008, 2009], *Bird* [2009], and *Howe & Bird* [2010]. This algorithm merges geologic offset rates, geodetic velocities, and principal stress directions to estimate the long-term velocity field at the top of the crust.

Zeng buried dislocation model

This method is described in a submitted manuscript by Zeng and Shen (2012). The block boundaries are represented with buried dislocations in a homogeneous elastic halfspace. Each fault segment slips at a solved-for slip rate beneath a locking depth except at a few fault segments where shallow creep is allowed. Slip vector continuity at fault nodes or intersections is imposed to regulate slip variability and to simulate block-like motion.

Elastic Block Models

There are two different elastic block models among the UCERF3 Deformation Models. The “Average Block Model” is a kinematically-consistent average of five different block kinematic models. The “Geologic Block Model” is an elastic block model with block-boundary slip rates bounded by the geologic slip rates. All of these block models are constrained by the same GPS and geologic data and use the same block-boundary geometry (Figure 1). The methodologies, however, are different for each of the block models.

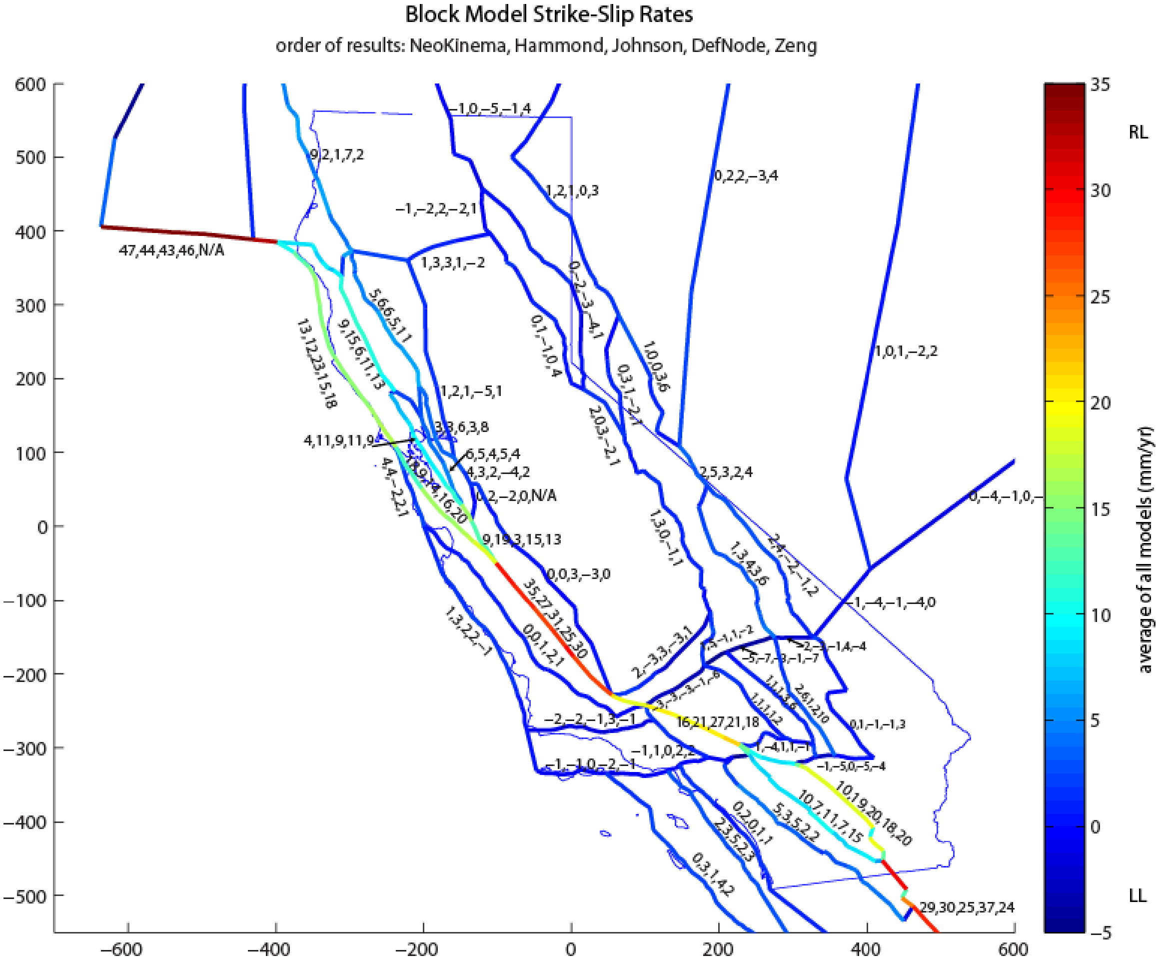

Figure 1. Comparison of all five block model estimates of strike-slip rates on block boundaries.

Averaged Block Model

The “Average Block Model” for UCERF3 is a kinematically-consistent average of five different kinematic block models. All five of these block models adopted the same GPS and geologic data and the same block-boundary geometry (Figure 1). The five block models include implementations of the Zeng model and NeoKinema using the block geometry and three traditional elastic block models:

DefNode (Rob McCaffrey, Portland State, formerly RPI; McCaffrey, 2002)

Hammond Block Model (Bill Hammond, University of Nevada, Reno; Hammond and Thatcher, 2007).

Johnson elastic quasi-block model (Kaj Johnson, Indiana University; Johnson and Fukuda, 2010)

The strike-slip rates from the five block models are summarized in Figure 1. Each of the models (except Zeng) include parameterized block strain rates that are not shown here for brevity.

We combine the results of these five block models into a single average model, called the "Averaged Block Model". This averaging is done in a kinematically consistent way by using the model slip rate estimates from all five inversions as 'data' in a unified block model inversion. The block model used for this averaging inversion is a modified version of the Johnson quasi-block model formulation. The long-term velocity field includes a contribution from rigid body motion, and spatially variable strain rates. Because these two contributions to the velocity field introduce fault-normal velocity discontinuities across vertical faults, and because UCERF3 does not allow this component of motion on faults, we distribute this discontinuity into long-term distributed off-fault strain by cancelling the velocity discontinuity above the locking depth with opening mode dislocations. Also, because some of the block boundaries do not have corresponding UCERF3 fault traces (there are places where discontinuous UCERF3 fault traces were connected to form contiguous block boundaries), we distribute the modeled slip on these phantom fault segments into permanent off-fault block strain by canceling the fault-parallel slip rate above the locking depth using elastic dislocations.

The final step in the block modeling is to compute slip rates on faults that are not on block boundaries. This achieved by integrating the long-term block strain rates across the smaller faults. We do this by taking half of the strain within a 20-km swath (10 km on each side) along a fault and integrating to compute the fault-parallel and fault-normal velocity across the fault, which we consider to be the fault slip rate. Half of the strain remains as off-fault strain.

Geologic Block Model (bounded block model)

The final deformation model uses the same methodology as the Averaged Block Model described previously, but we do not use slip rate constraints from other block models, but instead we bound the slip rates on block boundaries by geologic rates. The geologic bounds on slip rates for this inversion are taken from a compilation put together by Tim Dawson and Ray Weldon. The bounds are extrapolated from ranges of slip rates determined at individual geologic sites to entire fault sections. Some faults are assigned slip rate bounds based on the USGS slip rate category designation. We solve for the fault slip rates and block strain rates using a bounded least squares solver in Matlab (lsqlin).

Summary of Model Slip Rates

We show some plots comparing model slip rates along the major California faults in Figure 2. A notable feature of the model slip rates in these plots is that the model rates tend to track each other. Although the models do not predict the same rates for all the faults, the model rates tend to have the same along-strike gradients. There are some notable discrepancies between the model rates and the geologic bounds, especially on the SAF. The model rates are systematically lower or at the low end of the geologic bounds along the entire SAF, except for the southernmost SAF, the Coachella segment. Model rates agree well with geologic bounds for the San Jacinto Fault, The Maacama-Hayward system, the Hosgri-San Clemente system, and the ECSZ.

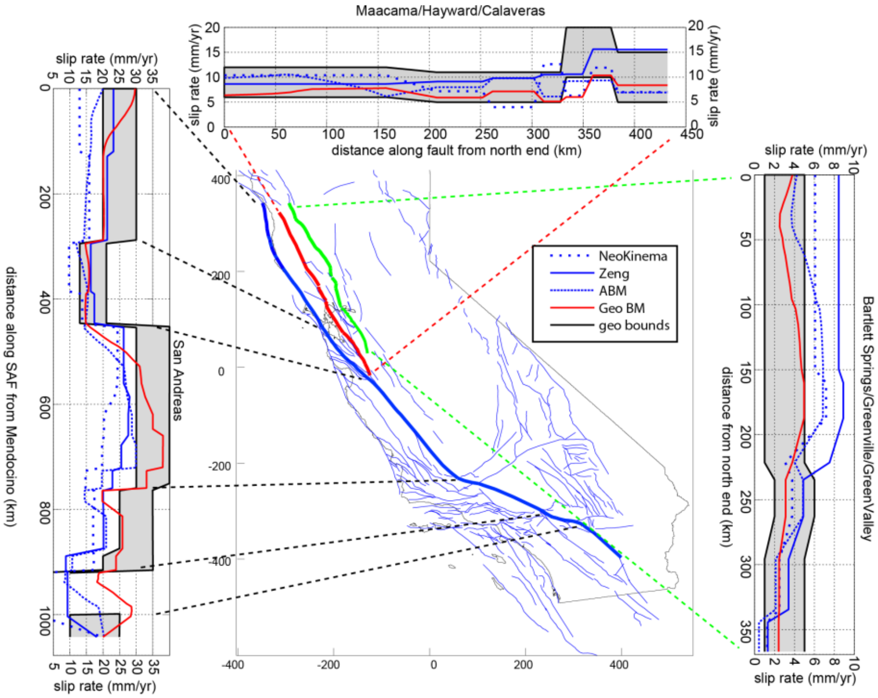

Figure 2a. Comparison of model slip rates and geologic bounds on some high slip rate faults in California. ABM is "Averaged Block Model". Geo BM is "Geologic Block Model" which is the bounded block inversion. And, geo bounds is the geologic upper and lower bounds.

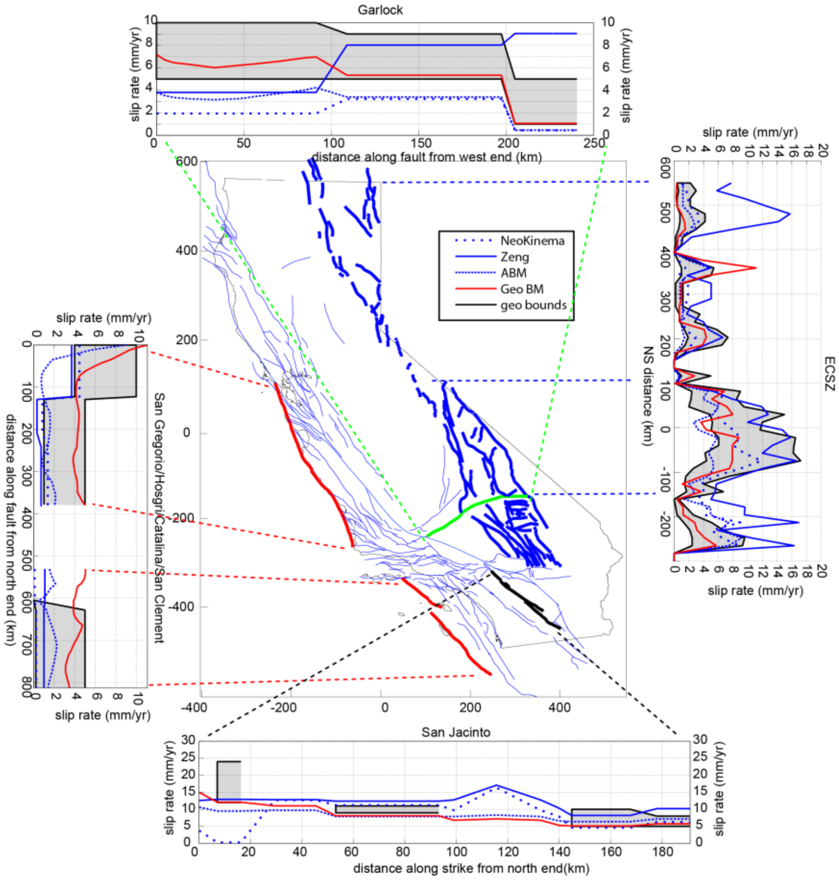

Figure 2b. Comparison of model slip rates and geologic bounds on some high slip rate faults in California. ABM is "Averaged Block Model". Geo BM is "Geologic Block Model" which is the bounded block inversion. And, geo bounds is the geologic upper and lower bounds.

Off-fault Strain Rates

There is not enough space in this report to show computed off-fault strain rates for all models. In Figure 3 we show the off-fault strain rates for the Averaged Block Model. Qualitatively, the strain rate pattern and magnitudes are similar for all four deformation models. The strain rates are converted to gridded moment rates (Figure 3, right) using a formula proposed by Savage and Simpson (1997): Mo = 2*mu*H*A*max(|E1|,|E2|,|E1+E2|), where H is seismogenic thickness (11 km in this case), A is area of 0.1x0.1 degree cell, and E1,E2 are principal horizontal strain rates in that cell.

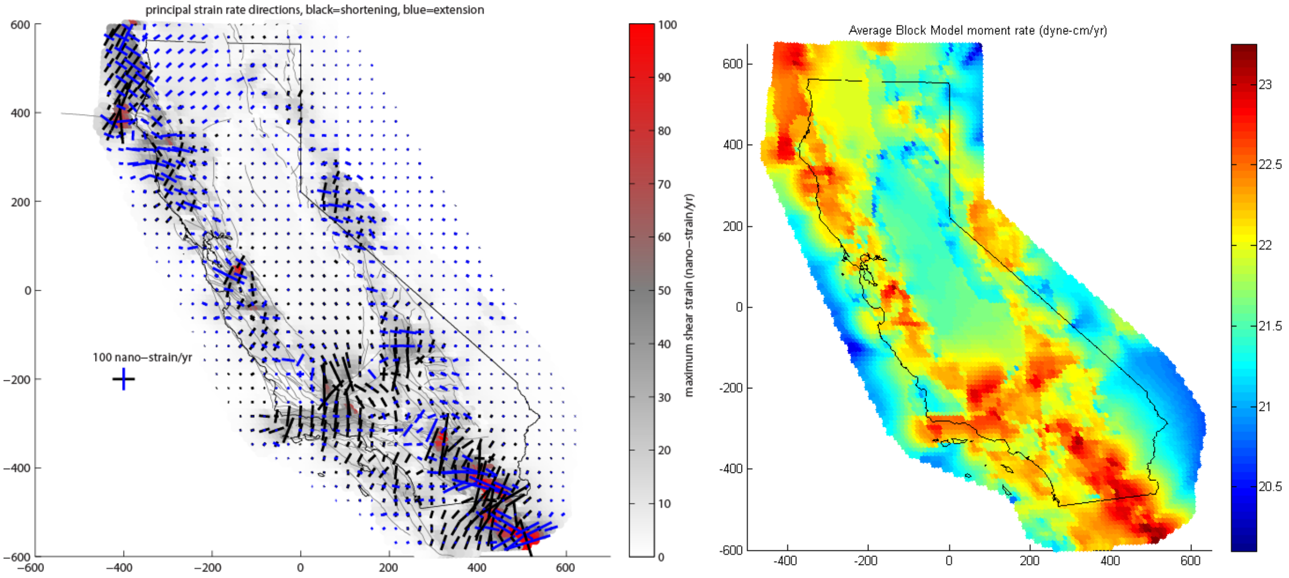

Figure 3. Left. ABM prinicipal strain rates. Color scale shows maximum shear strain rates in nano-strain/year. Axes show principal directions and magnitudes. Black is shortening, blue is extension. Right. Gridded moment rates computed from strain rates on left.

References

Bird, P. [2009] Long-term fault slip rates, distributed deformation rates, and forecast of seismicity in the western United States from joint fitting of community geologic, geodetic, and stress direction data sets, *J. Geophys. Res., 114*(B11), B11403, doi:10.1029/2009JB006317

Hammond, W.C. and W. Thatcher, 2007, Crustal Deformation across the Sierra Nevada, Northern Walker Lane, Basin and Range transition, western United States measured with GPS, 2000-2004, *J. Geophys. Res*., *112*, B05411, doi:10.1029/2006JB004625.

Johnson, K. M., and J. Fukuda (2010), New methods for estimating the spatial distribution of locked asperities and stress-driven interseismic creep on faults with application to the San Francisco Bay Area, California, J. Geophys. Res., 115, B12408, doi:10.1029/2010JB007703

McCaffrey, R., 2002. Crustal Block Rotations and Plate Coupling, in Plate Boundary Zones,Geodynamics Series 30, S. Stein and J. Freymueller, editors, 101-122, AGU.

McCaffrey, R. (2005), Block kinematics of the Pacific–North America plate boundary in the southwestern United States from inversion of GPS, seismological, and geologic data, J. Geophys. Res., 110, B07401, doi:10.1029/2004JB003307.

Savage, J.C., and R.W. Simpson, 1997, *Surface strain accumulation and the seismic moment tensor,* Bulletin of the Seismological Society of America, *v. 87 no. 5, 1345-1353.*

Wisely, B.A., Schmidt, D.A., and Weldon, R.J, II,. 2008, Compilation of surface creep on California faults and comparison of WGCEP 2007 deformation model to Pacific-North American Plate motion, *Appendix P in* The Uniform California Earthquake Rupture Forecast, version 2 (UCERF 2): U.S. Geological Survey Open-File Report 2007-1437P and California Geological Survey Special Report 203P, 43 p. [http://pubs.usgs.gov/of/2007/1437/p/].

Zeng, Y. and Z.-K. Shen (2012). Fault Network Modeling of Crustal Deformation in California Constrained Using GPS and Geologic Observations, submitted to TECTONOPHYSICS.