# SCEC Annual Report, 2015
# Using Mechanical Models to Test Ventura Special Fault Study Area Alternative Fault Models

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## Summary

This current project is the logical extension of several previous SCEC-funded projects relating to neotectonics of the greater Transverse Ranges region, CA. In the past year, our efforts have focused on updating the fault model to CFM version 5.0, which required re-meshing of the entire model and adding numerous additional faults. Furthermore, thanks to additional computing resources, we are now able to model the entire Transverse ranges (Los Angeles and Ventura regions) in a single model. Our previous model of the Ventura region [*Marshall et al.*, 2013], contained approximately 8,000 triangular elements and 44 faults, while the new model contains 70 faults and nearly 20,000 elements. Thus, we are now able to provide a more complete simulation of the regional fault network.

To better constrain fault slip rates and patterns of interseismic deformation in the western Transverse Ranges of southern California, we have processed and analyzed GPS and InSAR data. Anthropogenic motions were detected in several localized zones (using InSAR) but do not significantly affect the vast majority of continuous GPS site locations. GPS measures contraction rates across the Ventura basin of ~7 mm/yr. oriented west-northwest with rates decreasing to the west and east. The Santa Barbara channel is accommodating ~6.5 mm/yr. in the east and ~2.5 mm/yr. in the western portions of N/S contraction. Inversion of horizontal GPS velocities highlights a zone of localized fast contraction rates following the Ventura basin that does not clearly correspond to any fault present in the CFM version 4.0; however, the updated CFM v5.0 model contains an updated representation of the Ventura-Pitas Point fault system that does follow this trend. The main geodetic conclusion is that while there is localized fast contraction across the Ventura basin, there is virtually no vertical deformation.

Using a mechanical model driven by geodetically-calculated strain rates, we have determined that there are no significant discrepancies between regional short term slip rates captured by geodesy and longer term slip rates measured by geology. Mechanical models reproduce the first-order interseismic velocity and strain rate patterns, but fail to reproduce strongly localized contraction in the Ventura basin. This inadequacy is likely due a combination of the inadequate homogeneous elastic properties of the model and/or an incorrect CFM 4.0 fault geometry. Existing two-dimensional models match horizontal rates, but predict significant vertical gradients that are not observed in the GPS data. Mechanical models predict zones of fast contraction in the Santa Barbara channel and offshore near Malibu, suggesting that offshore faults represent a significant seismic hazard to the region. Because many active faults throughout the region may produce little to no interseismic deformation, accurate seismic hazard assessment of the Ventura region is likely to be challenging.

## 1. Introduction

The recognition of the greater Ventura region as a Special Fault Study Area (SFSA) has largely been driven by recent work suggesting a significantly greater seismic hazard than was previously recognized for the region. For example, large coseismic offsets have been identified in the geologic record near the Ventura fault and the associated Ventura Avenue anticline, implying a local source for ~M8 earthquakes in the past [*Hubbard et al.*, 2014]. Such large magnitude events are difficult to reconcile with the previous SCEC Community Fault Model (CFM) v4.0 discontinuous fault geometry. Recent work by *Hubbard et al.* [2014] provides evidence for a previously unrecognized ~80 km long and continuous fault surface extending from the San Cayetano fault through the Ventura fault and ~30 km offshore. Because of different subsurface interpretations of the fault geometry at depth [e.g. *Hubbard et al.*, 2014; *Kammerling et al.*, 2003], two potential Ventura fault geometries were tested. Both models share the same surface trace but differ in that the *Hubbard et al.* [2014] or "Ramp" model contains a nearly horizontal ramp section at depth. The *Kammerling et al.* [2003] representation (or "No Ramp" model) utilizes a constant dip angle and merges with the Red Mountain fault at a depth of 10 km in the offshore. We have updated the entire model to contain all of the CFM v5.0 faults and have merged in all of the faults in the Los Angeles and Ventura regions into a single model. Creating two versions of the Ventura fault required modifications to ~10 faults since several faults are thought to be truncated by this or other structures. In the end, we find that the constant dip, or "No Ramp" model, fits the geologic slip rate data best. A comparison of interseismic deformation patterns may be able to help distinguish between the two Ventura fault geometries, although given the deep locking depth, the interseismic deformation patterns are likely to be rather diffuse.

## 2. Fault Meshing Efforts

In the fall of 2014, CFM v5.0 was released. This was a significant release with numerous additional faults being added and significant changes to many existing fault surfaces. To make our mechanical model comparisons consistent with the current state of knowledge, we have put in considerable effort into updating the model mesh to CFM v5.0. This required us to re-mesh all of the faults in the model, but while doing so, we have created a significantly more detailed mesh than our past efforts. Thanks to 64-bit computing and additional computational resources, we are now able to model nearly all of the faults west of the San Andreas fault in a single mechanical model. We hope that this work will lay the grounds for a future CFM-wide mechanical model of southern California, a task that in the past was not computationally feasible.

Our efforts thus far have mainly involved updating the Ventura regional fault mesh to CFM v5.0, and testing the mesh for numerical stability. There are remain a few numerical issues with the mesh, but these should be sorted out by summer 2015. Because of the fault network complexity and the significant changes proposed by the  geometry, this task has proven rather time-consuming, as was expected. While detailed 3D surfaces of the updated faults were provided by the SFSA group, these surfaces are not refined/optimized to work in a computational model. The faults must be down-sampled to a resolution that results in reasonable computation time. For example, the model of the entire western Transverse Ranges of *Marshall et al.* [2013], contained approximately 8,000 elements, but the fault surfaces provided by the SFSA group contain > 8,000 elements on the Ventura fault, alone. Furthermore, intersections between faults do not occur exactly at element edges, which is numerically intractable. We have also updated the Oak Ridge fault onshore and offshore to form a more kinematically compatible continuous fault surface, which is now included in the CFM v5.0 as the preferred Oak Ridge fault surface. To date, our remeshing efforts have altered the geometry on approximately 70 faults and the new model contains a total of ~18,000 triangular elements, up from 40 faults and ~8,000 elements in our CFM v4.0 models.

We have also began providing meshes to other researchers by posting our modeler-ready mesh on PI Marshall's webpage at http://www.appstate.edu/~marshallst/research/3D_faults.html. Researchers at the University of California Riverside are using these meshes for testing dynamic rupture codes and Indiana University researchers are using the meshes for inverse geodetic models. To facilitate sharing, we have created conversion scripts that convert the gocad fault mesh files into facet and MATLAB formats. In the mesh packages, we have also provided some basic tools for visualizing fault meshes in MATLAB. This way groups wishing to model the region do not have to invest the significant time required to make a stable mesh. It is our hope that the resultant meshes will be used by many other modeling groups within the SCEC community. The CFM v5.0 meshes will be posted once the meshes are numerically stable.

## 3. Preliminary Results

Preliminary models predict that the average slip rates of many faults in the region are not significantly altered by the inclusion of the updated Ventura-Pitas Point fault system (Figure 1). For example, the overall average reverse slip rate of the Ventura fault only changes from 2.3 mm/yr in the CFM v4.0 model to 2.6 - 3.5 mm/yr in CFM v5.0 models with the significantly larger and through-going Ventura fault. This result is potentially misleading because the slip on both Ventura fault representations is highly variable (Figure 2). Analysis of the full three-dimensional model-predicted slip distributions indicates that while the maximum slip rates at the surface of the Earth are approximately 3-4 mm/yr in the Ramp model and 5-6 mm/yr in the No Ramp model, more than 6 mm/yr of slip may occur at depth in both representations (Figure 2). Slower near surface slip on the Ramp model occurs because the flat ramp section of the fault makes the fault surface mechanically inefficient at accommodating slip and slows reverse slip rates dramatically locally in the flat ramp section (Figure 2). The net result is that the average slip rates of the Ramp model fault appear only marginally faster than the CFM4.0 Ventura fault (Figure 2A) while the No Ramp model slips faster. Thus a key preliminary result is that the No Ramp model appears to fit the geologic slip rate data while the Ramp model does not.

In mechanical models, faults interact with their neighbors. Therefore, even if a certain fault geometry does not change in the Ramp versus the No Ramp models, the slip rates may nonetheless change. For example, the Oak Ridge fault mesh is the same in both models, but in the Ramp model, the Oak Ridge fault slips faster (Figure 3). This is because less slip is taken up by the Ventura Ramp fault, so the Oak Ridge fault can accommodate additional slip compared to the No Ramp model. Thus, changing a single fault's geometry can change the slip rates and distributions on all nearby faults. This implies that if an incorrect fault geometry is included in a mechanical model, that slip rates on all faults may be affected.

Along with the faster slip rates of the CFM v5.0 Ventura fault representations, the updated Ventura fault geometry represents a dramatic change in potential rupture area for the regional fault system, which implies a much greater seismic potential compared to the CFM v4.0 representation. The Ramp model adds the most surface area to the regional system because the No Ramp system merges with the Red Mountain fault in the offshore.

## 4. Intellectual Merit

This project contributes to the understanding of crustal deformation in southern California by using a novel three-dimensional mechanical modeling approach to simulate both interseismic and long-term deformation. A primary goal of the Ventura Special Fault Study Area (SFSA) is to determine the most likely fault structure for the region, and this work contributes to this effort by directly testing an updated fault system geometry for the greater Ventura region using a physics-based method. The final version of this work will directly test whether any geologic/geodetic rate discrepancies exist in the western Transverse Ranges, and if the geologic slip rates are more compatible with the Ramp or No Ramp fault representations. Our approach offers a quantitative assessment of the ability of the CFM to reproduce variations in slip and interseismic deformation in southern California. Furthermore, a product of this study will be a significantly updated fault model, which will be posted on PI Marshall's website and provided for inclusion in a future release of the SCEC CFM.

## 5. Broader Impacts

This work has fostered collaborations between researchers at the Jet Propulsion Laboratory, the University of California Riverside, Harvard University, and Appalachian State University. At Appalachian State University, PI Marshall has now begun training undergraduate students in GPS processing, dislocation modeling, and stress/strain theory. Marshall recently trained a Ph.D. student at the University of Massachusetts on GPS processing, and is currently working with two undergraduate geology students at Appalachian State University on fault modeling and geodesy. One student is writing a dislocation modeling code and modeling the CFM in the Los Angeles region, while the other is doing GPS time series processing to determine seasonal aquifer motions. These efforts are aimed to produce future researchers that are better prepared for graduate school and the research community. Also, by training undergraduate students, interest and understanding of earthquake science is promoted. The results of this work will have an impact on society by more accurately characterizing the slip rates of faults, which in turn leads to improved seismic hazard estimates.

## 6. References


Hubbard, J., J. H. Shaw, J. F. Dolan, T. L. Pratt, L. McAuliffe, and T. K. Rockwell (2014), Structure and seismic hazard of the Ventura Avenue anticline and Ventura fault, California: Prospect for large, multisegment ruptures in the Western Transverse Ranges, *Bulletin of the Seismological Society of America*, *104*(3), 1070-1087.

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Marshall, S. T., G. J. Funning, and S. E. Owen (2013), Fault slip rates and interseismic deformation in the western Transverse Ranges, CA, *Journal of Geophysical Research*, *118*, 4511-4534.

## 7. Peer-Reviewed Publications Related to this Work *

*bold indicates student author


Marshall, S. T., G. J. Funning, and S. E. Owen 2013, Fault slip rates and interseismic deformation in the western Transverse Ranges, CA, *Journal of Geophysical Research*, 118, 4511-4534. doi: 10.1002/jgrb.50312.

**Herbert, J.W.,** Cooke, M.L., Marshall, S.T. 2014. Influence of fault connectivity on slip rates in southern California: Potential impact on discrepancies between geodetic derived and geologic slip rates. *Journal of Geophysical Research*, 119, 2342-2361, doi:10.1002/2013JB010472.


## 8. Conference Presentations Related to This Work*

*bold indicates student author


Marshall, S.T., **Phillips, J.R.,** Funning, G.J., Owen, S.E. 2014. Fast Horizontal Contraction without Vertical Strain: Puzzling Interseismic Geodetic Measurements in the Ventura Basin, CA. *Fall Meeting of the American Geophysical Union, San Francisco, CA.*

**Phillips, J.R.,** Marshall, S.T., Funning, G.J. 2014. InSAR Measurements of Non-Tectonic Deformation Patterns in the Western Transverse Ranges, CA. *Fall Meeting of the American Geophysical Union, San Francisco, CA.*

**Harper, H.A.,** Marshall, S.T. 2014. The Distribution of Fault Slip Rates and Oblique Slip Patterns in the Greater Los Angeles, CA Region. *Fall Meeting of the American Geophysical Union, San Francisco, CA.*

Marshall, S.T., Funning, G.J., Owen, S.E. 2013. Fault Slip Rates and Interseismic Deformation in the Ventura Basin Region, CA. *Fall Meeting of the Southern California Earthquake Center, Palm Springs, CA.*

Marshall, S.T., Funning, G. J., Owen, S.E. 2012. Spatial and Temporal Variations in Strain Rates in the Western Transverse Ranges, California. *Fall Meeting of the American Geophysical Union, San Francisco, CA.*

**Herbert, J.M.,** Cooke, M.L., Marshall, S.T. 2012. The Role of Fault Geometry on Geologic and Interseismic Deformation along the Southern SAF and ECSZ. *Fall Meeting of the Southern California Earthquake Center, Palm Springs, CA.*

Cooke, M.L., Resor, P.G., Marshall, S.T. 2012. Are trenches and GPS stations observing representative fault slip rates? *Structural Geology and Tectonics Forum, Williamstown, MA.*

Marshall, S.T., Funning, G.J., Owen, S.E. 2011 Deformation Rates in the Western Transverse Ranges, California from the San Andreas to the Santa Barbara Channel measured with GPS and Persistent Scatterer InSAR. *Southern California Earthquake Center Annual Meeting, Palm Springs, CA.*

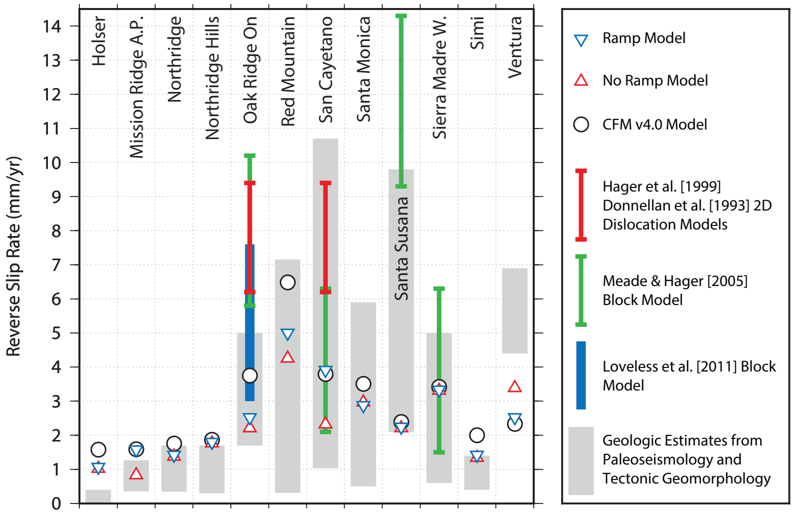


**Figure 1**: Area-weighted average reverse slip rates from mechanical models and comparisons to other studies. Note that the model-calculated avg slip rates generally match past studies. Slip appears too slow on the Ventura fault, but the geologic estimate of slip was made at a location that the model predicts to be slipping much faster than the average slip rate of this complex faul surface (see Figure 2).

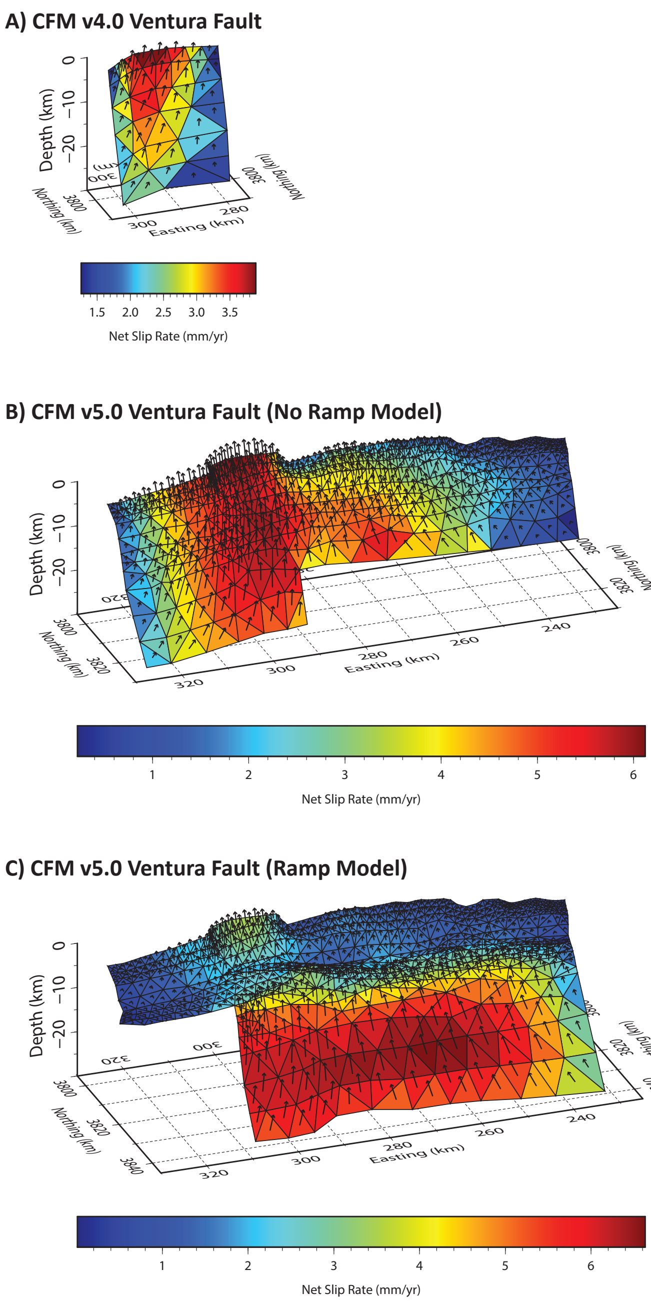


**Figure 2**: Mechanical model-predicted three dimensional slip distributions on the Ventura fault. A) The CFM v4.0 Ventura fault. B) The CFM v5.0 no ramp model. C) The CFM v5.0 ramp model.

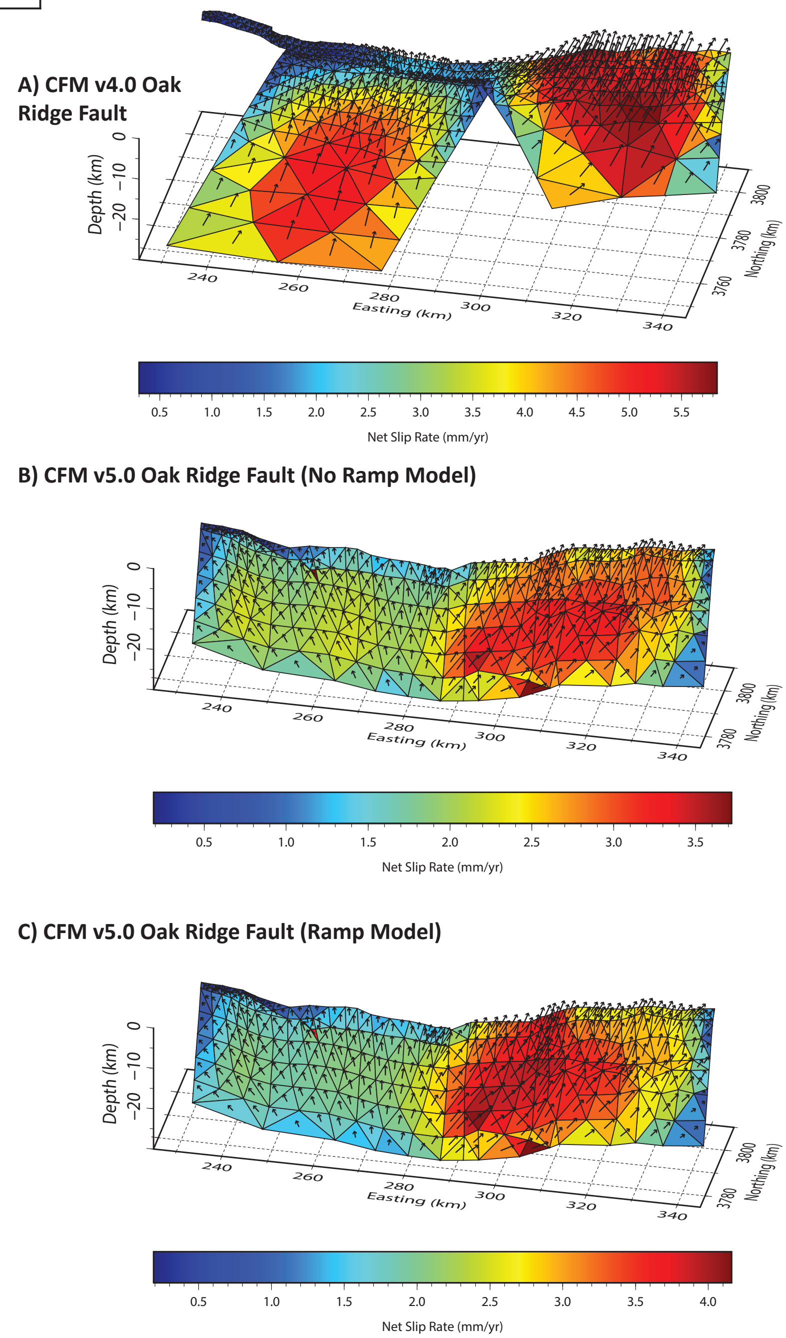


**Figure 3**: Mechanical model-predicted three dimensional slip distributions on the Oak Ridge fault. A) The CFM v4.0 Oak Ridge fault which had a differing dip onshore and offshore. B-C) The CFM v5.0 version has a consistent dip onshore and offshore. This fault surface is a product of this work and is now the preferred fault surface in CFM v5.0.