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Using Mechanical Models to Test Community Fault Model Updates to the Western Transverse Ranges Region, CA: Application to the Ventura Special Fault Study Area

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Summary

The current project is the logical extension of several previous SCEC-funded projects relating to neotectonics of the greater Transverse Ranges region, CA. Below, we describe our overall cumulative results to date. Given the late start of the most recent project due to the federal government sequester (funds arrived in November), the current project's end date has been extended for an additional year. Later in this report, we highlight our preliminary results, but in this summary section we focus on our cumulative results to date.

To better constrain fault slip rates and patterns of interseismic deformation in the western Transverse Ranges of southern California, we have analyzed both GPS and InSAR data and created three-dimensional mechanical and kinematic models of active faulting. Anthropogenic motions were detected in several localized zones 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, nor is there any fault in the current CFM that has sufficient surface area to create such a widespread zone of fast contraction. The current CFM geometry is therefore too disconnected to reproduce all aspects of the geodetic data. 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 [*Rockwell*, in review]. Such large magnitude events are difficult to reconcile with the current discontinuous fault geometry present in the SCEC Community Fault Model (CFM) for the Ventura region (Figure 1). Recent work by *Hubbard et al.* [in review] provides evidence for a previously unrecognized ~80 km long and nearly continuous fault surface (Figure 1) extending from the eastern tip of the San Cayetano fault through the Ventura fault and to ~30 km offshore. Adding this previously unrecognized fault to the CFM for the region requires changes of varying degrees to nearly all faults in the region (n > 15).

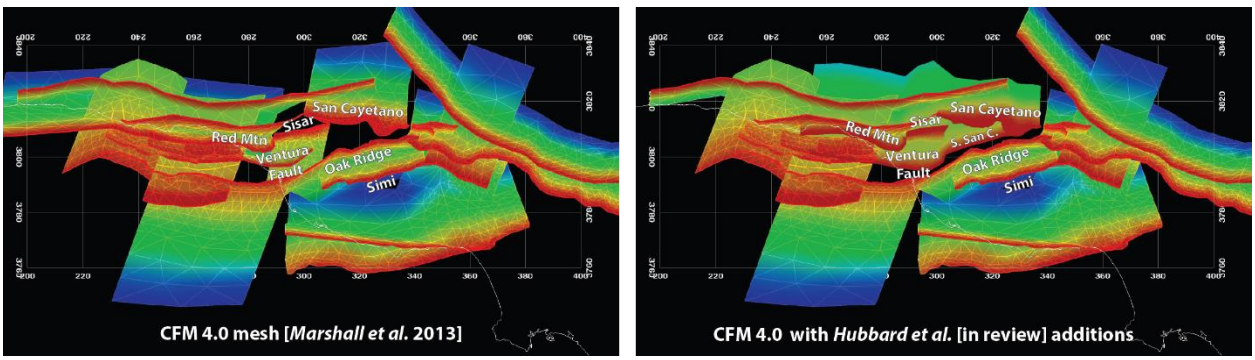

Figure 1: Map view comparison of the current CFM 4.0 fault surface geometry from *Marshall et al.* [2013] for the greater western Transverse Ranges region (left) and the *Hubbard et al.* [in review] updated geometry (right). The fault surfaces are colored by depth with red indicating shallow and blue indicating deep depths. Axes are in UTM km. Note that the *Hubbard et al.* [in review] geometry reflects the recognition of a large continuous fault surface from the eastern tip of the San Cayetano fault through the Ventura fault and into the offshore region may represent a significant and previously unrecognized seismic hazard. This updated Ventura fault intersects several existing CFM surfaces, both on and offshore, therefore developing a numerically stable mesh has proven time consuming, as was expected.

2. Fault Meshing Efforts

Our efforts thus far have mainly involved updating the Ventura regional fault mesh, and testing the mesh for numerical stability. Because of the fault network complexity and the significant changes proposed by the *Hubbard et al.* [in review] 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. So, far, we have meshed the Ventura-Pitas Point fault, and corrected all of the numerous fault intersections at depth with

this structure. We have also updated the Oak Ridge fault onshore and offshore to form a more kinematically compatible continuous fault surface. We have also added in the Lion fault, and merged the San Cayetano fault with the south San Cayetano fault. The offshore Red Mountain fault has also been updated to better follow the sea floor trace. To date, our remeshing efforts have altered the geometry on approximately 20 faults. We have also began providing meshes to researchers at the University of California Riverside for testing in dynamic rupture codes. To do so, we have created a conversion script that converts gocad files into facet format. This way both groups will be testing the same mesh. It is our hope that the resultant meshes will be used by many other modeling groups within the SCEC community.

3. Preliminary Results

Our preliminary models predict that the overall average slip rates of many faults in the region are not significantly altered by the inclusion of the Ventura-Pitas Point fault system (Figure 2). For example, the overall average reverse slip rate of the Ventura fault only changes from 2.3 mm/yr in the CFM4.0 model to 2.7 mm/yr in the model with the significantly larger and through-going Ventura fault (Figure 2A). This result is potentially misleading because the slip on the *Hubbard et al.* [in review], is highly variable, and in some locations, slip approaches 7 mm/yr according to model predictions. At the surface of the Earth, the model predicts a complex distribution of slip with maximum reverse slip rates being predicted near the coast along the Ventura fault (Figure 2B). It is noteworthy to mention that the model prediction of maximum slip at the surface of the Earth is near the sites of *Rockwell* [in review], which identified large coseismic uplifts in the geologic record. Model predictions also show the interplay between reverse slip and strike-slip along a bend in the surface trace of the Ventura fault (Figure 2B).

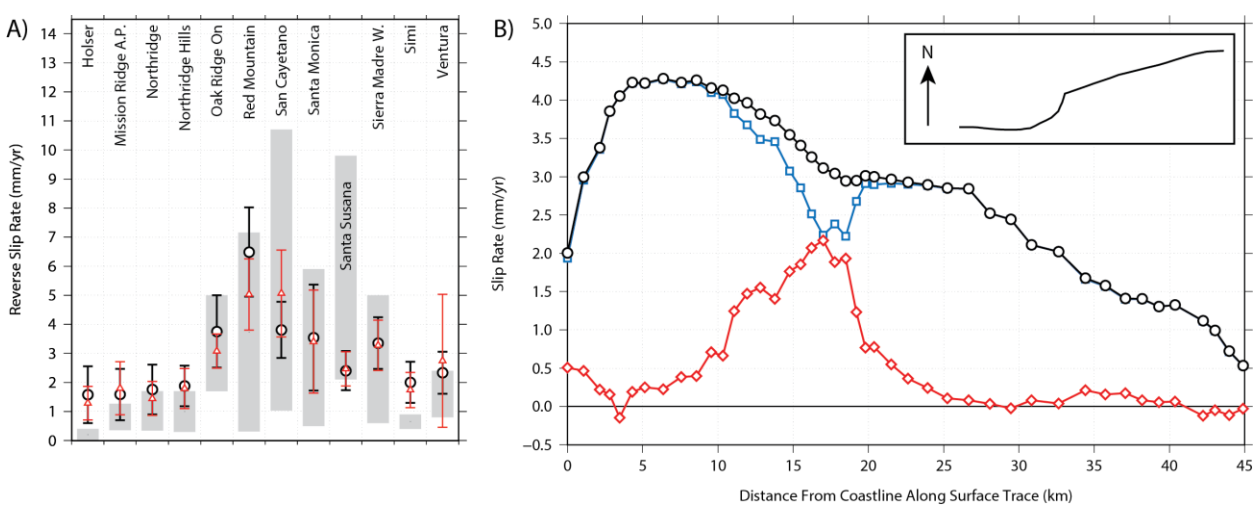

Figure 2. A) Area-weighted average reverse slip rates for faults in the Ventura region that have existing geologic slip rate estimates. The gray rectangles show geologic slip rate ranges, the black circles show CFM4.0 model results, and the red triangles show the updated model results that include the *Hubbard et al.* [*in review*] geometry. Error bars indicate the 1σ range on each 3D fault surface. B) Reverse slip (blue squares), strike-slip (red diamonds) and net slip rates (black circles) along the onshore portion of the surface trace (trace geometry shown in map view in inset rectangle at top right of figure) of the *Hubbard et al.* [*in review*] Ventura-Pitas Point-South San Cayetano fault geometry. Note that the maximum reverse and net slip rates are predicted near the coast.

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 4-4.5 mm/yr, more than 7 mm/yr of slip may occur at depth below the flat ramp section of the Ventura fault (Figure 3). Despite this, 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 3A). The net result is that the average slip rates of the *Hubbard et al.* [in review] Ventura fault appear only marginally faster than the CFM4.0 Ventura fault (Figure 2A). This is perhaps misleading because sections of the *Hubbard et al.* [in review] fault representation are predicted to slip much faster than this average value (Figure 3B). Furthermore, 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 CFM4.0 representation. The Ventura SFSA group has also proposed an alternative representation of the Ventura-Pitas Point fault that has nearly constant dip at depth. This fault surface should be tested/evaluated using similar methods to see which representation best fits the geologic slip rate data, as well as the interseismic geodetic data.

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. 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 old CFM4.0 fault geometry or the updated fault geometry of *Hubbard et al.* [in review]. Our modeling approach utilizes the CFM geometry and 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 included 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 is currently training a Ph.D. student at the University of Massachusetts on GPS processing, and working with two undergraduate geology students at Appalachian State University. One student is writing a dislocation modeling code, 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.

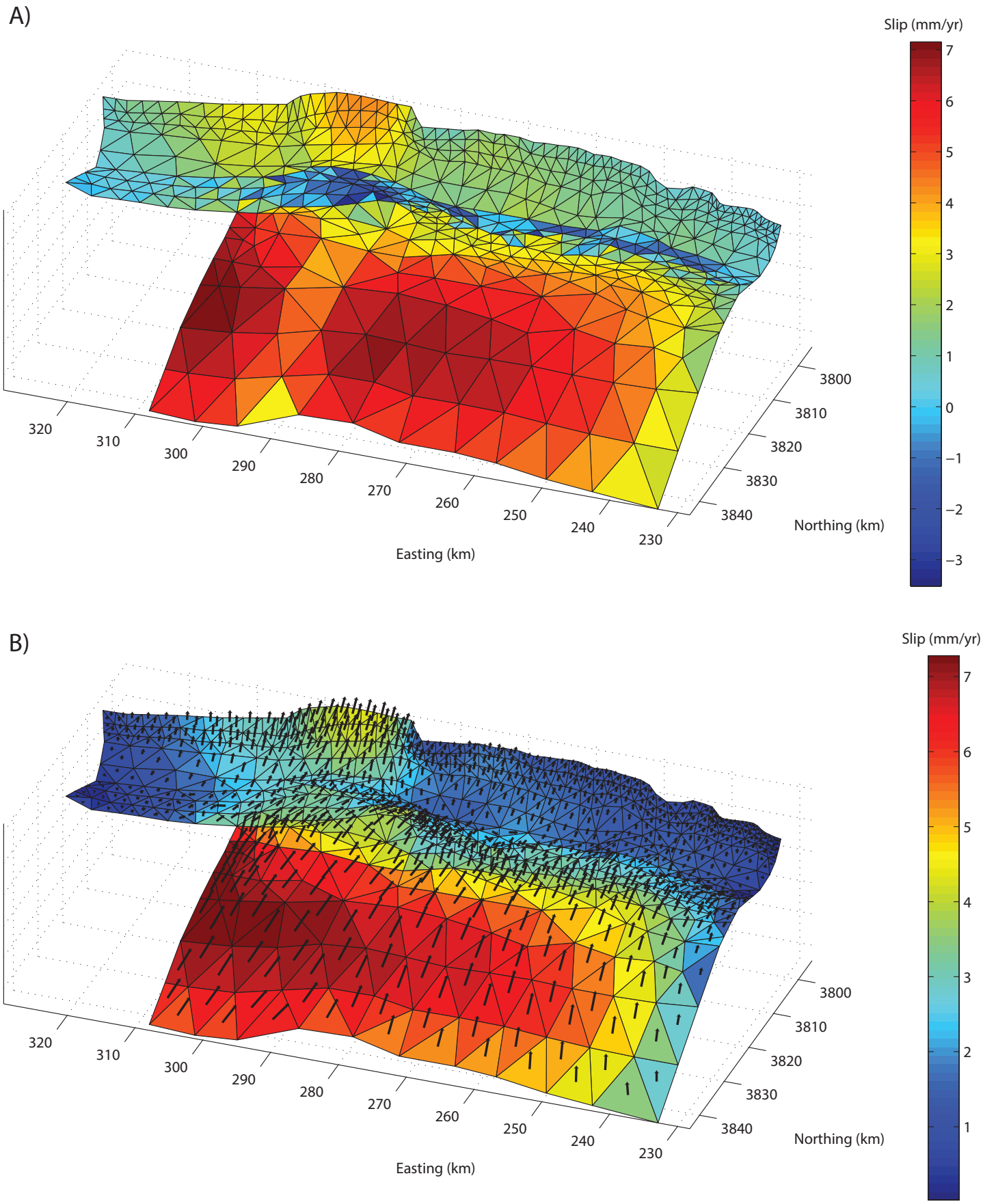

Figure 3. A) Reverse slip rates and B) net slip rates along the South San Cayetano-Ventura-Pitas Point fault system of Hubbard et al, [in review]. In B) the net slip vector is mapped onto the hanging wall of the fault. The view is oblique and to the southeast (refer to UTM axes). Note that the nearly horizontal ramp section causes slip rates to decrease dramatically locally. In the near surface, the fastest slip rates are near the Ventura Avenue anticline at the coastline near the city of Ventura. The apparent missing fault surface towards the left portion of the image is the San Cayetano fault, which is included in the models, but is not shown here.

6. 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. *accepted*. 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.

7. Conference Presentations Related to This Work*

*bold indicates student author

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.*

References

Hubbard, J., J. H. Shaw, J. F. Dolan, T. L. Pratt, L. McAuliffe, and T. K. Rockwell (in review), 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*.

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.

Rockwell, T. K. (in review), Great M8 Earthquakes in the Western Transverse Ranges of Southern California: Implications of large uplift events on the Ventura-Pitas Point thrust system, *Bulletin of the Seismological Society of America*.