High Resolution Geodetic Measurements of Deformation throughout the Ventura Special Fault Study Area Region

Report for SCEC Award #15079
Submitted March 14, 2016

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I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

In 2012, SCEC established the Ventura Special Fault Study Area (SFSA) largely based on recent work suggesting the potential for M7.5-8.0 earthquakes in the region [*Rockwell*, 2011; *Hubbard et al.*, 2014; *McAuliffe et al.*, 2015; *Rockwell et al.*, in review]. This project is a continuation of a multi-year SCEC funded project aimed at both modeling the faults of and processing/analyzing GPS and InSAR data for the greater Ventura region.

For the fault modeling component of this study, we have produced a refined three-dimensional model based on the SCEC CFM5.0 including two alternative geometries for the Ventura fault. Mechanical models of the regional faults show no significant geologic/geodetic slip rate discrepancies. Based on comparison of model results to geologic slip rates alone, we cannot distinguish between the flat ramp and constant dip fault representations of the Ventura fault. Both produce slip rates at the sites of measurement that are compatible with existing geologic data.

For the geodesy component of this study, we have increased our GPS velocities from 52 to 127 total sites throughout southern California. We have also processed InSAR data from the Envisat and ERS satellites and produced two dense persistent scatterer datasets for the region. The GPS and InSAR both show potential deformation north of the Ventura fault that may be consistent with interseismic deformation on a shallow dipping fault (similar to the ramp model). Our ongoing efforts involve improving the geodetic data quality and modeling these potential interseismic deformation patterns.

B. SCEC Annual Science Highlights

Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

1) Tectonic Geodesy
2) Unified Structural Representation (USR)
3) Stress and Deformation Through Time (SDOT)

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.

Figure 3. Persistent scatterer InSAR data from the Envisat satellite downsampled to 200 m spacing using a median filter. The largest deformation signals are near the northwestern end of the data where the ground is rapidly subsiding due to hydrocarbon extraction. The gradual increase in line of sight velocity from southwest to northeast is dominantly due to interseismic deformation on the San Andreas Fault. A zone of line of sight velocity increase is labeled with a dashed path that may be due to interseismic deformation associated with the Ventura fault, but this region has steep topography and is partly vegetated, so the InSAR data is noisy. This zone partly overlaps with a zone of uplift identified in the GPS data (Figure 1a).

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See *https://www.scec.org/research/priorities* for list of SCEC research priorities. *For example: 6a, 6b, 6c*

4a, 4b, 4c, 1a, 1b.

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

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 creating and directly testing an updated fault system geometry for the greater Ventura region using a physics-based method. Our approach offers a quantitative assessment of the ability of the CFM to reproduce variations in slip and interseismic deformation in southern California. Furthermore, the fault mesh produced in this study will be posted on PI Marshall's website and provided for inclusion in a future release of the SCEC CFM. Several other research groups have already been provided the mesh for use in their respective works.

While deformation related to the strike-slip faults in southern California are relatively well-studied, deformation due to reverse and/or oblique slip faulting is poorly understood. The geodetic component of this project has and will provide several high-resolution InSAR datasets for the relatively poorly studied western Transverse ranges region of southern California. This work will also provide a GPS velocity dataset that has the effects of the larger and faster San Andreas (and other) faults removed. This will facilitate future studies of the slower slipping (but still hazardous) faults in southern California, including the Los Angeles and Ventura basin regions.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

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 now routinely trains undergraduate students in GPS/InSAR 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 modeling the faults of the Los Angeles region using the CFM, while the other is processing GPS time series 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.

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at *http://www.scec.org/user/login* and select the Publications button to enter the SCEC Publications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance.

II. Technical Report

A. Project Objectives

In 2012, SCEC established the Ventura Special Fault Study Area (SFSA) largely based on recent work suggesting the potential for M7.5-8.0 earthquakes in the region [*Rockwell, 2011*; *Hubbard et al., 2014*; *McAuliffe et al., 2015*; *Rockwell et al., in review*]. For example, analysis of seismic reflection and borehole data support the presence of a large seismogenic reverse fault structure, the Ventura fault, which has an estimated slip rate of 4.4-6.9 mm/yr. [*Hubbard et al., 2014*; *McAuliffe et al., 2015*]. A reverse fault of this size and slip rate should be detectable with modern geodetic techniques; however, as discussed by *Marshall et al. [2013]*, continuous GPS data do not clearly delineate deformation associated with the Ventura fault. Accurate measurement of interseismic deformation across the Ventura fault requires further examination with a spatially denser data set.

Early geodetic horizontal strain rate measurements generally agree and show localized horizontal contraction in and around the Ventura basin [e.g. *Donnellan et al., 1993a*; *Donnellan et al., 1993b*; *Shen et al., 1996*; *Hager et al., 1999*]. More recently, *Marshall et al. [2013]* demonstrated that ongoing interseismic deformation associated with the reverse faults of the greater Ventura region should produce measurable uplift gradients given the regional fault geometries and slip rates. These uplift patterns were not clearly observed in the continuous Plate Boundary Observatory (PBO) GPS data in the Ventura basin region. It is likely that the spatial resolution of the continuous PBO GPS data, alone, is too diffuse (typically > 10 km spacing) to clearly and uniquely detect deformation related to the Ventura and other faults. Therefore, while the long-term geologic data are largely in agreement about the activity level and slip rates of the Ventura fault, past geodetic data do not clearly show any significant vertical strains associated with the known active reverse faults in the region.

The inability to clearly detect the Ventura fault using satellite geodetic techniques represents a fundamental shortcoming in our understanding of the seismic hazards of the Ventura fault and the Transverse Ranges in general. Solving these geodetic issues remains a priority for the Ventura SFSA. This project has sought to directly address the Ventura SFSA goal #3 and Specific tasks C-D in the current Ventura SFSA science plan. Here, we report on our results to date including our past related efforts of modeling the faults of the western Transverse ranges region. The overall objectives of this work are to:

1) Create a numerically-stable three-dimensional Boundary Element Method (BEM) fault mesh incorporating both SFSA candidate geometries for the greater Ventura region.
2) Use the updated fault mesh in three-dimensional mechanical models [e.g. *Marshall et al.*, 2009; 2013] to calculate the likely long term slip rates and slip distributions on the modeled surfaces.
3) Process and analyze InSAR data from the ERS and Envisat satellites for the region using a combination of the Persistent Scatterer and Small Baselines Method [*e.g. Hooper, 2008*].
4) Update and expand continuous GPS processing from the Plate Boundary Observatory and combine results with the crustal motion map of Shen et al. [*2011*] to yield a higher GPS station density.
5) Produce detailed quantitative images and analyses of the InSAR and GPS data along the entire onshore portion of the Ventura fault. This includes creating 1D profiles of the InSAR and GPS across the Ventura fault to determine if any subtle line of sight, horizontal, and/or vertical velocity changes are present. Other active faults in the region will also be analyzed.

B. Past Geodetic Studies of the Ventura Region

Early geodetic studies of the Ventura region documented fast and localized horizontal strain rates across the Ventura basin [*Donnellan et al., 1993a*; *Donnellan et al., 1993b*; *Hager et al., 1999*]. These works attributed the measured horizontal strain to steady creep on reverse faults below the interseismic locking depth [*Donnellan et al., 1993a*; *Donnellan et al., 1993b*], combined with the effects of the low rigidity basin sediments [*Hager et al., 1999*]. Because vertical motions were not sufficiently well recorded by GPS at the time, these studies did not attempt to model the predicted vertical components of deformation. *Marshall et al. [2013]* demonstrated that while these models fit the horizontal contraction rates well, the same models predict significant uplift gradients that are not observed in the vertical GPS data. Thus, the current interseismic deformation across these active reverse faults is not well understood, nor is there is single model that can explain both the vertical and horizontal GPS data. This highlights a fundamental gap in our understanding of the seismic hazards of the Ventura fault and the western Transverse Ranges in general.

It remains possible that there is a measurable horizontal and vertical signal across the Ventura fault, but given the >10 km PBO GPS station spacing the PBO GPS network, alone, cannot resolve the deformation. We therefore require a spatially denser data set to characterize the interseismic deformation across the greater Ventura fault region. Such a data set can be provided by combining GPS data with an advanced processing methodology applied to InSAR data.

C. GPS Processing and Results

In the last year, we have updated our GPS time series processing from 52 sites to 127 total sites. Figure 1a shows the horizontal and vertical velocities of sites within the greater Ventura region. To determine what the GPS velocity field would look like to an InSAR satellite, we have projected the GPS velocities into the LOS direction and cropped the result to the same region as is covered by the InSAR data (Figure 1b). Note that while there is a zone of localized fast horizontal strain rates near the Ventura basin [*Donnellan et al., 1993b*; *Hager et al., 1999*; *Marshall et al., 2013*], this zone should not be readily apparent in the LOS for the descending Envisat/ERS orbits. The GPS projected into LOS and InSAR appear to have some systematic differences, which we are still exploring.

To determine what the interseismic strain signal due to the Ventura fault might look like to the descending track InSAR data, we have created a simple kinematic model (Figure 2). The model uses the CFM5.0 Ventura-Pitas Point fault surface and applies a constant 5 mm/yr of slip everywhere below 15 km (the actual locking depth may be deeper). The model surface velocities are then projected into the LOS, revealing a clear deformation pattern (Figure 2). Based on this admittedly simple model, the interseismic deformation should be well north of the Ventura fault (due to the shallow dip and deep locking depth) and of a magnitude that should be detectable by the InSAR once the San Andreas and other fault strains are removed. Unfortunately the region of predicted interseismic strain for the Ventura-Pitas Point fault lies in a mountainous region where even persistent scatterer InSAR data is relatively diffuse and often noisy.

D. InSAR Processing and Results

To date, we have reprocessed the Envisat InSAR data that span 2005-2010 including a newly acquired scene (24 total), and ERS InSAR Data that span 1995-2000 (29 total scenes). A significant portion of the western Transverse Ranges is vegetated and/or contains steep topographic slopes, therefore backscattered radiation from c-band radar satellites imaging the region severely decorrelates with time [*Zebker and Villasenor, 1992*; *Hooper et al., 2004*], rendering traditional, '2-pass' InSAR methods ineffective. These problems are mitigated to a large degree by applying an advanced processing methodology to InSAR data for the region to identify 'persistent scatterers' – targets on the ground that provide radar returns that are stable throughout time. Using the Stanford Method for Persistent Scatterers (StaMPS) technique of *Hooper et al.* [*2004*; *2008*], we have calculated line of sight (LOS) velocities for ~1.7 million persistent scatterer pixels on the ground (Figure 3). The reprocessed data covers a larger region than our past efforts. We have also processed ERS data with ~600,000 total persistent scatterer pixels, which show similar deformation patterns. The dominant signals observed are related to hydrocarbon and groundwater extraction near the Central Valley (northwest end of Figure 3) and interseismic locking on the San Andreas fault (i.e. the gradual increase in line of sight velocities from southwest to northeast). Closer inspection reveals that the InSAR data show a region of LOS increase to the north of the Ventura fault which may be due to interseismic deformation (Figure 3); however such a conclusion requires further modeling and examination. To better quantify any deformation associated with the Ventura and other faults of the Transverse Ranges, we must remove the deformation due to the San Andreas and other fast-slipping regional faults (see section E).

E. Dislocation Model of the San Andreas and Other Regional Faults

In the past, we [*i.e. Marshall et al., 2013*] used a relatively crude dislocation model of the San Andreas to effectively correct the GPS data so that the resultant velocities only reflect deformation processes within the Ventura region. Given the larger spatial extent of our newly processed data and the relatively small strains expected for the Ventura fault (Figure 2), we must refine and improve the model used to correct the GPS and InSAR data. Since several studies have systematically estimated the best-fitting slip rates and locking depths for the southern California fault network, we are currently working to use the *Loveless and Meade [2011]* slip rates to effectively remove deformation associated with the larger and faster slipping strike-slip faults in southern California (e.g. San Andreas, Garlock, Elsinore, etc…).

F. Ongoing Related Work in the Ventura SFSA

PI Marshall is a co-leader of the Ventura SFSA and has great interest in helping to accurately characterize the neotectonic deformation seismic hazards of the region. PI Marshall has been active within the SFSA group and has submitted a proposal for a workshop to help to synthesize results of the SFSA. We have been funded in the past by SCEC to create mechanical models of the Ventura region and the work proposed here is a logical extension of the fault modeling work. Bill Hammond, Kaj Johnson, and Reed Burgette are also working on geodesy in the region (with different data sets) and PI Marshall has provided them with a fault mesh of the Ventura faults for their work. Marshall has also agreed to assist Tom Rockwell's group in creating new structural representations of the offshore Pitas Point fault.

The results of the proposed geodetic data analysis will be described in two manuscripts that will be submitted to a peer-reviewed scholarly journal. In addition to publications, we will post synopses of the project on the web and present results at annual AGU and SCEC meetings. For example, our past fault meshes are posted on PI Marshall's website, along with conversion scripts, and simple visualization tools. at *http://www.appstate.edu/~marshallst/research/3D_faults.html*.

G. Summary of Past Mechanical Modeling Results

Cooke and Marshall [2006] produced the first mechanical model that used the SCEC CFM and showed that the slip rates predicted by a CFM-based mechanical model matched geologic rates better than models with highly simplified fault geometries. Since then, PI Marshall and collaborators have tested several regions of the SCEC CFM and have shown that models that use the CFM's complex geometry produce slip rates that generally match geologic rates. These models have acted as a key quantitative test of the CFM fault geometries across some of the most complex regions of southern California. In testing the CFM, results indicate that the vast majority of the fault representations produce patterns of slip and deformation that generally match several disparate data sets including: slip rate estimates from paleoseismology, tectonic geomorphology, and balanced cross sections [*Cooke and Marshall, 2006*; *Marshall et al., 2008*], folding patterns [*Meigs et al., 2008*]. When mechanical models using the CFM have not agreed well with other types of data, alternative fault representations that produce a better match to these data sets were created [*Meigs et al., 2008*].

Building on our successes of modeling geologic timescale deformation, *Marshall et al. [2009]* created a technique for simulating interseismic deformation along complex three-dimensional fault surfaces. This required that the CFM fault surfaces extend beyond seismogenic depths. These models have since been applied in several regions and show generally good agreement with the first order features of interseismic geodetic data [*Marshall et al., 2009*; *2013*; *Herbert et al., 2014*].

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 (~70 total), but while doing so, we have created a significantly more detailed mesh than our past efforts. 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. 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.

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 further collaboration, 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 sometime this fall, but are available earlier upon request.

H. Current Mechanical Modeling Results

This project has yielded a suite of mechanical models of the greater Transverse Ranges region incorporating ~80 faults including two different representations of the Ventura fault system. These models predict that average slip rates of many faults in the region are not significantly altered by the inclusion of the updated Ventura-Pitas Point fault system (for either geometry). 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 3.4 - 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 spatially variable. Analysis of the full three-dimensional model-predicted slip distributions indicates that the maximum slip rates at the surface of the Earth are approximately 3.5-4.5 mm/yr in the Ramp model and 5.5-6.5 mm/yr in the No Ramp model, both within the 4.4-6.9 geologic estimate of *Hubbard et al.* [2014]; however, more than 6 mm/yr of slip may occur at depth in both representations. 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. The net result is that the average slip rates of the Ramp model fault appear only marginally faster than the CFM4.0 Ventura fault while the No Ramp model slips faster. Thus, a key result is that both CFM5.0 models are compatible with the geologic slip rate data at the site of measurement, but the distribution of slip vastly differs in both representations.

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. 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 has a steeper dip and merges with the Red Mountain fault in the offshore.

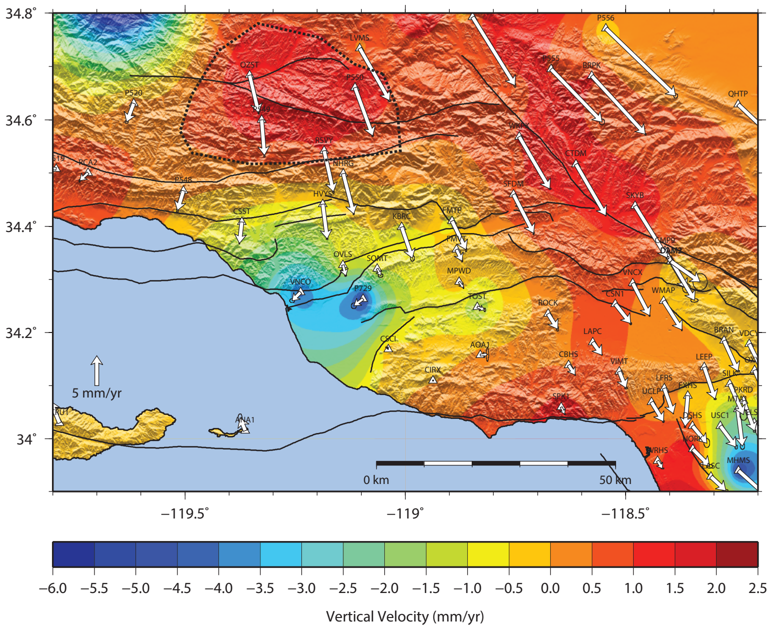

Figure 1a. Newly reprocessed continuous data from the PBO network. Arrows show horizontal velocities and the colormap shows the vertical rates. All rates are relative to site CIRX in the Santa Monica Mountains. An area of uplift north of the Ventura fault (labeled with a dashed path), may due to interseismic strain on the Ventura fault.

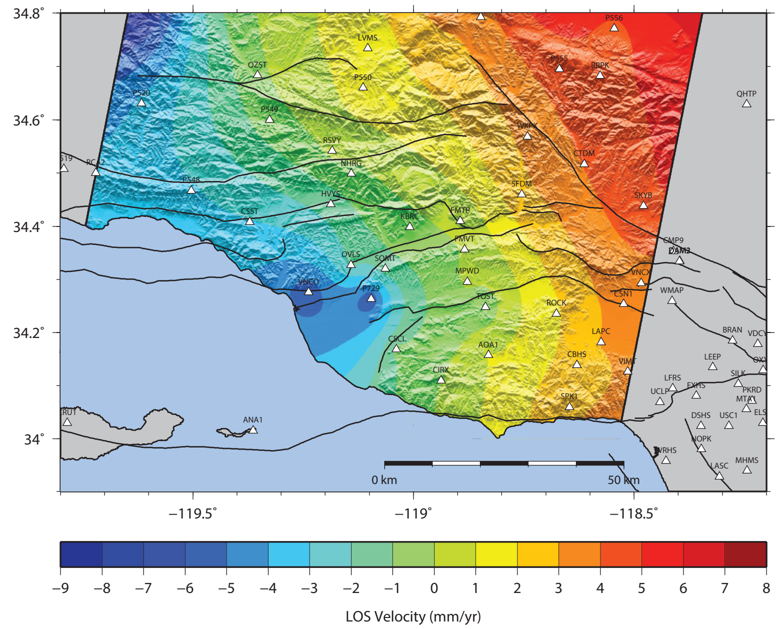

Figure 1b. Continuous GPS velocities projected into the line of sight of the Envisat satellite and cropped to show only the Envisat track 213 region. The region of uplift in the GPS data and LOS increase in the InSAR is not clearly delineated. The zone of LOS increase in the InSAR only contains one GPS site, so it is not surprising that the GPS LOS velocities do not detect this deformation.

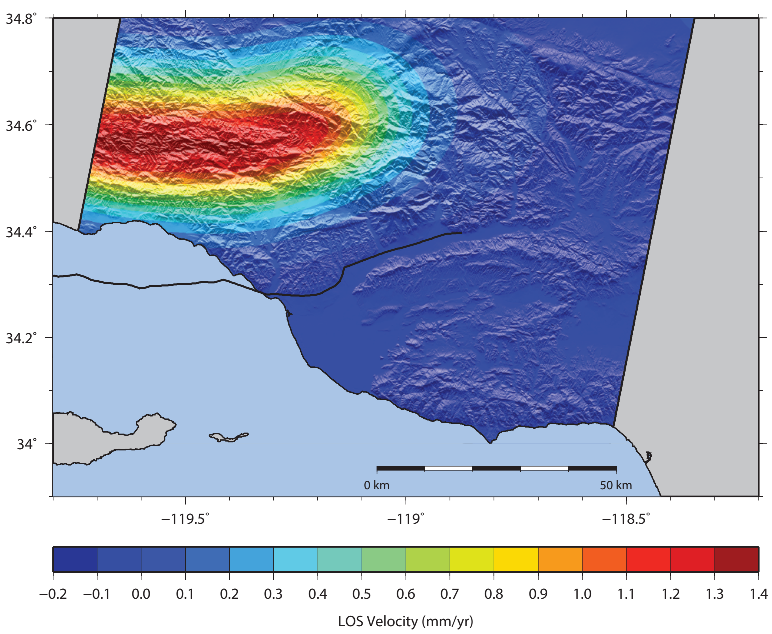

Figure 2. Simple kinematic model of 5 mm/yr of slip on the Ventura fault (from the CFM) below a 15 km locking depth cropped to the track 213 region. The model-predicted velocities have been projected into the LOS of the Envisat satellite to illustrate what the InSAR may be able to resolve. While the deformation is only about 1.5 mm/yr in the LOS, this may be detectable in the InSAR data, if all other sources of strain are first removed.

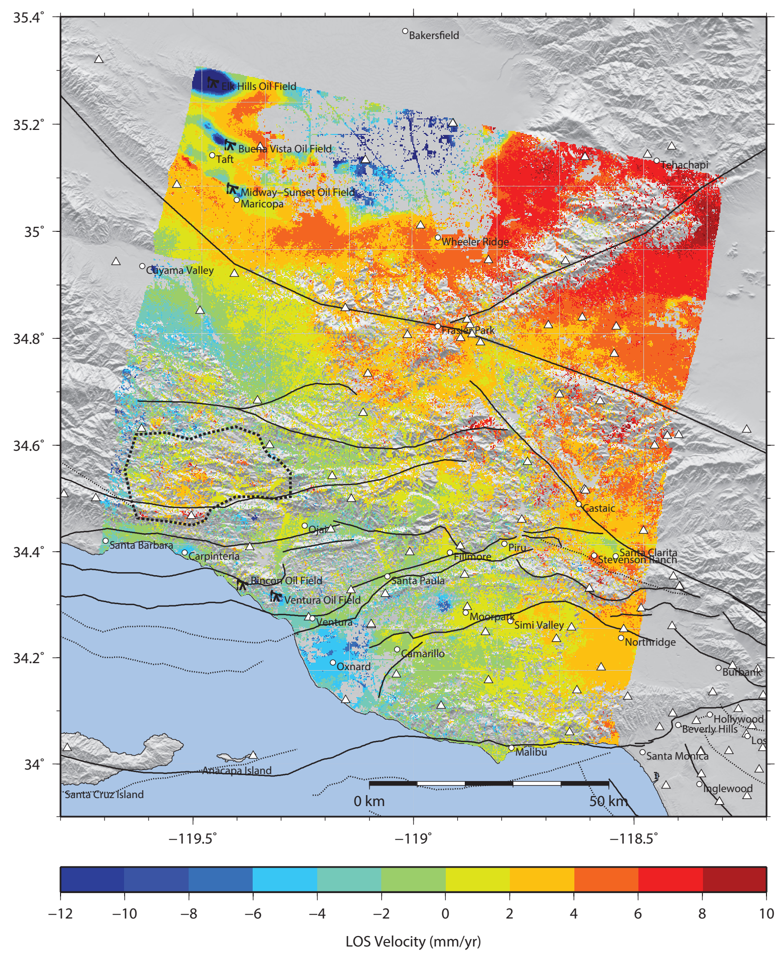

Figure 3. Persistent scatterer InSAR data from the Envisat satellite downsampled to 200 m spacing using a median filter. The largest deformation signals are near the northwestern end of the data where the ground is rapidly subsiding due to hydrocarbon extraction. The gradual increase in line of sight velocity from southwest to northeast is dominantly due to interseismic deformation on the San Andreas Fault. A zone of line of sight velocity increase is labeled with a dashed path that may be due to interseismic deformation associated with the Ventura fault, but this region has steep topography and is partly vegetated, so the InSAR data is noisy. This zone partly overlaps with a zone of uplift identified in the GPS data (Figure 1a).

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