Using focal mechanisms within regions of off-fault deformation to constrain active fault configuration of the southern San Andreas fault

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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.)

Geodetic data that can resolve slip rates along relatively isolated faults struggle to recover geologic slip rates along close parallel strands, such as the southern San Andreas fault. Because focal mechanisms occur at depth and often closer to the slipping portions of faults within the interseismic period, the stresses derived from focal mechanisms may better resolve some details of active faulting than surface GPS velocities within a joint inversion. Here, we develop and test a new approach to invert off-fault stress information for slip distribution. We test the approach by inverting stresses produced by two forward models, one with a single planar fault and a second with the CFM based configuration of active faults in the region. We use the planar fault models to ascertain the optimal distribution of off-fault stress data for recovering the interseismic slip distribution. The joint slip rate inversions perform better than either the velocity or stressing-rate tensor alone. Because focal mechanisms do not provide complete stress tensors, we also compare inversions using the deviatoric stressing rate tensors and normalized deviatoric stressing rate tensors. The normalized deviatoric stressing rate tensors, which are similar to the data currently derived from focal mechanisms, have large misfits due to the lack of magnitude information. The validation completed in this study demonstrate the potential improved resolution of constraining interseismic slip rates from joint inversion of surface velocity vectors and deviatoric stressing rate tensors, if we are able to infer stressing rate tensors from focal mechanisms.

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.

Stress and Deformation Through Time (SDOT)
San Andreas Fault System
CXM

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.

Fig. 1 A) Optimal spacing of surface velocities (triangles) and stress tensors (circles). Open circles show points with sufficient nearby focal mechanism in the current catalog to infer stress state. B) Current focal mechanism catalog and GNSS stations.

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
3a. Refine the geometry of active faults across the full range of seismogenic depths, including structures that link and transfer deformation between faults.

1e Evaluate how the stress transfer among fault segments depends on time, at which levels it can be approximated by quasi-static and dynamic elastic mechanisms, and to what degree inelastic processes contribute to stress evolution.

1a Refine the geologic slip rates on faults in Southern California, including offshore faults, and optimally combine the geologic data with geodetic measurements to constrain fault based deformation models.

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?

Because focal mechanisms occur at depth and often closer to the slipping portions of faults within the interseismic period, they may improve the resolving power of surface GPS velocities in joint slip rate inversions. Here we test a new approach to invert off-fault stress information for interseismic slip distribution. We find that either full stressing rate tensors or deviatoric stressing rate tensors improve upon the recovery of forward model slip rates than those from surface velocities alone. The validation completed in this study demonstrate the potential improved resolution of constraining interseismic slip rates from joint inversion of surface velocity vectors and deviatoric stressing rate tensors, if we are able to infer stressing rate tensors from focal mechanisms.

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 study is the first to demonstrate that off-fault stress information from the interseismic period could inform slip distribution. The validations completed in this study test this new method with the goal of showing how stressing rate tensor information, if it were available from focal mechanisms, could constrain interseismic slip rates at depth. This project supports both a female UMass PhD candidate, Hanna Elston, who is also a 1st generation college student, and a female PI, Cooke, with deafness.

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. Introduction

Along the southern San Andreas fault (SAF) in the San Gorgonio Pass region, debate persists about the relative activity of parallel pathways for the fault (Fosdick & Blisniuk, 2018; Gold et al., 2015; Kendrick et al., 2015; Yule, 2009; Fig. 1). Geologic studies in the region provide conflicting interpretations that recent ruptures either were limited to the southern pathway (Kendrick et al., 2015) or passed through both the southern and northern pathways of the SAF (Fosdick & Blisniuk, 2018). Crustal deformation models incorporating single and double SAF pathways produce slip rates and surface velocities that cannot be distinguished using the available slip rate and geodetic data (Beyer et al., 2018). We need additional constraints in order to assess the activity level of these faults. During the interseismic period, microseismicity off of major faults may reflect loading from interseismic slip as well as regional tectonics (Cooke & Beyer, 2018). Because focal mechanisms occur at a range of depths and typically closer to the slipping portions of faults within the interseismic period, adding stress information from focal mechanisms to a joint inversion with interseismic velocities at the Earth’s surface may better resolve interseismic slip rates that those inferred only from GPS data. Here, we develop and test a new approach to invert off-fault stress information for slip distribution.

Before we perform slip rate inversions from crustal data, we need to test how well such inversions can recover interseismic slip from forward models. In this continuation of a SCEC 2020 project, we test the approach by inverting stresses produced by two forward toy models, one with a single planar fault and a second with the CFM based configuration of active faults in the region. The ideal placement of stress information is assessed from performance of the planar model and applied to the complex model. Then we compare inversions for slip rate from surface velocities with inversions from stressing rate tensors as well as joint inversions. We find that adding stressing rate information to the inversion improves performance even when the stressing rate information is limited to the deviatoric stress.

B. Methods

We use a two-step modelling approach to test the inversions. First, forward models that replicate interseismic deformation produce surface velocities and stressing rate tensors at prescribed points within the seismogenic crust. Then we use inverse models to see how well the inversion of the velocities and stressing rate tensors recover the interseismic slip rate distribution prescribed in the forward models.
B1. **Forward models.** We use 3D BEM models, to simulate deformation along the southern San Andreas Fault system. The models simulate the active fault geometry of the southern San Andreas fault, the San Jacinto fault, and the Eastern California Shear Zone based on the SCEC Community Fault Model (Plesch et al., 2007). By using triangular elements, the models can accurately replicate the branching and curving fault surfaces and provide an appropriate approach for simulating complex faulting of the SAF. The shear traction-free faults throughout the model slip freely in response to both the tectonic loading and fault interaction. We prescribe tectonic loading far from the investigated faults at the base of the model, following Herbert & Cooke (2012) to simulate plate motions that are geodetically constrained. Furthermore, we implement a new iterative technique that uses a correction ratio for successive iterations to ensure a uniform tectonic velocity parallel to the plate boundary and a linear gradient in the tectonic loading across the plate boundary (Beyer et al., 2018). To estimate interseismic deformation of the crust, we use an approach that is equivalent to back slip. This approach simulates interseismic deformation by applying slip rates from the long-term steady state model below a prescribed locking depth along the faults (Marshall et al., 2009). From this interseismic model, we can compute both velocities at the Earth’s surface and the stressing rate tensor at any subsurface location within the model. Modeled interseismic surface velocities using this approach have shown good match to GPS station velocities in regions of complex 3D faulting within southern CA (e.g., Herbert et al., 2014; Marshall et al., 2009, 2013; Rollins et al., 2018). The $\sigma_{\text{Hmax}}$ of the model-calculated interseismic stressing rate tensors show good match to the $\sigma_{\text{Hmax}}$ inferred from focal mechanisms (Fig. 2).

B2. **Inverse models.** Velocities and stressing rates tensors, such as from GPS and focal mechanisms, can be independently inverted for slip distributions on the triangular dislocation elements used to represent CFM fault surfaces (e.g., Becker et al., 2005; Loveless et al., 2016). These inversions yield slip rate distributions interpreted to reflect spatially variable interseismic locking, primarily above the locking depths found from the steady-state models. Implicit in the inversion of the earthquake-based stress data for slip on CFM surface is the idea that these small “off-fault” earthquakes occur in response to stress imposed by slip and/or locking on the faults we include in the model. Loveless et al. (2017) demonstrated the feasibility of such an analysis in the case of the 2014 Iquique, Chile earthquake, inverting a distribution of forearc surface cracks, taken as coseismic stress indicators, for slip on the underlying subduction interface. The resulting slip distribution is comparable to that inverted from more typical geophysical datasets such as GPS and seismic waveforms (Loveless et al., 2016).
**B3. Model setup.** The first test of a planar fault has a 35 km high vertical strike-slip fault with 1 mm/yr of dextral slip prescribed below the locking depth (15 km). The base of the fault intersects a horizontal crack that has prescribed slip that replicates on-going slip at depth in the interseismic period; this set-up effectively simulates a semi-infinite fault (Marshall et al., 2009). The interseismic slip prescribed to elements below the locking depth, including those of the horizontal crack, serves to simulate deep creep below the seismogenic crust during the interseismic period (Marshall et al., 2009). Elements with centroids within 2.5 km of the locking depth have transitional slip rates of one-half the deep creep rate. We sample the resulting surface velocity and stressing rate tensors at regularly spaced points and input these in the inversion. The surface velocities have a 15 km gridded spacing consistent with typical spacing of permanent GPS stations near the southern SAF. The stressing-rate tensor spacing is adjusted iteratively in order to minimize misfit. We sum slip rate misfit for each element, $n$, weighted by element area, $A_n$.

$$
\text{Misfit} = \frac{\sum_{n} |\text{inversion - prescribed}| A_n}{\sum_{n} A_n}
$$

The second model is more complex and simulates the active fault configuration based on the SCEC Community Fault Model within the San Gorgonio Pass region. In this model, faults also sole into a horizontal crack with prescribed slip. We prescribe slip rates to the fault elements below the 20 km locking depth according to the results of a steady state model that simulates accumulation of slip over many earthquake cycles following Beyer et al. (2018). We sampled surface velocities and stressing-rate tensors at optimal points that minimized misfit for the planar fault (Fig. 1). For another set of inversions that are constrained by the crustal data available, we sampled surface velocities at the positions of permanent GPS stations and stressing-rate tensors at points where > 39 focal mechanisms lie within 7.5 km, which provides sufficient data to perform a stress inversion of the focal mechanism data.

The inversion results depend on weighting and regularization. Because shear stresses provide more direct information about slip than normal stresses, we weight the three normal stresses in the 6 component stressing rate tensors one order-of-magnitude lower than the shear stress components. In addition to inverting the full stress tensor inversion, we invert the deviatoric stressing rate tensors and the normalized deviatoric stressing rate tensors; the latter is the most closely related to the products of current focal mechanism inversions (e.g., Martínez-Garzón et al., 2014; Fig. 2). The relative weighting of shear and normal stresses remains the same for all variations of the stressing-rate tensors. We weight the horizontal surface velocity components equally because the uncertainty of horizontal components at GPS stations generally have similar magnitude in our region of interest. The vertical components of GPS station velocities have greater uncertainty than the horizontal components and may be more strongly affected by non-tectonic sources, so we exclude the vertical velocities from the inversion. The inversion applies Laplacian smoothing-based regularization to ensure smoothly varying slip rate distribution, including across branched fault segment boundaries to avoid abrupt changes from one fault segment to another. The strength of the regularization is selected iteratively to balance misfit to the constraining data with physical feasibility of estimated slip rates (i.e. avoiding rates that exceed or show opposite sign of the modeled long-term rates).

**C. Results**

**C1. Planar fault model.** Both the surface velocity and the stressing rate tensor inversions produce smoother slip distributions across the locking depth than the abrupt transition applied to
the forward model. This is an expected consequence of the regularization used and highlights the limit of this inverse approach to capture sharp changes in slip rate along faults. Because we don’t have evidence that the locking depth transition along crustal faults is as sharp as depicted in the forward models, this smoothing across the locking depth does not cause concern.

The stressing rate tensor grid that minimizes misfit to the forward model samples stressing rate tensors at 7.5 and 15 km depth at points that are 10 km away from the fault with along-strike spacing of 10 km. From this investigation, we learned that we don’t need a dense network of stressing rate tensors to recover slip. For the planar model, the joint inversion of the surface velocities and full stressing rate tensors produces overall misfit that is lower than that of either surface velocities or stressing rate tensors alone. Due to the simple geometry of this model, the misfit is primarily due to smoothing across the locking depth.

**C2. Simulation of San Gorgonio Pass fault configuration.** To test the recovery of slip rates for the more complicated active fault network of the San Gorgonio Pass region, we calculate overall slip rate mismatch in the same manner as the planar fault model and we also compare forward and inverted slip rates for elements below the locking depth along each fault segment (Fig. 3). To test the inversion, we supply a fault mesh that includes the northern pathway for slip along the Mill Creek fault but we use surface velocities and stressing rate tensors from a model that has no slip along the northern pathway. Because activity of this pathway is debated, we want to determine if data predicted by a forward model with no slip along the northern pathway can be recovered in the inversion. We first assess the inversion with the optimal distribution of surface velocities and stressing rate tensors and then assess performance when input data is limited to locations with available crustal data.

**C2.1 Optimal position of surface velocities and stressing rate tensors.** As with the planar model, the inverted slip rates are smoother across the locking depth, which results in underestimates of slip rate on elements just below the locking depth plotted on Fig. 3. The inversion recovers the forward model locking depth and most slip rates within ~3 mm/yr. As with the planar model, the joint inversion has lower mismatch than either the inversions from the surface velocities or stressing rate tensors alone (1.5 < 2.0 & 2.2 mm/yr; Fig. 3). Joint inversions also correctly resolve only minor amounts of slip on the northern pathway elements (Fig. 3e inset).

Furthermore, the average misfit increases from the inversion with full stressing rate tensor to the deviatoric (2.2 mm/yr) and normalized deviatoric stressing rate tensors (10.4 mm/yr). Although the deviatoric stressing rate tensors lack mean normal stress information of the full stressing rate, the lack of this information does not greatly impact the average mismatch. However, the normalized deviatoric stressing rate tensor, which additionally lacks stress magnitude information, performs much more poorly than the deviatoric stressing rate tensors (10.4 > 2.2 mm/yr). Unfortunately, current focal mechanism inversions only provide normalized deviatoric stress tensors (Fig. 2).

**C2.2. Surface velocities and stressing rate tensors limited to available crustal data.** If surface velocities are limited to the sites of permanent GPS stations in the region and the off-fault stressing rate tensors are limited to points with sufficient nearby focal mechanisms, the average misfit of the joint inversion increases from 1.5 to 2.2 mm/yr but still correctly recovers minor to no slip along the northern pathway. With time and additional microseismicity, focal mechanism catalogs may enable additional tensor locations to be included in the model, which could reduce the misfit. However, the more critical challenges are 1) that the stress states inferred from focal
mechanisms provide relative stress but not magnitudes and 2) that focal mechanisms respond to the total stress state, which includes the effect of accumulated tectonic loading and not just off-fault stressing rates from interseismic slip rates.

D. Conclusions
The validation completed in this study demonstrates the potential improved resolution of interseismic slip rates from joint inversion of surface velocity vectors and off-fault deviatoric stressing rate tensors (Fig. 3f), if we are able to infer deviatoric stressing rate tensors from focal mechanisms. Because focal mechanisms occur at depth and closer to the portions of faults that slip during the interseismic period, they could provide valuable information to augment that from surface GPS velocities. We show that the inversions do not need a dense array of stressing-rate data to recover the prescribed slip and that the joint inversions have lesser misfit than those from either stressing rates tensors or surface velocity alone. If we can derive stressing rate information from focal mechanisms, this approach will be particularly useful in regions with closely spaced parallel fault strands where inversions of interseismic GPS velocities struggle to resolve slip rates. Here, we show that the zero slip applied in the forward model along the northern pathway of the San Andreas fault is much better recovered by the joint inversions of surface velocity and stressing rate than the inversions of surface velocity alone (Fig. 3 insets).

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**Fig. 3** Comparison of applied and inverted strike-slip rates for elements below the locking depth. Inset histograms show the absolute difference between the applied and inverted slip rates for elements that had no slip in the forward model. A, C and E show results for the individual and joint inversions of optimally positioned surface velocities ($u_{\text{optimal}}$) and stressing rate tensors ($\sigma_{\text{optimal}}$). The joint inversion produces the lowest misfit and best recovers no slip along the northern pathway. B, D and F show results for the individual and joint inversions of 53 surface velocities ($u_{\text{GPS}}$) at GPS station locations and 54 stressing rate tensors ($\sigma_{\text{dev,FM}}$) at locations with >39 focal mechanisms within 7.5 km. All three inversions produce larger misfits than their optimally positioned counterparts, yet the joint inversion of $u_{\text{GPS}}$ and $\sigma_{\text{dev,FM}}$ recovers no slip along the northern pathway better than all other inversions.
E. References


