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.)

The San Gorgonio Pass region hosts multiple nearby active strands for which both subsurface active configuration and slip rate are under-constrained. Geodetic data that can resolve slip rates or fault geometry along relatively isolated faults struggle to recover geologic slip rates along close parallel strands of the San Andreas fault in this region. Because focal mechanisms occur at depth and closer to the slipping portions of faults within the interseismic period, they can, in some instances, better resolve details of active faulting than interseismic surface GPS velocities. Here we develop and test a new approach to invert off-fault stress information from the interseismic period for slip distribution. 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. We varied the location and spacing of off-fault stress data in the planar model to pin-point the ideal configuration for recovering the interseismic slip distribution. We compare slip rate inversions of both the forward model produced surface velocities at the permanent GPS sites and the stressing rate tensor at 10-15 km spaced points throughout the seismogenic crust, where focal mechanisms might occur. The stressing rate tensor inversion recovers the prescribed slip rates better than the surface velocity inversion (misfit 1.1 and 2.5 mm/y respectively). The validation completed in this study demonstrate the utility of new method for constraining interseismic slip rates from stress tensors inverted from the focal mechanisms catalog.

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. 3 A) Forward model interseismic strike-slip rate distribution with a 20 km locking depth. B, C) Correlation of prescribed slip rate and inversions from surface velocity (B) or stressing rate tensor (C) inversion predicted average strike-slip rates for elements below 20 km.

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 closer to the slipping portions of faults within the interseismic period, they can, in some instances, better resolve details of active faulting than interseismic surface GPS velocities. Here we test a new approach to invert off-fault stress information from the interseismic period for slip distribution. We find that the stressing rate tensors may recover the forward model slip rates better than the surface velocities. The validations completed in this study demonstrate the utility of new method for constraining interseismic slip rates from stress tensors inverted from the focal mechanisms catalog. This approach may be particularly useful in regions with closely space parallel fault strands where inversions of interseismic GPS velocities struggle to resolve slip rates.

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 can be inverted to reliably inform slip distribution. The validations completed in this study test this new method with the goal of using stress tensors inverted from focal mechanisms to constrain interseismic slip rates at depth. This project supports a female UMass PhD candidate, Hanna Elston, who is also a 1^{st} generation college student, and a female PI 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 GPS data (Beyer et al., 2018). We need additional constraints in order to assess the activity level of these faults. Because focal mechanisms occur at a range of depths and closer to the slipping portions of faults within the interseismic period, they can, in some instances, better resolve details of active faulting than interseismic GPS velocities at the Earth's surface. Here we test a new approach to invert off-fault stress information from the interseismic period for slip distribution.

Before we can invert stress states derived from the focal mechanism catalog for slip rate, we need to test how well such inversions can recover slip from forward models. 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 at points of permanent GPS stations (Fig. 1) with inversions from stressing rate tensors throughout the seismogenic crust (blue circles Fig1). We find that the slip inversions from stress rates perform as well as and, in some cases, better than those from surface velocities.

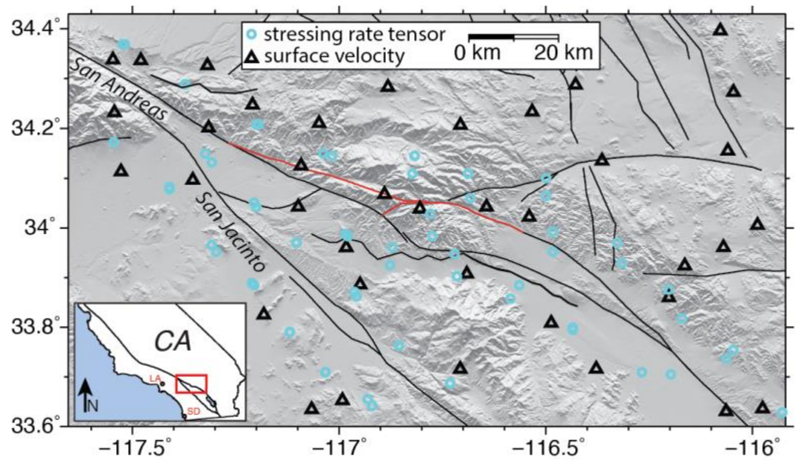

Fig. 1 Map of modeled fault traces within the study area denoted in inset. Red lines indicate faults of debated activity level. Forward models prescribe interseismic slip below the locking depth along these faults. Black triangles indicate location of surface velocities used in the inversion to recover slip distribution. Their pattern replicates permanent GPS station locations. Blue circles indicate map location of stressing rate tensors at 5 and 15 km depth.

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 slip rate distribution prescribed in the forward models.

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) using triangular elements that 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. Interseismic surface velocities found using this approach have shown good match to GPS station velocities in regions of complex 3D faulting within southern California (e.g., Herbert et al., 2014; Marshall et al., 2009, 2013; Rollins et al., 2018).

Inversion 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. We have 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).

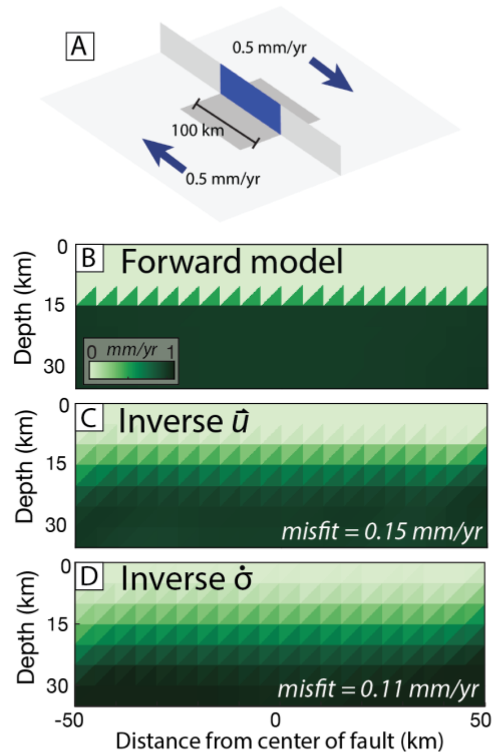

Fig. 2 A) Diagram of planar fault model. Blue patch denotes the region shown in B-D. B) Forward model prescribed slip rate distribution. C) Slip rate inverted from gridded surface velocities. D) Slip rate inverted from gridded off-fault stressing rate tensors.

Model setup. The first test of a planar fault (Fig. 2A) 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. The interseismic slip prescribed to elements below the locking depths, including those of the horizontal crack, serves to simulate deep creep below the seismogenic crust during the interseismic period; slip on the horizontal crack replicates the effect of a slip on a semi-infinite vertical fault (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 (Fig. 2B). We sample the resulting surface velocity and stressing rate tensors at gridded points and apply these to the inversion. The surface velocities have 15 km gridded spacing consistent with typical spacing of permanent GPS stations near the southern SAF. The stressing-rate tensor spacing was adjusted iteratively in order to minimize misfit. We sum slip rate misfit for each element, n, weighted by element area, A_n.

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

The second model simulates the interpreted active fault configuration represented in the Community Fault Model (Fig. 3A). In this model faults also sole into a horizontal crack with prescribed slip. We prescribe slip rates to the elements along faults and the horizontal crack 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 at the positions of permanent GPS stations and stressing-rate tensors along similar grid spacing as that which minimized misfit for the planar fault.

The inversions of both models employed conditioning to ensure smooth and reliable results. Because the shear stresses provide more direct information about slip than normal stresses, the three normal stresses in the 6 component stressing rate tensors were weighted one order-of-magnitude lower than the shear stress components. We weighted the horizontal surface velocity components equally because the uncertainty of horizontal components at GPS stations have similar magnitude. The vertical components of GPS station velocities have greater uncertainty than the horizontal so we exclude these velocities from the inversion. The inversion applies smoothing-based regularization to ensure smoothly varying slip rate distribution, including across contiguous fault segment boundaries to avoid abrupt changes from one fault segment to another. The strength of the regularization was 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

Planar fault model

Both the surface velocity and the stressing rate tensor inversions produce more smooth slip distributions across the locking depth than the abrupt transition applied to the forward model. This is a consequence of the inversion regularization used and highlights the limit of this inversion approach to capture sharp changes in slip rate along faults. Because we don't have evidence that the locking depth is as sharp as depicted in the forward models, this smoothing across the locking depth does not cause us concern.

The ideal stressing rate tensor grid that minimizes misfit to the forward model samples stressing rate tensors at 5 and 15 km depth at points that are 10 km away from the fault with lateral spacing of 15 km. This configuration of points for stressing-rate tensors produces misfits about 11% (Fig 2D). From this investigation, we learned that we don't need a dense network of stressing rate tensors to recover the slip. The inversion of the surface velocities produces overall misfit of 15%, which exceeds that of the stressing rate tensor inversion. This misfit is primarily due to smoothing across the locking depth, which causes slip rates in both models to differ from the prescribed slip rate of the forward models, but the lower misfit of the stress-based inversion implies its ability to better resolve slip patterns at depth.

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 each fault segment. For five of the seven active faults in the San Gorgonio Pass region, the stressing rate tensor inversion has lesser misfit than the surface velocity inversions, particularly along closely spaced faults, such as the Mission Creek and Garnet Hill strands of the SAF. The overall misfit on all faults is lesser for the stressing rate tensor inversion (1.1 mm/yr) than the surface velocity inversion (2.5 mm/yr). As with the planar fault, some of this misfit for both models is due to smoothing over the 20 km locking depth.

To compare the strike-slip rate for each fault we consider only slip below the 20 km locking depth. Figure 3 reports the slip rate with ellipse axis length representing one standard deviation from the mean slip of all elements on each fault segment. The stressing rate tensor inversions have ellipse centers that align more closely to the 1:1 line than the surface velocity inversions consistent with the lesser calculated misfit.

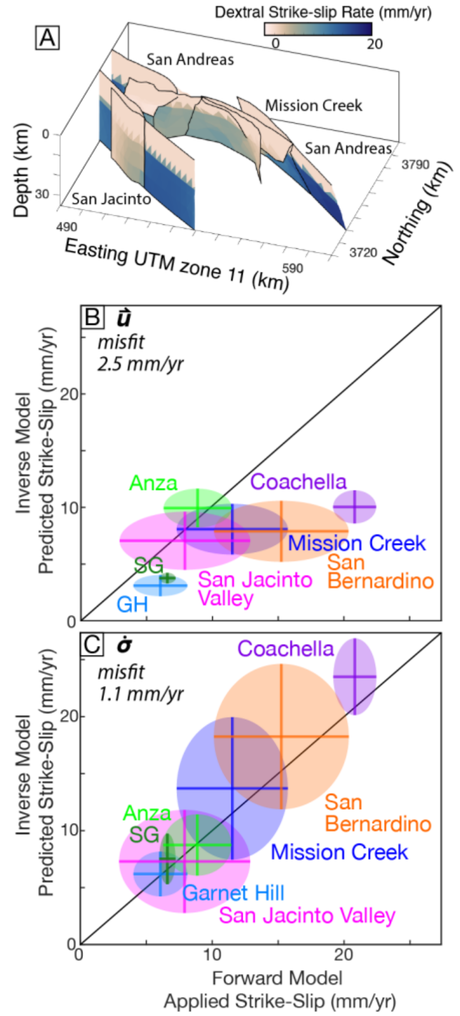

Fig. 3 A) Forward model interseismic strike-slip rate distribution with a 20 km locking depth. B, C) Correlation of prescribed slip rate and inversions from surface velocity (B) or stressing rate tensor (C) inversion predicted average strike-slip rates for elements below 20 km.

D. Conclusions

This study demonstrates the validity of using off-fault stress information, such as available from the focal mechanism catalog, to invert for interseismic slip rates. Because focal mechanisms occur at depth and closer to the slipping portions of faults within the interseismic period, they may better resolve details of active faulting than interseismic 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 stressing-rate inversions have lesser misfit than with surface velocity inversions. Using stress information from focal mechanisms may be particularly useful in regions with closely spaced parallel fault strands where inversions of interseismic GPS velocities struggle to resolve slip rates.

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