

1 **A New Method to Invert for Interseismic Deep Slip Along Closely Spaced**
2 **Faults using Surface Velocities and Subsurface Stressing-Rate Tensors**
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11 **Key Points:**

- 12 ● Joint inversions of velocity and stressing-rate data can better estimate slip rates along complex
13 faults than individual inversions.
- 14 ● Inverting data at multiple depths can better estimate fault locking depth than inverting data at a
15 single depth.
- 16 ● Application of the new method requires estimates of crustal deviatoric stressing-rate tensors with
17 magnitude.
18

19 **Abstract**

20 Inversions of interseismic geodetic surface velocities often cannot uniquely resolve the three-
21 dimensional slip-rate distribution along closely spaced faults. Microseismic focal mechanisms
22 reveal stress information at depth and may provide additional constraints for inversions that
23 estimate slip rates. Here, we present a new inverse approach that utilizes both surface velocities
24 and subsurface stressing-rate tensors to constrain interseismic slip rates and activity of closely
25 spaced faults. We assess the ability of the inverse approach to recover slip rate distributions from
26 stressing-rate tensors and surface velocities generated by two forward models: 1) a single strike-
27 slip fault model and 2) a complex southern San Andreas fault system (SAFS) model. The single
28 fault model inversions reveal that a sparse array of regularly spaced stressing-rate tensors can
29 recover the forward model slip distribution better than surface velocity inversions alone. Because
30 focal mechanism inversions currently provide normalized deviatoric stress tensors, we perform
31 inversions for slip rate using full, deviatoric or normalized deviatoric forward-model-generated
32 stressing-rate tensors to assess the impact of removing stress magnitude from the constraining
33 data. All the inversions, except for those that use normalized deviatoric stressing-rate tensors,
34 recover the forward model slip-rate distribution well, even for the SAFS model. Jointly inverting
35 stressing rate and velocity data best recovers the forward model slip-rate distribution and may
36 improve estimates of interseismic deep slip rates in regions of complex faulting, such as the
37 southern SAFS; however, successful inversions of crustal data will require methods to estimate
38 stressing-rate magnitudes.

39 **1 Introduction**

40 During interseismic periods, elastic strain accumulation around isolated locked faults
41 produces a broad zone of geodetically measurable velocity gradients that may be more than 30
42 km wide for faults with locking depths greater than 10 km (e.g., Savage and Burford, 1973). In
43 regions with multiple closely spaced (i.e., < 30 km) and branching faults that have locking depths
44 greater than 10 km, such as the southern San Andreas fault system (SAFS) through the San
45 Gorgonio Pass region (Figure 1), the geodetic velocity signatures of individual faults can overlap
46 one another (e.g., McGill et al., 2015). As a result, inversions of geodetic velocity data alone
47 often cannot uniquely resolve the slip rate distribution on these closely spaced faults (e.g.,
48 Spinler et al., 2010). Inversions of geodetic data for slip rates continue to improve with the

49 increasing availability of geodetic surface velocity estimates (e.g., d'Alessio et al., 2005; Evans
 50 et al., 2012; Guns et al., 2021; Wang et al., 2021). However, jointly inverting geodetic data with
 51 an independent dataset, such as stress information, could provide more robust slip rate
 52 distribution estimates. Previous studies have inverted stress orientations inferred from surface
 53 cracks for coseismic slip (John P. Loveless et al., 2016) and regional stress orientations to
 54 estimate long-term slip rates (e.g., Becker et al., 2005). Stress states derived from focal
 55 mechanisms of microseismicity during the period between large ground rupturing earthquakes,
 56 which have not yet been used within inversions, may reflect local stress conditions and provide
 57 valuable information about deep interseismic slip rates on closely spaced faults because, unlike
 58 surface velocities, the microseismicity occurs at depth, closer to the deep portions of faults that
 59 slip during interseismic periods.

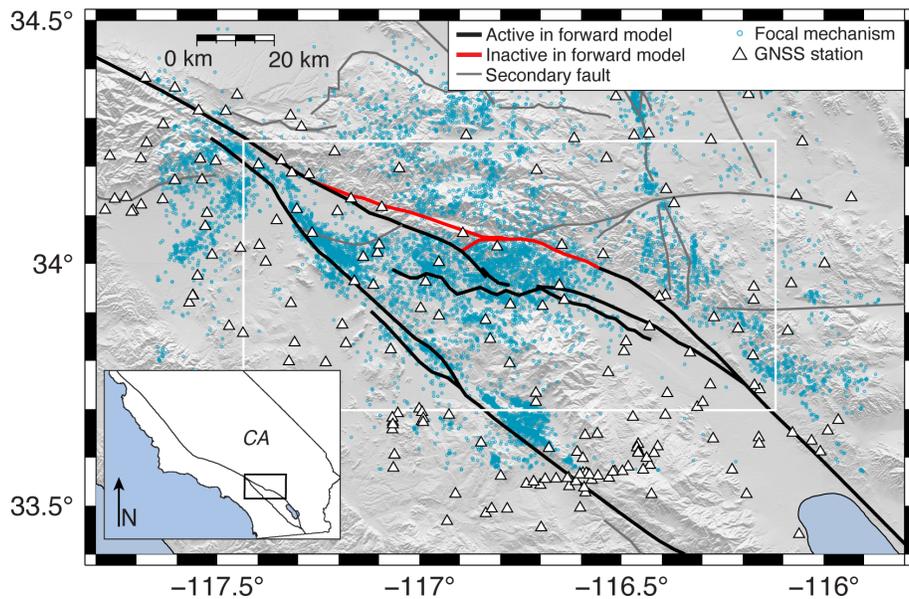


Figure 1. Map of the San Geronio Pass region with the modeled fault surface traces for the region of interest. Black fault traces indicate active faults in all complex forward models. Red traces indicate faults that are inactive in all forward models. Gray traces indicate the secondary faults that are active in the long-term forward models only. Blue open circles show microseismicity from the declustered catalog. White triangles show GNSS stations that we use. White box shows the area we use to calculate the inverse model misfits.

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61 Here, we present and assess a new inverse approach that utilizes both surface velocities
 62 and subsurface stressing-rate tensors to estimate three-dimensional fault slip-rate distributions
 63 (Figure 2). We perform joint and individual inversions of forward model-generated surface
 64 velocities and stressing-rate tensors to assess the potential of using stressing-rate tensors to infer

65 interseismic slip rates (Figure 2). Using a simple fault model consisting of a single, planar strike-
 66 slip fault (Figure 3A), we determine the spacing of stressing-rate tensors that minimizes the
 67 inverse model misfit to the forward model applied slip rate distribution. To assess how well
 68 individual and joint inversions of surface velocities and subsurface stressing-rate tensors recover
 69 slip along closely spaced and branching faults, we utilize a complex, geologically constrained
 70 fault model that simulates the southern SAFS and San Jacinto fault system (SJFS) through the
 71 San Gorgonio Pass region (Figure 3B). The SAFS consists of two subparallel pathways for
 72 earthquake rupture through the San Gorgonio Pass region, but the relative activity of the two
 73 pathways remains a topic of debate (e.g., Kendrick et al., 2015; Blisniuk et al., 2021). Because
 74 these two pathways are less than one locking depth apart from one another, inversions of GNSS
 75 velocities alone may not uniquely recover slip-rate distributions along the pathways and at the
 76 fault branches. For the complex fault inversion, we intentionally include fault surfaces that are
 77 inactive in the forward models to assess how well the inversions can recover zero slip along
 78 inactive fault surfaces. The method we present here provides a new approach that may constrain
 79 the relative activity of closely spaced parallel faults, such as the two pathways for earthquake
 80 rupture through the San Gorgonio Pass.

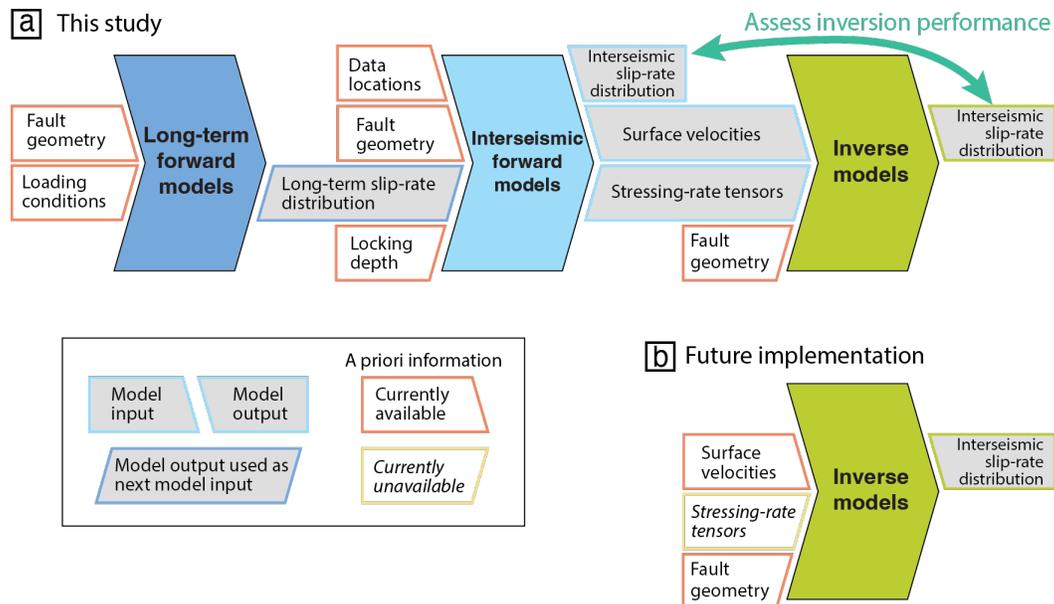


Figure 2. Flow chart showing the a) the methods we use to assess the new inverse method and b) the steps for a future application of the inverse method. Polygons on the left of a model are inputs. Polygons on the right of a model are outputs. Parallelograms indicate a model output is used as an input in the next model.

82 **2 Methods**

83 2.1 Crustal data processing

84 We utilize focal mechanism-derived stress states and GNSS estimated velocities in
85 southern California for multiple purposes. Previous studies show that long-term forward
86 mechanical models of the SAFS produce slip rates that fit geologic slip rate estimates well (e.g.,
87 Cooke and Dair, 2011; Devine et al., 2022; Hatch et al., 2023), and that the interseismic forward
88 model-generated surface velocities agree well with GNSS velocities (e.g., Herbert et al., 2014).
89 Previous studies have not compared stress states generated by a complex SAFS model to focal
90 mechanism-derived stress states. Here, we compare the horizontal maximum compression
91 orientations from interseismic forward models to focal mechanism-derived orientations to further
92 validate a complex SAFS model. Additionally, we use the locations of microseismicity and
93 GNSS stations to assess how deviations from the optimal spacing of data impact the inversions.
94 We also use the data uncertainties to weight the constraining data within the inversions. As the
95 purpose of this study is to test the new approach and stressing-rate tensors are not currently
96 available from crustal data, we do not directly invert the actual GNSS estimated velocities or the
97 focal mechanism-derived stress data, but instead use model-generated data.

98 2.1.1 GNSS surface velocity locations

99 We generate surface velocities within the complex SAFS forward models at the locations
100 of 201 permanent GNSS station locations (Figure 1) in the Southern California Earthquake
101 Center's Community Geodetic Model version 1 (Sandwell et al., 2016). We only use the
102 horizontal velocities to constrain the inverse models because this is what would be typically used
103 in GNSS inversions (e.g., Zeng, 2023).

104 2.1.2 Focal mechanism-derived stress states

105 Prior to deriving stress information from focal mechanisms of microseismicity, we assess
106 the completeness of and decluster the focal mechanism catalog to reduce effects of local events
107 (details provided in the Supporting Information; Martínez-Garzón et al., 2016; Abolfathian et al.,
108 2019). We start with 41,110 focal mechanisms from the Southern California Earthquake Data
109 Center from 1981 to 2020 (Hauksson et al., 2012; Yang et al., 2012) that have a nodal plane
110 uncertainty of $< 45^\circ$. Removing focal mechanisms with magnitudes below the limit of

111 completeness reduces bias of small events that occur close to seismic stations but are not
112 represented across the entire region of interest. Following Cooke and Beyer (2018), we calculate
113 the completeness magnitude using the maximum curvature method (Wiemer & Wyss, 2000) and
114 identify three periods with completeness magnitudes that decrease as the density of seismic
115 stations increases. For 1981-2001 the completeness magnitude is 2.0, which decreases to 1.6 for
116 2002-2011 and to 1.1 for 2012-2020.

117 To decluster the focal mechanism catalog, we follow the nearest-neighbor approach
118 described by Zaliapin and Ben Zion (2013a, 2013b) and define a nearest-neighbor distance
119 threshold in the space-time-magnitude domain by assessing the distribution of the nearest-
120 neighbor distance for all the events. We exclude events that have a nearest-neighbor distance
121 smaller than the threshold because they may reflect short-term perturbations in the stress field
122 resulting from large events rather than background seismicity. The declustered catalog consists
123 of 10,758 events that have an average fault plane uncertainty of $27 \pm 9^\circ$. The consistent average
124 slip sense over the 40-year catalog and the consistent rate of seismicity over each completeness
125 magnitude period (Supporting Information) confirms that the declustered catalog represents
126 background seismicity and does not include temporal stress state variations.

127 The MSATSI code, which is based on the SATSI algorithm (Hardebeck & Michael,
128 2006), performs formal stress inversions to derive normalized deviatoric stress tensors from
129 groups of focal mechanisms (Martínez-Garzón et al., 2014). Because the declustered catalog of
130 focal mechanisms generally has fault plane uncertainties $< 40^\circ$, each group of focal mechanisms
131 must include a minimum of 40 events to robustly estimate the stress tensor (Martínez-Garzón et
132 al., 2016). The 40-year catalog along the southern SAFS and San Jacinto Fault system (SJFS)
133 yields 54 clusters of focal mechanisms from which we derive stress states. From 1000 bootstrap
134 resamplings of the fault plane, we estimate $\pm 10^\circ$ uncertainty of the orientation of the principal
135 stress axes and 25% uncertainty of the deviatoric stress tensor components. We compare the
136 horizontal maximum stress orientations for the 54 stress states to those of the forward model.

137 2.2 Forward models

138 We utilize the Boundary Element Method (BEM) code Poly3D (Thomas, 1993), which
139 solves the governing equations of continuum mechanics to calculate displacements and stresses
140 within the model to simulate faulting within the crust (e.g., Crouch and Starfield, 1990). The

141 forward models simulate both long-term and interseismic loading of 1) a simple, isolated and
 142 vertical strike-slip fault and 2) the complex southern SAFS and SJFS in the San Gorgonio Pass
 143 region within a homogeneous and linear-elastic half space (Figure 3). For the complex fault
 144 forward models, we utilize the inactive northern slip pathway geometry from Hatch et al. (2023),
 145 which is primarily based on the Southern California Earthquake Center’s Community Fault
 146 Model version 5.3 (Marshall et al., 2021) with some modifications that improve the model fit to
 147 geologic slip rates and uplift (e.g., Herbert and Cooke, 2012; Fattaruso et al., 2014; Hatch et al.,
 148 2023). We discretize the fault surfaces into triangular elements that can capture fault curvature
 149 and branching. Within all forward models, we prescribe zero opening/closing along all faults.
 150 Faults in the long-term forward models intersect a horizontal basal crack at 35 km depth that
 151 simulates distributed deformation below the seismogenic zone (Supporting Information;
 152 Marshall et al., 2009).

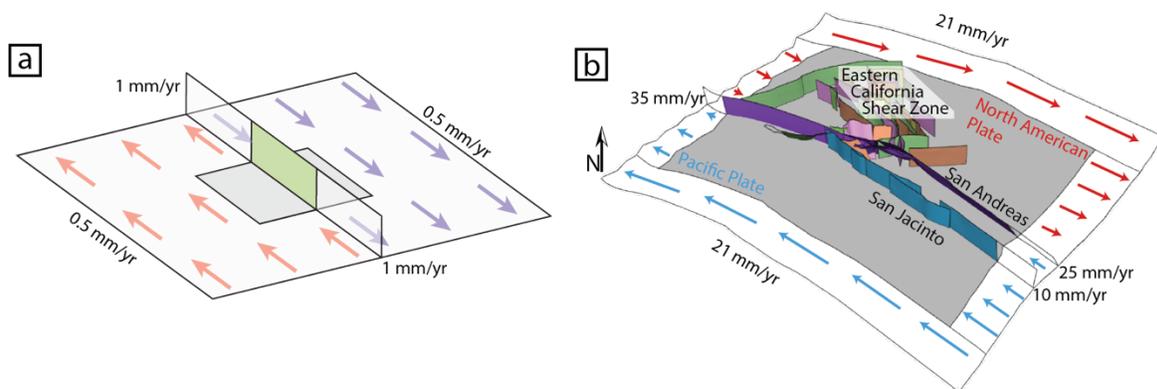


Figure 3. The long-term forward model geometries of the a) simple and b) complex fault models. a) The green surface indicates the area we use to calculate the inverse model misfit and show in Figure 4 and 5b-h. Rates adjacent to extended fault patches indicate the applied slip rates. Arrows on the far-field basal crack show applied loading. b) Modified from Beyer et al. 2018. Arrows indicate the applied tectonic velocities along the far-field basal crack.

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 154 We simulate interseismic deformation in a two-step back-slip-like approach following
 155 Marshall et al. (2009). In the first step, a suite of forward models simulates deformation over
 156 several earthquake cycles. Shear-traction-free faults slip freely in response to loading along far-
 157 field horizontal basal patches and slip along nearby faults. The zero shear traction condition
 158 simulates low dynamic strength conditions, which is when most of the fault slip occurs (e.g., Di
 159 Toro et al., 2006; Goldsby and Tullis, 2011). Following Beyer et al. (2018), we implement an
 160 iterative technique to prescribe the desired loading velocity at the model edges (Figure 3). To
 161 prevent fault slip rates from artificially going to zero at the lateral edges of the model, we apply

162 slip to driving patches for all faults that extend past the bounds of both models. For the simple
163 fault model of an idealized strike-slip fault, we prescribe far-field loading along the basal crack
164 and apply slip to driving patches that produces a nearly uniform strike-slip rate of 1 mm/yr along
165 the vertical fault (Figure 3a). For the complex fault model, we prescribe slip along far-field basal
166 patches consistent with 42 mm/yr of far-field loading at an orientation of 322° following Herbert
167 and Cooke (2012)(Figure 3b). Following Beyer et al. (2018), we apply slip rates to driving
168 patches in the complex fault model based on published slip rate estimates for each fault segment
169 (e.g., Sharp, 1981; Weldon and Sieh, 1985; Fay and Humphreys, 2005; Meade and Hager, 2005;
170 McPhillips and Scharer, 2018)

171 In the second suite of forward models, we apply the long-term model slip rates below a
172 prescribed locking depth to simulate interseismic deformation. For the simple fault model, we
173 test the inverse approach with forward model locking depths of 10, 15, and 20 km. For the
174 complex fault model, we utilize a locking depth of 20 km based on the maximum depth of
175 seismicity across the San Gorgonio Pass region (e.g., Yule and Sieh, 2003). To reduce artifacts
176 that would result from an abrupt change in prescribed slip at the locking depth, we create a
177 transition zone by prescribing half of the long-term slip rate to elements that have centroids
178 within 2.5 km of the locking depth. This study tests if the new inverse approach can recover deep
179 interseismic slip rates along complex fault geometries that include closely spaced and branched
180 faults. For simplicity of this test, the complex interseismic model only applies deep slip from the
181 first suite of forward models along the primary faults in the region, the San Andreas and San
182 Jacinto faults. The interseismic models produce surface velocities and stressing-rate tensors at
183 regularly spaced points for both the simple and complex fault models. Within the complex fault
184 model, we additionally query surface velocities at specific GNSS station locations and stressing-
185 rate tensors at locations of recorded microseismicity. To compare the interseismic principal
186 stress orientations with those derived from crustal focal mechanisms, the model includes all of
187 the faults shown in Figure 1, not only the primary faults.

188 2.3 Inverse models

189 We use the MATLAB code TriInv (Loveless & Evans, 2020), which is based on
190 algorithms from Meade (2007), to calculate partial derivatives that relate the stressing rates or
191 surface velocities at specific locations to unit slip rate on each triangular dislocation element

192 within each model. Because MSATSI produces normalized deviatoric stress tensors, we set up
193 separate inversions for the forward model-generated full, deviatoric, and normalized deviatoric
194 stressing-rate tensors. For deviatoric and normalized deviatoric stressing-rate tensor inversions,
195 we remove the mean stress component of the partial derivative. Laplacian smoothing within the
196 inversions prevents abrupt steps in slip rates that would not be expected along crustal faults. We
197 test a range of smoothing weighting parameters to optimize the surface velocity, stressing rate,
198 and joint inverse model performance. The results of the smoothing parameter value testing are
199 independent of the surface velocity and stressing-rate tensor spacing. Within all inversions,
200 elements in direct contact with the free surface of the model (0 km depth) are locked and
201 opening/closing is prohibited. However, we do not constrain the locking depth or sense of slip on
202 any faults in the inverse models.

203 We assess the performance of individual and joint inversions that use forward model-
204 generated surface velocities and stressing-rate tensors. The simple fault model allows us to
205 determine the optimal stressing-rate tensor configuration and smoothing weight. Inversions of
206 regularly gridded surface velocities have 10 km spacing, which is based on the approximate
207 current permanent GNSS station density in the San Gorgonio Pass region (Figure 1). We test 60
208 stressing-rate tensor configurations that are based on the microseismicity in the San Gorgonio
209 Pass region, which generally occurs above 20 km depth. Because each stressing-rate tensor
210 represents a potential centroid of a group of microseismic focal mechanisms with a radius
211 between 2.5 and 7.5 km, we limit the stressing-rate tensor depths to between 15 and 7.5 km. All
212 the stressing-rate tensor configurations include either a single row of tensors at a single depth
213 (7.5, 10, 12.5, or 15 km) or two rows of tensors at two separate depths (7.5 and 15 km) on either
214 side of the simple fault. To reduce overlap of focal mechanisms within each group, we define a
215 10 km minimum along-strike spacing of stressing-rate tensors and only test two rows for
216 stressing-rate tensors at 7.5 and 15 km depths. To reduce the chance that a focal mechanism
217 group would include microseismicity on both sides of the same fault, all stressing-rate tensor
218 locations are at least 5 km away from the fault. We assess the same spacings for the simple
219 interseismic forward model with three different locking depths: 10, 15, or 20 km; this allows us
220 to assess the impact of locking depth on the stressing-rate tensor configuration that best recovers
221 the forward model slip rates.

222 We use the complex fault model to assess the performance of inversions on a
 223 geometrically complicated fault system consisting of multiple closely spaced (< 12 km) and
 224 interconnected faults. We invert the forward model-generated stressing-rate tensors and surface
 225 velocities using a model with two slip pathways from Hatch et al. (2023) to assess how well the
 226 inversions recover slip along the portion of the northern slip pathway that is inactive in the
 227 forward models. The complex fault model inversions utilize regularly spaced surface velocities
 228 and the configuration of stressing-rate tensors that optimizes the simple fault model inversion
 229 performance as well as surface velocities at GNSS station locations and stressing-rate tensors at
 230 locations of microseismicity groups. We prescribe an uncertainty of 0.3 mm/yr to all surface
 231 velocity components, which is based on the lowest estimates of GNSS errors for stations that we
 232 include (Sandwell et al., 2016). We query stressing-rate tensors at 100 locations following the
 233 optimal distribution informed by the simple fault model. Inverse models utilize either all 100
 234 tensors or only 54 tensors at locations with more than 39 nearby cataloged focal mechanisms,
 235 which allows for a robust stress state estimate. We prescribe a conservative uncertainty of 25%
 236 to all stressing-rate tensor components, at the high end of the estimated uncertainty. When
 237 describing the inversions that use only the 54 stressing-rate tensors at locations with more than
 238 39 nearby focal mechanisms and the surface velocities at locations of GNSS stations, we refer to
 239 these inversions as using crustal limited locations or as crustal limited inversions.

240 To assess how well each inversion of forward model-generated stress rate and velocity
 241 predictions recovers the prescribed fault slip rates, we calculate the misfit of the inverse model
 242 slip rate distribution to the forward model applied slip rate. Because the root-mean-square error
 243 can overestimate the model error by emphasizing outliers (Willmott et al., 2017), we define the
 244 model performance based on the inverse model misfit to the forward model slip distribution with
 245 the area-weighted average misfit per element using Equation 1, where j is the number of
 246 elements, S_I is the inversion estimated slip rate for an element, S_F is the forward model slip rate
 247 for an element, and A is the area for an element.

$$248 \quad \text{Misfit} = \frac{\sum_1^j |S_I - S_F| * A}{\sum_1^j A} \quad (\text{Equation 1})$$

249 **3 Simple Fault Model Results**250 **3.1 Determination of the optimal stressing-rate tensor spacing**

251 An assessment of 60 different stressing-rate tensor configurations reveals the spatial
 252 configuration of stressing-rate tensors that best recover the forward-model slip rate distribution
 253 (Figure 4a-e). Figures 4 and 5 present results from inversions of stressing-rate tensors and
 254 surface velocities generated by a forward model with a 15 km locking depth, and the Supporting
 255 Information contains results from the models with 10 and 20 km locking depths. The forward-
 256 model prescribed locking depth does not significantly impact the optimal stressing-rate tensor
 257 spacing (Figure S2). Twenty-three of the 60 stressing-rate tensor spacings that we test produce
 258 misfits less than or equal to the surface velocity inversion misfit of 0.08 mm/yr. Increasing the
 259 tensor depth and distance from the fault generally improves the inverse model performance
 260 (Figure 4a-d). Inverting stressing-rate tensors at two separate depths rather than at a single depth
 261 improves model performance (Figure 4a-e). Inverting stressing-rate tensors at both 7.5 and 15
 262 km depth at points that are 5 or 10 km away from the fault with along-strike spacing of 10 km
 263 best recover the forward model prescribed slip rate distribution (Figure 4a-e and Figure S2). As
 264 the along-strike spacing increases to 15 and 20 km, the inverse model performance generally
 265 decreases.

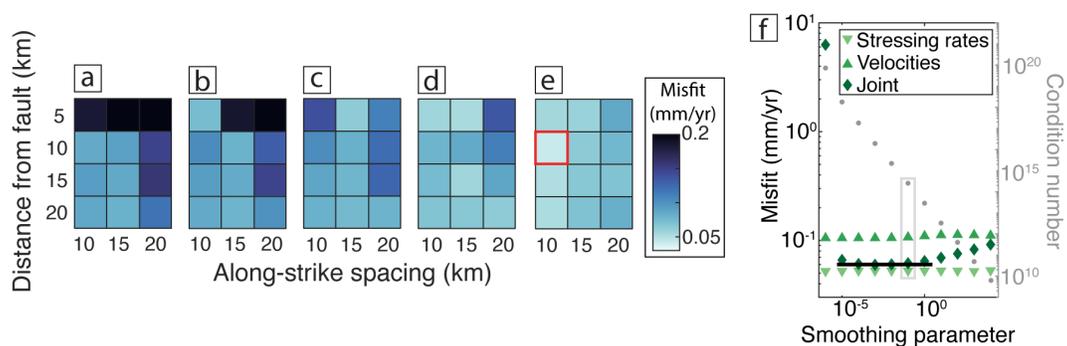


Figure 4. a-e) Each square represents one stressing-rate tensor spacing with the color indicating the average element misfit. We invert one row of stressing-rate tensors at a) 7.5, b) 10, c) 12.5, or d) 15 km depth or two rows of stressing-rate tensors at e) 7.5 and 15 km depths. The red box indicates the optimal spacing. f) Average element misfit (left y-axis) and joint inversion condition number (right y-axis) against smoothing parameter for inversions that use surface velocities with 10 km spacing and stressing-rate tensors with the optimal spacing (red box in e). The black line shows the minimum misfit for the joint inversion. The gray rectangle indicates the smoothing parameter value we use.

267 We present the smoothing parameter value assessment results from inversions that utilize
268 two rows of stressing-rate tensors at 7.5 and 15 km depths that are 10 km away from the fault
269 with 10 km along-strike spacing (Figure 4f). Varying the smoothing parameter impacts both the
270 inversion misfit and condition number. A lower condition number indicates the inversion has
271 greater numerical stability. Because using a smoothing parameter value of 0.1 produces misfits
272 within 2% of the minimum misfit and a condition number three orders of magnitude lower than
273 the inversions that produce minimum misfits (Figure 4f), we use this smoothing parameter value
274 for all the inversions.

275 3.2 Assessment of the inversion performance

276 We compare the area-weighted average element misfit for the portion of the fault
277 displayed in Figure 5a to determine which inverse model best recovers the forward model slip
278 rate distribution (Figure 5b). The inversions that use surface velocities and stressing-rate tensors
279 that include magnitude recover both the magnitude and pattern of forward model slip rates well
280 (Figure 5c-g). Even without prescribing a locking depth within the inversion, the inverse models
281 recover the forward-model locking depth well. The inversions estimate a broader locking depth
282 transition zone than is prescribed in the forward model, but the inversions recover slip rates
283 slower than 0.1 mm/yr for all elements above 10 km, which are locked in the forward model
284 (Figure 5). The inversion of the surface velocities produces a misfit of 0.08 mm/yr, which
285 exceeds that of the stressing-rate tensor inversion of 0.06 mm/yr. The joint inversion that utilizes
286 both full stressing-rate tensors and surface velocities outperforms both individual inversions
287 producing a misfit of 0.04 mm/yr.

288 The largest difference between the inverse models and the forward model applied slip
289 rates are along elements with at least one vertex at the locking depth of 15 km (Figure 5c-h). The
290 inversions overestimate slip on elements just above the locking depth transition zone and
291 underestimate slip on elements within and below the locking depth transition zone. This result
292 highlights the limit of this inverse approach to capture sharp changes in slip rate along faults due
293 to the applied Laplacian smoothing. Because we do not have evidence that locking depth
294 transition zones within the crust are as sharp as we prescribe in the forward models, this
295 smoothing across the locking depth does not cause concern. However, implementing a sparsity-
296 promoting regularization instead of Laplacian smoothing could better recover sharp changes in

297 slip rates (e.g., Evans and Meade, 2012).

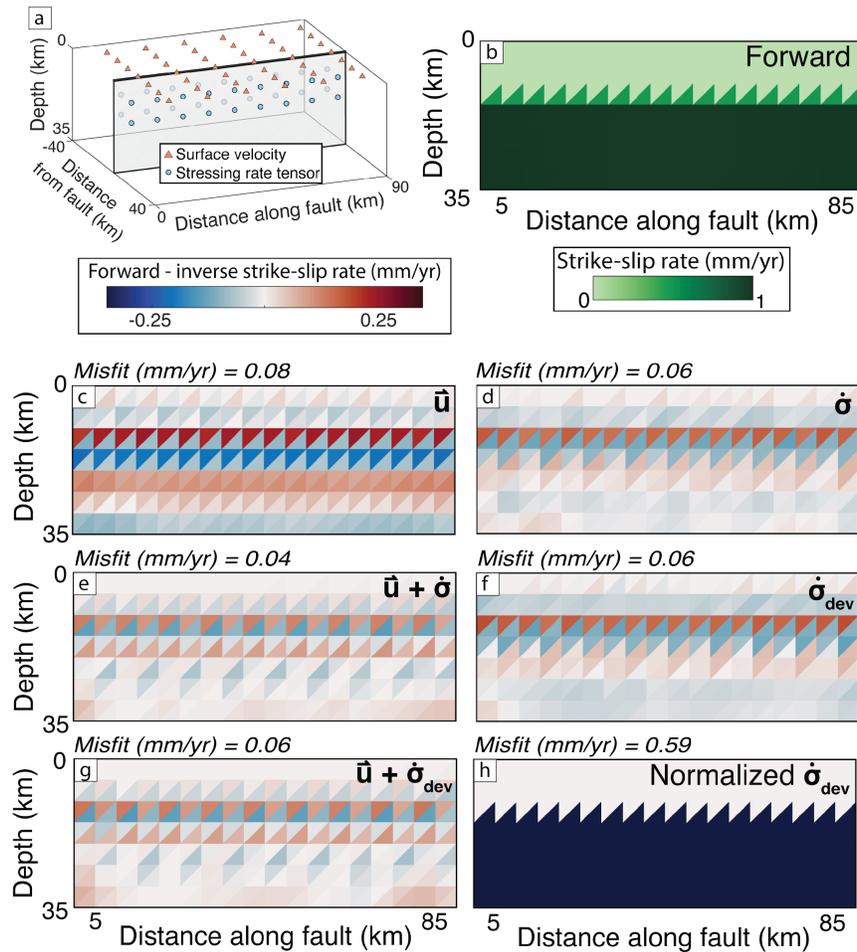


Figure 5. a) The 3-D fault model geometry with the optimal stressing-rate tensor spacing and the grid of surface velocities. b-h show the strike-slip rate or strike-slip rate difference for the patch shown in a. b) The 15 km locking depth interseismic forward model applied strike-slip rates. c-h) The difference between the forward model applied strike-slip rates and the inversion estimated strike-slip rates. Blue indicates the inversion underestimates slip rates and red indicates the inversion overestimates slip rates.

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Because current methods of deriving stress information from focal mechanisms produce normalized deviatoric stress tensors (e.g., Martínez-Garzón et al., 2014), we assess the performance of inverse models that use either deviatoric or normalized deviatoric stressing-rate tensors. These inversions reveal the impact of removing the mean normal stress component and stress magnitude from the inverse model constraint. Removing the mean normal stress from the full stressing-rate tensor does not significantly impact the inverse model performance. The deviatoric stressing-rate tensor inversion produces a misfit equal to that of the full stressing-rate tensor inversion (0.06 mm/yr). Because the normalized deviatoric stressing-rate tensors lack

307 magnitude, the inversion is poorly posed to recover slip rates with magnitude. As we expect,
308 removing the stressing-rate tensor magnitude leads to the inverse model estimating near zero slip
309 rates along the entire fault. Consequently, the inversion recovers the locked, shallow portion of
310 the fault well but not the deep slip rates or the locking depth. Because the normalized deviatoric
311 stressing-rate tensor inversion for the simple fault model failed to recover the forward model slip
312 rate distribution, henceforth, we only discuss results from model inversions that use full or
313 deviatoric stressing-rate tensors that include magnitude.

314 Overall, the joint inversions recover the forward model slip better than or as well as the
315 individual inversions (Figure 5). Although the individual deviatoric and full stressing-rate tensor
316 inversions perform similarly, the joint inversion that utilizes the deviatoric stressing-rate tensors
317 does not recover the slip rates near the locking depth transition zone as well as the joint inversion
318 that utilizes the full stressing-rate tensors. Simultaneously inverting the surface velocities and
319 deviatoric stressing-rate tensors recovers the forward model slip rate distribution better than or as
320 well as all the individual inversions.

321 **4 Complex Fault Model Results**

322 4.1 Forward model validation

323 To validate the complex forward fault models, we compare the maximum horizontal
324 compression orientation for the model and focal mechanism-derived stress tensors (Figure 6). At
325 29 of the 54 crustal locations, the forward interseismic model produces maximum horizontal
326 compression orientations that are within 2 standard deviations ($3\text{-}15^\circ$) of the crustal orientations.
327 The stress states derived from focal mechanisms show spatial variations in the maximum
328 horizontal compression orientation whereas the forward model-generated stressing-rate tensors
329 produce relatively uniform approximately north-south oriented maximum horizontal
330 compression orientations across the region of interest. Most of the locations where the model
331 results do not match the crustal data well are at 7.5 km depth and near the inactive portion of the
332 northern slip pathway (Figure 6). Where the model results differ from crustal data, the model
333 may not completely capture the crustal faulting behavior. For example, some fault structures may
334 be oversimplified or missing from the model, such as the Cox Ranch and Beaumont Plain fault
335 zones (e.g., Yule and Sieh, 2003), which could impact the maximum horizontal compression
336 orientation at specific locations. Further exploration of the activity and geometry of faults along

337 and near the northern slip pathway along the SAFS in the San Geronio pass region may provide
 338 insight on how to improve the model fit to the crustal data. Overall, the forward model results are
 339 consistent with regional studies that invert focal mechanisms for the entire area and show
 340 approximately north-south oriented horizontal maximum compression (e.g., Hardebeck and
 341 Hauksson, 2001).

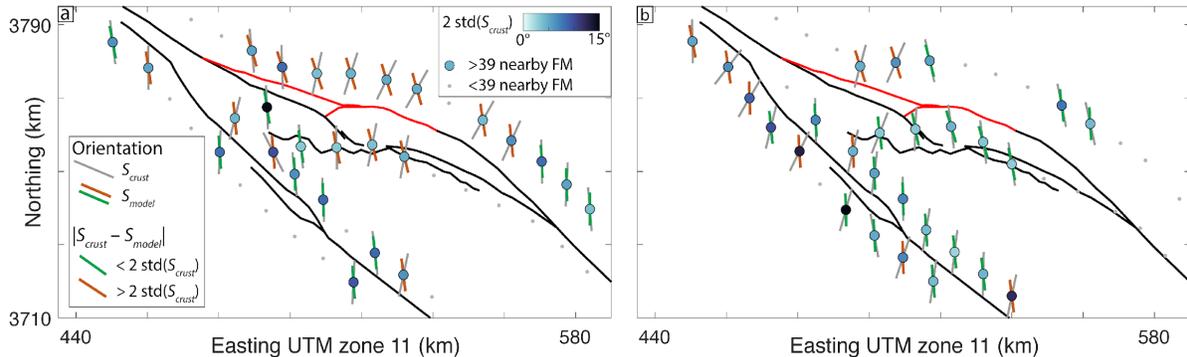


Figure 6. Maximum horizontal compression orientation (red line) for the focal mechanism derived normalized deviatoric stress tensors (S_{crust} , gray lines) and the forward model generated stressing-rate tensors (S_{model} , green/orange lines) at 7.5 (a) and 15 km (b) depths. Green lines indicate the model results are within 2 standard deviations (std) of the focal mechanism derived results. Circle color shows 2 std of the focal mechanism derived results. Black lines show surface traces of active faults in the forward interseismic models and red lines indicate surface traces of faults that are inactive in the forward models.

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343 4.2 Inverse model results

344 We present results from inversions of forward model-generated deviatoric stressing-rate
 345 tensors and surface velocities that are either regularly spaced or only at locations where data is
 346 currently available from the southern California focal mechanism catalog and GNSS stations
 347 (Figures 1 & 7). Similar to the simple fault model inversions, all the complex inverse models
 348 recover the approximate locking depth applied in the forward model. For all the complex fault
 349 model inversions, the area-weighted average element misfit increases with depth until ~22.5 km
 350 depth, below which the average misfits remain high (Figure 8a). In general, the misfit for the
 351 joint inversions increases less with depth compared to the individual inversions, meaning that for
 352 the joint inversions, the resolution of slip rates is more equal at all depths compared to individual
 353 inversions (Figure 8a). As a consequence of the smoothing, the inversion underestimates slip
 354 rates below the locking depth. Because this misfit is pervasive across the entire model and is not
 355 localized to one fault strand or segment, the overall misfit with depth is generally largest within 5

356 km of the 20 km locking depth (Figure 8a). The joint inversions produce smaller misfits than
 357 both individual inversions that use regularly spaced and crustal limited locations (Figure 8).

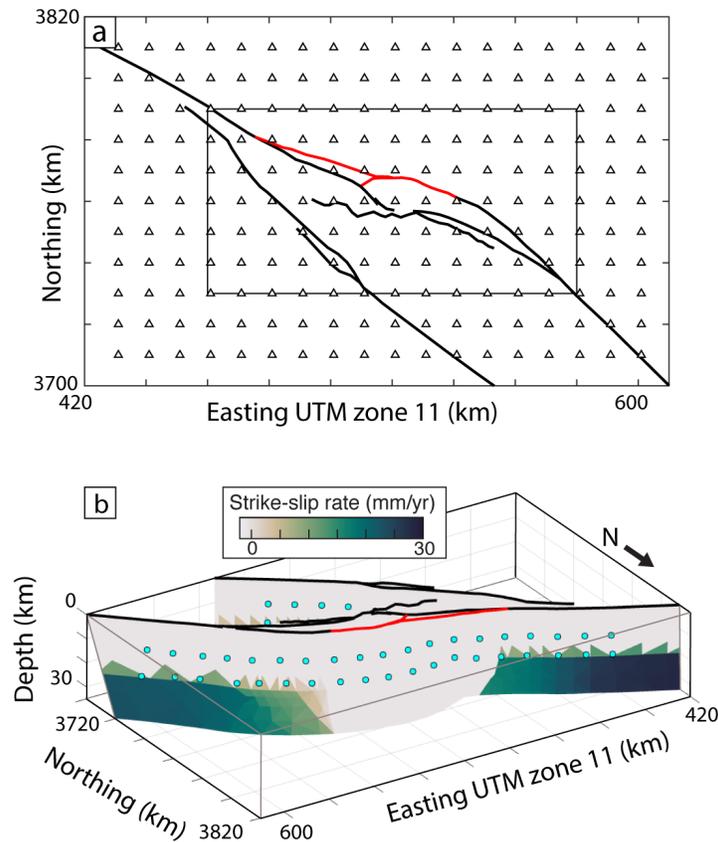


Figure 7. Locations of regularly spaced a) surface velocities (triangles) and b) stressing-rate tensors (circles) for the complex fault model. Red fault trace indicates the inactive portion of the northern slip pathway in forward models. a) Map view with black box indicating the region used for misfit calculations. b) Oblique view of SAFS and SJFS geometry colored by the forward model slip rates.

358

359 To determine which inversion of regularly spaced data best recovers the forward model
 360 slip distribution for the entire region of interest, we compare the area-weighted average element
 361 slip rate misfit (Equation 1; Figure 8). The regularly spaced surface velocity inversion produces
 362 an overall slip rate misfit of 1.4 mm/yr, which is slightly larger than the 1.3 mm/yr misfit of the
 363 regularly spaced deviatoric stressing-rate tensor inversion (Figure 8b). The regularly spaced
 364 stressing-rate tensor inversion recovers forward model slip better above and within the locking
 365 depth transition zone than the regularly spaced surface velocity inversions (Figure 8b). Inverting
 366 the regularly spaced data jointly produces the lowest misfit (1.0 mm/yr; Figure 8b).

367 Inversions that utilize stressing-rate and velocity data only at crustal limited locations
 368 generally recover the forward model locking depth and slip rate distribution (Figure 8). For
 369 individual inversions, inverting crustal limited deviatoric stressing-rate tensors produces a larger
 370 misfit than the crustal limited surface velocity misfit ($1.8 > 1.4$ mm/yr). Below the locking depth,
 371 the inversion of deviatoric stressing-rate tensors at crustal limited locations does not recover
 372 deep slip rates as well as the inversion of surface velocities at GNSS station locations (Figure 8).
 373 The crustal limited joint inversion produces a lower misfit (1.2 mm/yr) than the individual
 374 crustal limited and regularly spaced inversions (Figure 8b).

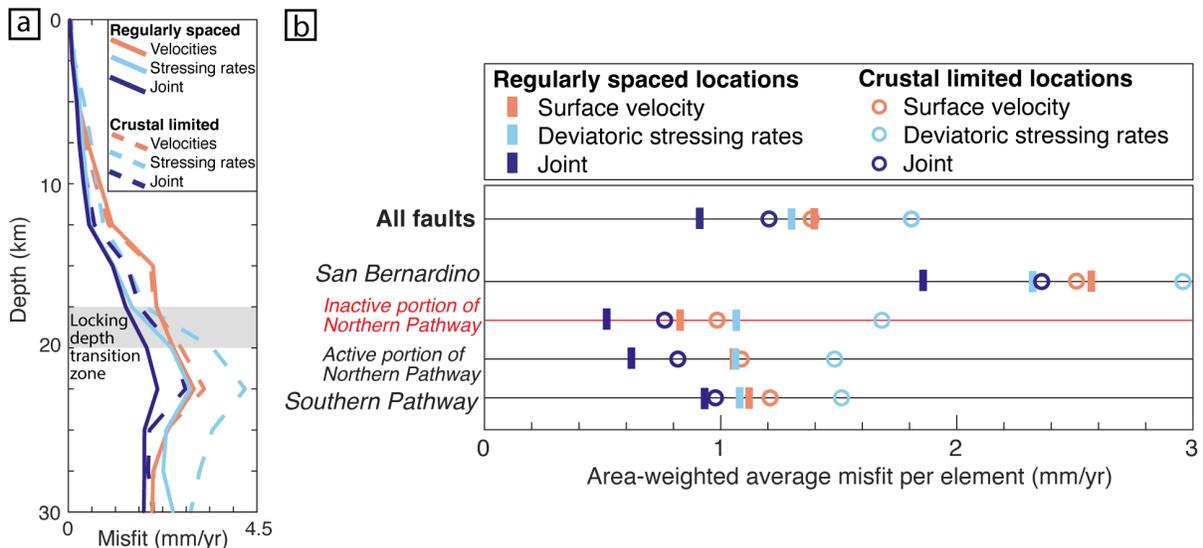


Figure 8. The area-weighted average element misfit a) with depth and b) for the entire region of interest and individual fault segments for the deviatoric stressing-rate tensor (light blue), surface velocity (orange) and joint (indigo) inversions. a) Each point is the misfit for elements within 2.5 km of the specified depth. Solid lines – regularly spaced inversions. Dashed lines – crustal limited inversions. b) Vertical lines – regularly spaced inversions. Open circles – crustal limited inversions.

375
 376 Inverting regularly spaced stressing-rate tensors and surface velocities improves the
 377 overall inversion performance compared to inverting only information at crustal limited
 378 locations. The regularly spaced surface velocity inversion includes 198 surface velocity
 379 locations, and the crustal limited surface velocity inversion includes 201 locations. The small
 380 difference in the number of constraining data may explain the similar misfit of both surface
 381 velocity inversions, but the difference in spatial distribution of the constraining data could
 382 contribute to the differences in the misfits along individual fault strands or segments (Figure 8).
 383 Reducing the number of deviatoric stressing-rate tensors that constrain the individual inversions

384 from 100 to 54 leads to an overall increase in the inverse model misfit to the forward model slip-
 385 rate distribution. Furthermore, the 54 deviatoric stressing-rate tensor crustal limited locations are
 386 not evenly distributed across the region of interest. A significant gap in microseismicity along
 387 the southern SAFS reduces the number of stressing-rate tensors constraining the inversion by
 388 33% (Figures 1 & 6). This reduction could explain why the crustal limited deviatoric stressing-
 389 rate tensor inversion cannot resolve slip rates along some fault segments as well as the regularly
 390 spaced deviatoric stressing-rate tensor inversion.

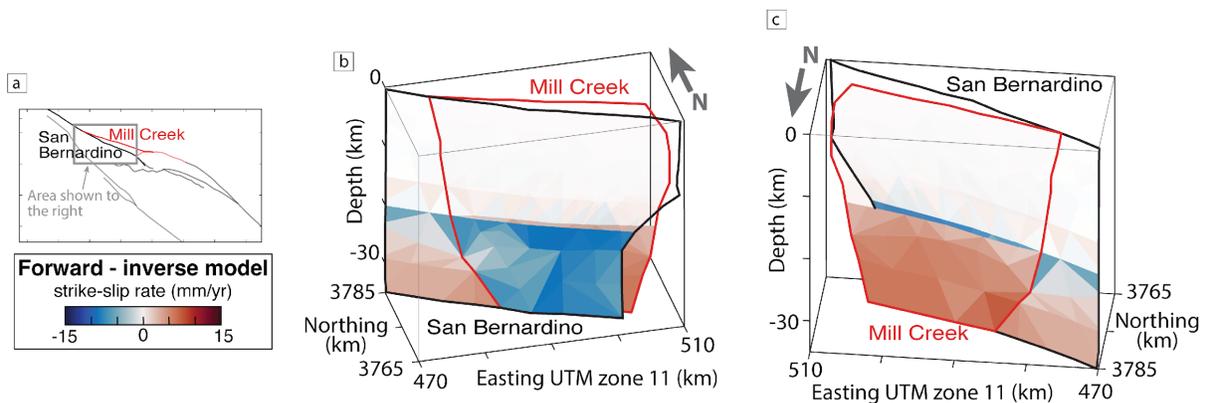


Figure 9. The difference between the forward model applied and the regularly spaced stressing-rate tensor inversion estimated strike-slip rates along the Mill Creek strand (red outline) and the San Bernardino segment (black outline). a) Map of region of interest with gray box indicating the area shown in perspective views in b (from the south) and c (from the north). b and c) Red elements indicate the inverse model overestimates slip rates while blue elements indicate the inverse model underestimates slip rates. Fault elements are transparent above the 20 km locking depth.

391
 392 We expect the largest misfits around fault branches and along closely spaced faults where
 393 inversions cannot uniquely resolve slip rates. The San Bernardino segment directly connects to
 394 both the inactive portion of the northern slip pathway and the active southern pathway of the
 395 southern SAFS forming a branched fault (Figure 1). Comparing the slip rate misfits along
 396 individual fault segments and strands provides insight on how well each inversion can recover
 397 slip rates at fault branches and along the two subparallel slip pathways of the southern SAFS.
 398 The San Bernardino segment of the SAFS yields the greatest misfit for all the inversions (Figure
 399 8b). Due to smoothing of slip rate across faults within the inversion, the inverse models
 400 overestimate slip rates along the inactive portion of the northern pathway (Figure 9 red colors)
 401 and underestimate slip rates along the adjacent San Bernardino segment (Figure 9 blue colors).
 402 The tradeoff in slip rates among the branched fault segments is lesser for the joint inversion. As a

403 result, the joint inversion misfits along the inactive portion of the northern pathway and the San
404 Bernardino segment are smaller than the misfits for the inversions of individual constraints.

405 **5 Discussion**

406 5.1 Constraint weighting in joint inversions

407 The weighting of surface velocities and stressing-rate tensors within the inversions
408 depends on three parameters: 1) the relative numbers of constraint components, 2) the prescribed
409 uncertainties, and 3) smoothing weighting. Because multiple factors impact the weighting of
410 differing data types, the surface velocities and stressing-rate tensors are likely not equally
411 weighted in the joint inversions. Each stressing-rate tensor consists of six components (three
412 shear and three normal), and each surface velocity consists of two components (east and north).
413 For the regularly spaced joint inversions, a greater number of stressing-rate tensor components
414 constrain the inversion than surface velocity components; this means that the stressing-rate
415 tensors may have more weight in the joint inversion than the surface velocities. In contrast, for
416 the crustal limited joint inversions, a greater number of surface velocity components constrain
417 the inversion than stressing-rate tensor components. Regardless of the ratio of stressing-rate
418 tensor to surface velocity components constraining the inversions, increasing the amount of
419 constraining information improves the inverse model's recovery of forward model slip rates.
420 Increasing the number of surface velocity locations by utilizing campaign GNSS stations or
421 InSAR data could potentially improve the inversion performance. The second factor that impacts
422 the weighting of the two data types is the uncertainty we prescribe to each component. Because
423 each component for surface velocities and stressing-rate tensors has uncertainty of 20-40% of the
424 component, the two data types have similar weighting in the joint inversions. Since the
425 smoothing weighting can also impact how the inverse model constraining information is
426 weighted, we assess the impact of varying the smoothing weighting on the slip rate misfit for the
427 complex fault inversions. We find that a range of smoothing weightings (varying by a factor of
428 10^4) for all the inversions produce slip rate misfits that vary by < 0.05 mm/yr (Supporting
429 Information), which suggests that the inversions are more sensitive to the number and location of
430 constraining data than the smoothing weighting.

5.2 Comparison of individual inverse model results

The regularly spaced stressing-rate tensor inversions may have better overall performance than the surface velocity inversions because the stressing-rate tensors are at depth, closer to the locking depth transition zone and the slipping portion of faults. The stressing-rate tensor spacing assessment shows that for inversions that utilize stressing-rate tensors at a single depth the misfit generally decreases as the stressing-rate tensor depth increases. Many of the simple fault model stressing-rate tensor inversions that utilized tensors at a single depth outperformed the surface velocity inversion, and the addition of stressing-rate tensors at a second depth further improved the stressing-rate tensor inversion performance. Furthermore, the joint inversions include constraints at three separate depths (0, 7.5 and 15 km) and best recover forward model slip rates for both the simple fault and complex fault models. Inverting velocity and stressing-rate data at multiple depths may more robustly capture spatial variations in the stressing-rate and velocity field than inversions that utilize constraints at a single depth. More information on spatial variations of conditions may yield more accurate inversions for slip rate.

For the complex fault model, the surface velocity inversions can recover deep interseismic slip rates (> 25 km depth) better than stressing-rate tensor inversions (Figure 8a). The assessment of the optimal spacing of stressing-rate tensors shows that decreasing the along-strike tensor spacing from 20 km to 10 km can improve the inversion performance (Figure 4a-e), suggesting that stressing-rate tensors may provide higher resolution slip rate information over short distances (10-15 km). Consequently, the stressing-rate tensors provide better slip rate information along portions of faults closest to the tensors (< 25 km depth) than below the locking depth. Even though the interseismic surface velocities are farther from the slipping portions of faults than the subsurface stressing-rate tensors, the ability of the surface velocities to resolve slip rates is less sensitive to their distance from the fault. As a result, surface velocity inversions may better constrain interseismic slip rates along deep portions of the fault (> 25 km depth) than stressing-rate tensor inversions (Figure 8a). In addition to having a greater number of inputs, the joint inversion takes advantage of the benefits of both data types, which improves the inverse model performance compared to individual inversions (Figure 8).

5.3 Future application to natural fault systems

The complex fault models show that joint inversions of stressing-rate tensors and surface velocities could improve current estimates of slip rates along closely spaced and branching faults; the distribution of these rates can help constrain both the locking depth and relative activity of closely spaced faults. For example, joint inversions resolve slip rates well along the northern pathway of the southern SAFS through the San Gorgonio Pass where fault activity remains debated (e.g., Kendrick et al., 2015; Blisniuk et al., 2021).

Implementing the inverse method that we present here for any crustal fault system requires a priori information including geodetic and microseismic catalogs as well as a three-dimensional fault geometry, and uncertainty or inaccuracy in the inverse model inputs propagates through the model. Because we invert forward model generated stressing-rate tensors and surface velocities, we know that the fault geometry used in the inversions is accurate. As a consequence, the inversion misfits that we calculate exclude uncertainty that may stem from uncertainty or inaccuracy in the model fault geometry. In addition to uncertainty related to the a priori information, model parameters, such as fault element size, may impact the inverse model performance. In this study, the simple and complex fault models have average element lengths of 3-5 km. Future applications of the inverse method we present here should consider that the average element length could impact the optimal stressing-rate tensor spacing.

Because microseismicity in the crust is generally not evenly distributed across a region (Figure 1), the optimal regular spacing that we determine from the idealized simple fault model may not be available for crustal data sets. For the complex SAFS model, limiting the stressing-rate tensor locations to points with sufficient nearby recorded focal mechanisms increases the average misfit of the joint inversion, but the inversion estimates < 2.0 mm/yr of strike-slip along the inactive northern pathway. With time and additional microseismicity, focal mechanism catalogs may enable additional tensor locations to be included in the model, which would improve the spatial consistency in model performance.

Another challenge prevents us from applying this new method to crustal data at this time: we do not know of a method to reliably estimate deviatoric stress magnitude and stressing rate within the crust. The results of this study show that inversions of deviatoric stressing-rate tensors perform as well as inversions that utilize full stressing-rate tensors, meaning that inversions of crustal data would not require mean normal stress state information. The stress states inferred

490 from focal mechanisms provide normalized stress due to microseismicity but not magnitudes. A
491 recent study provides a method to estimate absolute stress magnitude from focal mechanisms and
492 precisely located earthquakes (Fialko, 2021). However, absolute stress does not directly
493 correspond to interseismic stressing rates that are necessary to invert for slip rates. Absolute
494 stress evolves with time since the last earthquake so that microseismicity responds to the total
495 stress state, which includes the effect of accumulated tectonic loading, not solely stressing rates
496 from interseismic loading. If we can derive crustal deviatoric stressing rates, then we may be
497 able to provide additional constraint on deep slip rates along faults in the San Gorgonio Pass
498 region, which would reveal locking depths and relative fault activity.

499 **6 Conclusions**

500 We present a new method that utilizes interseismic surface velocities and subsurface
501 stressing-rate tensors to estimate three-dimensional slip rate distributions along a simple, isolated
502 strike-slip fault model and a complex fault model that simulates the southern SAFS. The
503 inversions of forward model-generated stressing-rate tensors and surface velocities for the simple
504 fault model reveal that a sparse, regularly spaced distribution of stressing-rate tensors can
505 recover the forward model slip rate distribution better than surface velocity inversions alone.
506 Additionally, inversions that utilize deviatoric stressing-rate tensors recover the slip rates along
507 faults as well as inversions of full stressing-rate tensors. Inverting forward-model-generated
508 surface velocities and subsurface stressing-rate tensors jointly recovers both the simple and
509 complex forward model applied slip rate distributions better than inverting velocity and stress
510 information individually. For the complex fault model that simulates the SAFS through the San
511 Gorgonio Pass region, inversions of regularly spaced velocity and stress information recover the
512 forward model slip rates better than inversions of velocity and stress information only at
513 locations where crustal data is currently available.

514 Joint inversions of surface velocities from GNSS stations and subsurface deviatoric
515 stressing rates potentially derived from microseismic focal mechanisms could provide additional
516 constraint on the deep slip distribution and as a result both the interseismic locking depth and
517 relative activity of faults along closely spaced faults. The complex fault inversions generally
518 recover very slow slip rates along the northern pathway of the SAFS that is inactive in the
519 forward model, suggesting that the method we present here could be used to inform the activity

520 of the northern and southern pathways of the SAFS through the San Gorgonio Pass. However,
521 prior to applying this new method to invert crustal datasets, we require a method to reliably
522 estimate the deviatoric stressing rates that include magnitude. With an increase in the number of
523 available microseismic focal mechanisms with time and a method to calculate stressing rates
524 from focal mechanisms or other data, the method we present here could improve constraints on
525 fault slip rate distributions in regions with closely spaced and branching faults.

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530 **Open Research**

531 The crustal deformation software Poly3D is made available by the Stanford Tectonic
532 Geomorphology lab at <https://github.com/stgl/poly3d>. The inversion software TriInv is available
533 at <https://github.com/jploveless/triinv>. The Poly3D and TriInv input files for the simple and
534 complex fault models are available for download via figshare (Elston et al., 2023).

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