Sensitivity of deformation to activity along the Mill Creek and Mission Creek strands of the southern San Andreas fault

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ABSTRACT

Assessment of seismic hazards in southern California may be improved with more accurate characterization of the active San Andreas fault strands within the San Gorgonio Pass region. Ongoing debate centers on the activity and geometry of the Mill Creek and Mission Creek strands. Here, we investigate crustal deformation models with six geologically plausible geometries of the Mill Creek and Mission Creek strands. Model results suggest that differences in active fault geometry along the San Andreas fault impact slip rates along the San Jacinto fault by up to 3 mm/yr. Each model fits many but none fits all of the available geologic strike-slip rates. The calculated misfits to the geologic strike-slip rates reveal two best-fitting models: the Inactive Mill Creek model and the West Mill Creek model, which incorporate active portions of the Mill Creek, Mission Creek, and Galena Peak strands, consistent with recent studies. The cumulative strike-slip rates across faults of the two best-fitting models differ from each other by ~5 mm/yr, suggesting that fault slip rates do not always sum to the rate plate. Consequently, kinematic slip budgets should consider off-fault deformation. The two best-fitting models produce uplift patterns with significant differences in the hanging walls of dipping faults. New uplift rate data in these regions and additional geologic strike-slip rates along the northern fault strands could further support plausible interpretations of active fault configuration. An assessment of the seismic hazard of the region indicates the potential for a rupture through the San Gorgonio Pass region with Mw ~7.8.

INTRODUCTION

Within the San Gorgonio Pass region (SGPr), the San Andreas fault forms a restraining stepover characterized by complex active faulting along multiple strands. Within this region (Fig. 1), the San Andreas fault consists of several nonvertical segments (e.g., San Gorgonio Pass fault zone, Garnet Hill, and Banning strands) (e.g., Matti et al., 1992; Yule, 2009). Dynamic rupture models suggest that restraining bends may serve as a structural barrier to earthquake rupture propagation (Kase and Kuge, 2001; Oglesby, 2005; Tarnowski, 2017). Since the start of continual recording of seismic events, the San Andreas fault south of Cajon Pass has had fewer earthquakes than smaller nearby faults (e.g., Yang et al., 2012), and consequently, the geometry and activity of fault strands through the northern SGPr remain poorly constrained.

Ongoing debate centers on the relative activity of the Mill Creek and Mission Creek strands, which provide a northern path for rupture through the SGPr (Fig. 1). Several studies have pointed out that unruptured colluvial and debris fan sediments across the Mill Creek strand at Upper Raywood Flat (site 5 in Fig. 1) limit recent surface breaching rupture activity (Matti et al., 1992; Kendrick et al., 2015). To the west of Upper Raywood Flat, Kendrick et al. (2015) used reconstructed drainage segments across the Mill and Mission Creek strands (site 6 in Fig. 1) and luminescence dating of alluvial surfaces to reveal that the slip on both northern strands discontinued at ca. 100 ka. However, another study along the southern portion of the Mission Creek strand (site 10 in Fig. 1), only 60 km from Upper Raywood Flat, reveals fast strike-slip rates (17–24 mm/yr) within the past ~70,000 years, supporting the interpretation of recent activity along the northern strands through the SGPr (Blisniuk et al., 2012). Furthermore, slow dextral slip rates on the Banning strand (sites 8 and 9, located in the southern strands of Fig. 1) suggest that greater slip may pass through other strands, such as the northern strands or the Garnet Hill strand (Gold et al., 2015). A.E. Morelan (2017, personal commun.) documents fault scarps that demonstrate recent activity along the Galena Peak strand, which may provide a path for slip to bypass the Upper Raywood Flat section of the Mill Creek strand. The disagreement between different geologic interpretations highlights the need to improve understanding of the kinematics of slip transport along the many strands of the San Andreas fault through the San Gorgonio Pass region.

In this study, we use three-dimensional boundary-element method models that simulate deformation over many earthquake cycles to investigate six geologically plausible fault configurations through the SGPr to better understand the impact of differing fault geometries on slip distributions in the region (Fig. 2). We compare slip rates from the models to geologic slip-rate data in order to distinguish between the alternative active fault configurations. The results highlight regions where additional uplift and slip-rate constraints could be used to delineate between plausible fault geometries of the San Andreas fault through the SGPr.
2. GEOMETRY AND QUATERNARY SLIP RATES ON THE SAN ANDREAS AND SAN JACINTO FAULTS

2.1 San Andreas Fault

The southern San Andreas fault forms a left-stepping restraining bend at the San Bernardino Mountains with several geometrically complex fault segments and strands within the SGPr (Matti et al., 1983; Matti et al., 1985; Fig. 1). Like laboratory and other crustal restraining bends (e.g., Cooke et al., 2013; Elliott et al., 2018), dextral slip rates are greatest along the San Andreas fault outside of the San Gorgonio Pass and decrease within the restraining bend (Cooke and Dair, 2011; McGill et al., 2015). Here, we describe the segments and strands of the San Andreas fault from northwest to southeast through the SGPr, and when applicable, we reference the slip-rate site number in Figure 1. Dextral slip-rate estimates along the subvertical San Bernardino segment decrease southeastward from 24.5 mm/yr in Cajon Pass (site 1; Weldon and
the western portion of the Mill Creek may also include the full Mission Creek strand. Models 4 and 5 pass Upper Raywood Flat. Models 1 and 2 investigate the impact of an active vertical Mill Creek strand. Models 3–6 provide alternative slip paths through the San Gorgonio Pass that may allow slip to bypass Upper Raywood Flat (yellow star), where Kendrick et al. (2015) observe no evidence of slip; however, there may still be slip at the Mission Creek alluvial complex. Model 3 includes the Galena Peak strand. The extent of the Galena Peak strand in this model is greater than in subsequent models because the western segment of the Mission Creek strand is not present in this model. Thus, the authors chose to extend the Galena Peak fault to merge with the Mill Creek strand on both ends, as a way to bypass Upper Raywood Flat. Models 4 and 5 also include the full Mission Creek strand. Model 6 explores the possibility that only the western portion of the Mill Creek may be active.

Figure 2. Alternative active fault configurations through the San Gorgonio Pass. The southern strands are consistent in all six models. Dip of faults is indicated along the fault traces. Models 1 and 2 investigate the impact of an active vertical Mill Creek strand. Models 3–6 provide alternative slip paths through the San Gorgonio Pass that may allow slip to bypass Upper Raywood Flat (yellow star), where Kendrick et al. (2015) observe no evidence of slip; however, there may still be slip at the Mission Creek alluvial complex. Model 3 includes the Galena Peak strand. The extent of the Galena Peak strand in this model is greater than in subsequent models because the western segment of the Mission Creek strand is not present in this model. Thus, the authors chose to extend the Galena Peak fault to merge with the Mill Creek strand on both ends, as a way to bypass Upper Raywood Flat. Models 4 and 5 also include the full Mission Creek strand. Model 6 explores the possibility that only the western portion of the Mill Creek may be active.

The southern pathway of the San Andreas fault within the SGPr consists of the San Gorgonio Pass fault zone, Garnet Hill strand, and Banning strand (Fig. 1). The San Gorgonio Pass fault zone is a north-dipping thrust fault with a corrugated geometry at the Earth’s surface (Matti et al., 1985; Matti et al., 1992; Matti and Morton, 1993; Yule and Sieh, 2003). Although the western end of the San Gorgonio Pass fault zone does not connect to the active trace of the San Bernardino segment at the Earth’s surface, they likely connect in the subsurface (Yule and Sieh, 2003). The San Gorgonio Pass fault zone has a reverse slip rate of 6.8–16.3 mm/yr at Plunge Creek (site 3; McGill et al., 2013), to 4–12 mm/yr at the southeastern tip (site 4; Orozco, 2004) (Fig. 1 and Table 1).

The northern pathway of the San Andreas fault through the SGPr consists of the Mill Creek, Galena Peak, and Mission Creek strands (Fig. 1). Together, the Mill Creek and Mission Creek strands provide a continuous fault structure north of the San Gorgonio Pass, but at finer scale, the complex surface expression of the two strands, including branches, etc., reflects their distinct activity histories (e.g., Matti et al., 1992; Kendrick et al., 2015). The Mill Creek strand has evidence of no recent slip at Upper Raywood Flat (site 5; Kendrick et al., 2015). The Mission Creek alluvial complex suggests that neither the Mission Creek nor Mill Creek faults have slipped at this location over the past 100 k.y. (site 6; Kendrick et al., 2015). In contrast, a dextral slip rate of 10–14 mm/yr on the Mission Creek strand in the Indio Hills (site 11; Munoz et al., 2016) and a high dextral slip rate of 17–24 mm/yr on the Mission Creek strand near Pushawalla Canyon (site 10; Blisniuk et al., 2012) support an active northern pathway for slip through the SGPr via the Mill Creek strand. The subvertical Galena Peak strand (Dibblee, 1964; Dibblee, 1967; Matti et al., 1983; Matti et al., 1985; Kendrick et al., 2015) is located between the Mill Creek strand and western segment of the Mission Creek strand (Fig. 1). Evidence of recent slip along the Galena Peak strand may indicate that this strand acts as an alternative slip pathway that bypasses the site of Upper Raywood Flat on the Mill Creek strand (Dibblee, 1964; Dibblee, 1967; Matti et al., 1983; Matti et al., 1985; Kendrick et al., 2015; A.E. Morelan, 2017, personal commun.).

The Banning and Mission Creek strands merge into the Coachella segment of the San Andreas fault just south of the Indio Hills (Fig. 1). The northeast-dipping Coachella segment (e.g., Lin et al., 2007; Fattaruso et al., 2014; Fuis et al., 2017) continues to the eastern shore of the Salton Sea. Just south of the junc-

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tion with the Banning and Mission Creek strands, an offset alluvial fan at Biskra Palms provides a dextral slip rate for the Coachella segment of 12–22 mm/yr with a preferred range of 14–17 mm/yr (site 12; Behr et al., 2010).

### 2.2 San Jacinto Fault

From the Cajon Pass southward, the San Jacinto fault is composed of a series of strike-slip segments. The northernmost San Jacinto Valley segment has a dextral slip rate of 12.8–18.3 mm/yr dextral slip for the past 1500–2000 years in the north San Timoteo Badlands, where the fault is called the Claremont fault (site 13; Onderdonk et al., 2015), northeast of the releasing stepover that forms the transition from the San Jacinto Valley segment to the Anza segment. Dextral slip rate of >20 mm/yr has been inferred from off-fault deformation in the San Timoteo Badlands (Kendrick et al. 2002); however, because the deformation of dated surfaces within a restraining bend is not a direct measurement of fault slip, we do not use this rate in the following analyses. The Anza segment has dextral slip rates of 12.8–18.3 mm/yr (site 14; Blisniuk et al., 2013), which has been refined from previous estimates by Sharp (1981) and Rockwell et al.(1990). Dextral slip rates along the Clark segment decrease from 8.9 ± 2 mm/yr in the north to 1.5 ± 0.4 mm/yr in the south (sites 15 and 16; Bilaniuk et al., 2010), where this segment forms a releasing stepover with the Coyote Creek segment. The Coyote Creek segment has slip rates of 4.1 ± 1.1 mm/yr in the north (site 17; Janecke et al., 2010) and 2.9–5 mm/yr in the south near its termination (site 18; Sharp, 1981).

### 3. METHODS

The six active fault configurations modeled here (Fig. 2) investigate alternative slip pathways through the SGPr via the northern fault strands. The first two models investigate the deformation with and without an active vertical Mill Creek strand, while the other four models provide alternative slip pathways north of the San Gorgonio Pass. These four alternative fault configurations explore potential variations in active fault dip and connectivity that may allow for dextral slip to bypass Upper Raywood Flat, site 5, where no evidence of recent slip is observed (Kendrick et al., 2015). However, slip along the alternative northern pathways might not honor the evidence of no recent slip through the Mission Creek alluvial complex, site 6 (Kendrick et al., 2015).

While a location needs to meet a specific set of geologic conditions for a slip-rate estimate to be possible, numerical models can be queried at any location, providing additional information where we currently have no geologic constraints. We use Poly3D, a quasi-static, three-dimensional boundary-element method code, to simulate deformation along the southern San Andreas fault system. Poly3D solves the relevant equations of continuum mechanics to calculate stresses and displacements throughout the model (e.g., Crouch and Starfield, 1990; Thomas, 1993). In models presented here, faults are discretized into triangular elements of constant slip (no opening and/or closing is permitted) within a linear-elastic and otherwise homogeneous half-space. Triangular elements can more accurately replicate the branching and curving fault surfaces than rectangular elements. Average element size along faults within the SGPr is ~4 km, allowing for fault irregularities as small as ~10 km.

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**TABLE 1. DEXTRAL SLIP RATES FOR AVAILABLE SITES ALONG THE SAN ANDREAS AND SAN JACINTO FAULTS**

| Slip-rate site | Fault strand | Dextral slip rate (mm/yr) | References |
|----------------|--------------|---------------------------|------------|
| 1              | San Bernardino | 21–28 | Weldon and Sieh, 1985 |
| 2              | San Bernardino | 11–17 | McGill et al., 2010 |
| 3              | San Bernardino | 6.8–16.3 | McGill et al., 2013 |
| 4              | San Bernardino | 4–12 | Orozco, 2004 |
| 5              | Mill Creek | 0 | Kendrick et al., 2015 |
| 6              | Mill Creek and Mission Creek | 0 | Kendrick et al., 2015 |
| 7              | San Gorgonio Pass fault zone | 4.2–8.4 | Heermance and Yule, 2017 |
| 8              | Banning | 3.9–4.9 | Gold et al., 2015 |
| 9              | Banning | 2–6 | Scharer et al., 2015 |
| 10             | Mission Creek | 17–24 | Blisniuk et al., 2012 |
| 11             | Mission Creek | 10–14 | Munoz et al., 2016 |
| 12             | Coachella | 14–17 | Behr et al., 2010 |
| 13             | Claremont | 12.8–18.3 | Onderdonk et al., 2015 |
| 14             | Anza | 9.5–15.5 | Blisniuk et al., 2013 |
| 15             | Clark | 6.9–10.9 | Blisniuk et al., 2010 |
| 16             | Clark | 1.1–1.9 | Blisniuk et al., 2010 |
| 17             | Coyote Creek | 2.4–6 | Janecke et al., 2010 |
| 18             | Coyote Creek | 2.8–5 | Sharp, 1981 |

Note: Site numbers are as in Figure 1.
Our 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 Southern California Earthquake Center’s Community Fault Model (CFM) version 4.0, which is compiled from geologic mapping, seismicity, and geophysical data (Plesch et al., 2007). All the faults of interest in our models, with the exception of the Galena Peak strand, are included in the CFM v4.0 as a simplified representation of the more complex geologic structures. Modifications to the CFM fault geometries improve the match to geologic slip rates in the SGPr (Cooke and Dair, 2011; Herbert and Cooke, 2012) and Eastern California shear zone (Herbert et al., 2014b), as well as match to uplift patterns within the San Bernardino Mountains (Cooke and Dair, 2011) and Coachella Valley (Fattaruso et al., 2014). The model extends from the Salton Sea in the south to north of the intersection of the San Andreas fault with the Garlock fault (see Fig. S1 for a map of the all modeled faults). Faults of the CFM are only defined to the base of the seismogenic crust (10–15 km). To avoid artifacts that would develop if long-term slip rates were to zero at the depth extent of the CFM-defined faults, we extend the faults in the model down to a freely slipping, horizontal basal crack at 35 km depth that simulates distributed deformation below the seismogenic zone (Marshall et al., 2009). The shear traction-free faults throughout the model slip freely in response to both the tectonic loading and fault interaction (Fig. 3). Zero shear traction along the faults simulates the low dynamic strength of faults during rupture (e.g., Di Toro et al., 2006; Goldsby and Tullis, 2011), when most of the deformation accumulates. Any faults incorporated within the model will have some component of resolved shear stress, and therefore will accrue slip. Consequently, to make a fault inactive, we exclude it from the model. The six different fault configurations modeled test different interpretations of active and inactive fault segments by including or excluding specific segments. Because the fault geometry exerts a first-order control on the deformation patterns across many earthquake cycles (e.g., Dawers and Anders, 1995; Herbert et al., 2014b), we do not consider the impact of heterogeneous and/or anisotropic rock properties within the southern San Andreas fault system.

Tectonic loading is prescribed far from the investigated faults at the base of the model. We follow Herbert and Cooke (2012) and simulate plate motions that are geodetically constrained to be 45–50 mm/yr at 320°–325° (e.g., DeMets et al., 2010). Faults that extend outside our model area (San Andreas and San Jacinto faults and Cucamonga–Sierra Madre system) are driven by applying slip rates to edge patches of the faults. These edge patches are required to prevent these regional faults from having slip rates arbitrarily slow to zero at the edge of the model. At the northwestern edge of the model, we apply 35 mm/yr dextral slip to the central segment of the San Andreas fault (Weldon and Sieh, 1985), and at the southeastern edge of the model, we apply 25 mm/yr dextral slip to the San Andreas fault and 10 mm/yr dextral slip to the San Jacinto fault (e.g., Sharp, 1981; Becker et al., 2005; Fay and Humphreys, 2005; Meade and Hager, 2005). Redistributing the applied dextral slip to the San Andreas and San Jacinto faults at the southeastern edge of the model, such that the two faults have equal slip rates, produces changes in slip rate of <1 mm/yr along the San Andreas fault within the SGPr (Fattaruso et al., 2014). Therefore, variations in partitioning of slip rates between the San Andreas and San Jacinto faults at the southern edge of the model do not significantly impact slip rates of faults within the SGPr.

Figure 3. Northward oblique view of the model setup. Tectonic loading is prescribed at the boundaries of the model base while allowing the shear traction-free faults to slip freely in response to the loading and fault interaction. Uncertainties in the tectonic loading are considered by testing a range of plate velocities and orientation. SAF—San Andreas fault; SJF—San Jacinto fault.
which are largely controlled by local fault geometry (Fattaruso et al., 2014). We apply 5 mm/yr reverse slip to the edge of the Cucamonga fault (Morton and Matti, 1987) in order to account for deformation along the Cucamonga–Sierra Madre fault system. Because these various applied fault slip rates are all far from our region of interest, the local geometry of the faults, rather than the distally prescribed slip rate, controls the distribution of slip along the modeled faults within the SGPRs. Furthermore, any changes to the applied slip rates at the modeling boundaries would impact all models equally and would not alter the relative misfit of the models to the geologic data.

3.1 Refining the Tectonic Loading

Previous boundary-element method models of the region estimated tectonic velocities around the edges of the model using blocks of elements each with uniform velocity, separated by discrete steps (e.g., Fattaruso et al., 2014; Herbert et al., 2014a, 2014b). In this study, we replace the stepwise model edge velocities with linear velocity gradients along the northwest and southeast edges of the model. Another refinement of this study improves the accuracy of the applied velocity. The basal crack in the Poly3D model is embedded within a half-space that separates the region we are interested in (i.e., above the basal crack) from the rest of the half-space. Because Poly3D allows the user to prescribe the slip rate across a fault element, but not how displacement rates are distributed on both sides of a fault element, we cannot directly prescribe the tectonic velocity on the top side of the basal crack. In previous studies, we approximated the desired velocities, resulting in local velocity variations occasionally exceeding 5 mm/yr. To improve upon previous approaches, we follow Stern (2016) and implement an iterative technique that refines the applied slip rate over successive iterations to ensure a uniform tectonic velocity parallel to the plate boundary (sides labeled I on Fig. 3) and a linear gradient in the tectonic loading across the plate boundary (sides labeled II on Fig. 3). The iterative approach begins with a first estimate for tectonic loading via prescribed slip rates along the boundaries of the model that follows the approach of previous models. The output velocities from the top side of the basal crack in this first iteration are then used to calculate a correction ratio used to adjust the slip rate applied to each element along the outer ring of the model base (Fig. 3). We refine the applied slip rate iteratively until we obtain the desired velocity distribution along the top sides of elements along the model boundaries. Three iterations successfully converge the boundary velocities to within ~1% of the desired tectonic loading (Fig. S2 [footnote 1]).

3.2 Assessment of Model Fit to Geologic Slip-Rate Data

To assess the match of strike-slip rates produced by the models to geologic strike-slip rates at sites along the San Andreas and San Jacinto faults (Fig. 1), we calculate for each site investigated the misfits of the model slip rate extracted from equivalent location of the site to the preferred geologic strike-slip rates using the mean absolute error (Equation 1). We use the mean absolute error (MAE), rather than root-mean-square error (RMSE), to assess the model fit because RMSE emphasizes the outliers and overestimates the average model error (Willmott et al., 2017).

\[
\text{MAE} = \frac{1}{n} \sum_{i=1}^{n} |m_i - g_i|
\] (1)

A range of geologic strike-slip rates is often given at investigated sites. Unless the author of the geologic study specifies a preferred strike-slip rate, the mean rate is used for the misfit calculations. For each investigated slip-rate site from Figure 1 (i), the geologically interpreted strike-slip rate (\(g_i\)) is compared to the mean modeled strike-slip rate at the equivalent site location from the four tectonic loadings applied (\(m_i\)). In addition to total misfit to preferred slip rates, we also calculate a permissible misfit that excludes from the misfit sum sites where the model range of slip rates overlaps the geologic range. Slip-rate overlap suggests that the model slip rates at these sites are permissible with the geologic data; consequently, these sites do not contribute to the permissible misfit. For sites where the model and geologic slip-rate ranges do not overlap, the permissible misfit for each site is calculated from the underlap between the slip-rate ranges.

3.3 Uplift Patterns

We investigate uplift of a horizontal grid of observation points along the top of the modeled half-space. We adjust the resulting surface uplift rates to account for isostasy using a crustal flexure model following Cooke and Dair (2011), Fattaruso et al. (2014), and Fattaruso et al. (2016). This isostatic correction generally reduces the amplitude and increases the wavelength of the uplift patterns. We use a mantle density of 3350 kg/m³ (Christensen and Mooney, 1995), crustal density of 2700 kg/m³, and a flexural rigidity of the crust of \(2 \times 10^{23}\) Pa·m³ for our correction. We also subtract the mean uplift rate of the grid from the pattern to produce the relative uplift pattern.

4. RESULTS FOR FIVE ALTERNATIVE FAULT CONFIGURATIONS

4.1 Dextral Slip Rates

Each of the six modeled fault configurations produces dextral slip rates that are within the range of geologic slip rates at some, but not all, sites (Fig. 4 and Table 2). Ranges in geologic and model slip rates for each site are plotted as ellipses with the assumption that the mean geologic and model slip rates are the preferred slip rates. Ranges in model slip rates arise from the range in tectonic loading applied to the models. Wider ellipses represent sites with a larger range in geologic strike-slip rates, and taller ellipses occur at sites where the
model strike-slip rates are more sensitive to changing tectonic loading. Both the total misfits to preferred slip rates and the permissible misfits (Table 2) show that the Inactive Mill Creek model provides the best match to the geologic strike-slip rates from sites along the San Andreas and San Jacinto faults (Fig. 4). The Inactive Mill Creek model produces a total dextral slip-rate misfit >0.6 mm/yr lower than the misfits of four of the active Mill Creek models but only 0.4 mm/yr lower than that of the West Mill Creek model. The misfits show that the Inactive Mill Creek and West Mill Creek models provide better misfits to both the preferred geologic slip rates and also to the range of permissible geologic slip rates (Table 2).

The lower dextral slip rates inside the restraining bend mean that mismatched sites within the bend contribute less to the total calculated misfits than the sites outside of the restraining bend. Strike-slip rates at sites along the San Bernardino segment of the San Andreas fault, especially near the intersection with the Mill Creek strand, are highly sensitive to the active fault configuration of the northern strands through the SGPr (Fig. 4A). Sites 2 and 3 (Badger

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**Figure 4.** Correlation of modeled and geologic strike-slip rates along the (A) San Andreas fault (SAF) and (B) San Jacinto fault (SJF) for the six modeled active fault geometries. Colors delineate models. (A) 1:1 line is plotted in black. The Inactive Mill Creek model provides the best fit to the preferred geologic strike-slip rates for both the San Andreas and San Jacinto faults. The second best-fitting model is the West Mill Creek model. (C) Modeled strike-slip rates at Upper Raywood Flat (site 5 in Fig. 1) for the six models. (D) Modeled strike-slip rates at the Mission Creek alluvial complex (site 6 in Fig. 1). Investigated slip rate sites along the San Andreas and San Jacinto faults are the same as in Figure 1.
Canyon and Plunge Creek, respectively) flank the intersection of the San Bernardino segment with the Mill Creek strand. The Inactive Mill Creek and West Mill Creek models better match the geologic strike-slip rates at Badger Canyon (site 2), whereas the other models better match strike-slip rates at Plunge Creek (site 3). The models that include greater dextral slip along the northern pathway have lower slip rates along the San Bernardino segment south of its intersection with the Mill Creek strand, which better matches the mean slip rate at Badger Canyon (site 2) from McGill et al. (2010). Consequently, none of the models tested match well slip rates at both the Badger Canyon and Plunge Creek sites. Similarly, sites 10 and 11 (Pushawalla Canyon and Three Palms, respectively) also highlight the difficulty in determining an active fault configuration that honors all of the available geologic strike-slip rates. These two sites are only a few kilometers apart, yet have non-overlapping slip-rate ranges. Both the Inactive Mill Creek and West Mill Creek models produce the best matches of the six models to the geologic strike-slip rates at Three Palms but produce the worst fits to the slip rates at Pushawalla Canyon. The two models match the geologic slip rates at Three Palms and underestimate the geologic slip rates at Pushawalla Canyon.

Dextral slip rates at Upper Raywood Flat along the Mill Creek strand of the San Andreas fault (site 5) vary by ~13 mm/yr among the models (Fig. 4C). Activity along this portion of the Mill Creek strand is more sensitive to the alternative active fault configuration in the SGPr than the other investigated sites. The Inactive Mill Creek and West Mill Creek models are the only models that honor the observation of no recent slip at site 5 (Kendrick et al., 2015). Incorporating an active Mill Creek strand in the models results in varying amounts of strike slip at site 5. Dextral slip rates at the Mission Creek alluvial complex (site 6) vary by ~12 mm/yr among the six models (Fig. 4D). At this site, only the Inactive Mill Creek model is consistent with no recent slip at site 6 (Kendrick et al., 2015).

The total calculated misfits for sites along the San Jacinto fault (Fig. 4B and Table 2) are smaller than misfits calculated along the San Andreas fault. While the models match well the geologic dextral slip rates at only one or two sites along the San Jacinto fault, all models underestimate by >2 mm/yr the slip rate at San Timoteo Badlands (site 13). The variation in slip rates among the models indicates that the activity along the San Jacinto fault responds to changes in fault geometry along the San Andreas fault. While none of the models fit the geologic slip rates at a majority of investigated sites, the misfits show that the Inactive Mill Creek and West Mill Creek models produce better fit to the geologic data along both the San Andeas and San Jacinto faults than the other models.

The sites of geologic slip-rate investigations are often separated by tens of kilometers from the next site. Numerical models can provide fault slip-rate estimates along the entire surface of the fault, allowing us to investigate how slip rates may vary between existing geologic slip-rate sites. Figure 5 shows the strike-slip rates along the fault trace (at Earth's surface) of each strand of the San Andreas fault through the SGPr for the two best-fitting models, the Inactive Mill Creek model (Fig. 5A) and the West Mill Creek model (Fig. 5B). Both models overestimate slip rates at Badger Canyon (site 2) and underestimate slip rates at Pushawalla Canyon (site 10). Furthermore, the West Mill Creek model underestimates the dextral slip rate along the San Gorgonio Pass fault zone that Millard Canyon (site 7). In the Inactive Mill Creek model (Fig. 5A), the dextral rate along the San Bernardino segment (purple) gradually decreases to the south. Along the southern pathway, the Banning strand (light blue) accommodates more dextral slip than both the San Gorgonio Pass fault zone and the Garnet Hill strand. The modeled San Gorgonio Pass fault zone accommodates ~13 mm/yr reverse slip (not shown in Fig. 5), which is less than geologic observations of >2.5 mm/yr (Yule and Siese, 2003). The dextral slip rate on the active portion of the Mission Creek fault (orange) increases near the fault's connection with the Coachella segment (red).

In the West Mill Creek model (Fig. 5B), the dextral slip rate along the San Bernardino segment (purple) decreases sharply northwest of Plunge Creek (site 3), where a portion of the dextral slip is transferred onto the modeled Mill Creek strand (green). This dextral slip is then transferred to the Galena Peak strand (pink) where the Mill Creek strand terminates. In this model, the western portion of the Mission Creek strand (orange) has a slow slip rate that sharply increases where the Galena Peak strand merges into the Mission Creek strand. To the southeast of this merger (>80 km from Cajon Pass), the Mission Creek

| Model fit to investigated sites | Slip-rate misfits (mm/yr) |
|--------------------------------|--------------------------|
| SAF (× 12 sites) | SJF (× 6 sites) | Total | Permissible |
| Inactive Mill Creek | 5 | 2 | 2.8 | 1.0 |
| Active Mill Creek | 5 | 1 | 4.4 | 1.6 |
| Mill Creek + Galena Peak | 4 | 1 | 4.3 | 1.6 |
| Vertical Mission Creek | 4 | 1 | 4.2 | 1.7 |
| North-dipping Mission Creek | 4 | 2 | 3.4 | 1.4 |
| West Mill Creek | 6 | 2 | 3.2 | 1.3 |

SAF—San Andreas fault; SJF—San Jacinto fault.

**TABLE 2. MODEL FIT TO THE INVESTIGATED SITES, SHOWING HOW MANY SITES ALONG THE SAN ANDREAS AND SAN JACINTO FAULTS EACH MODEL MATCHES AND THE TOTAL AND PERMISSIBLE MISFITS TO THE GEOLOGIC STRIKE-SLIP RATES FOR EACH OF THE FIVE MODELED ACTIVE FAULT CONFIGURATIONS**
strand takes up most of the dextral slip within this portion of the restraining bend. This is in contrast to the Inactive Mill Creek model where the Banning strand carries most of the slip at 80–110 km from the Cajon Pass.

4.2 Patterns of Uplift Rates

To gather information about the non–strike-slip deformation across the SGPr, we calculated uplift rates for the Inactive Mill Creek model (Fig. 6A) and the West Mill Creek model under the mean applied tectonic loading (Fig. 6B). The two models produce similar uplift rate patterns throughout most of the SGPr. Uplift rate is greatest in the San Bernardino Mountains with largest subsidence rate in the San Bernardino Basin. Model subsidence rates of the San Bernardino Basin from both models are consistent with depositional rates within the San Bernardino Basin of ~1 mm/yr (Matti and Morton, 1993; Wisely and Schmidt, 2010). The model uplift patterns from the two models differ significantly in several key locations (labeled A–D in Fig. 6).

In the hanging wall of the San Gorgonio Pass fault zone (location A on Fig. 6), the Inactive Mill Creek model produces a relative uplift rate of 4 mm/yr, whereas the West Mill Creek model produces a lower relative uplift rate of 2.5 mm/yr. The lower rate may be more consistent with estimates of 1 mm/yr over the past 13 k.y., determined from offset markers across the San Gorgonio Pass fault zone (Yule and Sieh, 2003). Furthermore, the lower uplift rate from the West Mill Creek model may indicate that local contraction within the restraining bend is accommodated elsewhere, potentially as slip along the north-dipping Mission Creek strand near Raywood Flat (location D in Fig. 6).
Within the San Bernardino Mountains, Binnie et al. (2008) report a northward decrease in 10^–10^ year time-scale denudation rates from 1.5 ± 3 mm/yr at Yucaipa Ridge, location B on Figure 6, to 0.4 ± 0.6 mm/yr in the San Gorgonio block north of location B. The uplift pattern from the Inactive Mill Creek model also shows a northward decrease in uplift rate north of Yucaipa ridge, but the uplift rates of ~3 mm/yr at location B exceed the denudation rates of Binnie et al. (2008). The model produces zero slip at site 5 within Upper Raywood Flat (site 5) and the Mission Creek alluvial sequence (site 6) by Kendrick et al. (2015), it produces slightly excessive dextral slip rates along the southern pathway through the San Gorgonio Pass. Relatively low dextral slip rates along the Banning strand (Gold et al., 2015; Scharer et al., 2015), high dextral slip rates along the Mission Creek strand at Pushawalla Canyon by Binnie et al. (2015), and field studies along the northern portion of the Mill Creek strand (A.E. Morelan, 2017, personal commun.) suggest recent slip transfer through the SGPr via the northern pathway, indicating that the western part of the Mill Creek strand may be active.

The West Mill Creek model also provides a good fit to the geologic slip rates (Fig. 4) but produces 7 mm/yr dextral slip rate at site 6 in the Mission Creek alluvial complex (Fig. 5B). The Inactive Mill Creek and West Mill Creek models produce zero slip at site 5 within Upper Raywood Flat (site 4C) and zero slip and ~6–9 mm/yr dextral slip, respectively, at site 6 in the Mission Creek alluvial complex (Fig. 5D). These two models produce better agreement with the observations of no slip at sites 5 and 6 than the other four models. Although the Inactive Mill Creek model produces the smallest misfit to the geologic data for recent uplift.

5. DISCUSSION

5.1 Preferred Models

Our analysis of the dextral slip rates produced along the San Andreas and San Jacinto faults by the six alternative fault geometries results in two preferred models. The Inactive Mill Creek model gives the best overall fit to the geologic slip rates (Fig. 4). The sites along the San Bernardino segment, especially Badger Canyon (site 2 on Fig. 4), are best matched by this model. However, the absence of the Mill Creek strand of the San Andreas fault within this model increases the dextral slip rates along the southern pathway (Fig. 1), just exceeding the range of geologic slip rates along the Banning strand of the San Andreas fault (Fig. 5A). Although the Inactive Mill Creek model honors the observation of no slip on the Mill Creek strand near Upper Raywood Flat (site 5) and at the Mission Creek alluvial sequence (site 6) by Kendrick et al. (2015), it produces slightly excessive dextral slip rates along the southern pathway through the San Gorgonio Pass. Relatively low dextral slip rates along the Banning strand (Gold et al., 2015; Scharer et al., 2015), high dextral slip rates along the Mission Creek strand at Pushawalla Canyon by Binnie et al. (2015), and field studies along the northern portion of the Mill Creek strand (A.E. Morelan, 2017, personal commun.) suggest recent slip transfer through the SGPr via the northern pathway, indicating that the western part of the Mill Creek strand may be active.

The West Mill Creek model also provides a good fit to the geologic slip rates (Fig. 4) but produces 7 mm/yr dextral slip rate at site 6 in the Mission Creek alluvial complex (Fig. 5B). The Inactive Mill Creek and West Mill Creek models produce zero slip at site 5 within Upper Raywood Flat (site 4C) and zero slip and ~6–8 mm/yr dextral slip, respectively, at site 6 in the Mission Creek alluvial complex (Fig. 5D). These two models produce better agreement with the observations of no slip at sites 5 and 6 than the other four models. Although the Inactive Mill Creek model produces the smallest misfit to the cur-
rently available geologic strike-slip rates, the West Mill Creek model provides a good fit to many of the strike-slip rates while also honoring field evidence of recent slip along the northern Mill Creek, western Mission Creek, and Galena Peak strands (A.E. Morelan, 2017, personal commun.).

The active fault configuration through the SGPr impacts the relative uplift rate patterns, producing model uplift patterns that are significantly different in several key locations (labeled A-D in Fig. 6). Of these locations, A, B, and D are located on bedrock exposures. The exhumation rate information collected from bedrock exposures may record uplift over longer time scales than the lifetime of the active current configuration of the southern San Andreas fault. Consequently, comparison of such uplift rates to results from models of active fault configuration may have limited use. The most promising site for uplift rate comparisons may be site C in the alluvial fan between North Palm Springs and Desert Hot Springs, where young sediments are exposed. Unfortunately, active reworking of the alluvial fan may inhibit analysis of uplift rate in this region. Low hills along the trace of these faults (e.g., Garnet Hill) confirm a degree of local uplift consistent with both models. Additional 10^6–10^7 year time scale uplift rate data from any of the locations labeled in Figure 6 may provide additional information about the active subsurface fault configuration in the San Gorgonio Pass region.

5.2 Additional Slip-Rate Data Needed to Constrain Active Fault Geometries

This study highlights regions where we have insufficient characterization of the fault geometry within the SGPr. Models approximate the active fault geometry through the SGPr but inevitably incorporate inaccuracies due to the lack of constraints on subsurface fault configuration (Fig. 1). Additional subsurface imaging of the north San Gorgonio Pass could provide further constraints on the geometries of active fault strands (e.g., Fuis et al., 2017). A single best-fitting geometric configuration cannot be determined from the available strike-slip rates, as both preferred models match many, but not all, geologic strike-slip rates at investigated sites. Although the Inactive Mill Creek model better fits the available geologic strike-slip rates, the West Mill Creek model better honors the evidence of recent slip along the Galena Peak and northwestern portion of the Mission Creek strands (Morelan et al., 2016). The difference in model-predicted slip rates along most fault segments within this region is too small to be resolved by slip-rate resolution of typical geologic investigations. However, additional geologic dextral slip-rate estimates along the Mission Creek and Mill Creek strands within the black-boxed regions in the map of Figure 5 could potentially delineate between the two preferred models for slip partitioning through the SGPr. In both of these regions, the Inactive Mill Creek model asserts these portions of the faults inactive, while the West Mill Creek model predicts dextral strike-slip rates >5 mm/yr. These locations are ideal for future slip-rate studies because of the large difference in predicted slip rate between models. Furthermore, additional information about Holocene and younger uplift rates from locations A–D on Figure 6 would lend additional support for preference of one active fault geometry or the other.

5.3 Accommodation of Slip across the Region

The different active configuration of faults within the SGPr may affect the dextral slip budget of the region. Do changes in active fault configuration that produce increases in strike-slip rate along one fault produce commensurate decreases in strike-slip rates along other faults in the system? To address this, we investigate the sensitivity of fault slip budget to fault geometry of the two preferred models, the Inactive Mill Creek and West Mill Creek models. For faults that are contiguous (the northern pathway of the San Andreas fault, and the San Jacinto fault), we calculate a weighted average dextral slip rate. For faults with parallel strands and/or segments (the southern pathway of the San Andreas fault and the Eastern California shear zone), we sum the average dextral slip rate for each fault.

The addition of the northern active strands of the San Andreas fault through the SGPr increases the overall strike-slip rate across all strands of the San Andreas fault. The total strike-slip along the southern pathway of the San Andreas fault through the pass (Banning and Garnet Hill strands) decreases from 10.9 ± 5.2 mm/yr in the Inactive Mill Creek model to 9.1 ± 3. mm/yr in the West Mill Creek model. However, the addition of the northern pathway (Mill Creek, Mission Creek, and Galena Peak strands) in the West Mill Creek model provides an additional 6.5 ± 3.3 mm/yr of strike-slip along the San Andreas fault. The uncertainties reported for the mean slip rates reflect the spatial variability of strike-slip rates along the fault surfaces. The total accommodation of strike slip along both the southern and northern pathways of the San Andreas fault through the SGPr increases the overall strike-slip rate of the SAF by ~4.5 mm/yr.

Changes to the active fault geometry along the San Andreas fault increase strike-slip rates along the San Andreas fault and decrease strike-slip rates along the northern San Jacinto fault. The addition of the northern pathway of the San Andreas fault through the SGPr decreases the average strike-slip rate along the San Jacinto Valley and Anza segments of the San Jacinto fault from 7.5 ± 3.4 mm/yr in the Inactive Mill Creek model to 7.0 ± 3.2 mm/yr in the West Mill Creek model. This 0.5 mm/yr decrease in strike-slip rate is less than the 4.5 mm/yr increase in strike-slip along the San Andreas fault. Consequently, the addition of the modeled northern pathway produces a net increase in strike slip across the region of ~4 mm/yr.

The average strike-slip rates across the Helendale, Lenwood, Camp Rock, Calico, Pisgah, and Ludlow faults of the Eastern California shear zone (ECSZ) are not greatly affected by changes to fault configuration along the San Andreas fault. The total strike-slip rate along these major faults of the ECSZ is 6.8 ± 2.0 mm/yr for the Inactive Mill Creek model and only drops to 6.5 ± 2.0 mm/yr with the addition of the northern pathway of the San Andreas fault. To further refine the strike-slip budget, additional work is needed in other areas, particularly in the Mill Creek and Mission Creek strands of the SGPr.
fault within the West Mill Creek model. Both models are close to the upper range in total strike-slip rate across the ECSZ of 6.2 ± 1.9 mm/yr (Oskin et al., 2008). The 0.3 mm/yr decrease in total strike-slip rate across the ECSZ is less than the ~4 mm/yr net increase in strike-slip rate along the San Andreas and San Jacinto faults. These results show that the lack of northern slip pathway through the San Gorgonio Pass would not significantly load faults of the Eastern California shear zone.

The addition of the active northern strands of the San Andreas fault in the SGPr increases an increase strike-slip rate along this fault that is not compensated by corresponding decreases in strike-slip rate along both the San Jacinto fault and faults of the Eastern California shear zone. The West Mill Creek model produces ~5 mm/yr greater dextral slip rate along all three fault systems than the Inactive Mill Creek model. Because all models have the same applied velocities on the model boundaries, the difference in net strike-slip rate indicates that some strike-slip deformation in the Inactive Mill Creek model may be accommodated as off-fault deformation, such as pervasive shear and/or folding within the host rock in the SGPr. This off-fault deformation is consistent with the uplift rate patterns that show more uplift, which can be associated with folding, along the southern strands in the Inactive Mill Creek model than in the West Mill Creek model (Fig. 6).

5.4 Implications for Seismic Hazard

The geometry of active faults plays a fundamental role in the assessment of seismic hazard of restraining bends, such as in the SGPr (e.g., Wesnousky, 2008). Dynamic rupture models indicate that ruptures are more likely to terminate at complicated fault systems, such as the restraining bend along the San Andreas fault within SGPr (e.g., Kase and Kuge, 2001; Tarnowski, 2017). However, paleoseismic evidence reveals that ruptures through the San Gorgonio Pass have occurred in the past, with the last event occurring in 1400 A.D. along the southern fault strands (Yule et al., 2014). The West Mill Creek model shows that the northern pathway through the SGPr can accommodate a substantial portion of the dextral slip along the Mission Creek strand, Galena Peak strand, and Mill Creek strand north of Upper Raywood Flat. This result supports the interpretation that slip may bypass site 5 along Upper Raywood Flat, where geologic evidence suggests no slip, via the Galena Peak strand. While this model does not honor the evidence for no recent slip at site 6 along the Mission Creek fault, the northern strands may still present the potential for a large, throughgoing rupture on the San Andreas fault north of the San Gorgonio Pass.

If both the southern and northern fault strands provide viable slip pathways through the SGPr, the likelihood of a throughgoing rupture, and thus the seismic hazard, increases. We explore the moment magnitude of an earthquake that nucleates near Bombay Beach on the Salton Sea and propagates up to Cajon Pass via either the southern or northern pathways of the San Andreas fault through the SGPr (Fig. 1). Using the model net-slip rates, time since last event (TSLE) for each fault segment (Table 3), and the assumption of complete stress drop between events, we estimate the total seismic moment that could be released in a large throughgoing rupture for the fault geometries of the West Mill Creek model. A rupture that propagates up along the Coachella segment to Cajon Pass via the southern pathway in the San Gorgonio Pass will have a seismic moment of 3.64 × 1023 Nm (Mw ~7.9). Alternatively, a rupture that travels along the northern pathway of the San Gorgonio Pass will have a seismic moment of 6.21 × 1020 Nm (Mw ~7.8). Furthermore, a branching rupture that travels along both the southern and northern pathways would release a seismic moment of 7.25 × 1020 Nm (Mw ~7.9). An analysis of this kind has several assumptions, such as fault geometry, rupture extent, TSLE, and a complete stress drop between events. Alternatively, if we use a regression of rupture area on magnitude, the rupture areas for these scenarios give similar magnitudes of 78–79 (Wells and Coppersmith, 1994). Any of these throughgoing rupture scenarios could result in peak ground velocities of ≥2 m/s hitting the Los Angeles Basin (Porter et al., 2011), which could be devastating for the region.

6. CONCLUSIONS

Ongoing debate in the SGPr centers on the relative activity of the Mill Creek and Mission Creek strands. These strands may provide an alternative slip pathway north of the active faults within the San Gorgonio Pass. We utilize a suite of three-dimensional boundary-element method models to investigate six potential active fault geometries through the SGPr. All of the tested models fit many of the geologic strike-slip rates at investigated sites along the San Andreas and San Jacinto faults, but none of the models match the geologic strike-slip rates at every site. Model misfits to the geologic strike-slip rates reveal two best-fitting models: the Inactive Mill Creek model with activity limited to the southern strands and the West Mill Creek model, which has activity on both the northern and southern strands of the San Andreas fault within the SGPr. The Inactive Mill Creek and West Mill Creek models match 7/18 and 8/18 of the strike-slip rates at investigated sites, respectively. Model slip rates vary up to 3 mm/yr along the San Jacinto fault for different fault configurations in the SGPr, indicating that activity on this fault responds to changes in fault geometry and subsequent slip-rate changes along the San Gorgonio Pass.

| Fault                  | TSLE (years) | References |
|-----------------------|--------------|------------|
| San Bernardino segment| 200          | Biasi and Weldon, 2009 |
| Southern SGPr strands | 600          | McBurnett, 2011 |
| Northern SGPr strands | 1000         | Blisniuk et al., 2013 |
| Coachella segment     | 300          | Philibosian et al., 2011 |
| SGPr—San Gorgonio Pass region | | |
Andreas fault. Slip rates at the Upper Raywood Flat site along the Mill Creek strand and the Mission Creek alluvial complex site have the greatest sensitivity to changes in the active fault geometry through the SGPr, with dextral slip rates ranging from 0 to 13 mm/yr and 0 to 12 mm/yr, respectively, among the models tested. Of the tested fault configurations, the Inactive Mill Creek model best honors the observation of no recent slip at both Upper Raywood Flat (site 5) and the Mission Creek alluvial complex (site 6) and provides the smallest misfit to all of the investigated sites. However, the West Mill Creek model includes additional active portions of the Mission Creek, Mill Creek, and Galena Peak strands that could provide a better match to geologic indications of recent slip on these strands. We compare uplift rate patterns for the two preferred models. The Inactive Mill Creek and the West Mill Creek models show similar general spatial patterns of uplift rate, with greatest uplift rate in the San Bernardino Mountains and fastest subsidence in the San Bernardino Basin. Uplift rate data from areas that have different uplift rate patterns in the two models, as well as additional strike-slip rates along the Mission Creek and Mill Creek strands of the San Andreas fault, may give additional support for one or the other model.

The West Mill Creek model produces ~5 mm/yr greater overall strike-slip rate than the Inactive Mill Creek model, suggesting that some strike-slip deformation in the Inactive Mill Creek model may be accommodated as off-fault deformation. This means that decreases in slip in one part of the system are not compensated by corresponding increases in another part of the system. Off-fault deformation should be considered in slip budget analyses. Models with and without a northern pathway to slip in the SGPr produce similar slip rates within the Eastern California shear zone, refuting the idea that a lack of northern pathway for slip through the SGPr requires greater slip rates in the Eastern California shear zone. While a better understanding of the active fault geometries within the SGPr could shed light on how a rupture is likely to propagate through the region, a throughgoing rupture propagating from the Salton Sea to Cajon Pass through the SGPr along either of the best-fitting fault configurations could result in a Mw 7.7–7.9 earthquake.

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