NUMERICAL MODELING OF DEFORMATION WITHIN RESTRAINING BENDS AND THE IMPLICATIONS FOR THE SEISMIC HAZARD OF THE SAN GORGONIO PASS REGION, SOUTHERN CALIFORNIA

Jennifer Hatch

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NUMERICAL MODELING OF DEFORMATION WITHIN RESTRAINING BENDS AND THE IMPLICATIONS FOR THE SEISMIC HAZARD OF THE SAN GORGONIO PASS REGION, SOUTHERN CALIFORNIA

A Dissertation Presented

by

JENNIFER L. HATCH

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

September 2019

Department of Geosciences
NUMERICAL MODELING OF DEFORMATION WITHIN RESTRAINING BENDS AND THE IMPLICATIONS FOR THE SEISMIC HAZARD OF THE SAN GORGONIO PASS REGION, SOUTHERN CALIFORNIA

A Dissertation Presented
by
JENNIFER L. HATCH

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DEDICATION

To my loving family who supports me through all the ups and the downs.
ACKNOWLEDGMENTS

I owe most of my success to my remarkable advisor and mentor, Michele Cooke. She has spent countless hours training me to be an independent researcher and refining my scientific writing. Her patience and guidance have been invaluable on this journey. I will always consider her a role model and aspire to be the inspiring teacher and mentor that she is for so many.

I would also like to thank my devoted family. My parents have supported my pursuit of education since the beginning, through all of the emotional and financial turmoil. My husband, Ben, bravely joined me in the middle of my Ph.D., and I will be forever grateful for his ability to bring some fun to even the most stressful times. My beloved dog, Kelsie, provided unconditional love throughout it all, especially when no one else was around.
ABSTRACT

NUMERICAL MODELING OF DEFORMATION WITHIN RESTRAINING BENDS AND THE IMPLICATIONS FOR THE SEISMIC HAZARD OF THE SAN GORGONIO PASS REGION, SOUTHERN CALIFORNIA

SEPTEMBER 2019

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Assessment of seismic hazards in southern California may be improved with more accurate characterization of active geometry, stress state, and slip rates along the active San Andreas fault strands within the San Gorgonio Pass region. For example, on-going debate centers on the activity and geometry of the Mill Creek and Mission Creek strands. Calculated misfits of model slip rates to geologic slip rates for six alternative active fault configuration models through the San Gorgonio Pass reveal two best-fitting models, both of which fit many but not all available geologic slip rates. Disagreement between the model and geologic slip rates indicate where the model fault geometry is kinematically incompatible with the interpreted geologic slip rate, suggesting that our current knowledge of the fault configuration and/or slip rates may be inaccurate.

Focal mechanism of microseismicity can estimate stress state; however, within the San Bernardino basin, some focal mechanisms show slip that is inconsistent with the interseismic strike-slip loading of the region. We show that deep creep along the nearby northern San Jacinto fault can account for this discrepancy. Consequently, if local stresses are estimated using these focal mechanisms, the resulting information about fault
loading may be inaccurate. We also use another way to estimate the present-day, by calculating evolved fault tractions along a portion of the San Andreas fault using the time since last earthquake, fault stressing rates (which account for fault interaction), and coseismic models of the impact of recent nearby earthquakes. Because this method considers the loading history of each fault, the evolved tractions differ significantly from the resolved regional tractions and can provide more accurate initial conditions for dynamic rupture models within regions of complex fault geometry.

Numerical models of restraining bends in a viscoelastic material have implications for how we model the Earth’s crust. Deforming the model at faster velocities decreases the amount of visco-relaxation, allowing the model to behave more elastically. Viscoelastic models allow for velocity-dependent deformation, which could improve our understanding of crustal deformation, especially within complex fault systems.
PREFACE

Chapter 1

Chapter one has been published in the *Seismotectonics of the San Andreas fault in the San Gorgonio Pass region* special issue of the Geologic Society of America’s *Geosphere* (2018) with coauthors Michele Cooke and Scott Marshall. This manuscript aims to determine the active fault configuration of the San Andreas fault through the San Gorgonio Pass. We investigate six plausible active fault configurations through the San Gorgonio Pass region of southern California. This chapter concludes with two preferred fault configurations, which we cannot further delineate due to lack of geological observations on the northern pathway through the San Gorgonio Pass. However, our models can be used to determine locations for future geophysical investigations. An analysis of the potential rupture area indicates that the active fault configuration may not significantly impact the size of a rupture through the region.

Chapter 2

This chapter investigates the compatibility of interpreted subsurface fault geometry and slip rates from geologic investigations within the San Gorgonio Pass of southern California. How reliable are interpretations of active subsurface fault geometries and geologic slip rates? What if geologically determined slip rates are incompatible with interpreted fault geometries? Where slip rates are incompatible with fault geometry, deformation cannot be efficiently accommodated as fault slip and is accommodated as off-fault deformation. This chapter assesses the interpreted fault geometry and geologic slip rates to highlight regions of incompatibility that would benefit from further
geophysical investigations. Regions of incompatibility are the Indio Hills region, the area around the Mission Creek Alluvial Complex, and to a lesser degree, the Cajon Pass region. This project will likely result in publication.

Chapter 3

Chapter three has been published in *Geophysical Research Letters* (2018), with Michele Cooke as the lead author. We use crustal deformation models to investigate enigmatic microseismic events in the San Bernardino basin, southern California. These enigmatic earthquakes have normal slip sense, which is inconsistent with the interseismic strike-slip loading of the region. We investigate the impact of different locking depths of the San Jacinto fault to show that these enigmatic normal slip events may be due to deep creep along the northern San Jacinto fault. Due to the close proximity of the San Jacinto and San Andreas faults, inversions of geodetic data cannot distinguish the locking depths for these two faults. We argue that these events may provide inaccurate information about fault loading and should not be included in stress inversions from the seismic catalog.

Chapter 4

Chapter four has been submitted for publication to the *Seismotectonics of the San Andreas fault in the San Gorgonio Pass region* special issue of the Geologic Society of America’s *Geosphere*, and it is a collaboration between the University of Massachusetts Amherst (Michele Cooke and Aviel Stern) and the University of California Riverside (Roby Douilly and David Oglesby). No changes were made here to the submitted manuscript. We focus on a new methodology for estimating the stress state of faults,
which is critical for forecasting seismic hazard. While many dynamic rupture modelers resolve the regional stress tensor onto faults of interest, we evolve fault tractions by considering the time since last earthquake, interseismic fault stressing rates (which accounts for fault interaction), and the impact of recent nearby earthquakes. The resulting estimates of shear tractions are significantly different from the resolved regional tractions and may produce a more accurate estimate of the current stress state for dynamic models of future earthquakes. Additionally, an analysis of the time needed to accumulate shear tractions that exceed a typical earthquake stress drop of 3 MPa shows some faults in the San Gorgonio Pass region already exceed 3 MPa and may be near failure.

Chapter 5

Chapter five investigates the impact of loading rate on the spatial and temporal deformation around strike-slip faults with a restraining bend hosted within bi-viscous material. This project is motivated by physical experiments in the University of Massachusetts Amherst Geomechanics claybox (Cooke et al., 2013; Hatem 2015). While the physical experiments show the evolution and distribution of incremental displacements and strain, the stresses within the clay cannot currently be monitored. We use finite element method models to simulate a restraining bend in a Burger’s material that approximates the rheology of the wet kaolin clay, providing further insight into the mechanics of deformation within the claybox. Models with faster loading rates are kinematically more efficient, producing less off-fault deformation and more fault slip than the slower loading rate models. However, an assessment of the external work of the numerical models indicates that while the faster loading rate models are more
kinematically efficient, they are less mechanically efficient because they consume greater work to deform the system. This project will likely result in publication.
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CHAPTER 1

SENSITIVITY OF DEFORMATION TO ACTIVITY ALONG THE MILL CREEK AND MISSION CREEK STRANDS OF THE SOUTHERN SAN ANDREAS FAULT

1.1 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. On-going 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 incorporates 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 plate rate. 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 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.

1.2 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 (Figure 1.1), the San Andreas fault consists of several non-vertical 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 remains poorly constrained.

On-going debate centers on the relative activity of the Mill Creek and Mission Creek strands, which provide a northern path for rupture through the SGPr (Figure 1.1). Several studies have pointed out that unruptured colluvial and debris fan sediments across the Mill Creek strand at Upper Raywood Flat (site 5 in Figure 1.1) 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 Figure 1.1) and luminescence dating of alluvial surfaces to reveal that the slip on both northern strands discontinued at ~ 100 ka. However, another study along the southern portion of the Mission Creek strand (site 10 in Figure 1.1), 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 Figure 1.1) suggest that greater slip may pass through other strands, such as the northern strands or the Garnet Hill strand [Gold et al., 2015]. Morelan et al. [pers. communication] document 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 (Figure 1.2). 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.

1.3 Geometry and Quaternary Slip Rates on the San Andreas and San Jacinto Faults

1.3.1 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. 1.1]. 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 1.1. Dextral slip rate estimates along the subvertical San Bernardino segment decrease southeastward from 24.5 mm/yr in Cajon Pass [site 1; Weldon and Sieh, 1985] to 11-17 mm/yr at Badger Canyon [site 2; McGill et al., 2010] and 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] (Figure 1.1 and Table 1.1).

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 (Figure 1.1). 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 et al., 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 >2.5 mm/yr at Millard Canyon [Yule and Sieh, 2003], and a dextral oblique slip rate of $5.7 \pm 2.7$ mm/yr [site 7; Heermance et al., 2017]. The eastern end of the fault zone appears to connect to the Garnet Hill and Banning strands of the San Andreas fault. The north-dipping Garnet Hill and Banning strands are approximately parallel in strike and have a variety of subsurface interpretations [Yule and Sieh, 2003;
Plesch et al., 2007; Fuis et al., 2017; Nicholson et al., 2017]. For this study, we represent the faults with a sub-vertical Banning strand that is only active in the hanging wall of the Garnet Hill strand. The Banning strand has 3.9-4.9 mm/yr dextral slip at its western end near Whitewater Canyon [site 8; Gold et al., 2015] and 2-6 mm/yr near its junction with the Mission Creek strand of the San Andreas fault [site 9; Scharer et al., 2015].

The northern pathway of the San Andreas fault through the SGPr consists of the Mill Creek, Galena Peak, and Mission Creek strands (Figure 1.1). 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 last 100 ka [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 sub-vertical 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 (Figure 1.1). 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; Morelan, pers. communication].

The Banning and Mission Creek strands merge into the Coachella segment of the San Andreas fault just south of the Indio Hills (Figure 1.1). 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 junction with the Banning and Mission Creek strands, an offset alluvial fan at Biskra Palms provide 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].

1.3.2 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 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 $12.1 \pm 3.4 \text{ mm/yr}$ [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 $8.9 \pm 2 \text{ mm/yr}$ in the north to $1.5 \pm 0.4 \text{ mm/yr}$ in the south [sites 15 and 16; Blisniuk et al., 2010], where this segment forms a releasing
stepover with the Coyote Creek segment. The Coyote Creek segment has slip rates of $4.1 \pm 1.9$ mm/yr in the north [site 17; Janecke et al., 2010] and 2.8-5 mm/yr in the south near its termination [site 18; Sharp, 1981].

1.4 Methods

The six active fault configurations modeled here (Figure 1.2) 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/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 to be captured. 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 Figure 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 go 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 (Figure 1.3). 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, 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
SGPr. 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.

1.4.1 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. Herbert et al., 2014a&b; Fattaruso et al., 2014].
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 Figure 1.3), and a linear gradient in the tectonic
loading across the plate boundary (sides labeled II on Figure 1.3). 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 (Figure 1.3). 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 (Figure S.1.2).

1.4.2 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 (Figure 1.1), 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 1.1). 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].

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

Equation 1.1

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 1.1 (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.

1.4.3 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/m$^3$ [Christensen and Mooney, 1995], crustal density of 2700 kg/m$^3$, and a flexural rigidity of the crust of $2 \times 10^{23}$ Pa·m$^3$ for our correction. We also subtract the mean uplift rate of the grid from the pattern to produce the relative uplift pattern.
1.5. Results for Five Alternative Fault Configurations

1.5.1 Dextral Slip Rates

Each of the six modeled fault configurations produce dextral slip rates that are within the range of geologic slip rates at some, but not all, sites (Figure 1.4 and Table 1.2). 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 1.2) 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 (Figure 1.4). The Inactive Mill Creek model produces a total dextral slip rate misfit >0.8 mm/yr lower than the misfits of four of the active Mill Creek models but only 0.5 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 1.2).

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 (Figure 1.4a). Sites 2 and 3 (Badger 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 slightly overestimate 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 (Figure 1.4c). 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 (Figure 1.4d). 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 (Figure 1.4b and Table 1.2) are smaller than misfits calculated along the San Andreas fault. While the models match well the geologic dextral slip rates at only 1-2 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 Andreas 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 1.5 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 (Figure 1.5a) and the *West Mill Creek* model (Figure 1.5b). 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 at Millard Canyon (site 7). In the *Inactive Mill Creek* model (Figure 1.5a), 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 ~1.3 mm/yr reverse slip (not shown in Figure 1.5), which is less than geologic observations of > 2.5 mm/yr [Yule and Sieh, 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 (Figure 1.5b), 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 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.

1.5.2 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 (Figure 1.6a) and the West Mill Creek model under the mean applied tectonic loading (Figure 1.6b). 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 et al., 2010]. The model uplift patterns from the two models differ significantly in several key locations (labeled A-D in Figure 1.6).

In the hanging wall of the San Gorgonio Pass Fault zone (location A on Figure 1.6), 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 Figure 1.6).

Within the San Bernardino Mountains, Binnie et al. [2008] report a northward decrease in $10^2$-$10^4$ year time-scale denudation rates from 1.5+/−3 mm/yr at Yucaipa Ridge, location B on Figure 1.6, to 0.4+/− 0.6 mm/yr in the San Gorgonio block north of location B (under San Bernardino Mtns text on Figure 1.6a). 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 uplift rate at Yucaipa Ridge from the West Mill Creek model of 1.5 mm/yr matches the denudation rate of Binnie et al. [2008], but the model uplift pattern shows increased uplift rate to the north as the San Bernardino block rises along the north dipping Mission Creek fault. Low temperature thermochronometry data from sites along the Yucaipa Ridge reveal uplift rates over the past 1.8 Ma [Spotila et al., 2001]. Unfortunately, the active configuration of the southern San Andreas fault has
changed within this time-frame [e.g., Matti and Morton, 1993; Kendrick et al., 2015], so these rates don’t directly correlate to those produced by the active fault models.

The alluvial fan between North Palm Springs and Desert Hot Springs, and the hanging wall of the Mission Creek strand at Raywood Flat (locations C and D, respectively) show significantly different uplift rate patterns between the two models, with the *Inactive Mill Creek* model producing ~2 mm/yr greater uplift rates in the alluvial fan than the *West Mill Creek* model. The dextral slip along the Mission Creek strand in the *Inactive Mill Creek* model may contribute to uplift in the alluvial fan as local contraction develops south of the fault’s tip where slip decreases to zero.

In the *Inactive Mill Creek* model, dip slip along the San Gorgonio Pass Fault zone, Garnet Hill strand, and Banning strand accommodates contraction within the restraining bend, whereas in the *West Mill Creek* model, the local contraction is accommodated along these faults as well as along the north-dipping Mission Creek strand, allowing the uplift to be redistributed from just along the southern strands to both the southern and northern strands. While both models match some trends in the geologic data for recent uplift, neither of these models match well all of the geologic data for recent uplift.

1.6 Discussion

1.6.1 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 (Figure 1.4).
The sites along the San Bernardino segment, especially Badger Canyon (site 2 on Figure 1.4), 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 (Figure 1.1), just exceeding the range of geologic slip rates along the Banning strand of the San Andreas fault (Figure 1.5a). 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 Blisniuk et al. [2012], and field studies along the northern portion of the Mill Creek strand [Morelan et al., pers. communication] 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 (Figure 1.4) but produces 7 mm/yr dextral slip rate at site 6 in the Mission Creek alluvial complex (Figure 1.5b). The Inactive Mill Creek and West Mill Creek models produce zero slip at site 5 within Upper Raywood Flat (Figure 1.4c) and zero slip and ~6-8 mm/yr dextral slip, respectively, at site 6 in the Mission Creek alluvial complex (Figure 1.4d). 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 currently 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 [Morelan et al., pers. communication].

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 Figure 1.6). 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 \(10^2-10^4\) year time scale uplift rate data from any of the locations labeled in Figure 1.6 may provide additional information about the active subsurface fault configuration in the San Gorgonio Pass region.

1.6.2 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 (Figure 1.1). 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 1.5 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 1.6 would lend additional support for preference of one active fault geometry or the other.

**1.6.3 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/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 that increase strike-slip rates along the San Andreas fault also 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 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 produces 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 along the southern strands in
the *Inactive Mill Creek* model than in the *West Mill Creek* model, which can be associated with folding (Figure 1.6).

### 1.6.4 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 AD 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, through-going 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 through-going 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 (Figure 1.1). Using the
model net-slip rates, time since last event (TSLE) for each fault segment (Table 1.3), and the assumption of complete stress drop between events, we estimate the total seismic moment that could be released in a large through-going 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 $3.64 \times 10^{20}$ Nm (Mw ~7.7). Alternatively, a rupture that travels along the northern pathway of the San Gorgonio Pass will have a seismic moment of $6.21 \times 10^{20}$ Nm (Mw ~7.8). Furthermore, a branching rupture that travels along both the southern and northern pathways, would release a seismic moment of $7.25 \times 10^{20}$ 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, using a regression of rupture area on magnitude, the rupture areas for these scenarios give similar magnitudes of 7.8-7.9 (Wells and Coppersmith, 1994). Any of these through-going rupture scenarios could result in peak ground velocities of 2 m/s or greater hitting the Los Angeles Basin [Porter et al., 2011], which could be devastating for the region.

1.7 Conclusions

On-going debate in the SGPr centers on the relative activity of the Mill Creek and Mission Creek strands, which may provide an alternative slip pathway north of the active faults within the San Gorgonio Pass. We utilize a suite of three-dimensional BEM 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. Both the *Inactive Mill Creek* model and *West Mill Creek* model match 8/18 of the strike-slip rates at investigated sites. 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 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 0-13 mm/yr and 0-12 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 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 through-going 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.
1.8 Figures

Figure 1.1: Map of the potential active faults of the San Gorgonio Pass region (SGPr) showing the sites with available dextral slip rates with yellow dots. Thicker, colored lines denote San Andreas fault strands. The Galena Peak strand is denoted by GP. Slip rates for these sites are listed in Table 1. Note the lack of slip rates along the northern strands. Sites 5 and 6 are the locations of Upper Raywood Flat and the Mission Creek alluvial complex, respectively, where evidence of no recent slip is observed [Kendrick et al., 2015]. Inset: map of southern California showing the location of the SGPr. Major cities are labeled in red: San Francisco (SF), Los Angeles (LA), and San Diego (SD).
Figure 1.2: 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 is 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 1.3: 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.
Figure 1.4: Correlation of modeled and geologic strike-slip rates along the A) San Andreas fault and B) San Jacinto fault 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 Figure 1) for the six models. D) Modeled strike-slip rates at the Mission Creek alluvial complex (site 6 in Figure 1). Investigated slip rate sites along the San Andreas and San Jacinto faults are the same as in Figure 1.
Figure 1.5: Surface dextral slip rates along strands of the San Andreas fault for the two best fitting models: A) Inactive Mill Creek and B) West Mill Creek. Fault strand colors are the same as in Figure 2. Vertical bars show the range in strike-slip rates from geologic studies (Table 1). The bands show modeled strike-slip rates along each strand with the height of the band showing range of slip rate for the uncertainty in tectonic loading. New geologic slip rates along the Mission Creek and Mill Creek strands within the black-boxed regions on the map would help delineate between these models.
Figure 1.6: Model uplift rates for the two best-fitting models: A) *Inactive Mill Creek* and the B) *West Mill Creek* models. The uplift patterns are isostatically adjusted and filtered to remove model artifacts. The two models produce similar uplift patterns throughout the SGP region. Key differences between the models are in the A) hanging wall of the San Gorgonio Pass Fault zone, B) Yucaipa ridge, C) alluvial fan between North Palm Springs and Desert Hot Springs, and D) hanging wall of the Mission Creek strand near Upper Raywood Flat.
1.9 Tables

<table>
<thead>
<tr>
<th>Slip Rate Site</th>
<th>Fault strand</th>
<th>Dextral slip rate (mm/yr)</th>
<th>Reference</th>
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<tbody>
<tr>
<td>1</td>
<td>San Bernardino</td>
<td>21-28</td>
<td>Weldon and Sieh, 1985</td>
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<tr>
<td>2</td>
<td>San Bernardino</td>
<td>11-17</td>
<td>McGill et al., 2010</td>
</tr>
<tr>
<td>3</td>
<td>San Bernardino</td>
<td>6.8-16.3</td>
<td>McGill et al., 2013</td>
</tr>
<tr>
<td>4</td>
<td>San Bernardino</td>
<td>4-12</td>
<td>Orozco, 2004</td>
</tr>
<tr>
<td>5</td>
<td>Mill Creek</td>
<td>0</td>
<td>Kendrick et al., 2015</td>
</tr>
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<td>6</td>
<td>Mill Creek and Mission Creek</td>
<td>0</td>
<td>Kendrick et al., 2015</td>
</tr>
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<td>7</td>
<td>San Gorgonio Pass Fault Zone</td>
<td>4.2-8.4</td>
<td>Heermance and Yule, 2017</td>
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<td>8</td>
<td>Banning</td>
<td>3.9-4.9</td>
<td>Gold et al., 2015</td>
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<td>9</td>
<td>Banning</td>
<td>2-6</td>
<td>Scharer et al., 2015</td>
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<td>10</td>
<td>Mission Creek</td>
<td>17-24</td>
<td>Blisniuk et al, 2012</td>
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<tr>
<td>11</td>
<td>Mission Creek</td>
<td>10-14</td>
<td>Munoz et al., 2016</td>
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<td>12</td>
<td>Coachella</td>
<td>14-17</td>
<td>Behr et al., 2010</td>
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<td>Claremont</td>
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<td>16</td>
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<td>17</td>
<td>Coyote Creek</td>
<td>2.4-6</td>
<td>Janecke et al., 2010</td>
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<tr>
<td>18</td>
<td>Coyote Creek</td>
<td>2.8-5</td>
<td>Sharp, 1981</td>
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Table 1.1: Dextral slip rates for available sites along the San Andreas and San Jacinto faults. Site numbers are as in Figure 1.
<table>
<thead>
<tr>
<th>Model fit to investigated sites</th>
<th>Slip rate misfits (mm/yr)</th>
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<td>SAF (x/12 sites)</td>
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<td>Inactive Mill Creek</td>
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<tr>
<td>Active Mill Creek</td>
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<tr>
<td>Mill Creek + Galena Peak</td>
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<tr>
<td>Vertical Mission Creek</td>
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</tr>
<tr>
<td>North-dipping Mission Creek</td>
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</tr>
<tr>
<td>West Mill Creek</td>
<td>6</td>
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Table 1.2: Model fit to the investigates sites, showing how many sites along the San Andreas and San Jacinto faults each model matches, and the preferred and permissible misfits to the geologic strike-slip rates for each of the five modeled active fault configurations.
<table>
<thead>
<tr>
<th>Fault</th>
<th>TSLE (years)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Bernardino segment</td>
<td>200</td>
<td>Biasi et al., 2009</td>
</tr>
<tr>
<td>Southern SGPr strands</td>
<td>600</td>
<td>McBurnett, 2011</td>
</tr>
<tr>
<td>Northern SGPr strands</td>
<td>1000</td>
<td>Blisniuk et al., 2013</td>
</tr>
<tr>
<td>Coachella segment</td>
<td>300</td>
<td>Philibosian et al., 2011</td>
</tr>
</tbody>
</table>

*Table 1.3: Times Since Last Event (TSLE) for the faults of the San Gorgonio Pass region.*
1.10 Supplemental information

1.10.1 Iterating the tectonic loading

Previous studies using Boundary Element Method models of the region estimated the tectonic velocities and applied a velocity gradient across the San Andreas fault using blocks of elements each with uniform velocity, separated by discrete steps [e.g. Herbert et al., 2014; Fattaruso et al., 2014]. However, Poly3D prescribes the slip rate across the model base, rather than the displacement rate on the upper side of the base, often resulting in inaccurate approximations of the desired velocity. To correct for this, we implement an iterative technique following Stern [2016].

The approach begins with a first estimate for the tectonic loading, following the approach of previous models, followed by a correction to improve the blocky gradient to a linear gradient across the San Andreas fault (sides labeled II on Figure 3). After the linear gradient is applied, we calculate a correction ratio from the output displacement rates to adjust the slip rate applied to each element along the outer ring of the model base. After each run of the model, we adjust the applied slip rate iteratively until the desired displacement rate along the upper side of the elements around the model boundaries is obtained. We use three iterations to smooth the boundary velocities to within 1% of the desired tectonic loading (Figure S2).
Figure S.1.1: Regional map showing the complete modeled fault traces in models presented here. Dashed lines show the upper tiplines of blind faults.
Figure S.1.2: Displacements along the A) east model boundary patch and B) northeast model boundary patch with successive iterations. The northeast patch shows a linear gradient in the displacements, decreasing from the tectonic rate to the rate of the San Andreas fault. By the third iteration (red), displacements are generally within 1% of the desired displacements.
CHAPTER 2

ASSESSING KINEMATIC COMPATIBILITY OF GEOMETRY AND SLIP RATES WITHIN THE SAN GORGONIO PASS REGION, SOUTHERN CALIFORNIA

2.1 Abstract

Assessment of seismic hazards in southern California may be improved with more accurate characterization of geometry of and slip rates along the active San Andreas fault strands within the San Gorgonio Pass region. Crustal deformation models with two alternative and currently debated three-dimensional active fault geometries through the San Gorgonio Pass region produce fault slip rates that match some, but not all, of the available geologic strike-slip rates at sites along the southern San Andreas fault. Sites with disagreement between the model and geologic slip rates indicate where the model fault geometry is incompatible with the interpreted geologic slip rate. We investigate the kinematic compatibility of slip rates and fault geometry using mechanical models that limit the dextral strike-slip rates to within the range of observed slip rates at the sites of the geologic investigations. The faults outside of these regions slip freely in response to tectonic loading and fault interaction. Off-fault distortion maps of the model results reveal regions of kinematic incompatibility at the branch of the San Andreas fault near Indio Hills, in the hanging wall of the San Gorgonio Pass thrust, and near Cajon Pass. Local concentration of off-fault distortion indicates that geologic fault slip rates are not effectively accommodated along the simulated fault surfaces in these regions. This new approach reveals incompatibilities that suggest that our current knowledge of the fault
configuration and/or slip rates may not accurately inform seismic hazards of these regions.

2.2 Introduction

The southern San Andreas fault forms a restraining stepover in the San Gorgonio Pass region (SGPr), characterized by multiple active fault strands and complex interactions (Figure 2.1). Due to the lack of large ground rupturing earthquakes during the span of the seismic catalog (e.g., Yang et al., 2012), the activity and subsurface geometry of the San Andreas fault through the SGPr remains uncertain. The available geologic observations at the surface and geophysical subsurface data provide conflicting interpretations of fault geometry in many portions of the SGPr.

For example, on-going debate centers on the relative activity of the Mill Creek and Mission Creek strands, which provide a northern path for rupture through the SGPr (Figure 2.1; Gold et al., 2015; Kendrick et al. 2015; Fosdick and Blisniuk, 2018). Whereas Kendrick et al. [2015] used reconstructed drainage segments across the Mill and Mission Creek strands (site 6 in Figure 2.1) to show that both strands have been inactive for ~ 100 ka, a provenance study in this same area by Fosdick and Blisniuk (2018) suggests that these strands are active. Further to the east along the Mission Creek fault, two sites within 5 km of each other (sites 9 and 10) have slip rates that differ by > 10 mm/yr (17-24 mm/yr at site 9, Blisniuk et al. 2012; 10-14 mm/yr at site 10, Munoz et al. 2016; Figure 2.1). Uncertainties in active geometry of the San Andreas fault also impede confident fault interpretation in other regions of the SGPr.

One approach to constrain fault geometry uncertainty is to test plausible fault configurations by comparing results of alternative mechanical models with geologic slip
rates, uplift and/or geodetic data (e.g. Cooke and Dair, 2011; Herbert et al., 2014; Fattaruso et al., 2014; Beyer et al., 2018). For example, Beyer et al. (2018) find that two among five plausible configurations of the San Andreas fault through the SGPr fit well the available geologic slip rates. One limitation of this forward modeling approach is that the explicit set up of the fault configurations does not inform the feasibility of alternatives outside of those tested. What if none of the tested fault configurations is accurate? Furthermore, few geologic slip rates studies assess uncertainty of their findings. What if some slip rates are unreliable? Kinematic compatibility of a fault system quantifies how deformation is partitioned through the system (e.g., Gabrielov et al., 1996). If interpreted fault geometries and slip rates are kinematically compatible, the system is efficient, and deformation will be accommodated as on fault slip rather than off-fault deformation. In contrast, if interpreted fault geometries and slip rates are kinematically incompatible, such as fast slip rates through a sharp bend, the system is inefficient, and deformation cannot be effectively accommodated as fault slip, resulting in strain partitioning into off-fault deformation.

In this study, we use three-dimensional Boundary Element Method models that simulate deformation over many earthquake cycles and investigate kinematic compatibility of interpreted fault geometry with interpreted slip rates through the San Gorgonio Pass region (Figure 2.1). Rather than letting faults slip in response to tectonic loading (Beyer et al. 2018), here we prescribe geologic slip rates at the sites of the investigation. This allows the models to incorporate both interpreted slip rates and fault geometry at the same time so that we can assess their compatibility. We compare off-fault distortion from an unconstrained slip rate model to those of models where we limit
slip rates at the geologic slip rate sites. Regions of high off-fault deformation indicate kinematic incompatibility which highlights regions where our knowledge of fault geometry and/or slip rate may be insufficient.

2.2.1 Fault systems evolve to be mechanically efficient

Fault systems grow new faults in order to increase mechanical efficiency, minimizing the work required to accommodate the strain of the system (e.g., Mitra and Boyer, 1986; Masek and Duncan, 1998; Cooke and Murphy, 2004; Del Castello and Cooke, 2007; Cooke and Dair, 2011; Cooke et al., 2013; Hatem et al., 2015; Fattaruso et al., 2016). If the tectonic loading changes, the efficiency of a system may decrease, producing less fault slip and greater off-fault deformation. In response, the fault system may reorganize and grow new faults to accommodate a greater portion of the regional strain as slip along faults. The new faults that grow are ideally oriented such that their geometries are kinematically compatible with the tectonic loading.

2.2.2 Geometry and slip rates of the southern San Andreas fault

The San Gorgonio Pass, sometimes called the little ‘Big Bend’, is where the southern San Andreas fault forms a left-stepping restraining bend and becomes geometrically complex, with multiple active fault strands (Matti et al., 1983; Matti et al., 1985; Figure 2.1). The southern pathway of the San Andreas fault within the SGPr consists of the San Gorgonio Pass thrust, Garnet Hill strand, and Banning strand (Figure 1). The San Gorgonio Pass thrust is a north-dipping thrust fault that intersects the Earth’s surface with a scalloped trace (e.g., Matti et al., 1985; Matti et al., 1993; Yule and Sieh, 2003). The San Gorgonio Pass thrust has a reverse slip rate of >2.5 mm/yr (Yule and
Sieh, 2003), and a dextral slip rate of $5.7 \pm 0.7 \text{ mm/yr}$ (site 5; Heermance et al., 2017).

The north-dipping Garnet Hill and Banning strands are nearly parallel in strike but have several different interpreted subsurface geometries (Yule and Sieh, 2003; Plesch et al., 2007; Fuis et al., 2017; Nicholson et al., 2017). For this study, we represent the subsurface faults with a sub-vertical Banning strand only active within the hanging wall of the Garnet Hill strand. The Banning strand has 3.9-4.9 mm/yr dextral slip at its western end (site 7; Gold et al., 2015) and 2-6 mm/yr dextral slip to the east near its intersection with the Mission Creek strand of the San Andreas fault (site 8; Scharer et al., 2015).

The northern pathway of the San Andreas fault through the SGPr consists of the Mill Creek, Galena Peak, and Mission Creek strands (Figure 2.1). The geometry and activity of these strands, which provide an additional pathway for slip through the San Gorgonio Pass, are still under debate (e.g., Kendrick et al., 2015; Beyer et al., 2018; Fosdick and Blisniuk, 2018). A study of the Mission Creek alluvial complex suggests that neither the Mission Creek nor Mill Creek faults have slipped at this location for 100 ka (site 6; Kendrick et al., 2015). In contrast, a sedimentary provenance study of modern drainages just a few kilometers away suggests that the Mission Creek fault may accommodate most of the deformation in the region (Fosdick and Blisniuk, 2018).

Further to the east on the Mission Creek strand, high dextral slip rates of 10-14 mm/yr in the Indio Hills [site 10; Munoz et al., 2016] and 17-24 mm/yr near Pushawalla Canyon [site 9; Blisniuk et al., 2012] support the transfer of slip through the SGPr via a northern pathway. The sub-vertical Galena Peak strand (e.g., Dibblee, 1964; Matti et al., 1983; Kendrick et al., 2015) connects the Mill Creek strand and western segment of the Mission Creek strand (Figure 2.1).
The Banning and Mission Creek strands merge into the Coachella segment of the San Andreas fault just south of the Indio Hills (Figure 2.1). The Coachella segment dips to the northeast (e.g., Lin et al., 2007; Fattaruso et al., 2014; Fuis et al., 2017) and continues from the Indio Hills, southward to the eastern shore of the Salton Sea. Just south of the junction with the Banning and Mission Creek strands at Biskra Palms, the Coachella segment slips at a preferred rate of 14-17 mm/yr [site 11; Behr et al., 2010].

2.3 Methods

We evaluate the kinematic compatibility of fault geometry with geologic slip rates within the San Gorgonio Pass region using Poly3D, a quasi-static, three-dimensional boundary element code. Poly3D calculates stresses and displacements throughout the model by solving the relevant equations of continuum mechanics (e.g., Thomas, 1993; Crider and Pollard, 1998). In addition to detailed three-dimensional representation of faults within the San Gorgonio Pass region, the models incorporate 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 (Plesch et al., 2007; Nicholson et al., 2017; Figure 2.2). We include modifications to the CFM v.4.0 fault geometry as described in Herbert et al. (2014), Fattaruso et al. (2014) and Beyer et al. (2018) that improve match of model slip rates to geologic slip rates.

Faults are discretized into triangular elements that can replicate complex fault geometries within a linear-elastic and otherwise homogeneous half-space (Figure 2.2). Within the San Gorgonio Pass region, the average element size is ~4 km, allowing for the models to capture fault irregularities as small as ~10 km. Following Marshall et al. (2009), we extend the faults of the CFM down to a horizontal basal crack that is freely
slipping at 35 km depth to simulate distributed deformation below seismogenic depths. This adaptation allows us to simulate long-term deformation without the fault slip rates going to zero at the base of the CFM-defined faults. Furthermore, we do not consider impacts of heterogeneous and/or anisotropic rock properties. Over multiple earthquake cycles, fault geometry provides a first-order control on deformation patterns (e.g., Dawers and Anders, 1995; Fay and Humphreys, 2005; Herbert and Cooke, 2012).

Within the reference models, the shear traction-free faults throughout the model slip freely in response to both the tectonic loading and fault interaction. Zero shear traction is consistent with low dynamic strength of faults during rupture (e.g., Di Toro et al., 2006; Goldsby and Tullis, 2011). Tectonic loading is prescribed far from the investigated faults at the base of the model, following Herbert & Cooke (2012) to simulate plate motions that are geodetically constrained to be 45-50 mm/yr at 320°-325° (e.g., DeMets et al., 2010). Following Beyer et al. (2018), we also implement an iterative technique that uses a correction ratio for successive iterations to ensure a uniform applied tectonic velocity parallel to the plate boundary (sides labeled I on Figure 2.2) and a linear gradient in the tectonic loading across the plate boundary (sides labeled II on Figure 2.2). This technique provides applied velocities that are within ~1% of the desired tectonic loading.

To prevent slip from artificially going to zero on faults that extend outside our model area (i.e., the San Andreas, San Jacinto, and Cucamonga-Sierra Madre fault systems), we prescribe slip rates to patches of these faults at the edge of our model. For the San Andreas fault, we apply 35 mm/yr dextral slip (Weldon and Sieh, 1985) at the northwestern edge of the model. At the southeastern edge of the model, we apply 25
mm/yr and 10 mm/yr dextral slip to the San Andreas and San Jacinto faults, respectively (e.g., Sharp, 1981; Becker et al., 2005; Fay and Humphreys, 2005; Meade and Hager, 2005). Deformation within the SGPr is not significantly impacted by variations in the partitioning of slip rates between the San Andreas and San Jacinto faults at this model edge because slip rates primarily respond to interaction among complex faults within the San Gorgonio Pass region (Fattaruso et al., 2014). Finally, we apply 1.6 mm/yr reverse slip (McPhillips and Scharer, 2018) to the western edge of the modeled Cucamonga fault to account for deformation along the Sierra Madre fault, which is not included in our model.

2.3.1 Tested fault configurations

Of the six plausible fault configurations tested by Beyer et al. (2018), we explore the kinematic compatibility of the two models that best fit the geologic slip rates and field observations of active slip. The first model considers an inactive Mill Creek strand and consists of the green strands in Figure 2.1. The second model expands from the first fault configuration and additionally incorporates active Mill Creek and Galena Peak strands (orange fault strands in Figure 2.1). We refer to these fault configurations as the Active Mill Creek and the Inactive Mill Creek models.

2.3.2 Assessing kinematic compatibility

We assess the kinematic compatibility of geologic slip rates with interpreted fault geometry by limiting slip rates to within the geologic range at sites of slip rate investigations. Because geologic investigations produce a range of possible slip rates, we allow for a variety of slip rates at each site of geologic investigation in the model. In the
absence of probability density functions for the slip rates, we treat the geologic slip rate as having uniform probability within the published range. The reference models use the results from Beyer et al. (2018), where the faults slip freely in response to tectonic loading and fault interaction. The slip rates and the kinematic compatibility of this model will be used as reference for the subsequent models that limit the slip rates to within the geologic ranges. The reference models have greater kinematic compatibility than the slip-limited models because faults are free to slip in accordance with the fault geometry.

In a second set of models, we limit the slip rates at geologic sites within the models to within the geologic range. This is an iterative process starting from the reference models. If the slip rates from the reference model exceed the geologic range, then we prescribe the slip rate at the site to be either the upper or lower limit of the geologic slip rate range. If the slip rate in the reference model is closer to the upper bound then we prescribe this slip rate at the site, otherwise the patch has the lower bound slip rate. At each slip rate site along the fault, the prescribed slip rate patch is ~6 km by 6 km, extending down from the surface trace. Because altering slip rates on some sites may impact other portions of the fault, we implement this approach iteratively until the modeled slip rate at each site falls within the geologic slip rate range for that site. Locations along the faults between the prescribed slip rate sites freely slip in response to tectonic loading, fault interaction, and the effects of prescribed slip patches.

We assess the kinematic incompatibility of each of the two fault configurations by calculating maps of the off-fault deformation rate, here defined as the sum of the vorticity rate (2×curl) and the divergence rate of the surface velocity field. For each tested fault configuration, we compare the resulting deformation pattern and also the total
deformation integrated across the region compared to that of the reference models. The spatial pattern of deformation reveals the regions where geologic slip rates are incompatible with interpreted fault geometry, while total deformation provides a metric for the relative compatibility.

2.4 Results

Here, we present maps of off-fault deformation and plots of fault slip rates through the SGPr for both fault configurations.

2.4.1 Off-fault distortional strain

The off-fault deformation increases with increasing constraints on fault slip. The reference model for each fault configuration (Figure 2.3) has the least constrained slip rates as it allows all faults to slip everywhere in response to tectonic loading and fault geometry. The model with an inactive Mill Creek fault configuration has more off-fault deformation than the model with active Mill Creek and Galena Peak strands (Figure 2.3 and Table 2.1). This result suggests that the fault configuration with an active Mill Creek strand is more efficient at accommodating plate motion as fault slip. High off-fault deformation develops near fault intersections of both fault configurations. The inactive Mill Creek geometry (Figure 2.3a) shows areas of off-fault deformation in the hanging wall of the 1) along the San Bernardino strand between slip rate sites 3 and 4, 2) near the northern extent of the Mission Creek strand, 3) north of the Pinto Mountain fault, 4) where the Banning and Mission Creek strands merge into the Coachella segment, and 5) north of the Blue Cut fault going northward towards the Eastern California Shear Zone. These areas of off-fault deformation decrease with the presence of an active northern
pathway in the active Mill Creek geometry (Figure 2.3b), because the introduction of the northern pathway decreases strike-slip rates along the southern pathway and accommodates more slip along the northern pathway (Beyer et al., 2018). The total integrated off-fault deformation is less (1.5%) for the active Mill Creek fault than when this fault is inactive (Table 2.1).

When we limit slip rates at the sites of the geologic investigations in the model, regions of large off-fault deformation develop. Figure 2.4 shows the change in off-fault deformation relative to the reference models (Figure 2.3). In the inactive Mill Creek fault configuration (Figure 2.4a), off-fault deformation increases in the Cajon Pass, at the juncture of the Banning, Mission Creek and Coachella strands at Indio Hills, and to a lesser degree in the hanging wall of the San Gorgonio Pass thrust (SGP thrust). With the exception of the Indio Hills region, these same regions of increased off-fault deformation are amplified in the active Mill Creek fault configuration (Figure 2.4b). Additionally, the active Mill Creek geometry produces a region of high off-fault deformation along the Mission Creek fault near the Mission Creek Alluvial Complex (site 6) where the fault is pinned such that it does not slip. The total off-fault deformation integrated over the study area of these models can be compared to the reference models (Table 2.1). For both fault configurations, the total integrated off-fault deformation increases by 5.3 to 10.4% when the fault slip rates are constrained to be within the geologic slip rate range at each investigated site (Table 2.1). However, the active Mill Creek model has 3.2% greater off-fault deformation than the inactive Mill Creek model.
2.4.2 Surface slip rates through the San Gorgonio Pass region

While geologic slip rate investigations only provide slip rate estimates at one location along a fault, numerical models provide slip rate estimates along the entire fault surface. This gives insight into how fault slip rates vary between sites of investigation. Figure 2.5 shows the dextral slip rates along each strand of the San Andreas fault through the SGPr. Figure 2.5a and 2.5c show the surface slip rates for the unconstrained reference models for each of the fault configurations. Both models overestimate slip rates at Badger Canyon on the San Bernardino strand (site 2) and at site 8 along the Banning strand, while also underestimating slip rates at Pushawalla Canyon (site 9) along the Mission Creek strand and overestimating slip rates at Biskra Palms (site 11) along the Coachella segment.

In the unconstrained inactive Mill Creek geometry (Figure 2.5a), the dextral slip rate along the San Bernardino strand (purple) gradually decreases to the south, with a slight stepped decrease in slip between Plunge Creek (site 3) and Burro Flats (site 4) where the San Gorgonio Pass Thrust (dark blue) begins to take up some dextral slip. Within the restraining bend, the San Gorgonio Pass Thrust accommodates a maximum of ~8 mm/yr dextral slip near its intersection with the Banning strand (light blue). The Banning strand accommodates more dextral slip than the sub-parallel Garnet Hill strand (green) and the active portion of the Mission Creek strand (orange). Dextral slip along the Mission Creek strand increases to the east as it merges with the Coachella segment (red).

In the unconstrained active Mill Creek geometry (Figure 2.5c), the dextral slip rate along the San Bernardino strand (purple) decreases as it enters the restraining bend, similar to the inactive Mill Creek geometry (Figure 2.5a); however, the dextral slip rate
abruptly decrease between Badger Creek (site 2) and Plunge Creek (site 3), due to slip being transferred onto the Mill Creek strand (dark green). Further to the east, dextral slip along the Mill Creek strand is transferred onto the Galena Peak strand (pink). The westernmost Mission Creek strand (orange) has a low slip rate, but the slip rate abruptly increases where the fault accommodates slip transferred from the Galena Peak strand.

The dextral slip rates along the Mission Creek and Banning (light blue) strands gradually increase to the southeast where they merge with the Coachella segment (red).

In the unconstrained reference models (Figure 5a and 5c), the range in model slip rates along the length of each fault corresponds to the uncertainty in tectonic loading. However, in the models where slip rates are constrained to within the geologic slip rate range at sites of investigation (Figure 2.5b and 2.5d), model slip rates are pinned to the limiting value at sites that did not fall within the range in the reference model. This produces sharp jumps in the dextral slip rate along the length of the fault, which is most pronounced at the intersection of the Mission Creek strand (orange) with the Coachella segment (red). For both fault geometries (Figure 2.5b and 2.5d), the Mission Creek strand is pinned to the lower limit of the geologic range at Pushawalla Canyon (site 9) and the upper limit at Three Palms (site 10) and the Coachella segment is pinned to the upper limit of the geologic range at Biskra Palms (site 11). The dextral slip rate on the Mission Creek strand gradually decreases to the west in the inactive Mill Creek geometry model (Figure 2.5b). In the active Mill Creek geometry model (Figure 2.5d), the dextral slip rate decreases from Pushawalla Canyon (site 9) to the Mission Creek Alluvial Complex (site 6), where it is thought to be inactive, before increasing towards the intersection with the Galena Peak strand (pink) and again decreasing to its western termination. By increasing
the dextral slip rate at site 3 on the San Bernardino strand to the lower limit of the
geologic range, the slip rates on the western portions of the Mill Creek strand decrease
substantially from the reference model.

2.5 Discussion

The off-fault deformation, both spatial distribution (Figure 2.3 and 2.4) and total
integrated deformation (Table 2.1), increases with increasing constraints on fault slip.
The reference model for each fault configuration (Figure 2.3) allows all faults to slip
freely everywhere in response to tectonic loading and fault interaction. Constraining the
faults of the San Gorgonio Pass region to be within the geologic slip rate range at
investigated sites produces regions of higher off-fault deformation (Figure 2.4). Little to
no increase in off-fault deformation occurs where the fault slip rates are within or near
the limits of the geologic ranges in the reference models, such as along the San
Bernardino strand. Consequently, prescribing the slip rate limit that is closest to the
reference model slip rate produces little increase in off-fault deformation (Figure 2.4).
This suggests that the geologic slip rates at these sites (sites 1-4 on Figure 2.5) are
kinematically compatible with the interpreted fault geometry used here.

Regions of significant off-fault deformation (Figure 2.4), such as the Mill Creek
Alluvial Complex, Indo Hills, and to a lesser degree the Cajon Pass, indicate that slip
rates in these regions may be kinematically incompatible with the interpreted fault
geometry. While the traces of the San Andreas and San Jacinto faults at Cajon Pass are
within several km of each other at the surface, debate continues on whether the faults are
connected at depth (e.g. Matti and Morton, 1993; McGill et al., 2013; Herbert et al.,
2014). Off-fault deformation maps (Figure 2.4) show slightly increased off-fault
deformation near Cajon Pass in the constrained models. The addition of a hard linkage between the San Andreas and San Jacinto faults in the Cajon Pass may improve the kinematic compatibility through this region.

The relative activity of the Mission Creek strand is still currently under debate (e.g., Kendrick et al., 2015; Beyer et al., 2018; Fosdick and Blisniuk, 2018). While it is agreed that the Mission Creek strand is active near the intersection with the Banning strand, whether or not it is active near the Mission Creek Alluvial Complex is still unclear. The region of high off-fault deformation along the Mission Creek strand near the intersection with the Pinto Mountain fault (Figure 2.4b) indicates that inactivity at this location inferred by Kendrick et al. (2015) is incompatible with our current knowledge of the fault geometry in this area.

Near the Indio Hills, the Banning and Mission Creek strands merge into the Coachella strand of the San Andreas fault. The subsurface geometry of these fault strands near this intersection is not well constrained, particularly the orientation of the Coachella segment (e.g., Fuis et al., 2017). The off-fault deformation in this region (Figure 2.4) could be a result of an incorrectly inferred fault geometry. Additionally, where slip rate sites are close to one another (e.g., Indio Hills region), the geologic slip rates may be incompatible with each other. Surface slip rates of the reference models (Figures 2.5a and 2.5c) show relatively smooth variations in slip rate along the length of the faults, with the exception of fault intersections. Prescribing slip rates different from the reference rates at sites of investigation produces large discrete jumps in slip rate (Figures 2.5b and 2.5d). In the Indio Hills region, three slip rate sites are within ~15 km of each other (Figure 2.1). These three sites have geologic slip rates that range from a minimum of 10 mm/yr at
Three Palms (site 10; Munoz et al., 2016) to a maximum of 24 mm/yr at Pushawalla Canyon (site 9; Blisniuk et al., 2012). This variation in geologic slip rates over such a short distance leads to kinematic incompatibilities, potentially between the fault geometry and fault slip rate, but also between neighboring slip rate estimates.

2.6 Future work

Figure 2.4 highlights three regions of significant off-fault deformation: the Indio Hills region, along the Mission Creek strand near the Mission Creek alluvial complex, and to a lesser degree, Cajon Pass. These regions of increased off-fault deformation indicate kinematic incompatibilities, which require additional investigation.

2.6.1 Indio Hills region

Future studies will address both possible sources (fault geometry and slip rate) of kinematic incompatibility. To test the possibility of incompatibility due to inaccurate fault geometry, we will incorporate alternative interpreted geometries of the Coachella strand (e.g., Fuis et al., 2017) to determine the geometry that minimizes off-fault deformation. We will then test the possibility of incompatibility due to inaccurate slip rates by systematically removing each slip rate site to determine which combination of slip rate sites minimizes off-fault deformation.

2.6.2 Mission Creek Alluvial Complex

To test compatibility of this area, we will remove our no-slip constraint at this location, allowing the fault to slip freely. Ongoing work by Morelan and Oskin
(University of California, Davis) on the Mission Creek fault to the west of the Mission Creek Alluvial Complex may provide additional slip rate constraints that can be tested.

2.6.3 Cajon Pass region

Future studies will assess if connecting the San Andreas and San Jacinto faults within the subsurface at Cajon Pass impacts the match between model and geologic slip rates. To do so, we will employ the alternative fault meshes developed by Herbert et al. (2014). The disconnected fault mesh extrapolates to depth with vertical faults from the mapped surface fault traces. For the connected fault mesh, we will extend the San Jacinto fault mesh by one element length to the north to merge with the San Andreas fault, from the surface to depth.

2.7 Conclusions

We use three-dimensional crustal deformation models to assess the kinematic compatibility of interpreted active fault geometries with geologic estimates of slip rates within the San Gorgonio Pass region. We investigate the compatibility of the two fault configurations of Beyer et al. (2018), among 6 tested, that exhibit the best match to available geologic slip rates, the Inactive Mill Creek and Active Mill Creek models. The unconstrained reference models allow all faults to slip freely everywhere in response to tectonic loading and fault interaction. High off-fault deformation develops near fault intersections throughout the model for both fault configurations, with the total off-fault deformation being greater in the inactive Mill Creek fault configuration. The additional faults within the active Mill Creek fault configuration increases the kinematic compatibility and efficiency of the system.
The unconstrained slip rate models allow the faults to slip at rates outside the estimated range of slip rates at some sites of geologic investigation. To further assess incompatibilities between geometry and slip rate, we utilize a new approach and constrain the slip rates along the faults to within the geologic range at each geologic slip rate site. Maps of off-fault deformation for the inactive Mill Creek fault configuration highlight regions of kinematic incompatibility at the branch of the San Andreas fault near Indio Hills, at Cajon Pass, and to a lesser degree within the hanging wall of the San Gorgonio Pass thrust. The active Mill Creek fault configuration amplifies the same regions of off-fault deformation and reveals an additional region of incompatibility in the hanging wall of the Mission Creek strand. These incompatibilities suggest that we have either incorporated inaccurate fault configuration or slip rates in these areas or included incorrect slip rates. Further geological and geophysical investigations should constrain active fault geometry and slip rate uncertainties at regions of high off-fault deformation.
2.8 Figures

Figure 2.1: Map of the San Gorgonio Pass region, with thick colored lines highlighting San Andreas fault strands. Green fault strands are included in the Inactive Mill Creek fault configuration, while the addition of the orange strands make up the Active Mill Creek fault configuration. The Galena Peak strand is marked by GP. Sites with available dextral slip rates are indicated with yellow dots.
Figure 2.2: Oblique view of the model setup. Tectonic loading is prescribed far from investigated faults, at the boundaries of the model base. Faults are traction-free and slip freely in response to loading and fault interaction. A range of plate velocities and orientations account for uncertainty in tectonic loading. SAF – San Andreas fault; SJF – San Jacinto fault.
**Figure 2.3:** Off-fault distortional strain maps from the A) Inactive Mill Creek fault geometry and the B) Active Mill Creek fault geometry. In these models, faults are unconstrained and slip freely in response to tectonic loading and fault interaction. At sites marked with red circles, the model slip rates exceeds the range of geologic slip rates.
Figure 2.4: Maps of the change in off-fault distortional strain from the A) Inactive Mill Creek fault geometry and the B) Active Mill Creek geometry relative to the respective reference model. The color of the circles indicates the difference between the prescribed slip rate and the rate from the unconstrained slip model.
Figure 2.5: Surface dextral slip rates along strands of the San Andreas fault for the unconstrained slip rate models (A and C) and the limit iteration modes (B and D) for each fault configuration. Vertical bars show the range in geologic slip rates at sites labeled in Figure 1. The shaded bands show the range in modeled strike-slip rates along each fault.
### 2.9 Tables

<table>
<thead>
<tr>
<th></th>
<th>Reference models with unconstrained slip rates (mm/yr)</th>
<th>Constrained to geologic slip rate range (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inactive Mill Creek</td>
<td>489</td>
<td>515 (5.3% increase)</td>
</tr>
<tr>
<td>Active Mill Creek</td>
<td>482</td>
<td>532 (10.4% increase)</td>
</tr>
</tbody>
</table>

**Table 2.1:** Total integrated distortion for the unconstrained and constrained models for each fault configuration.
CHAPTER 3

OFF-FAULT FOCAL MECHANISMS NOT REPRESENTATIVE OF
INTERSEISMIC FAULT LOADING SUGGEST DEEP CREEP ON THE
NORTHERN SAN JACINTO FAULT

3.1 Abstract

Within the San Bernardino basin, some focal mechanisms show normal slip that is inconsistent with the expected interseismic strike-slip loading of the region. The discrepancy may owe to deep (> 10 km depth), creep along the nearby northern San Jacinto fault. The enigmatic normal slip microseismicity occurs to the northeast of the fault and primarily below 10 km depth, consistent with off-fault deformation due to spatially non-uniform on-going slip. Consequently, if these normal focal mechanisms are included in stress inversions from the seismic catalog, the results may provide inaccurate information about fault loading. Here, we show that off-fault loading from models with deep interseismic creep on the northern San Jacinto fault match the first-order pattern of observed normal slip focal mechanisms in the basin and that this deep creep cannot be detected with GPS data due to the proximity of the San Andreas fault.

3.2 Introduction

Earthquake rupture simulations that can inform regional seismic hazards are sensitive to estimates of current stress state along active faults (e.g., Harris et al., 2009; Ryan et al., 2015). Whereas borehole data from some localities can provide stress state information within the near surface, we rely exclusively on microseismicity data to
inform the stress state throughout the seismogenic crust (e.g., Hardebeck & Hauksson, 2001; Heidbach et al., 2010). One assumption built into estimates of stress state from microseismicity is that the seismic catalog collected over the past several decades accurately represents the loading of active faults within California. This assumption is challenged by the limited duration of the seismic catalog compared to the 100-1000-year recurrence intervals along most faults within California. For example, in the earthquake catalog, the San Andreas fault (SAf) south of Cajon Pass has had fewer earthquakes than nearby faults (e.g. Yang et al., 2012). Although the San Andreas fault has the greatest potential for large earthquakes in southern California (e.g. Field et al., 2014), it is relatively under-sampled within the seismic catalog because the fault is locked between the times of large earthquakes. Furthermore, small earthquakes in the crust may record off-fault deformation rather than slip along the primary slip planes of active faults (Cheng et al., 2018). Where off fault deformation differs from loading of the primary faults, the stress state inferred from microseismicity may not accurately reflect the interseismic loading of the major active faults capable of producing ground rupturing earthquakes.

While we might expect the focal mechanisms from recorded microseismicity along the southern SAf system to reveal that dextral deformation dominates this system, Yang et al. (2013) show that some regions, such as the San Bernardino basin, produce predominantly normal-slip microseismicity (Figure 3.1a). These focal mechanisms contrast the observations of long-term strike-slip along the nearby SAf (e.g., McGill et al., 2013, 2015) and San Jacinto fault (SJf) (e.g., Anderson et al., 2004; Onderdonk et al., 2015). The normal slip focal mechanisms also disagree with crustal deformation models
of the region that show dextral interseismic loading of the region (e.g., Johnson, 2013; Loveless & Meade, 2011; Smith-Kanter et al., 2011). Because dipping faults loaded in strike-slip will still produce strike-slip (e.g., Fattaruso et al., 2014), a non-vertical northern SJF, such as inferred along other portions of the SJf (Ross et al., 2017), could not explain the normal slip focal mechanisms. The observation of normal slip suggests that some of the recent microseismicity in the San Bernardino basin is not consistent with the expected strike-slip interseismic loading of the SAF and SJF flanking the basin.

Slip gradients along strike-slip faults, such as near the tips of earthquake ruptures, can produce off-fault stresses and subsequent aftershocks that differ from the loading of the faults (e.g., Hardebeck, 2014; Oppenheimer, 1990). Yang et al. (2012) report temporary changes in focal mechanism slip sense after large magnitude earthquakes in southern California. Cheng et al. (2018) report off-fault aftershocks that have different slip sense from the earthquakes that occur along the Anza segment of the San Jacinto fault, to the south of the study area of this paper. Some of the normal slip earthquakes within the San Bernardino basin have been associated with secondary normal faults revealed by geophysical imaging of the top of the basement (Anderson et al., 2004). Small normal faults trend sub-parallel to the SJF and bound the edges of a local graben that developed where the SJF changes strike (Figure 3.1b). While strike-slip along the San Jacinto and/or San Andreas faults could promote extension of this graben and normal slip microseismicity in the San Bernardino basin, all faults in the region are presumed to be locked during the interseismic period of the seismic catalog. Furthermore, the last large slip event in the region was over 200 years ago in 1812 (e.g., Lozos, 2016), and the current seismic catalog should be free of effects from that earthquake. Three-dimensional
deformation models of the region can simulate the interseismic accumulation of slip along faults below the seismogenic crust where the faults are presumed to be locked (Figure 3.1c; e.g. Marshall et al., 2009). Such models with 20 km locking depth consistent with the base of seismicity in this region (e.g., Yang et al., 2012) produce off-fault stress tensors at the 3D positions of focal mechanisms that show the preferred slip sense of off-fault deformation. Because this predicted slip sense assumes the presence of a preferentially oriented slip surface at each focal mechanism position, we add random noise to the model predictions equivalent to the \(45^\circ\) uncertainty in focal mechanism rake (Yang et al., 2012). The model predicts overall strike-slip deformation of the region (Figure 3.1d). Consequently, the observation of normal slip microseismicity in the San Bernardino basin remains enigmatic in this region of dextral interseismic loading.

We propose that some degree of unlocking of the San Jacinto fault could account for the observation of recent normal slip earthquakes in the San Bernardino basin. Spatially non-uniform creep at depth along the northern SJf may produce some degree of local extension within the basin. Consequently, the microseismicity in our multi-decadal catalog may record both interseismic dextral loading of the region as well as off-fault deformation associated with deep creep on the northern SJf. We use crustal deformation models to show the potential for slip to produce off-fault microseismicity that obfuscates our interpretation of fault loading from the seismic catalog.
3.3 Methods

3.3.1 Reliable catalog of focal mechanisms in the San Bernardino basin

We analyze the three-dimensional distribution of focal mechanisms in the San Bernardino basin to assess the spatial pattern of the enigmatic normal slip microseismicity. A catalog of relocated southern California focal mechanisms from January 1981 through September 2016 are available from the Southern California Earthquake Center database (Hauksson et al., 2012; Yang et al., 2012). We limit the analysis to focal mechanisms described by Yang et al. (2012) to have nodal plane uncertainty < 45°. Figure 3.2a shows the 6108 focal mechanisms between Easting 455000 and 500000 meters UTM zone 11 and Northing 3740000 and 3795000 meters. In this region, the mean slip sense assessed with a 600-earthquake moving window remains around 1.2 during the time period of the seismic catalog, indicating overall normal and strike-slip focal mechanisms (black line on Figure 3.2a).

Excluding earthquakes smaller than the magnitude completeness limit eliminates bias of including small earthquakes that are recorded because they occur close to seismic instruments. The completeness limit of the San Bernardino basin subset of the seismic catalog improves with time as seismic stations are added to the network. We calculate the evolving magnitude completeness limit using the maximum curvature method (Wiemer & Wyss, 2000) for a moving window of 600 earthquakes advanced in increments of 100 earthquakes. The magnitude completeness reduces around 2002 and 2011 so that we can define three epochs of magnitude completeness limits (red line on Figure 3.2b). To determine a reliable focal mechanism catalog that exceed completeness, we exclude earthquakes smaller than M1.9 for epoch1 (1981 – 2001), smaller than M1.5 for epoch2
(2002-2010), and smaller than M1.1 for epoch3 (2011 – September 2016). The resulting catalog of 4304 reliable focal mechanisms shows consistent slip sense (1.2) throughout the 37-year catalog, suggesting that the catalog is not significantly impacted by transient changes, such as stress changes from nearby large earthquakes or anomalous periods of enhanced normal faulting (Figure 3.2c).

3.3.2 Steady-state and interseismic crustal models of the region

To simulate the stresses in the San Bernardino basin that drive interseismic microseismicity, we have developed 3D Boundary Element Method stressing rate models that simulate interseismic loading between earthquakes using a two-step approach. For the first step, multiple earthquake cycles are simulated in a steady-state model where all portions of the fault surfaces slip. The second step of the approach implements a backslip approach to simulate the interseismic loading of the faults, where the slip distribution from the steady-state model is applied to faults below the prescribed locking depth (e.g., Marshall et al., 2009).

For the first stage of interseismic model development, we produce a steady-state model of crustal deformation over many earthquake cycles. The model incorporates active fault surfaces of the region based on the SCEC Community Fault Model v. 4.0 (Nicholson et al., 2013; Plesch et al., 2007) and re-meshed for more uniform triangular element size and coincident nodes along fault intersections (Figure 3.1c). While based on version 4.0 of the CFM, the fault model includes revised fault surfaces in the Eastern California Shear Zone and elsewhere that give better match to geologic slip rates (e.g., Fattaruso et al., 2014; Justin W. Herbert et al., 2014) and honors the mapped active fault traces of the USGS fault and fold database (USGS & CGS, 2006). The fault geometry
used in this study follows that of the preferred model of Beyer et al. (in press) with revised resolution of the San Jacinto fault (average element length ~ 2.6 km). Within the 3D models, faults are extended to 35 km depth, where they merge with a horizontal crack. Deformation along this crack simulates distributed deformation below the seismogenic crust. Following Beyer et al. (in press), this study applies a plate tectonic movement equivalent to 47.5 mm/yr at 322.5° (e.g., DeMets et al., 2010) to the sides of the model that parallel plate velocity and a velocity gradient along the sides of the model perpendicular to plate velocity. Where faults meet the lateral edges of the model, the applied velocity has a step and corresponding slip rates are applied to the endmost patch of the fault to avoid slip rates going to zero at these artificial fault tips (Figure 3.1c). The shear traction-free faults in the center of the model slip in response to tectonic loading and interaction with each other. This low shear traction simulates dynamic conditions when most of the fault slip occurs.

To simulate interseismic loading between large earthquakes, the interseismic models apply slip rates from the long-term model below a prescribed locking depth. Using this approach, these interseismic models can simulate deep creep. To avoid a sharp step between slipping and locked regions, fault elements within a 2.5 km high transitional band above the locking depth are prescribed 50% of the slip rate values of the long-term model. We explore the impact of varying locking depth from 7.5 to 20 km along the San Jacinto fault while all other faults have a 20 km locking depth. In all the models, stress tensors are sampled at points in the model corresponding to the three-dimensional locations of reliable focal mechanisms. This allows the model results to be directly compared to the observed seismicity.
3.4 Focal mechanism distribution supports deep creep along the northern San Jacinto fault

Three aspects of the three-dimensional distribution of interseismic microseismicity in the San Bernardino basin are consistent with some degree of deep on-going interseismic slip along the northern SJf. Firstly, the contrast of high rate of microseismicity along the SJf compared to the quiet nearby SAF (Figure 3.3a). Observations of abundant microseismicity adjacent to creeping faults (e.g., Harris, 2017) support the inference that the SJf could have active creep whereas the SAf is currently locked. Secondly, projecting the focal mechanisms of the reliable catalog into a north-south profile reveals that most of the normal slip focal mechanisms of the San Bernardino basin occur below ~7.5 km depth (Figure 3.3b). If the on-going SJf slip is contributing to the off-fault normal slip microseismicity, then the fault below this depth may be creeping. Along the Anza section of the San Jacinto fault, south of this study area, normal slip microseismicity also occurs near the SJf at depths of 10-13 km (Cheng et al., 2018). The discrepancy between locking depth of the Anza section of the SJf inferred from geodesy (11±3 km; Fialko, 2006) and the base of seismicity in this region (17±3 km) led to the inference of local creep below 10 km (Wdowinski, 2009), which is consistent with the depths of off-fault normal microseismicity along this section of the SJf (Cheng et al., 2018).

The third aspect of the focal mechanism distribution that supports deep on-going interseismic slip is that the normal slip focal mechanisms are primarily located northeast, and not southwest, of the SJf (Figure 3.3a). Regional extension should produce normal slip microseismicity on both sides of interseismic locked faults. However, this pattern is consistent with the results of steady-state crustal deformation models of the region that
simulate deformation over multiple earthquake cycles (Resor et al., 2018; Figure 3.4b). This model shows a southward increasing dextral slip rate along the northern San Jacinto fault that produces a region of positive dilation (increased mean normal tension) within the San Bernardino basin. This long-term dilation can promote normal slip microseismicity at distances far from the fault by unclamping potential slip surfaces relative to those outside of the basin. The location of off-fault dilation correlates to the location of slip rate gradient along the SJf (Figure 3.4b). Consequently, deep dilation consistent with the occurrence of normal slip microseismicity below ~7.5 km in the San Bernardino basin may be associated with on-going slip along the SJf below ~7.5 km. Deep on-going slip on the San Andreas fault could also produce dilation in the San Bernardino basin but the lack of microseismicity along the SAf suggests that this fault is locked. Taken together, the three-dimensional distribution of focal mechanisms within the San Bernardino basin is consistent with southward increasing creep rate along the northern SJf at depth.

3.5 Simulating deep creep on the northern San Jacinto fault

To investigate the impact of deep interseismic creep on the northern San Jacinto fault, we investigate the sensitivity of focal mechanism slip sense within the San Bernardino basin to locking depth along the northern SJf (San Bernardino and San Jacinto Valley segments). The interseismic models apply 20 km locking depth on all other faults, consistent with the general base of seismicity of the region (e.g. Yang et al., 2012; Figure 3.3b). The overall slip sense of microseismicity within the San Bernardino basin (grey region in Figure 3.5a) is best matched by interseismic models with locking depth < 12.5 km along the northern SJf (Figure 3.5b). Results for locking depths of 7.5
and 10 km show similar fit within 1σ. The interseismic model with 10 km locking depth produces normal slip that is spatially consistent with the observed enigmatic normal slip focal mechanisms within the San Bernardino basin (Figure 3.5a). The normal slip in the interseismic model occurs to the northeast of the San Jacinto fault near the gradient in dextral slip rate along the fault.

While creep below 10-13 km has been inferred along the southern San Jacinto fault from geodetic evidence of shallow locking depths (Fialko, 2006; Smith-Konter et al., 2011; Wdowinski, 2009), geodetic inversions for the northern San Jacinto fault suggest a deep (~20 km) locking depth (Smith-Konter et al., 2011). Because the San Jacinto and San Andreas faults approach within 10 km of each other at the San Bernardino basin, the inversions of geodetic data for locking depth in this region may not distinguish the locking depths of the SJf and SAf. To explore this, we compare the interseismic velocities at GPS sites from two models: one that has 20 km locking depth on all faults and another that has 10 km locking depth on the northern SJf and 20 km on all other faults. The station velocities from the two models cannot be distinguished from the observed GPS station velocities determined by Herbert et al. (2014) (Figure 3.5c). Consequently, geodetic data cannot eliminate deep creep on the northern San Jacinto fault as a potential mechanism for the off-fault normal slip microseismicity within the San Bernardino basin.

3.6 Discussion

Both the observed focal mechanisms and the model predicted slip show both normal and strike-slip microseismicity in the San Bernardino basin. Some differences in the predicted interseismic slip sense at locations of microseismicity and observed slip
sense reveal aspects of the model that may not adequately capture the 3D complexity of active deformation along the San Jacinto fault. Within the model, normal slip microseismicity occurs within a narrow band adjacent to the SJf with strike- and reverse slip outside of this band where the catalog records a combination of normal and strike-slip focal mechanisms. The model may over-predict the proportion of normal focal mechanisms for several potential reasons. Firstly, the model calculates the slip sense on the most preferentially oriented slip plane off of the fault but, if instead, the microseismicity occurs on preexisting structures, the observed slip sense may differ from the model prediction. Similarly, the model does not consider interaction between earthquakes such as local normal microseismicity after small strike-slip earthquakes (Cheng et al., 2018). Another consideration is that the model may over-predict normal slip because the model incorporates complete unlocking of the SJf below the locking depth whereas partial unlocking may provide an off-fault stress state between that of dilation and interseismic strike-slip loading of the region.

Within the model, faults that may have damage zones and complex secondary structures are modeled as single slip surfaces discretized into elements with constant slip. The nature of fault surface discretization within the model leads to artificially linear and abrupt transitions from slipping to transitional (1/2 long term slip rate) to locked portions of the fault. These abrupt transitions may produce a more localized pattern of normal slip microseismicity than observed. Furthermore, the model does not consider host rock heterogeneities and deformation along secondary faults (e.g. Anderson et al., 2004) that could act to promote interseismic normal slip microseismicity over a wider region. For example, deep creep along strands parallel to the modeled San Jacinto fault would
broaden the predicted zone of off-fault normal faulting. Our analysis does not distinguish between localized creep on a single plane and a narrow zone of distributed creep, and either of these scenarios may be occurring at depth along the SJf.

A rich aftershock catalog from the recent Borrego Springs 2016 earthquake shows evidence for a distributed zone of on-going deformation along southern San Jacinto fault where it splits into three sub-parallel strands (Ross et al., 2017). A similar investigation for the northern San Jacinto fault may yield further insight into the detailed structure of the fault. For example, such a study might confirm secondary structures that were interpreted from early seismic catalogs by Nicholson et al. (1986).

Deep creep along the northern San Jacinto fault may impact seismic hazard estimates on this fault. Both the accommodation of slip along the fault and the accommodation of off-fault deformation within the adjacent crust via microseismicity and aseismic pervasive deformation mechanisms may reduce the interseismic loading on the deeper portion of the northern SJf, thereby reducing seismic hazard. We might also expect moderate or large earthquakes to nucleate at the transition between creeping and locked portions (Harris, 2017). Shallow sections of the northern SJf may have increased loading due to deep creep and greater potential for large earthquakes.

The correlation between the slip sense of focal mechanisms in the San Bernardino basin and patterns of off-fault stressing rate from interseismic models with ~10 km locking depth on the San Jacinto fault suggests that the interseismic microseismicity of the basin records a component of permanent distributed off-fault deformation in the basin. This result is consistent with a recent study of normal slip focal mechanisms along the Anza section of the SJf (Cheng et al., 2018). If the focal mechanisms of the basin
were inverted to estimate interseismic stresses on the SJf and SAf, they would predict normal loading contrary to the long-term slip record of these faults. Using microseismicity that records this off-fault deformation may produce erroneous estimates of interseismic fault loading. Within the San Bernardino basin, the errors of focal mechanism inversions for fault stressing rate are compounded by the under-sampling of strike-slip earthquakes along the relatively quiet SAf. This study suggests that where faults creep, spatially non-uniform creep rates may produce heterogeneous off-fault deformation. Geodesy around the juncture of the creeping section of the San Andreas fault with the locked Carrizo section show off-fault dilation due to similar spatial gradient in creep rate as proposed here (Titus et al., 2011). Where faults exhibit creep at any crustal level, caution should be used when incorporating off-fault focal mechanisms to infer interseismic fault loading.
3.7 Figures

Figure 7: a) Focal mechanisms with nodal plane uncertainty $10^\circ$-$45^\circ$ from 1981 through September of 2016 in the relocated catalog of (Yang et al., 2012 and subsequent updates available from SCEC) with surface traces of faults active within the last 15 ka (USGS & CGS, 2006). Colors show slip sense as rake scaled to the 0-3 slip sense range of $A\phi$ (Simpson, 1997). b). Basement depth inverted from gravity data shows secondary normal faults that flank the San Jacinto fault (taken from Anderson et al., 2004). The normal slip focal mechanisms extend beyond the interpreted graben. c) Model of 63 active faults in the region used to build the steady state and interseismic models of crustal deformation. The lateral edges of the horizontal crack are loaded with plate velocities to simulate the regional tectonic loading (taken from Beyer et al., 2018). d) Slip sense predicted by interseismic crustal deformation model of c at locations of the earthquakes recorded in the catalog. Traces of modeled faults shown in black. Insets of a) and d) show histograms of slip sense. The normal slip focal mechanisms within the San Bernardino basin are not expected from interseismic loading of completely locked San Andreas and San Jacinto faults.
Figure 3.2: a) Focal mechanisms within the region of Figure 1. The average slip sense for a moving window of 600 earthquakes shown with black line. Warm colors are normal, cool colors are reverse, and green are strike-slip earthquakes. b) Magnitude completeness limit for a moving window of 600 earthquakes advanced in 100 earthquake increments shown in blue. The stepped red line shows the three estimated stages of magnitude completeness during the record. C) The 4304 focal mechanisms that exceed the three-phased magnitude completeness limit have mean slip sense of 1.2 ± 0.04, indicating limited variation in slip sense during the record. These earthquakes range in magnitude from 1 to 4.8 and depths from 1.2-20 km. (d-e) The log of frequency demonstrates the completeness of the catalog for each epoch: 1981 through 2001 (d), 2002 through 2010 (e) and after 2011 (f). The completeness limit (red dashed line) decreases in each successive epoch.
Figure 3.3: a) Map view of reliable focal mechanisms that pass the completeness test, colored by slip sense. Normal slip focal mechanisms occur within the San Bernardino basin, between the San Andreas and San Jacinto faults. Dashed fault traces are the graben bounding normal faults imaged by Anderson (2004) in Fig. 1c. b) Focal mechanisms of the San Bernardino basin (grey region of a) projected into the A-A’ profile perpendicular to the San Jacinto fault. Slip sense color same as in a). The normal slip focal mechanisms within the San Bernardino basin occur predominantly below 7.5 km depth.
Figure 3.4: Green arrows show the velocities from the steady state model that simulates many earthquake cycles. The divergence of this velocity field reveals regions of overall contraction (negative dilation blue) and extension (positive dilation red) due to slip distribution along the faults. Inset cartoon shows the set-up of the steady-state model.
Figure 3.5: a) Slip sense at locations of microseismicity from the interseismic model with locking depth of 10 km on the San Jacinto fault to simulate deep creep. The locking depth on all other faults is 20 km. Color indicates slip sense with random -45° to 45° noise added to the model results (distribution in top inset). Inset cartoon shows the set-up of the interseismic model. Normal loading occurs at focal mechanism sites within the San Bernardino basin. GPS stations shown with labeled triangles. b) Mean interseismic loading within light grey region of A shown with 1σ vertical bars. Models with SJf locking depth < 12.5 km better match the mean slip sense of focal mechanisms in the San Bernardino Basin. c) Transect along A-A’ (shown in A) of GPS station velocity parallel to the San Jacinto fault (J.W. Herbert et al., 2014), and velocity predictions from the interseismic model with a shallow locking depth on the SJf (pink star, same as results shown in A) and interseismic model with a 20 km locking depth on all faults (blue circle). The surface velocities cannot resolve deep slip on the SJf because of its proximity to the SAF.
4.1 Abstract

Present-day shear tractions along faults of the San Gorgonio Pass region can be estimated from stressing rates provided by three-dimensional forward crustal deformation models. Modeled dextral shear stressing rates on the San Andreas and San Jacinto faults differ from rates resolved from the regional loading due to fault interaction. In particular, fault patches with similar orientations and depths on the two faults show different stressing rates. We estimate the present-day, evolved fault tractions along faults of the San Gorgonio Pass region using the time since last earthquake, fault stressing rates (which account for fault interaction), and co-seismic models of the impact of recent nearby earthquakes. The evolved tractions differ significantly from the resolved regional tractions, with the largest dextral traction located within the restraining bend comprising the pass, which has not had recent earthquakes, rather than outside of the bend, which is more preferentially oriented under tectonic loading. Evolved fault tractions can provide more accurate initial conditions for dynamic rupture models within regions of complex fault geometry, such as the San Gorgonio Pass region. An analysis of the time needed to accumulate shear tractions that exceed typical earthquake stress drops shows that present-day tractions already exceed 3 MPa along portions of the Banning, Garnet Hill, and Mission Creek strands of the San Andreas fault. This result highlights areas that may be
near failure if accumulated tractions equivalent to typical earthquake stress drops precipitate failure.

4.2 Introduction

The southern San Andreas fault system consists of multiple active faults that accommodate the deformation between the North American and Pacific plates. Accurate estimates of the earthquake hazard in California require an accurate assessment of the potential for large through-going earthquakes and the ability for ruptures to propagate through fault intersections and complexities (e.g., Field et al., 2013). One region of such complexity is the San Gorgonio Pass region (SGPr), a restraining stepover along the southern San Andreas fault (Figure 4.1). Accurate dynamic rupture models of the SGPr that simulate potential rupture paths will help us assess the potential for large and damaging earthquakes through this region (e.g., Tarnowski, 2017; Douilly et al., 2017).

Dynamic rupture models show that, in general, the size and extent of earthquake ruptures can depend highly on the initial conditions of the model (e.g., Oglesby et al., 2005). These conditions include physical aspects, such as fault geometry and location of rupture nucleation (e.g., Lozos et al., 2012; Lozos, 2016; Tarnowski, 2017), and time-dependent aspects, such as state of stress and frictional parameters (e.g., Kame et al., 2003; Aochi and Olsen, 2004; Kase and Day, 2006; Duan and Oglesby, 2007). Dynamic rupture models typically prescribe initial shear and normal tractions by resolving the remote stress tensor, constrained from focal mechanism inversions, onto individual fault elements (e.g., Kame et al., 2003; Oglesby et al., 2003). This approach provides spatially variable ‘resolved’ tractions that capture the first-order loading of the faults but does not take into account the loading history, nor the prior stress interactions between faults. Not
only can individual earthquake events change tractions along nearby faults, advancing or retarding each faults’ earthquake clock (e.g., King et al., 1994; Stein, 1999; Duan and Oglesby, 2005), but interaction among neighboring active faults influences their long-term slip rates and stressing rates (Willemse and Pollard, 1998; Maerten et al., 1999; Loveless and Meade, 2011). Stressing rates on any given fault can be estimated using geodesy (e.g., Smith and Sandwell, 2006). However, the total accumulated traction along any given fault segment depends on the accumulated tractions during the interseismic period as well as nearby rupture history (e.g., Smith-Konter and Sandwell, 2009; Richards-Dinger and Dieterich, 2012; Tong et al., 2014).

To account for loading history and fault interaction and produce more accurate estimates of fault stress, we simulate deformation within the San Gorgonio Pass region using three-dimensional forward models that provide both slip rates over multiple earthquake cycles and stressing rates between earthquake events. Because we use slip rates over multiple earthquake cycles to drive models that simulate interseismic deformation, the resulting shear stressing rates incorporate the interactions between faults of the southern San Andreas fault system. The interseismic shear stressing rates along with information about time since last earthquake event can be used to estimate the shear traction on faults through the SGPr following the approach employed by Tong et al. (2014). The resulting estimates of shear traction may differ from resolving the remote stress tensor onto faults in that our models explicitly include fault interaction and fault loading from depth during the interseismic period. Furthermore, we incorporate the effects of recent earthquakes on faults near the SGPr to produce a more accurate estimate of the current stress state of this system. Using tractions that incorporate fault interaction
and loading history may enhance the accuracy of dynamic rupture models, refining our insight into the nature of potential earthquake rupture propagation within the San Gorgonio Pass region.

4.3 Regional Geology – The San Gorgonio Pass region

Through the San Gorgonio Pass region (SGPr), deformation is partitioned onto multiple, active and nonvertical fault strands (e.g., Matti et al., 1992; Figure 4.1). The San Bernardino strand of the San Andreas fault lies at the northwest end of the San Gorgonio Pass. Two potential rupture pathways go through the restraining bend connecting the San Bernardino strand to the Coachella segment of the San Andreas fault. The southern pathway consists of the San Gorgonio Pass thrust, Garnet Hill strand, and Banning strand of the San Andreas fault (Figure 4.1). The San Gorgonio Pass thrust dips to the north and has a corrugated geometry near the Earth’s surface (e.g., Matti et al., 1992). The eastern end of the San Gorgonio Pass thrust connects to the Garnet Hill and Banning strands. The north-dipping Garnet Hill and subparallel Banning strands have approximately the same strike. The northern pathway through the SGPr consists of the Mill Creek, Mission Creek, and Galena Peak strands of the San Andreas fault (Figure 4.1). Ongoing debate centers on the geometry and activity of these fault strands through the northern part of the SGPr (e.g., Kendrick et al., 2015; Beyer et al., 2018; Fosdick and Blisniuk, 2018). The San Jacinto fault is sub-parallel to the San Andreas fault and extends to within 2 km of the San Andreas fault at Cajon Pass. While the San Jacinto fault lies outside of the SGPr, it interacts with the San Andreas fault and consequently impacts both long-term slip rates (e.g., Herbert et al., 2014) and earthquake rupture paths (Lozos, 2016) on the San Andreas fault.
Recent paleoseismic data within the SGPr suggest that previous large through-going earthquakes have a recurrence interval of ~ 1000 years, with the most recent earthquake rupture through the San Gorgonio Pass along the southern pathway in 1400 AD (Heermance and Yule, 2017). Earthquakes along the San Bernardino strand (north of the restraining bend) and Coachella segment of the San Andreas fault (south of the bend) occur more frequently, with recurrence intervals of 200-300 years (e.g., Philibosian et al., 2011; Field et al., 2013; Onderdonk et al., 2018). The difference in recurrence intervals outside of and inside of the restraining bed suggests that previous earthquakes that have ruptured along the San Bernardino and Coachella segments terminated at the restraining bend, which may be acting as an ‘earthquake gate’. During the interseismic period since the last rupture event through the bend, shear tractions have been accumulating along faults within the SGPr. Furthermore, recent earthquakes along faults surrounding the SGPr could impact the state of stress within the San Gorgonio Pass, and thus the shear and normal tractions along the faults.

**4.3.1 Recent earthquakes near the San Gorgonio Pass region**

To calculate the stress interaction effects from past earthquakes, we consider records of three ground-rupturing earthquakes that occurred within the past 300 years near the SGPr. While many smaller earthquakes have occurred within this region, these larger ground-rupturing events have the greatest potential to impact tractions along nearby faults.
4.3.1.1 1992 Landers earthquake

The Landers earthquake occurred on June 28, 1992, rupturing five fault segments, striking northwest-southeast, in the Eastern California Shear Zone (Hart et al., 1993). The interaction of these faults created a linked fault network that generated an M7.3 earthquake, which is larger than expected for any single fault involved in the rupture (Aydin and Du, 1995). The total rupture length is estimated at 85 km on the primary rupture trace (Sieh et al., 1993). The epicenter was located on the south portion of the Johnson Valley Fault, and the rupture traveled northward along the Landers-Kickapoo, Homestead Valley, Emerson, and Camp Rock faults, crossing two extensional stepovers and one compressional stepover (e.g., Aydin and Du, 1995; Madden and Pollard, 2012), while only rupturing parts of the Johnson Valley, Emerson, and Camp Rock faults (Sieh et al., 1993). All of the involved faults were previously mapped, with the exception of the Landers-Kickapoo fault (Hart et al., 1993). The Johnson Valley and Landers-Kickapoo faults each slipped locally more than 2 m and the central portion of the Homestead Valley fault slipped more than 3 m (Sieh et al., 1993; Aydin and Du, 1995). Slip exceeded 4 m on the Emerson fault, and a maximum dextral slip of approximately 6 meters occurred on the North Emerson Fault (Bryant, 1992; Sieh et al., 1993; Bryant, 1994).

4.3.1.2 1812 Wrightwood earthquake

The ~M7.5 earthquake that occurred on December 8, 1812 (here referred to as the Wrightwood earthquake), is one of the earliest earthquakes documented in the historical records of California; the rupture origin and extent are still uncertain. Evidence of this event has been observed within several paleoseismic trench sites along the San Andreas fault north of Cajon Pass (Weldon and Sieh, 1985; Seitz et al., 1997; Biasi et al., 2002;
Fumal et al., 2002; Weldon et al., 2002), with a maximum dextral slip of 4-6 m and possible northern rupture extent ~100 km north of the Cajon Pass (Bemis et al., 2016). The southern extent of rupture is not well constrained. The most recent event recorded at Plunge Creek on the San Bernardino strand (site 3 on Figure 4.1) is dated to within the 1600s (McGill et al., 2002), but minor slip on secondary structures farther south along the San Bernardino strand, near Burro Flats (site 4 on Figure 4.1), dates to the early 1800s (Yule and Howland, 2001). Several paleoseismic sites along the northernmost strand of the San Jacinto fault record 1.8-3 m of slip during an early 1800s earthquake event (Kendrick and Fumal, 2005; Onderdonk et al., 2013; Onderdonk et al., 2015). Several have suggested the plausibility of the 1812 earthquake jumping the < 2 km extensional stepover between the San Andreas and San Jacinto faults (Figure 4.1) and involving both faults (Onderdonk et al., 2013; Onderdonk et al., 2015; Rockwell et al., 2015). Lozos (2016) used dynamic rupture models to investigate rupture scenarios that best fit the paleoseismic evidence and historical accounts of the Wrightwood earthquake. The models of Lozos (2016) suggest that the Wrightwood earthquake nucleated near Mystic Lake on the San Jacinto fault (site 8 on Figure 4.1), produced a maximum of 6 m of slip near Colton, and propagated north onto the San Andreas fault (maximum of 4-5 m of slip between Cajon Pass and Wrightwood).

4.3.1.3 1726 Coachella Valley earthquake

The Coachella segment of the southern San Andreas fault has not experienced a large earthquake in historical time. Paleoseismic studies reveal that the most recent earthquake is dated to 1726 ± 7 (Rockwell et al., 2018), with a possible rupture trace extending from Salt Creek site along the Salton Sea (site 7 on Figure 4.1; Sieh and
Williams, 1990) to the Thousand Palms oasis site on the Mission Creek strand (site 5 on Figure 4.1; Fumal et al., 2002), with at least 2 m of dextral offset at the Indio site on the Coachella segment (site 6 on Figure 4.1; Sieh, 1986).

4.4 Methods

We use Poly3D, a quasi-static, three-dimensional boundary element method code, to simulate loading and interseismic 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., Thomas, 1993; Crider and Pollard, 1998). Faults are discretized into triangular elements of constant slip (no opening/closing is permitted) within a linear-elastic half-space. The element size along the faults of the San Gorgonio Pass region (SGPr) average ~4 km and allow for our models to capture fault irregularities as small as ~10 km. We simulate the active fault geometry of the southern San Andreas fault, the San Jacinto fault, and the Eastern California Shear Zone (Figure 4.2) based on the Southern California Earthquake Center’s Community Fault Model (CFM) version 4.0 (Plesch et al., 2007; Nicholson et al., 2017). The CFM is compiled from geologic mapping, seismicity, and geophysical data. While the CFM has been updated to version 5.2, the interpreted active fault geometry of the San Gorgonio Pass region is still under debate (e.g., Kendrick et al., 2015; Beyer et al., 2018; Fosdick and Blisniuk, 2018). We use version 4.0 of the CFM but include fault geometry modifications that serve both to improve the representation of the mapped active fault geometry and to improve the match of model and geologic uplift patterns and slip rates in the San Gorgonio Pass region (e.g., Cooke and Dair, 2011; Herbert and Cooke, 2012; Fattaruso et al., 2014; Beyer et al., 2018).
Faults in the CFM are defined to the base of the seismogenic crust. To simulate long-term and interseismic deformation, we extend the faults down to a freely slipping, horizontal basal crack at 35 km depth that simulates distributed deformation below the seismogenic zone (Marshall et al., 2009). This modification eliminates artifacts that develop when the long-term slip rates go to zero at the base of the CFM-defined faults (Figure 4.2). Across many earthquake cycles, deformation patterns are primarily controlled by fault geometry (e.g., Dawers and Anders, 1995; Fay and Humphreys, 2005; Herbert and Cooke, 2012). Therefore, to capture the first-order loading of active faults, we do not consider potential secondary impacts of heterogeneous and/or anisotropic rock properties.

We prescribe the tectonic loading on the boundaries of the model base, far from investigated faults. Following Beyer et al. (2018), we implement an iterative technique that ensures a uniform tectonic velocity, determined from geodetic estimates (DeMets and Dixon, 1999) at the model edges that are sub-parallel to the plate boundary (sides labeled I on Figure 4.2) and a linear velocity gradient at the models edges that cross the plate boundary (sides labeled II on Figure 4.2). The iterative approach of Beyer et al. (2018) ensures that applied velocities are within ~1% of the desired tectonic loading. For faults that extend beyond our model area (San Andreas, San Jacinto, and Cucamonga-Sierra Madre fault systems), we apply slip rates to distal edge patches of these faults to prevent non-zero slip rates on these faults at the edge of our model. We apply 35 mm/yr dextral slip to the San Andreas fault at the northwestern edge of the model (Weldon and Sieh, 1985). At the southeastern edge, we prescribe 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;
Because of complex fault geometry and interaction among faults, deformation within the SGPr is not impacted significantly by variations in the partitioning of slip rates between the San Andreas and San Jacinto faults at this model edge (Fattaruso et al., 2014). We apply 1.6 mm/yr reverse slip (McPhillips and Scharer, 2018) to the western edge of the modeled Cucamonga fault to account for deformation along the Sierra Madre fault not included in our model.

We use a two-step modeling approach to estimate the interseismic stressing rates along the southern San Andreas fault system. The first model simulates deformation over many earthquake cycles (steady state model) providing slip-rate information to a second model (interseismic model) that simulates the build-up of stress between earthquakes due to constant slip below the locking depth. In the steady state model, tectonic loading is prescribed along the model edges at the base of the model, far from the investigated faults. The faults throughout the model have zero shear traction and slip freely in response to tectonic loading and fault interaction. This zero-shear traction simulates the low dynamic strength of faults during rupture (e.g., Di Toro et al., 2006; Goldsby and Tullis, 2011). We simulate interseismic deformation by applying the distribution of slip rates determined with the steady state model to fault surfaces below the prescribed locking depth and lock fault elements above the locking depth. The abrupt transition from locked to slipping at the specified locking depth used here produces stresses that are unreliable within one element of the transition, or ~ 5 km. We use a locking depth of 25 km to ensure that our model results provide reliable fault tractions to about 20 km depth that can be used within dynamic rupture simulations within the full depth of the
seismogenic crust.

4.4.1 Estimating the impact from nearby recent earthquakes

We simulate the 1992 Landers earthquake, 1812 Wrightwood earthquake, and 1726 Coachella Valley earthquakes by prescribing the interpreted co-seismic slip distribution associated with each earthquake (e.g., Sieh, 1986; Hart et al., 1993; Onderdonk et al., 2015) to the modeled fault surfaces. We segment the rupture surface into multiple vertical segments and prescribe each segment a uniform slip according to the observations at the rupture trace (Figure 4.4). All other faults in the model are locked, and we do not consider the effect of tectonic loading while simulating each earthquake due to the short rupture time. The resulting static stress changes due to each earthquake alters tractions along the faults within the SGPr.

4.4.2 Estimating evolved tractions

The interseismic model determines stressing rates due to deep movement below the seismogenic crust and uses these stressing rates to calculate current shear tractions along the fault segments of the southern San Andreas fault within the SGPr using the time since the last rupture. Estimating both shear and normal tractions from stressing rates requires an assumption on how such accumulated tractions may dissipate with time. This approach relies on the premise that shear tractions that accumulate during the interseismic period are released during earthquake events. Because normal tractions that accumulate in the interseismic period, such as within restraining bends, are not necessarily relieved upon fault slip, models of earthquake cycles require dissipation mechanisms in order to avoid singular-valued normal tractions. Duan and Oglesby (2006)
simulate multiple earthquake cycles by coupling a viscoelastic interseismic model with an elastic dynamic rupture model, such that normal stresses are relaxed during the interseismic period in the viscoelastic model and used as input to the dynamic rupture model. Alternatively, the Rate and State Earthquake Simulator (RSQSIM) employs a constant, but spatially variable normal stress distribution and disregards accumulated normal tractions (e.g., Richards-Dinger and Dieterich, 2012). Here, we follow the approach of RSQSIM and do not carry the normal stressing rates through the rest of the analysis.

To estimate the shear traction that evolves over the earthquake cycle, henceforth called the evolved shear traction, we follow Tong et al. (2014) and use the stressing rate information from the interseismic model and the time since last event for each fault. In this approach, we only consider large ground-rupturing events that are preserved in the paleoseismic record. The approach analyzes a coseismic stress drop corresponding to the change from static friction to dynamic friction during large ground-rupturing earthquakes (shaded region in Figure 4.3). If the dynamic strength of the fault is near zero, a complete stress drop is associated with these events. Such complete stress drop is consistent with recent field measurements of low temperatures along recently ruptured fault surfaces, a result of a very low dynamic friction (e.g., Carpenter et al., 2012, Fulton et al., 2013, Li et al., 2015), as well as high-speed laboratory frictional experiments cited above.

Consequently, the associated shear traction at any time in the earthquake cycle is

\[ \tau = \dot{\tau} \cdot t \]

Equation 4.1

where \( \tau \) is the evolved shear traction, \( \dot{\tau} \) is the shear stressing rate and \( t \) is the time since last event. We sum the evolved shear tractions calculated by Equation 4.1 and the static
stress changes due to nearby earthquakes to produce the present-day evolved shear tractions along the faults within the SGPr. This simplified approach to estimate the distribution of present-day shear tractions may provide more accurate initial conditions than the approach employed by dynamic rupture models of estimating tractions by resolving the remote loading onto the faults because the evolved tractions also incorporates both loading history and fault interaction, by including long term slip rates at depth and recent nearby earthquake events (Figure 4.3).

4.4.3 Consideration of geometric and tectonic uncertainty

Using models of deformation over multiple earthquake cycles, Beyer et al. (2018) compared the slip rate distribution from six plausible active fault configuration models to available geologic slip rate data. The analysis revealed that two active fault configurations provide the best fit to the geologic observations. For this study, we use both of the two best-fit models: the Inactive Mill Creek and West Mill Creek models from Beyer et al. (2018). The most pronounced fault geometry difference between the two configurations is the addition of a through-going Mission/Mill Creek strand through the northern part of the SGPr in the West Mill Creek model. Here, we present the results of the Inactive Mill Creek model geometry, and the Supplemental Material contains the results of the West Mill Creek model geometry. Following Herbert and Cooke (2012), Beyer et al. (2018) also tested each of the plausible fault configurations under a range of reasonable tectonic loading (45-50 mm/yr at 340°-345°; DeMets and Dixon, 1999); for this study, we use the mean slip rate from the end members of permissible tectonic loadings.
4.5 Results

We present the interseismic stressing rates for faults of the San Gorgonio Pass region (SGPr) and show the impact of fault interaction on these rates. We analyze the results of the models that simulate three recent ground-rupturing earthquakes and the impact of these earthquakes on fault tractions within the SGPr. We then calculate the total evolved shear tractions that incorporate the impacts of both fault interaction and loading history.

4.5.1 Stressing rates

Maps of interseismic shear stressing rate along the southern San Andreas fault reveal how the fault geometry controls the stressing rate distribution (Figure 4.5). Figure 4.5 shows stressing rates for the Inactive Mill Creek model configuration (Figure 4.5a and 4.5c) and the difference in stressing rates between the two plausible active fault geometries (Figure 4.5b and 4.5d). Dextral shear stressing rates are larger (maximum 12 kPa/yr) than the reverse-shear stressing rates (maximum ~3 kPa/yr) along the San Andreas fault. Furthermore, portions of the faults parallel to the overall plate motion, outside of the restraining bend, have greater dextral stressing rate than faults within the bend. Dextral shear stressing rates are largest along the San Bernardino and Mission Creek strands of the SAF and decrease within the restraining bend of the SGPr (Figure 4.5a). The San Gorgonio Pass thrust has an undulating strike and small sinistral shear stressing rates occur locally along patches of the western San Gorgonio Pass thrust where the strike is less than ~265°. The reverse-shear stressing rates are near zero outside the restraining bend and increase within the bend along north-dipping fault strands that strike obliquely to the plate motion and accommodate uplift (Figure 4.5c). Stressing rates increase with
depth, consistent with the deep slip that is applied to faults in the interseismic model. The difference in stressing rates between the two best-fitting model geometries (Figure 4.5b and 4.5d) are lower than 1 kPa/yr and indicate that the West Mill Creek fault geometry produces higher dextral stressing rates (blue) throughout most of the region. The greatest difference in reverse-shear stressing rates is limited to within and just outside the bend. We only consider the Inactive Mill Creek fault geometry for the rest of our analysis, and consequently, reported shear tractions may underestimate by ~2% shear tractions if the true active fault geometry is closer to the configuration of our West Mill Creek model.

To the first order, the strike-parallel shear stressing rate along the southern San Andreas fault correlates with the orientation of the fault segments relative to the applied model loading that simulates plate motions. Previous models of the region have shown significant interaction between the San Andreas and San Jacinto faults (Herbert et al., 2014; Fattaruso et al., 2014), so we expand the analysis of stressing rates to include both of these faults in order to investigate the influence of fault interaction on stressing rates. The model produces different interseismic dextral shear stressing rates along similarly oriented portions of the San Andreas and San Jacinto faults. Figure 4.6 shows a gridded surface fit through model data points (white circles) of dextral stressing rates for different strikes and depths of the San Andreas (Figure 4.6a) and San Jacinto faults (Figure 4.6b). Stressing rates for both faults increase with depth, and in general, dextral stressing rates are higher on the San Andreas fault than on the San Jacinto fault for locations with the same strike and depth. For the San Andreas fault, maximum dextral stressing rate occurs at strikes between 300°-305°. Relative to the San Andreas, the variation of dextral stressing rate with strike along the San Jacinto fault is more subdued, but the distribution
shows a maximum strike stressing rate along segments that strike ~310°. Both of these maximum shear orientations differ from the orientation expected from resolving the regional stress tensor (black line in Figure 4.6). The difference between dextral stressing rates along the San Andreas and San Jacinto faults and the expected distribution from resolved tractions demonstrates the strong impact of fault interaction on the distribution of fault stressing rates.

The impact of fault interaction is also demonstrated in the relative stressing rates on the Banning and Mission Creek strands, which differs between the two plausible fault configurations (Figure 4.5). The presence of a through-going Mission Creek fault in the West Mill Creek model geometry (Figure S.4.1) shifts strike-parallel shear stressing rates from the Banning strand to the Mission Creek strand by ~ 0.1 kPa/yr. These differences in stress accumulation rates over the interseismic period demonstrates that fault interaction impacts the distribution of accumulated tractions along faults within a complex system.

4.5.2 Impact of stresses from regional earthquakes

To assess the impact of the recent nearby earthquakes along faults within the SGPr, we numerically simulate three ground-rupturing earthquakes. We simulate the Landers Earthquake, Wrightwood Earthquake, and Coachella Valley Earthquake and examine the static stress change due to each event (Figure 4.7). Because we do not consider the potential relaxation of these crustal stresses over time (e.g., Pollitz and Sacks, 2002), the fault tractions from earthquakes modeled provide an upper bound to expected tractions.
The modeled static stress change from the 1992 Landers earthquake impacts tractions along faults within the San Gorgonio Pass restraining bend. The change in dextral tractions (positive) reach a maximum of ~0.1 MPa, along the San Gorgonio Pass thrust and a change in sinistral tractions (negative) of up to 0.15 MPa on the southern Garnet Hill, Banning, and Mission Creek strands of the SAF (Figure 4.7a). The San Gorgonio Pass region lies in the extensional quadrant of the Landers rupture, and as a result, the fault strands within the bend are loaded with normal dip-slip tractions of ~ 0.13 MPa. This dip-slip traction change effectively reduces the accumulated long-term reverse dip-slip traction on these faults.

Change in co-seismic dextral tractions due to the 1812 Wrightwood earthquake increase the most (1.3 MPa) just south of the rupture limit on the San Bernardino strand, while the southernmost portion of the San Bernardino strand experiences sinistral traction changes of ~ 0.25 MPa (Figure 4.7b). The western San Gorgonio Pass thrust is loaded with dextral tractions (~ 0.4 MPa), while the Garnet Hill, Banning and Mission Creek strands experience slight (<0.1 MPa) increases in sinistral shear tractions. Furthermore, the western-most extent of the San Gorgonio Pass thrust has normal dip-slip shear, while the rest of the thrust and Garnet Hill strand has reverse dip-slip shear. These complex fault stressing patterns result from the location and orientation of the faults in relation to the Wrightwood rupture path. The close proximity of the dextral slip on the SJF to the subparallel fault strands of the SAF results in sinistral co-seismic traction changes on the SAF, which sits in the stress shadow of the Wrightwood earthquake.

Traction changes imposed on the San Gorgonio Pass fault strands due to the 1726 Coachella Valley earthquake reach ~ 1 MPa on the Mission Creek ahead of the rupture
termination and ~ 0.8 on the Banning strands near the junction with the Coachella segment (Figure 4.7c). Dextral tractions of up to ~ 0.1 MPa extend into the restraining bend. While these nearby earthquakes are shown here to impact the SGPr, all the resulting static stress changes due to these earthquakes are small compared to the total tractions accumulated along these faults during the interseismic period.

4.5.3 Estimate of evolved stresses

Paleoseismic data provide estimates for the time since last event, \( t \), along active faults (e.g., Biasi et al., 2009; Table 4.1). We estimate the total present-day traction along each fault segment by summing the tractions from Equation 1 with the static traction change of each nearby earthquake. For the San Bernardino segment, we use time since last event from the compiled earthquake data of Biasi et al. (2009). Paleoseismic sites at Pitman Canyon (site 2 on Figure 4.1), Plunge Creek (site 3 on Figure 4.1), and Wrightwood (site 1 on Figure 4.1) provide a mean \( t \) of 207 years for the San Bernardino segment. Paleosismic constraints from the Thousand Palms Oasis site (site 5 on Figure 4.1; Fumal et al., 2002) is used for the Mission Creek strand and the Coachella site (site 6 on Figure 4.1; Philibosian et al., 2011) for the Coachella segment. These studies are in agreement that the last rupture event occurred circa 1680. This event has been re-dated by Rockwell et al. (2018) to be around the year 1726 ± 7. For the San Gorgonio Pass thrust, Banning, and Garnet Hill strands of the SAF, we use an earthquake rupture year of 1400 (Heermance et al., 2017; Yule et al., 2014).

Due to the variable time since last earthquake event across faults of the SGPr, the evolved shear traction distribution along the fault surfaces (Figure 4.8a) differs significantly from the shear stressing rate distributions (Figure 4.5). Whereas dextral-
shear stressing rates are lower along the north-dipping fault surfaces within the SGPr restraining bend than on fault surfaces outside of the bend (Figure 4.5a), the longer $t$ for the faults within the restraining bend increases the total accumulated dextral shear traction within the bend relative to other faults (Figure 4.8a). Similarly, although the Coachella segment and the San Bernardino strand of the SAF have greater dextral stressing rates than the restraining segment, the more recent rupture of these segments in the 1726 and 1812 events, respectively, reduces the accumulated tractions outside the bend. The largest evolved dextral shear tractions arise along the Banning and Garnet Hill strands of the SAF near the juncture with the Coachella segment of the SAF (Figure 4.8a). Regions of high dextral shear traction also arise along portions of the San Gorgonio Pass thrust. The evolved reverse shear tractions are greatest along the San Gorgonio Pass thrust within the restraining bend. We note that if the true active fault geometry is closer approximated by the alternative fault configuration (Figure S.4.1), the total evolved shear tractions may be underestimated by up to 2%.

These evolved shear tractions take into account fault interaction (Figure 6), the $t$ for each fault strand (Table 1), and the impact of recent nearby earthquakes (Figure 7). To assess the impact of fault history and interaction, we compare the evolved dextral shear traction (Figure 8A) to the fault tractions that result from resolving the regional stress tensor constrained from focal mechanism inversions onto the faults (Figure 8B). Following Tarnowski (2017), we use the orientation of the stress field and relative magnitude of the principal stress axes from Hardebeck and Hauksson (2001) and the stress ratio, $A\phi$ (Simpson, 1997), of 1.5, which indicates a mixed strike-slip and thrust stress regime. The resulting stress tensor is scaled such that the change from static to
dynamic friction results in a 3 MPa stress drop (e.g., Tarnowski, 2017) in order to represent the fault loading conditions preceding a large earthquake rupture. The larger magnitude of the resolved dextral shear tractions compared to the evolved tractions is due to the scaling of the regional stress to produce failure and a 3 MPa stress drop with a dynamic friction of 0.1. The evolved tractions to the current year (2019) are not explicitly at failure and these tractions exclude those required for dynamic sliding (non-shaded region of Figure 4.3). Consequently, we focus our comparison on the patterns of the evolved and resolved stresses rather than the absolute level of stress. The resolved tractions have greater lateral heterogeneity as the tractions range from 10 MPa dextral to -5 MPa sinistral shear traction, where portions of the San Gorgonio Pass thrust receives sinistral shear from resolved loading. In contrast, the evolved tractions show dextral shear tractions everywhere on faults of the SGPr. Whereas the evolved shear tractions increase with depth, the remote stress tensor is not resolved for different depths.

4.6 Discussion

Here we discuss the impact of including fault interaction and the effects of recent nearby earthquakes on fault tractions, and the implications of this study’s findings for seismic hazard assessment.

4.6.1 Resolved tractions likely oversimplify initial conditions for rupture

Rupture propagation within dynamic models highly depends on the initial conditions used for the model (e.g., Kame et al., 2003; Duan and Oglesby, 2007; Lozos et al., 2012). These models have the power to simulate potential rupture size and extent, as well as potential rupture paths (e.g., Oglesby et al., 2003). Most rupture dynamic studies
either use a homogeneous regional stress field (e.g., Lozos et al., 2012) or a regional stress field with spatially rotating principal stress (e.g., Aochi and Fukuyama, 2002) to estimate the initial shear tractions on fault segments. Resolving the regional stress tensor onto faults does not account for fault interaction or the rupture history of each fault. Whereas these effects may be minimal in regions with planar faults, we show here that within regions of fault complexity, fault interaction and loading history can advance, or retard, the fault towards failure. Prescribing tractions that incorporate the effects of fault interaction and the loading history of each fault may improve the accuracy of dynamic rupture models.

Due to fault interactions over multiple earthquake cycles and the variable time since last earthquake event across faults of the SGPr, the evolved shear traction distribution along the fault surfaces (Figure 4.8a) differs from the tractions resolved from the regional stress state (Figure 4.8b). Whereas resolved dextral-shear tractions are lower along the north-dipping fault surfaces within the SGPr restraining bend than on faults outside of the bend (also seen in the stressing rates in Figure 4.5), the longer $t$ for the faults within the restraining bend increases the total dextral shear traction compared to other faults (Figure 4.8a). Similarly, the more recent ruptures of the 1726 and 1812 earthquake events reduce the accumulated tractions outside the bend, but not within. The largest dextral shear tractions arise along the Banning and Garnet Hill strands of the SAF, especially near the juncture of the Banning strand with the Coachella segment of the SAF (Figure 4.8a). Furthermore, the evolved stresses do not produce enigmatic left-lateral loading on portions of the San Gorgonio Pass thrust of the resolved stresses. These structures do not show surface evidence for left-lateral slip (Yule and Sieh, 2003).
Consequently, the pattern of consistent dextral shear traction produced by the evolved stresses that include fault interaction and interseismic loading agrees with geologic evidence. Including evolved stress state for initial conditions within dynamic rupture models can produce more accurate assessment of rupture behavior along complex fault systems.

### 4.6.2 Implications for seismic hazard

To assess how close the faults of the San Gorgonio Pass region (SGPr) are to failure within our model of evolved fault tractions, we analyze the time until failure for each fault element. To consider this, we calculate how many years are required from the present day to accumulate evolved net shear tractions equivalent to typical earthquake stress drops of 3 MPa (Figure 4.9a) and 10 MPa (Figure 4.9b) (e.g., Allman and Shearer, 2009; Goebel et al., 2015). Using this criterion, fault elements on the easternmost Banning, Garnet Hill, and Mission Creek strands currently exceed 3 MPa at the base of the model (ellipse in Figure 4.9a). When using 10 MPa for the accumulated traction required to trigger the next earthquake, the first fault element to fail is on the San Bernardino strand at 584 years from now (ellipse in Figure 4.9b). The difference in vulnerable position within the fault system owes to the greater stressing rate along the San Bernardino strand compared to the other faults.

The time since last ground rupturing earthquake event for fault strands within and just outside the restraining bend are near or greater than the estimated recurrence interval for these fault strands, and paleoseismic studies in this region suggest these faults are probably overdue, or close to failure (Philibosian et al., 2011; Rockwell et al., 2018; Onderdonk et al., 2018). Consequently, while 3 MPa represents a low stress drop in the
SGPr (Goebel et al., 2015), this lower stress drop implies that these faults are close to failure, which is consistent with earthquake clock and recurrence intervals of these faults.

4.7 Conclusions

We use three-dimensional crustal deformation models to estimate present-day fault tractions in the San Gorgonio Pass region. The models that estimate interseismic stressing rates are loaded with deep slip rates determined from a multiple-earthquake-cycle model that explicitly includes fault interaction. Consequently, the interseismic stresses incorporate both regional tectonic loading and fault interaction. A gradient of increasing shear stressing rates with depth emerges from our models that is consistent with deep interseismic deformation. To investigate the role of fault interaction within our models, we compare our modeled dextral shear stressing rates for the San Andreas and San Jacinto faults, which have similar orientation. Subsequently, the interseismic stressing rates would be similar on the two faults if based solely on orientation with respect to remote loading. Significant differences in the patterns of stressing rates along patches of the San Andreas and San Jacinto faults with similar orientation and depth arise due to the interaction between these two faults.

The total evolved present-day shear tractions along the fault include both the accumulated stressing rates since the last earthquake event and the impact of nearby earthquakes. We simulate recent nearby ground-rupturing earthquakes with co-seismic models to investigate the impact of these rupture events on the stress state along the San Andreas fault within the San Gorgonio Pass region. The pattern of total evolved fault tractions differs from that of the interseismic stressing rates. Tractions are higher within the restraining bend than outside the bend because of the longer time since last event on
these faults. Fault strands within the restraining bend have been loading for twice as long as the Coachella segment to the south and three times as long as the San Bernardino strand to the north. Comparison of our evolved tractions to the tractions resolved from the local stress field shows distinct differences. While the linear gradient with depth emerges from our models, the resolved tractions are not depth dependent, and the gradient must be added. Because the evolved tractions account for loading history, the largest tractions occur within the restraining bend, which has the longer time since last event.

We investigate the time needed for the accumulated net shear traction on each fault element to exceed 3 MPa and 10 MPa, typical coseismic stress drop values. Because the interseismic stress rates differ for faults throughout the San Gorgonio Pass region, the location and timing of potential failure depends on the stress drop value used as the shear traction threshold. Assuming a lower stress drop value shows that faults in the San Gorgonio Pass are currently at failure, whereas higher stress drop values do not.

This approach provides a more heterogeneous, more accurate representation of the current stress state along the southern San Andreas fault than a simple regional stress tensor. In regions of complex fault geometry such as the San Gorgonio Pass region, an ‘earthquake gate’, the potential for a through-going rupture is unclear and stress state may have a large control on rupture behavior. Our evolved fault tractions can provide more realistic initial conditions for dynamic rupture models of these regions, and therefore improve seismic hazard assessments.
4.8 Figures

Figure 4.1: Map of the San Gorgonio Pass region (SGPr). While there has not been a rupture event in the SGPr since ~1400 AD, recent nearby earthquakes may impact the stress within the bend. Fault traces of the San Andreas fault are labeled (GP – Galena Peak, SGPT – San Gorgonio Pass Thrust). Rupture traces considered in this study are highlighted: Landers earthquake (dark red), Wrightwood earthquake (red), Coachella Valley earthquake (orange), and 1400 event (yellow). Paleoseismic sites are numbered as such: 1 – Wrightwood, 2 – Pitman Canyon, 3 – Plunge Creek, 4 – Burro Flat, 5 – Thousand Palms, 6 – Indio, 7 – Salt Creek, 8 – Colton, and 9 – Mystic Lake.
Figure 4.2: Northward oblique view of the model setup. Tectonic loading is prescribed at the boundaries of the model base, such that sides labeled (I) have a uniform tectonic velocity parallel to the plate boundary and sides labeled (II) are prescribed a linear gradient in the tectonic loading across the plate boundary. The shear traction-free faults slip freely in response to the loading and fault interaction. Black box outlines the San Gorgonio Pass region. SAF - San Andreas fault; SJF - San Jacinto fault.
Figure 4.3: Schematic sketch of fault loading through time. During the interseismic period, the earthquake clock of a fault can be advanced or retarded by earthquakes on other nearby faults. If the dynamic strength of the fault is near zero, then the stress drop associated with the change from static to dynamic friction is a complete stress drop.
Figure 4.4: Northward oblique view of the San Gorgonio Pass region showing the distribution of the applied slip (in meters) associated with the nearby 1992 Landers (dark red), 1812 Wrightwood (red), and 1726 Coachella Valley (orange) earthquakes.
Figure 4.5: Modeled interseismic stressing rates along faults within the San Gorgonio Pass. This region is primarily loaded in dextral shear (red in A). North-dipping faults are also loaded in reverse dip slip (red in C). B and D show the difference in stressing rates between the two plausible fault configurations of Beyer et al. (2018); difference is slip rate from Inactive Mill Creek minus slip rate from West Mill Creek model configuration.
Figure 4.6: Modeled dextral stressing rates plotted with depth and fault strike for the A) San Andreas fault and B) San Jacinto fault. Model results are plotted as white circles, and a best-fit surface is fitted through the data (background grid). Patches along the two faults with similar orientation and depth have different values of shear stressing rates due to fault interaction. The orientations of magnitude of dextral shear stressing rate for both faults differ from the maximum shear direction predicted from the regional stress tensor (vertical black lines).
Figure 4.7: Static stress changes from modeled recent, nearby earthquakes resolved as right-lateral tractions along faults of the SGPr. The Landers earthquake (A) increased dextral shear tractions along the San Bernardino strand and San Gorgonio Pass thrust, and decreased dextral shear tractions along the Garnet Hill, Banning, and Mission Creek strands. The Wrightwood earthquake (B) produces a complex change in tractions. The earthquake increased dextral shear tractions just east of the rupture termination on the San Bernardino strand but decreased dextral shear tractions further east due to the interaction with the neighboring San Jacinto fault, which had dextral slip. The Coachella Valley earthquake (C) increased dextral shear tractions on the easternmost Mission Creek and Banning strands.
Figure 4.8: Evolved (A) and Resolved (B) right-lateral tractions along faults of the SGPr. The increasing shear traction with depth emerges from the evolved stresses due to deep slip in the interseismic models. The resolved tractions show greater lateral variation than the evolved tractions. Arrows indicate the direction of principle compression.
Figure 4.9: Faults of the SGPr colored by years until failure. (A) shows time until net shear tractions since the last earthquake exceed 3 MPa. With this criterion, fault elements on the Banning, Garnet Hill, and Mission Creek strands are currently at failure. (B) shows time until net shear tractions since the last earthquake exceed 10 MPa. Under this assumption, the first fault element to fail is on the San Bernardino strand at 584 years from present. Ellipses highlight the first elements to fail.
### 4.9 Tables

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<th>Most recent EQ Year (AD)</th>
<th>Time since last event (yr)</th>
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<td>Pitman Canyon/Plunge Creek/Wrightwood (<em>Biasi et al.</em>, 2009)</td>
<td>1812</td>
<td>207</td>
</tr>
</tbody>
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**Table 4.1:** Time since last event data used to calculate absolute shear stress from the interseismic stressing rate.
4.10 Supplemental information

Figure S.4.1: Right-lateral (A) and reverse dip slip (B) stressing rates for the alternative fault configuration from Beyer et al. (2018).
CHAPTER 5

EFFECTS OF LOADING RATE ON THE SPATIAL AND TEMPORAL DEFORMATION OF RESTRAINING BENDS

5.1 Abstract

While scaled physical experiments show the evolution and distribution of strain, numerical simulations of the experiments provide information about both the stress and strain fields, which can then be used to compute the full work budget of the system and provide further insight into the mechanisms that drive fault growth. Here, we use numerical models to investigate the effect of loading rates on deformation within restraining bends hosted within viscoelastic material. We use 2D finite element method models of a restraining bend geometry that simulate the fault geometry and material properties of scaled physical experiments of wet kaolin clay, a bi-viscous Burger’s material. We test the behavior of the material under two different loading rates. The models simulate the deformation of a $10^\circ$ restraining bend with vertical fault segments. Off-fault deformation is concentrated at the fault bends and is more dispersed around the restraining segment of the fault. Faster loading rates produce less off-fault deformation around the restraining bend and more slip along the fault than slower loading rates. Kinematic efficiency of the system increases to steady state values of 90% for the fast loading rate and 80% for the slow loading rate. Lobes of increased Coulomb stress extend outward from the fault bends, indicating where new faults would initiate. While these results are consistent with observations from the physical experiments, the numerical models indicate new faults would initiate sooner with faster loading rates, which
contrasts observations of early new fault growth in the physical experiments with slow loading rates.

5.2 Introduction

Restraining bends are regions of contraction along a strike-slip fault that form at significant local deviations in fault strike. Restraining bends are mechanically inefficient, often associated with a decrease in fault slip and an increase in off-fault deformation (e.g., Gomez et al., 2007; Fitzgerald et al., 2014; McGill et al., 2015; Elliot et al., 2018). Analog models of the evolution of restraining bends (e.g., McClay and Bonora, 2001; Cooke et al., 2013; Hatem et al., 2015) have shown that restraining bends evolve over time to become more kinematically efficient, with multiple generations of new and dipping faults propagating from the fault bends and accommodating more fault slip.

Scaled physical experiments show the evolution and distribution of displacement/strain, providing information such as the kinematic efficiency of the system, defined as the ratio of fault slip rate to the applied velocity. Numerical simulations can provide information about both the stress and strain fields throughout the modeled domain, providing information about the mechanical efficiency, or the work required to deform the system (e.g., Dempsey et al., 2012; Cooke and Madden, 2014; Yagupsky et al., 2014; McBeck et al., 2017).

In this study, we simulate the scaled physical experiments of restraining bends in wet kaolin clay using finite element method models. Many numerical studies have used boundary element method models (e.g., Du and Aydin, 1993; Cooke and Dair, 2011; Cooke et al., 2013) and finite element method models (e.g., Harris and Day, 1999; Duan and Oglesby, 2006; Li et al., 2009; Liu et al., 2010; Nevitt et al., 2014; Nabavi et al.,
2017) to investigate the mechanics of restraining bends. While each method has their advantages, finite element method models are better suited than boundary element method models for simulating non-linear rheology, such as the bi-viscous rheology of the wet kaolin clay. While the shear strength of wet kaolin is rate independent (Cooke and van der Elst, 2012), the partitioning of fault slip to off-fault deformation that governs kinematic and mechanical efficiency depends on loading rate. Just as the crust deforms elastically on short time scales, such as an earthquake event, and viscously on long time scales, the clay can deform both elastically and viscously. The bi-viscous nature of the clay (and the crust) suggests that deformation within the clay may be influenced by the rate of applied deformation, such that faster loading rates produces more fault slip and less visco-relaxation. We explore the impact of loading rate on the deformation and efficiency of a restraining bend in a bi-viscous Burger’s material and discuss the implications for models of fault systems and the Earth’s crust.

5.2.1 Physical experiments of restraining bends in kaolin clay

Researchers in the UMass Geomechanics lab have run physical experiments of a 10° restraining bend with a 5 cm stepover in wet kaolin clay (e.g., Cooke et al., 2013; Hatem et al., 2015). The experimental apparatus is a steel box measuring 25 cm by 50 cm. We pour the clay to a depth of 2.5 cm on top two steel basal plates with the restraining bend geometry. We pre-cut the fault with restraining bend in the clay using an electrified wire probe along a template. A computer-controlled stepper motor displaces one side of the experimental box at a fixed rate while the other side remains stationary. Two cameras mounted above the surface of the clay take photographs after every 0.25 mm displacement. Digital Image Correlation (DIC) between successive photographs
provides incremental displacement fields that can track the evolution of the fault
geometry and off-fault deformation within a ~ 15 cm x 30 cm region of interest
throughout the physical experiment (e.g., Hatem et al., 2015; Toeneboehn et al., 2018).

Wet kaolin clay is a bi-viscous Burger’s material that can serve as an analog
material for the Earth’s crust. We adjust the water content of the kaolin such that the
shear strength ranges between 90-115 Pa, to ensure the kaolin scales to the crust (e.g.,
Cooke and Van der Elst, 2012). We measure the strength prior to each experiment using a
fall cone (DeGroot and Lunne, 2007) and adjust the water content accordingly. While we
know the material properties of the intact clay, we do not have constraints on the strength
of precut surfaces in the clay. Hatem et al. (2017) observed that before a through-going
strike-slip fault develops, deformation is accommodated in a wide shear zone with
echelon faults that eventually link up to form a through-going fault. Since models with a
pre-cut fault do not produce a wide shear zone (e.g., Hatem et al., 2017) we infer that the
strength of the pre-cut fault must be much lower than the intact clay, 100 Pa as
determined by Cooke and van der Elst (2012).

5.3 Methods

We use COMSOL Multiphysics® v.5.4, a commercial finite element method
software package, to investigate the effects of loading rate on restraining bend
deformation and efficiency. The two-dimensional model geometry (Figure 5.1) assumes
plane strain and the boundary conditions mimic those of the scaled physical experiments
of restraining bends (e.g., Hatem et al., 2015). We model a 10° restraining bend geometry
along a right-laterally slipping fault with a 5 cm stepover. The fault sits in a
homogeneous model domain measuring 50 cm x 50 cm, and we use tetrahedral elements
with variable mesh size, fining towards the fault. We implement material properties for a bi-viscous Burger’s material, which consists of a Maxwell component and a Kelvin component in series, using the properties of the wet kaolin clay (Cooke and van der Elst, 2012; Table 5.1).

Frictional contacts deform non-linearly, with zero displacement until stresses reach the frictional failure strength (Equation 5.1). To solve such problems numerically, it is necessary to define a contact pair between mated boundaries. We create the fault of the restraining bend by defining a contact pair, which obeys Coulomb’s Law for frictional fault slip (Equation 5.1)

\[ T = \mu_s \sigma_n + C, \]

Equation 5.1

with a coefficient of friction of \( \mu_s = 0.2 \) and cohesion of \( C = 20 \) Pa. These values are constrained to be less than those determined for the intact kaolin clay, which has internal friction of 0.6 and shear strength of 100 Pa. Thus, the values that we use for \( \mu_s \) and \( C \) along the precut surface are significantly weaker than the intact kaolin.

We impose a displacement boundary condition on the left plate, while holding the right plate fixed. We apply two boundary velocities, 0.6 mm/min and 6 mm/min, which correspond to motor speeds used for the scaled physical experiments and compare the deformation of the modeled fault system at steady state with that of the physical experiments. COMSOL Multiphysics® solves numerically for the displacement and stress fields through the duration of the model. A time-dependent solver loads each model for a total displacement of 40 mm. From the model results, we calculate 1) the
incremental deformation fields, defined as the sum of the incremental vorticity (2*curl) and incremental divergence of the horizontal displacement field, 2) the Coulomb stress field, 3) the kinematic efficiency of the system, defined as the ratio of median fault slip rate across the region to the applied velocity, and 4) the external work on the system, which describes the mechanical efficiency.

We calculate the incremental Coulomb stress following the methods outlined by King et al. (1994). Using a tension-positive convention, the orientation of the optimal failure plane can be defined as

$$\psi = \theta \pm \beta$$

where

$$\theta = \frac{1}{2} \tan^{-1} \left( \frac{2\sigma_{xy}}{\sigma_{xx} - \sigma_{yy}} \right) + \frac{\pi}{2}$$

and

$$\beta = \frac{1}{2} \tan^{-1} \left( \frac{1}{\mu} \right) .$$

We then calculate the Coulomb stress as

$$\sigma_c = \tau + \mu \sigma_n$$

where

$$\tau = \frac{1}{2} \left( \sigma_{yy} - \sigma_{xx} \right) \sin 2\psi + \sigma_{xy} \cos 2\psi$$

and

$$\sigma_n = \sigma_{xx} \sin^2 \psi - 2\sigma_{xy} \sin \psi \cos \psi + \sigma_{yy} \cos^2 \psi .$$

The external work ($W_{ext}$) of a fault system reflects the overall mechanical efficiency of the system. A mechanically efficient system requires less $W_{ext}$ to accommodate the same tectonic deformation as an inefficient system. We follow Cooke and Madden (2014) and calculate $W_{ext}$ as:

$$W_{ext} = \oint (\tau u_s + \sigma_n u_n) dB .$$
5.3.1 Mesh refinement

A mesh refinement study minimizes mesh sensitivity and model error due to spatial discretization. We use tetrahedral elements with a meshing scheme that fines inward from the boundaries to the fault. In COMSOL Multiphysics®, the contact pair includes source and destination boundaries. We define the contact boundary on the moving plate as the destination boundary. In order to minimize interpenetration of the contact, the destination boundary must be meshed finer than the source boundary, by at least a factor of two. Consequently, we use a relatively coarse mesh near the model boundaries and along the source boundary of the fault, with a maximum element length of 3 cm and test a range of element sizes along the destination boundary of the fault, from 0.5 cm to 1.5 cm. While finer meshes are generally more accurate, they also require greater computation time. The mesh refinement study allows us to find the mesh size that provides adequate accuracy balanced with CPU demands.

Figure 5.2 shows the distribution of cumulative slip along the length of the fault for the five different mesh sizes. The coarsest mesh size (1.5 mm; blue line) produces ~2.5 mm of slip within the restraining bend, while each of the finer mesh sizes produce similar slip (~2.4 mm) within the bend. The inset of Figure 5.2 plots the evolution of slip at the middle point in the fault bend (yellow star on model cartoon). The coarsest mesh (1.5 mm; blue line) shows a slight decrease in right-lateral slip after loading initiates. Finer mesh sizes converge, showing similar slip evolution curves. Due to the small difference in model results with smaller mesh sizes but significantly longer computation times, we chose to carry forth the mesh with 0.8 mm elements through the rest of the study.
5.3.2 Tolerance and initial time step study

To minimize model error due to temporal discretization within our models, we explore the effect of decreasing both the relative tolerance between time steps (Figure 5.3a) and the initial time step taken by the time-dependent solver (Figure 5.3b) on the fault slip at the middle of the restraining bend. Relative tolerance is the maximum amount of error that is permitted in the solution at each time step. Both the relative tolerance and initial time step only significantly impact the early slip along the fault. When evaluating the impact of changing the relative tolerance, we allow the solver to auto-determine the initial time step, which is based on the total duration of the model. With the default tolerance of $T = 0.01$ (blue line; Figure 5.3a), the fault produces a decrease in right-lateral slip (left-lateral slip) after the initial loading step. Subsequently, the fault once again slips right-laterally. As we decrease the tolerance (red and yellow lines; Figure 5.3a), the right-lateral slip along the fault increases monotonically. The cumulative fault slip of all models converges at $\sim 0.6$ mm of applied displacement.

Using a relative tolerance of $T = 0.0005$, we decrease the initial time step taken in the time-dependent solver (Figure 5.3b). Constraining the initial time step (red, yellow, and purple lines) produces similar slip rate that converge almost at the start of the model, while allowing the time-dependent solver to auto-determine the initial time step (blue line) produces greater slip rate ($\sim 0.02$ mm) on the fault at the start of the model. Again, all models converge at $\sim 0.6$ mm of applied displacement. The smallest initial time steps and tolerance tested here do not significantly impact our computation time, and thus, we use the model with 0.0005 relative tolerance and 0.001 s initial time steps for the remainder of this study.
5.4 Results

Numerical models that accurately simulate the physical experiments can estimate stresses within the clay and inform our current understanding of what drives fault growth. Here, we present maps of incremental off-fault distortion at steady state, plots of slip rate along the restraining bend at steady state, and the evolution of kinematic efficiency through the duration of the model. We define steady state reached when the slip rate along the fault no longer changes, so that the slope of the kinematic efficiency curve is near zero. We compare the results of the numerical models to observations of faulting in the wet kaolin physical experiments. Because new faults begin to form in the physical experiment, we use the experimental observations from the stage of the experiment when slip rates are constant and prior to new fault growth. The numerical models simulate deformation accumulated over ~5 cm of plate displacement within the experiments. To compare the model results with experimental observations, we report the incremental deformation associated with 0.25 mm increment of plate displacement at a total applied displacement of 3 mm.

5.4.1 Fault slip rate and kinematic efficiency

Incremental slip along the fault decreases along the restraining segment of the fault relative to outside of the bend in both the numerical and physical experiments (Figure 5.4). The camera height above the clay surface in the physical experiments optimizes photo resolution but doesn’t capture the full length of the fault within the apparatus. However, the physical experiments (red and blue points) show less decrease of slip rate from outside to within the restraining bend than the two-dimensional numerical models (red and blue triangles). The slow physical experiment has lesser slip along the
restraining fault system than the faster experiments, similar to the numerical model results. Near the edges of the numerical models, all of the applied displacement is accommodated as slip along the fault, an effect of the boundary conditions. Slip gradually decreases away from the boundaries and towards the restraining bend, and at the fault bends (vertical black lines), slip decreases sharply. The numerical model at the slow loading rate (red triangles) produces less slip through the restraining bend than the numerical model at the fast loading rate (blue triangles). Small bumps in the numerical model slip outside the restraining bend are within $1\sigma$ and are considered artifacts of the model.

5.4.2 Evolution of kinematic efficiency

We track the kinematic efficiency of the system through time (Figure 5.5) as the median incremental slip component in the x-direction accommodated along the length of the fault divided by the applied plate velocity. Kinematic efficiency is sampled at every 0.25 mm of applied displacement, and we compare the efficiency of the 2D numerical models (red and blue triangles) to that of the 3D physical experiments (red and blue points). Kinematic efficiency of the physical experiments is only shown prior to the growth of new faults in the experiment. Error in the numerical models, calculated as one standard deviation, is shown as thin red and blue lines.

Initially, the fault does not slip in any of the models (numerical or physical). As faults start to slip, kinematic efficiency increases sharply (Figure 5.5). The physical experiment with a slow loading rate (red points) reaches a steady state efficiency with less plate displacement than the fast loading rate experiment (blue points). The fast physical experiments have higher steady state kinematic efficiency, reaching a steady
state kinematic efficiency of ~ 85%, while the slow physical experiments only reach a steady state kinematic efficiency of 80%. Greater efficiency means greater portion of deformation is accommodated as fault slip. Unlike the physical experiments, the numerical models have a relative short delay of onset of slip (< 1 mm) compared to the physical models (slow - 9 mm and fast - 11.5 mm). The numerical model with the faster loading rate (blue triangles) shows a faster increase (steeper slope) in efficiency than the slower loading rate (red triangles). Furthermore, the faster loading rate model reaches a higher steady state kinematic efficiency (~ 90%) than the slower loading rate model (~ 80%). These results for steady state efficiency are consistent with the incremental slip (Figure 5.4), with greater slip through the restraining bend and lesser off-fault deformation in the fast loading rate models.

5.4.3 External Work

We calculate the external work of the numerical models up until the models reach steady state (Figure 5.6). The external work considers the applied forces and displacements on the boundaries of the system, providing insight on the mechanical efficiency of the system. In general, the external work is greater in the model with the fast loading rate (blue circles) than in the model with slow loading rate (red triangles). The applied boundary displacements are the same for both numerical models, so the difference owes to greater tractions required to deform the fast model. This implies that although the fast model is kinematically more efficient than the slow model because it has greater fault slip than the slow model (Figures 5.4 and 5.5), the fast model is less mechanically efficient because it consumes greater work to deform.
5.4.4 Off-fault distortional strain

We compare the patterns of incremental off-fault strain pattern of the model and the physical experiments prior to the formation of new faults. Off-fault deformation in the physical experiments (Figures 5.7c and 5.7d) is not as pronounced as in the numerical models due to the resolution of the DIC data. Some distortion can be seen at the fault bends of the experiment. The slow loading rate experiment shows greater off-fault deformation than the fast loading rate experiment (Figure 5.7c). In the numerical models, off-fault distortion is concentrated at the outside of the fault bends (Figure 5.7a and 5.7b). The numerical model with the slow loading rate produces a wider region of off-fault deformation than the model with a fast loading rate, with off-fault distortion encompassing the restraining segment of the fault (Figure 5.7a). In both the numerical and physical experiments, slower loading produces greater off-fault deformation of the bi-viscous material. The off-fault deformation arises at regions of changing fault slip at the fault bends, consistent with our expectations.

5.5 Discussion

The wet kaolin clay is a bi-viscous Burger’s material, so that deformation partitioning within the clay is velocity-dependent. We see this behavior in the timing of new fault growth and the overall kinematic efficiency of the experimental fault system. The numerical models are consistent with the experimental observations. The numerical models and physical experiments with a faster loading rate produce less off-fault distortion (Figure 5.7) and more slip along the fault (Figure 5.4). The high off-fault distortional strain at the fault kinks (Figure 5.7) highlight where the fault geometry is inefficient at accommodating the applied deformation due the local change in fault
geometry (Figure 5.4). As the velocity of applied deformation increases, off-fault distortion decreases, and kinematic efficiency of the system increases (Figure 5.5). The faster loading rate allows less time for viscous relaxation of the material, causing the material to behave more elastically.

We should note that these results differ from those presented in Hatch and Cooke (2018). The models of Hatch and Cooke (2018) were flawed due to the inclusion of inertial terms. Since we do not expect large accelerations of the material, the current models presented here are quasi-static.

The first order patterns presented here in the off-fault distortion and kinematic efficiency are similar between the numerical models and physical experiments; however, the magnitudes of the slip and distortion differ in the results of the numerical models and physical experiments. These differences may be due to the fact that the numerical models are currently only two-dimensional. In the physical experiments, deformation is being driven from the basal plates and faults propagate upward from the basal discontinuity (Hatem et al., 2017). The numerical models cannot, at this stage, capture the mechanics of the physical experiments at depth. Furthermore, we do not have tight constraint on fault strength. Varying fault properties will alter the incremental slip values in the models. For example, the coefficient of sliding friction may impact the peak steady state efficiency of the system, with higher friction decreasing the peak efficiency of the system, while greater cohesion may increase the delay of onset of initial slip along the fault (Figure 5.5).

The external work of the numerical models (Figure 5.6) indicates that the fast loading rate models are mechanically less efficient than the slow models. Because
external work considers the forces and displacements applied to the boundaries, we can infer how changes to fault strength will impact the external work required to deform the system. The kinematic efficiency of the system (Figure 5.5) shows how much of the applied displacement is accommodated as fault slip. If we were to increase the fault strength, we presume that the amount of fault slip would decrease and the external work would increase as greater force is needed to deform the model. An increase in fault strength would result in an increase in external work. However, because the model with a slow loading rate can more effectively dissipate stresses via visco-relaxation, the increase in external work related to an increase in fault strength would be greater in the model with a fast loading rate.

5.5.1 Growth of new faults

In the physical experiments, new faults grow from the outside of the fault bends (red tick marks on Figure 5.8). Coulomb stress maps show where stresses are nearest failure and can be used to predict the location and orientation of incipient faulting. These predictions can be compared to experimental observations of fault growth. Maps of incremental Coulomb stress (Figure 5.8) for planes of optimal orientation (orientation of black lines) at steady state show lobes of high Coulomb stress outside of the fault bends that can predict the locations of new fault growth. Slower loading rates (Figure 5.8a) produce smaller regions of high stress at the bends and lower values of Coulomb stress than the faster loading rates (Figure 5.8b) due to visco-relaxation in the Burger’s material. At slower loading rates, the material can flow around the fault bends. These regions of high shear stress indicate where we would expect new faults to grow if the
models allowed for it. The results are consistent with the record of faulting in the physical experiments.

5.5.2 Impact of longer relaxation times evident in numerical model with slow loading rate

If we were to run the numerical models for a total plate displacement of 40 mm, the fast loading rate model would simulate ~ 6.7 minutes and the slow loading rate model would simulate ~ 67 minutes. This difference in simulated time allows for greater visco-relaxation of the modeled Burger’s material in the model with a slow loading rate. The relaxation time of the Maxwell component of the Burger’s material is ~ 14 minutes, which means that models with the fast loading rate may not show significant effects of the viscous rheology since the loading is finished before the material has time to relax to 1/e of the initial stress.

To better understand the temporal impact of the Maxwell component of the Burger’s material, we run the slow and fast loading rate models to a total displacement of 40 mm, as well as a second slow loading rate model with double the relaxation time of the Maxwell component. Figure 5.9 compares the kinematic efficiency of the three numerical models. Once reaching steady state, the kinematic efficiency of the fast loading rate model (blue triangles) is consistent through the full applied displacement, while the kinematic efficiency of the slow loading rate model (red triangles) decreases from the peak efficiency at steady state. Increasing the Maxwell relaxation time of the Burger’s material in the slow loading rate model (orange triangles) increased the overall efficiency of the model so that the fault system had larger slip and less off-fault deformation. By increasing the relaxation time, less off-fault stress dissipates by viscous relaxation and the
fault has greater slip. This indicates that the deformation in models (and physical experiments) with slower loading rates is significantly impacted by the Maxwell component of the Burger’s material, whereas the models (and physical experiments) with faster loading rates may finish prior to significant Maxwell deformation.

5.5.3 Implications for crustal deformation and modeling

Crustal rocks demonstrate bi-viscous rheology similar to that of the kaolin clay. Consequently, regions of high strain rate may have different expression of faulting than regions of low strain rate. High strain rate regions may develop off-fault deformation at fault irregularities that promote growth of new faults that might subsequently increase the efficiency of the fault system. In contrast, inefficient geometric irregularities along faults may be longer-lived in slow strain rate regions because stresses do not accumulate to levels sufficient to grow new faults.

The velocity-dependent behavior of the clay may have implications for how the crust should be most accurately modeled. The faster we deform the clay, the more elastic it behaves. When the crust is modeled as elastic, we assume that the loading rate is too fast for any viscous response of the crust. This is appropriate for deformation that happens over earthquake time spans (seconds to minutes) but is less appropriate for deformation over longer time spans. Thus, elastic models may approximate too much slip in areas of complex fault geometries. For example, Beyer et al. (2018) investigate the active fault configuration within the San Gorgonio Pass region by matching numerical slip rates to available geologic slip rates. The fault geometry controls the first-order deformation. Furthermore, because most fault slip occurs during earthquakes, these elastic models match many of the geologic slip rates through the region. If similar models
were run in a Burger’s rheology, we could expect similar results because the Burger’s rheology reacts elastically under fast loading rates.

5.6 Future work

To the first order, many of the differences seen here between the numerical model results and the physical experiments may be explained by the two-dimensionality of the numerical models and unconstrained strength of the fault. Additional studies will develop three-dimensional models of the scaled physical experiments. Once the three-dimensional models are working and validated, we will calibrate the model to tune the fault strength values to the experimental observations. This may help constrain the strength of the clay along the pre-cut and slipping fault.

Once we expand our models to three dimensions, we can investigate the driving mechanisms for fault growth. By simulating snapshots in time of fault system evolution, we can solve for the stresses and strains throughout the modeled domain and calculate external work. This will allow us to see if the system evolves to minimize the external work of the system.

Additionally, our current model geometry of the restraining bend has sharp corners at the fault bends. These corners introduce singularities to our models. We will refine our fault geometry by adding rounded corners at the fault bends. In COMSOL, this is done with fillets of a small radius. Eliminating corners and smoothing out the restraining bend geometry may reduce artifact singularities and produce more robust results near the fault bends.
5.7 Conclusions

We use two-dimensional finite element models to investigate the impact of loading rate on the deformation of restraining bends in a bi-viscous Burger’s material. We simulate scaled physical experiments of a 10° restraining bend geometry along a right-laterally slipping fault with a 5 cm stepover in wet kaolin clay. Fault bends concentrate high off-fault distortional strain. Slip decreases at the fault bends and off-fault distortion increases. Loading rate impacts the relative amount of distortion and fault slip within the restraining bend. Faster deformation rates increase the efficiency of the system, decreasing off-fault deformation and increasing the amount of fault slip. These results differ in absolute value but are consistent with physical experiments of 10° restraining bends in wet kaolin clay.

Off-fault distortion maps indicate where the system is inefficient at accommodating the applied deformation, and Coulomb stress is greatest where off-fault distortion is concentrated. While the numerical models do not grow new faults, the maps of Coulomb stress indicate that new faults would grow outward from the fault bends, which is consistent with observations of new fault growth in the physical experiments.

Finally, deforming the clay at faster velocities decreases the amount of visco-relaxation, allowing the clay to behave more like an elastic material, while deforming the clay at slower velocities increases the amount of visco-relaxation. This has implications for how we should model the Earth’s crust. In low strain rate regions, fault models that approximate the crust as elastic may overestimate the efficiency of the system, and thus the amount of fault slip, which has consequences for seismic hazard assessments. However, models with a Burger’s rheology allows for velocity-dependent deformation,
which could improve our understanding of the deformation of complex fault systems in regions of different strain rates.
Figure 5.1: Schematic of numerical model geometry and boundary conditions. The fault has a 10° restraining bend with a 5 cm stepover. We hold the right side of the model fixed while applying a constant velocity to the left side.
Figure 5.2: Results of mesh refinement study. The model is most sensitive to mesh size within the restraining bend, where fault slip decreases significantly. Mesh sizes finer than 1.5 cm converge to a single slip value within the restraining bend. Inset: evolution of fault slip with applied displacement for the center point along the fault (indicated with gold star on cartoon). All mesh sizes converge to a single curve after 0.7 mm of applied displacement.
Figure 5.3: Results of the (A) tolerance and (B) initial step size studies. Fault slip at the center point along the fault is queried (gold star on cartoon). After 0.6 mm of applied displacement, both the tolerance and initial step size studies converged to a single curve. For all models henceforth, we use a tolerance of $T = 0.0005$ and an initial time step size of 0.001 second.
Figure 5.4: Kinematic efficiency at steady state through the restraining bend for the numerical models (triangles) and physical experiments (points), prior to new fault growth in the physical experiments. A best-fit line is fit through the physical experiment data. The slow (red) numerical model accommodates approximately the same amount of slip along the fault as the slow physical experiment, while the fast (blue) numerical model accommodates more slip than the fast physical experiment. Vertical black dashed lines indicate where the fault bends are located.
Figure 5.5: Plot of kinematic efficiency with applied displacement. The numerical models are plotted as triangles and the physical models are plotted as points. While the numerical models do not match the exact kinematic efficiency of the physical experiments, the patterns of evolution match well.
**Figure 5.6:** Evolution of external work for the fast and slow numerical models up until steady state at 3mm applied displacement. In general, the fast loading rate model is less mechanically efficient, requiring more external work.
Figure 5.7: Surface maps of off-fault distortional strain. A-B are the results of the slow and fast numerical models, respectively, and C-D are the slow and fast physical experiments, respectively. Off-fault distortion is concentrated at the fault bends in the numerical models, with the slow numerical producing significantly more distortion within the restraining bend. The physical models show more noise than the numerical models, but the slow physical experiment (C) shows slightly increased distortion near the fault bends.
Figure 8: Incremental Coulomb stress at 3 mm displacement, with an overlay of failure plane orientations, for numerical models with a A) slow loading rate and B) fast loading rate. Stresses are concentrated at the fault bends, indicating that new faults would likely propagate outward from the bends. Position and orientation of new fault growth in the physical experiments are indicated by a red fault increment.
Figure 5.9: Kinematic efficiency of numerical models with a total applied displacement of 40 mm. The model with a fast loading rate stays at a consistent kinematic efficiency through the duration of the model, whereas the model with the slow loading rate decreases after reaching an initial steady state. An additional slow loading rate model with twice the Maxwell viscosity shows the impact of the Maxwell viscosity on the relaxation of the Burger’s material. Because of the long model run time, the slow loading rate models are significantly impacted by the relaxation times of the modeled Burger’s material. As the viscosity (and relaxation time) of the material is increased, the effect on the deformation of the system is decreased.
5.9 Tables

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<th>Material Properties</th>
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<td>$G_m = 2.0 \times 10^4$ Pa</td>
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<tr>
<td>$G_k = 3.0 \times 10^4$ Pa</td>
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**Table 5.1**: Model material properties for a Burger’s material that simulates properties of the wet kaolin clay used in the University of Massachusetts Geomechanics scaled physical experiments, as determined by Cooke and van der Elst (2012).
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