Fault Interaction within Restraining Bend Fault Systems

Aviel Rachel Stern
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FAULT INTERACTION WITHIN RESTRAINING BEND FAULT SYSTEMS

A Thesis Presented

By

AVIEL RACHEL STERN

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

MASTER OF SCIENCE

September 2016

GEOSCIENCES
FAULT INTERACTION WITHIN RESTRAINING BEND FAULT SYSTEMS

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geology courses, and for the department’s strong community. I also need to thank the staff from the Geoscience office. They work diligently in keeping the Geoscience department active and I am grateful that I had the opportunity to work there for a year. The Geoscience office staff provides a positive energy, which makes working with them an enjoyable and rewarding experience.

I would like to thank my family and friends who are always there to support me, guide me, give me strength to continue pursuing my goals, and who keep me inspired. Because of them I continue to grow as a person.
Numerical simulations of a 15° restraining bend analog claybox experiment include considering the fault geometry, rheology, and boundary conditions. The numerical models show that a growing fault from an analog experiment propagates at depth rather than at the surface and is exposed in later stages of the experiment, and that the wet kaolin clay from the analog experiment is partially decoupled from the steel plate. The numerical models provide the stresses to predict accurate fault growth from the analog experiment and provide the evolution of external work within the fault system. The external work from the numerical models decrease as faults continue to grow, which agrees with the continuously increasing kinematic efficiency within the analog experiment.

Three-dimensional mechanical models are used to simulate the southern San Andreas fault. These models show that incorporating fault interaction, time since last earthquake rupture, and nearby earthquakes affects the stress state along a fault. Absolute shear tractions are calculated by multiplying time since last earthquake rupture with the simulated interseismic stressing rates for each fault strand. From our multi-cycle model, fault interaction affects local normal stressing rates so that the stresses are not relieved in between earthquakes. We
provide our absolute shear tractions and scale our multi-cycle normal stressing rates to be near to failure so that dynamic rupture modelers from University of California, Riverside use our results to simulate earthquake propagation for the complex fault region of the San Gorgonio Pass.
The San Andreas fault (SAF) is the plate boundary between the North American and Pacific plates with a record of large earthquakes with a largest magnitude of $M_w 7.2$ in the past 40 years (e.g. Lawson, 1908; Allen, 1968; Atwater, 1970). This 1287 km long fault is made up of multiple fault segments and strands that extends from Baja California and northward through California. These fault segments interact with each other as a network to distribute slip and stress. The slip distribution allows for regions along the fault to either relieve stress more readily or build up stress over hundreds of years affecting the magnitude and frequency of earthquake rupture (Segal and Pollard, 1980). As well, nearby faults accommodate plate motion and produce large ground rupturing earthquakes that changes the stress state along the San Andreas fault (King et al., 1994).

In the past 30 years, recent earthquake ruptures within California such as the 1989 $M_w 6.9$ Loma Prieta, 1994 $M_w 6.7$ Northridge, and 1992 $M_w 7.3$ Landers earthquake caused significant damage resulting in billions of dollars, injuries, and deaths including the loss of 63 casualties from the Loma Prieta earthquake leading to the re-evaluation of seismic risk and infrastructure (Cornell, 1968; Miller, 1998). The Uniform California Earthquake Rupture Forecast (version 3) suggests that the southern San Andreas fault has a strong likelihood to host a rupture of a $M_w \geq 6.7$ within the next 30 years, a seismic region where earthquakes will impact the Los Angeles metropolitan area (Jacoby et al., 1988).
Located along the southern San Andreas fault the presence of a left stepping restraining bend known as the San Gorgonio Pass traces the edge of the San Bernardino Mountains. An earthquake along the San Gorgonio Pass will significantly affect a population over four million, which includes the Los Angeles population and infrastructure present within this region. The San Gorgonio Pass region is comprised of a total of six strands causing complicated earthquake patterns. A restraining bend along a strike–slip fault system may impede rupture propagation (Harris, 2004, Kase and Kuge, 2001). However, recent earthquake ruptures prove that earthquakes are capable of propagating through multiple fault segments with complex fault geometries. For example the 1992 $M_w$ 7.4 Landers earthquake, located in the Eastern California shear zone, ruptured through five fault segments including two releasing stepovers (Madden and Pollard, 2012), the 1999 7.1 Hector Mine earthquake ruptured through 41 km in length of 3 fault segments in the Mojave desert. As well the Wasatch Fault located in Utah, part of the Basin and Range, is comprised of 10 fault segments where five of the fault segments produce earthquake ruptures every 900 – 1300 years since the Holocene. Paleoseismic data suggests that an earthquake rupture along the Watsatch Fault may have propagated through multiple fault segments (McCalpin and Nishenko, 1996; Machette et al., 1991).

Uncertainties in seismic hazard assessment result from forecast earthquake models relying on accurate geometries of large active faults and reliable slip-rates along these faults (Jones and Wesnousky, 1992; Yule and Sieh, 2003; Field et al., 2013). Geologic and geodetic data can be used to
constrain slip-rates, however the two methods lead to slip-rate uncertainties. Geologic studies collect slip rates at specific sites, which may not fully represent the deformation along a system with spatially varying slip rates (Cooke and Dair, 2011; McGill et al., 2015). Geodetic studies however, can provide overall deformation across fault zones, while their inversions cannot delineate slip on specific active strands within a complex system, such as the San Gorgonio Pass restraining bend of the SAF (McClusky, 2001; Meade and Hager, 2005).

Due to uplift along the regions of the San Gorgonio pass, unfaulted Quaternary alluvium covers portions of the fault strands inhibiting the capability to map portions of the San Andreas fault. As well, the Quaternary alluvium makes constraining slip-rates difficult along the Mission Creek strand, Banning strand, Garnet Hill strand, and San Gorgonio thrust (Matti and Morton, 1993; Mortin and Matti, 1993). The slip-rates along the Mission Creek strand are constrained from trench excavations (Behr et al., 2010), $^{10}$Be cosmogenic dating of boulders and cobbles from offset of alluvium channels (Fumel et al., 2002; Van der Woerd et al. 2006; Behr et al., 2010; Blisniuk et al. 2013), and geodetic measurements (Weldon and Sieh, 1985, Meade and Hager, 2005). Geologic slip-rates vary from 12 mm/yr – 20 mm/yr (van der Woerd et al. 2006, Behr et al., 2010, Blisniuk et al. 2013) while geodetic slip-rate measurements vary from 21 mm/yr – 37 mm/yr (Weldon and Sieh 1985; Meade and Hager, 2005). Numerical models provide the stresses and displacements along and near faults with complex fault geometries providing information about how faults partition slip due to fault interaction.
This thesis presents two chapters on the topic of fault interaction within restraining bend fault systems. Both chapters use a boundary element method code, Poly3D, to simulate deformation associated with restraining bends. The motivation for Chapter 1 is to simulate a general restraining bend that is less complex than crustal restraining bend fault systems. By controlling the boundary conditions I can gain insight into the mechanisms controlling an evolving restraining bend fault system.

In Chapter 1, “Numerical simulations of a restraining bend experiment”, I numerically simulate wet kaolin analog experiments and investigate the evolution of fault growth within a 15° restraining bend with a stepover width of 5 cm experiment. I repeat the analog restraining bend experiment with a 15° bend from Hatem et al. (2015) with the addition of stereopair photographs for higher resolution and to retrieve surface displacements in the horizontal and vertical direction. I simulated the analog experiment performed in the Geomechanics Physically Modeling Lab at University of Massachusetts, Amherst that is supervised by Professor Michele Cooke and facilitated by Master student, Kevin Toeneboehn. Kevin lead the 15° restraining bend experiment and provided the data and MatLab scripts necessary for analyzing the experimental data. The experimental data is used for calibrating the numerical models and for further analysis of the claybox experiment with the numerical models.

During the calibration process I consider the model mesh and fault geometry. I improve accuracy within the Poly3D model by developing a method to minimize the displacement gradient along the imposed plate and determine
the required slip to apply for each element so that the plate displaces uniformly. I hope that our improvements in providing a method to minimize the displacement gradient when applying an imposed slip along a fault in Poly3D will be utilized for future work such as when simulating an applied plate velocity.

I compare our uplift patterns, strike-slip rates, and kinematic efficiency from the numerical models with the analog experiment. The models are successful in capturing similar deformation observed from the analog experiment. Differences arise due to the rheology contrast of the numerical model and analog experiment. The linear elastic response in the numerical models produce less off fault deformation than what is observed from the viscoelastic wet kaolin used in the analog experiment.

The numerical simulations of the analog experiment provide a method for gaining insight into the mechanics of the analog experiment. The numerical models show that the clay from the analog experiment is partially decoupled from the plate and that faults from the analog experiment grow at depth that is exposed in later stages of the experiment. The numerical simulations are as well successful in predicting fault growth from the analog experiment.

For Chapter 2, titled “Calculating absolute stress in the San Gorgonio Pass region that incorporates fault interaction”, I explore whether incorporating fault interaction and the earthquake history along a fault influences the stress state for a multi-segmented complex restraining bend that is part of the San Andreas fault, known as the San Gorgonio Pass region. While recent earthquakes such as the 1999 Izmit earthquake demonstrates that an
earthquake can rupture through a restraining bend, simulating a dynamic rupture model that promotes failure through the restraining bend is complex and as well paleoseismic data is limited in providing the earthquake history (Sieh et al. 1989; Yule and Sieh, 2003; Harris et al., 2002; Kase and Day, 2006).

To predict the potential earthquake magnitude and length along a fault system, dynamic rupture models require accurate fault geometry, the stress state along the fault, and the rock properties. Absolute stresses along faults are not well constrained and are typically calculated by resolving the tectonic loading onto fault segments. I provide an alternative method for calculating a distribution of absolute stress, which incorporates the influence of fault interaction and time since last rupture for each fault strand. This project is in collaboration with University of Massachusetts Professor Michele Cooke, PhD student Jennifer Beyer and with University of California, Riverside Professor David Oglesby and PhD student Jennifer Tarnowski. This project is used to satisfy a chapter for my Masters thesis and a chapter for Jennifer Tarnowski’s PhD thesis in which Jennifer’s defense date is August 2016. Due to our collaboration with University of California, Riverside, Chapter 2 is a collective work so that Jennifer Tarnowski utilizes our documentation and stressing results in the dynamic rupture models. To complete this project, Jennifer Beyer contribution included simulating the Landers earthquake rupture so that I can observe the impacts of stress distribution along the southern San Andreas fault from nearby earthquakes. As well, Michele Cooke contributed in compiling figures, analysis for normal and shear stressing rates and for the impact from the Landers rupture, and made
significant revisions to this document. Jennifer Tarnowski will use our calculated absolute shear stresses without the affect of the Landers earthquake and our distribution of normal shear stressing rates to simulate dynamic rupture models along the San Gorgonio Pass region to determine the potential magnitude and rupture path in a region where large earthquakes will affect a metropolitan area. I hope that our approach in incorporating fault interaction and time since last earthquake rupture for determining the stresses along faults will offer a new approach for inputting accurate stresses into dynamic rupture models that will provide a more accurate solution for understanding earthquake hazards in regions where fault systems are complex.
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CHAPTER 1

NUMERICAL SIMULATIONS OF A RESTRAINING BEND

1.1 Abstract

I perform a 15° restraining bend wet kaolin claybox experiment with stereo-pair imagery to capture higher resolution documentation of fault growth and uplift and I numerically simulate five stages of deformation of a 15° restraining bend wet kaolin claybox experiment in order to gain insight into mechanisms controlling fault growth. Each stage of deformation is a snapshot of active fault deformation from the analog experiment. Accurate numerical simulations of the claybox experiment require constraining the rheology of the kaolin, fault topology, fault history, and the boundary conditions.

From calibrating the numerical models with the analog experiment, the numerical models show that with decreased coupling of the clay to the plate the numerical models better match the pattern of off fault deformation in the analog experiment suggesting that the clay is partially decoupled from the plate in the analog experiment. The numerical models show similar uplift patterns to the analog experiment. A sharp gradient of uplift in both models indicate the location of the fault trace. From stage d3, a lack of a sharp gradient in uplift from the numerical model compared to the uplift from the analog experiment suggests that a blind thrust is present above the stationary plate in the analog experiment that is exposed in later stages. The calculated coulomb shear stress in the numerical models accurately predicts fault growth for the analog experiment and confirms with the observations from uplift patterns that a fault grows at depth in the analog
experiment. The regions where the non-exposed fault may be propagating above the stationary at stage $d_3$, is a region of high coulomb shear stress indicating a zone of failure where faults can grow.

The evolution of fault growth from the kinematic efficiency and external work are observed from the numerical models. The numerical models reaches a steady-state kinematic efficiency of 0.9 while in the analog experiment the kinematic efficiency reaches a steady-state of 0.72 this is due to the difference in rheology of the experiment and model. A higher kinematic efficiency in the numerical model is consistent with the larger strike-slip values and lower off fault deformation. As the linear elastic material does not flow as the biviscous kaolin clay can. The evolution of external work from the numerical model increases for each stage of fault growth showing that from the analog experiment faults grow to minimize work and while becoming a more efficient fault system.
1.2 Introduction

A restraining bend is a strike-slip fault system with a left-stepping bend with right-lateral shear or a right-stepping bend with left-lateral shear where a zone of local contraction develops within the region of the bend (e.g. McClay and Bonora, 2001; Cunningham and Mann, 2007; Legg et al., 2007; Cooke et al., 2013). Restraining bends accommodate this local contraction through strain partitioning such as by secondary faulting, uplift, fractures, vertical rotation, and folding (e.g. Fitzgerald et al. 1993; Gomez et al., 2003; Cowgill et al., 2004), and can evolve so that multiple generations of faults propagate from the kinks along the bend (e.g. Matti and Mortin, 1993; Wakabayashi et al., 2004). Generally, strike-slip decreases along the two subparallel faults toward the bend. The restraining segment’s obliquity from plate motion causes the minimum strike-slip to be along the bend. The decrease in strike-slip reduces the overall slip rate on the fault system making it less efficient than a planar strike-slip fault. Inefficient fault systems may grow new faults in order to increase their mechanical efficiency and reduce work required for deformation (e.g. Hardy et al., 1998; Del Castello and Cooke, 2007; Cooke and Madden, 2014; Herbert et al., 2015).

Analog claybox experiments undertaken by Cooke et al. (2013) and Hatem et al. (2015) evaluated the partitioning of strain within restraining bends by calculating the evolution of kinematic efficiency for a fault system with a range of bend orientations from 0° to 30°. The bend orientation is the active angle between the overall fault and the restraining segment (Figure 1). The experiments show that for an evolving restraining bend the kinematic efficiency
reaches a steady-state as faults continue to propagate. The kinematic efficiency is expressed as the proportion of applied displacement that is partitioned as fault slip rather than off-fault deformation (Cooke et al., 2013; Hatem et al., 2015, Equation 1).

\[
\text{Kinematic Efficiency} = \frac{\sum \text{median(slip rate)}}{\text{plate velocity}}
\]  

Equation 1 defines kinematic efficiency as the sum of the median slip rate for all fault strands within a fault system divided by the plate velocity. The remaining deformation occurs from the faults. For example, a planar fault will have a higher kinematic efficiency than a fault with a complex geometry such as a large stepover width. A fault with a large stepover will correspondingly have high off-fault deformation.

Understanding how an inefficient restraining bend fault system evolves to accommodate plate loading gives insight into how the fault system evolves into a more efficient system. Parameters that affect the evolution of faults within a restraining bend include relative plate velocity and direction, fault geometry such as strike of the bend, stepover width, and dip of the growing faults (e.g. Dooley et al. 1999; McClay and Bonora, 2001; Cunningham and Mann, 2007; Cooke et al. 2013; Li et al. 2009; Fattaruso et al. 2014; Hatem et al. 2015). Experimental and numerical studies of restraining bends provide insight into the mechanics such as slip partitioning and fault evolution.

To further explore the evolution of a restraining bend fault system, I repeat the experiment setup for a 15° orientated restraining bend from Hatem et al. (2015) with higher resolution stereopair imagery and I numerically simulate the
analog claybox experiment. I compare strike-slip, uplift, and kinematic efficiency results from the numerical models with the analog experiments. The three-dimensional numerical models provide the evolution of stress so that I can predict fault growth from the Coulomb failure criterion and determine the evolving work of deformation to evaluate whether faults evolve to minimize work.

![Figure 1.1 Schematic drawing of a restraining bend](image)

**Figure 1.1 Schematic drawing of a restraining bend**
A schematic drawing of a left stepping right-lateral restraining bend in which the bend orientation is defined as θ, and stepover width is the width between the two subparallel faults.

1.3 Background

Restraining bends are inefficient fault systems because the local strike slip rate along the bend is lower than plate motion, leading to significant off-fault deformation. For a fault to be completely efficient, the fault plane must be planar and weak so that the fault slip equals the relative plate motion. In the crust, it is likely that faults will not be 100% efficient because they have non-zero strength and roughness (e.g., Jones and Tanner, 1995; Hatem et al. 2015). For example, Herbert et al., 2014 determined that the Eastern California Shear Zone is accommodated by 40% +- 23% of off fault deformation. Additionally, the Rinconada fault, a strand of the San Andreas fault (SAF) accommodates 80%
fault slip, and consequently accommodates 20% of plate motion through discrete and distributed deformation (Titus et al., 2007).

While kinematic efficiency is calculated from slip rates and plate displacement, a complete work budget can assess whether faults evolve following work minimization. The amount of work applied can be quantified along the plate boundaries by calculating the external work of the system ($W_{ext}$) (e.g. Cooke and Murphy, 2004; Cooke and Madden, 2014).

In addition to $W_{ext}$, the complete work budget includes the internal work of deformation, $W_{int}$, work against gravity, $W_{grav}$, work against friction, $W_{fric}$, the energy used for fault propagation, $W_{prop}$, and the energy used for ground shaking, $W_{seis}$ (2).

$$W_{ext} = W_{int} + W_{grav} + W_{prop} + W_{seis}$$ (2)

The external work for a fault system, such as a restraining bend along a strike-slip fault, is defined as:

$$W_{ext} = \oint (\tau u_d + \sigma_n u_n) dB$$ (3)

Where $\tau$ represents applied shear traction, $u_d$ represents applied shear displacement, $\sigma_n$ represents normal traction, $u_n$ is the normal displacement along the model boundaries, $B$.

Tracking $W_{ext}$ during fault evolution reveals how the mechanical efficiency of the fault system responds to new fault growth. If the mechanical efficiency correlates with $W_{ext}$ then the external work of the fault system decreases when the efficiency of the system increases. Cooke and Dair (2011) and Fattaruso et
al. (In press) assessed the evolution of external work along the restraining bend of the SAF through the San Gorgonio Pass region by modeling three successive active fault configurations reconstructed by Matti and Morton (1993). As the San Andreas fault through the San Gorgonio Pass region evolves, Fattaruso et al. (In press) calculated that the rate of external work decreases initially by ~932 TJ/yr from the model with the oldest dipping Mission Creek strand ~ 1 Ma to the model with the vertical Mill Creek strand of SAF. This result suggests that the SAF evolves towards greater efficiency. However, the rate of external work increases (~8 TJ/yr) from the model with the Mill Creek strand (500 – 120 ka) to the model with today’s discontinuous fault system (Figure 2). The relative decrease in efficiency for the present day SGPr may arise from uncertainties in the present day fault geometry. Alternatively, during fault network evolution, there may be episodes where fault systems become slightly less efficient. Analog experiments further our understanding of the evolution of fault growth from restraining bends because scaled physical experiments can reproduce crustal evolution within hours and deformation can be directly observed. From these experiments, digital image correlation reveals the incremental displacement field at the surface of the claybox. The incremental displacement allows for tracking fault growth and constraining slip distribution along all faults in order to calculate the evolution of kinematic efficiency.
The external work is calculated from the fault evolution along the sSAF near the San Bernardino Mountains. From top, a dipping Mission Creek fault at >500 kya evolves into the present complex San Gorgonio knot at 120 kya. Taken from Fattatuso et al. (In press). B) The change in external work is estimated to decrease ~ 932 TJ/yr from the active Mission Creek strand to a vertical Mill Creek strand and the external work increased to ~ 8 TJ/yr from a fault geometry with the Mill Creek strand to present day fault geometry.

A 15° restraining bend is an ideal experiment to simulate with numerical models because unlike restraining stepovers with >20° bends, the 15° bend experiment displays both continuous slip along the precut restraining bend throughout the experiment in addition to development of new faults (Hatem et al., 2015). In the 15° restraining bend experiment, the through-going fault remains active but is inefficient enough to promote new fault growth. In this experiment, a new inward dipping oblique-slip fault propagates and links to the precut strike-slip fault around the restraining bend above the stationary plate, while a new vertical...
fault propagates and links to the precut strike-slip fault above the moving base plate. The experiments indicate that within 180 – 450 Ma of simulated tectonic displacement, the restraining bend fault network, propagates new faults and these faults grow and link while inefficient fault segments are abandoned. The system ultimately converges to a steady-state of kinematic efficiency.

Numerical models of a restraining bend deepen our understanding of the mechanisms controlling fault evolution. Li et al. (2008) investigates a restraining bend using a three-dimensional finite element method model with a viscoelastoplastic rheology. The model couples a brittle crust with a ductile upper mantle and uses Drucker-Prager failure criterion to simulate fault growth. These models show a decrease in strike-slip along the restraining segment of the bend that matches crustal and experimental observations. However, the simulated fault propagation does not replicate observations from the analog experiments simulated by Hatem et al. 2015. From the numerical model (Figure 3a), the faults propagate parallel to the fault segments outside of the restraining bend rather than link to the two outside segments observed in the analog experiment for a 30° oriented bend with a stepover width 5 cm (Figure 3b). The experimental pattern of linked faults matches with field observations therefore the analog experiments provide observations for the evolution of a restraining bend that simulates a timespan of thousands of years within hours (e. g. Cunningham et al. 1996; Legg et al., 2007).
Figure 1.3 Simulations of fault propagation from previous models

Comparisons of the evolution of a left stepping restraining bend from A) numerical models taken from Li et al. (2009) with B) analog claybox experiments taken from Hatem et al. (2015). The arrows show the direction of fault propagation. Both models show faults that grow from the lower kinks that propagate away from the bend to become parallel to plate motion. The differences between the two models occur where in the analog experiment the growing faults link to the restraining bend.

1.4 Methods

I simulate an analog claybox experiment of a 15° restraining bend with a stepover width of 5 cm where stereopair imagery records uplift, PIV provides horizontal displacements, and a three-dimensional laser scan documents the exposed footwalls and fault geometry. The data from this experiment is used to calibrate the numerical simulations. The numerical models run in the three-dimensional boundary element method code Poly3D. In Poly3D, the models include simulating five stages of active faulting where each snapshot of the numerical model represents 0.25 mm of basal plate displacement at distinct stages throughout the experiment.
1.4.1 Physical experiment of restraining stepover

The experimental setup for the claybox includes two steel basal plates with the geometry of a 15° restraining bend (e.g. Cooke et al., 2014; Hatem et al., 2015; Figure 4). The claybox is 25 cm wide, 50 cm long, and 2.5 cm thick. Before simulating the analog experiment, the wet kaolin shear strength is scaled to the crustal shear strength by ensuring that the kaolin shear strength ranges between 90 – 115 Pa (e.g. Cooke and van der Elst, 2012; Cooke et al., 2014; Hatem et al., 2015). Next, I fill the steel box with wet kaolin clay, and use an electric probe to precut a fault along the geometry of the 15° restraining bend. A computer-controlled motor displaces one plate at a rate of 0.5 mm/min while the other plate remains stationary. Two cameras placed directly above the claybox take photographs every 30 seconds during the experiment capturing 0.25 mm displacement between each snapshot. The gathered processed successive photographs of the surface from the claybox experiment provide the velocity field, uplift patterns, and the evolving fault geometries in the physical experiment. A three-dimensional laser scan captures the exposed footwalls of the faults after reversing the moving plate back to its starting position at the end of the experiment (e.g. Cooke et al., 2013; Hatem et al., 2015).
In analog claybox experiments the model setup includes two steel basal plates that provide the geometry for a restraining bend. The arrow indicates the moving plate. During the experiment, a stepper motor connected to the computer displaces the moving basal plate while two cameras take pictures every minute from above the claybox.

### 1.4.2 Stages of fault growth

Five stages of fault evolution within the experiment are numerically simulated with each snapshot model simulating 0.25 mm of plate displacement. The selected stages of fault evolution correspond to changes in kinematic efficiency measured in the physical experiment ($d_1$, $d_2$, $d_3$, $d_4$, $d_5$) (Figure 5). Kinematic efficiency is calculated by the summation of the median slip in the x-direction along each fault and dividing this quantity by the incremental plate motion (Equation 1).

From Figure 5, the kinematic efficiency increases from 9% at the start of the experiment, $d_0$, to 60% at $d_1$. At $d_0$, segments of the precut strike-slip fault barely slips, by $d_1$ the slip is localized along the entire fault. For the rest of the experiment, the kinematic efficiency fluctuates by about ±10% and eventually
converges toward a final steady-state. These fluctuations are due to fault evolution within the restraining bend fault system. From stage $d_1$ to $d_2$ kinematic efficiency increases and reaches a peak of $\sim 70\%$ corresponding to a new vertical strike-slip fault that starts to grow from each kink of the restraining bend. Between stages $d_2$ and $d_3$, the kinematic efficiency decreases showing that for small durations of fault growth the fault system can be less efficient than previously. From stages $d_3$ to $d_4$, the kinematic efficiency again increases by 5%. At this time, the growing fault above the stationary plate links with the strike-slip fault, while the vertical fault above the moving plate continues to propagate. By the end of the experiment, the growing fault above the moving plate never links to the precut strike-slip fault at least a the surface of the claybox.

The kinematic efficiency reaches a steady-state of 72% at stage $d_4$ while faults continue to grow. The 72% steady-state kinematic efficiency in this experiment is lower than the 80% steady-state kinematic efficiency recorded in the 15° experiment from Hatem et al. (2015), because the improvements in resolution of the velocity field from this study’s experiment, I am able to map the strike-slip faults as more localized which captures more of the off fault deformation from that determined by Hatem et al. (2015).
Figure 1.5 Five stages of fault growth from the analog experiment

A plot of kinematic efficiency as the basal plate displaces for a 15° analog experiment with snapshots of active fault geometry. At b) 16 mm plate displacement ($d_1$), the fault slip is localized and a new fault begins to propagate. At c) 28 mm plate displacement ($d_2$), efficiency reaches a maximum efficiency while the faults begin to propagate, at d) 44 mm plate displacement ($d_3$) the fault continues to propagate while the efficiency has decreased at e) 56 mm plate displacement ($d_4$), the fault above the stationary plate has linked to the strike slip fault and kinematic efficiency again increased. Finally at f) 80 mm plate displacement ($d_5$), the propagating fault above the moving plate completes propagation and the restraining bend reaches a steady-state efficiency.
1.4.3 Poly3D

Poly3D is a linear elastic three-dimensional boundary element method (BEM) software that is used to numerically simulate the analog claybox experiment. In Poly3d, simulations of model fault displacements capture the stresses, strains, and displacement fields surrounding the faults that arise due the applied tractions or displacements (Thomas, 1993).

Poly3D uses polygonal elements where traction or displacements are applied at the center of an element. The triangular elements allow for a more accurate simulation of deformation along irregular fracture geometries than with rectangular elements. BEM models resolve continuum mechanics solutions for complicated fracture geometries, such as for non-planar faults, and uses less RAM compared to a finite element method (FEM). In a BEM model, the elements are only at the boundaries and discontinuities using two-dimensional elements for a three-dimensional object. Whereas a three-dimensional mesh for the entire model is required for FEM. Poly3D has the option to run in the command line or in a graphical user interface (GUI) (e.g. Madden and Pollard, 2008). The Poly3D GUI provides the capability to edit the fault mesh and fault geometry by transforming, lengthening, shortening, and changing orientation of a fault, as well deleting, adding, and transforming nodes. Although the Poly3D GUI provides the displacement components for observation grids, the software only provides the slip components for a boundary. When using the command line version of Poly3D, the output file includes the displacement components for both observation points and faults. For simulating the claybox, I use Poly3D GUI to
remesh the fault geometry and modeled boundaries, while the simulations use the command line version.

1.4.4 Model Setup

The numerical model setup includes two basal cracks mimicking the steel basal plates from the experiment and the active fault geometry from each of the five stages of the analog experiment. The side boundaries, which laterally contain the volume of clay in the analog experiment, are not included in these simulations, as the inclusion of the side boundaries does not impact fault slip. The dimensions of the numerical claybox simulated here are 50 cm by 24 cm by 2.4 cm with an additional 10 cm wide border around the basal crack that has prescribed displacement. Where the faults meet the edge of the model, I prescribe slip along fault-end patches (Figure 6). In Poly3D, slip goes to zero at the fault tips. Extending the size of the base of the model and the length of the faults allows for the fault slip and plate motion to not decrease at the edges of the region of interest within the model. While Poly3D is a linear elastic model, the wet kaolin clay from analog experiments is a bi-viscous material (Cooke and van der Elst, 2012). Cooke and van der Elst (2012) tested the wet kaolin clay with a range of constant loadings and measured a Young’s modulus for the Maxwell component and Kelvin component to vary between $1.9 \cdot 10^4$ Pa and $3 \cdot 10^4$ Pa. The wet kaolin clay’s water content is 65-70%. To set the material properties to best represent the wet kaolin clay in the numerical simulations, I use a Young’s modulus that is in between the measured range of Young’s modulus for the wet kaolin, $2.5 \cdot 10^4$ Pa and I assume the wet clay has a Poisson’s ratio near to
incompressible, 0.4999, due to the high water content in wet kaolin clay.

Figure 1.6 Numerical model setup for the claybox
A numerical model setup includes the moving (dark blue) and stationary plate (grey plate) with dimensions 50 cm X 24 cm. The moving plate is extended by 10 cm (light blue plate) to remove the boundary effects of zero displacements at the plate edges. Similarly, fault-edge patches are added with prescribed slip at either end of the fault (magenta). The fault geometry (green fault) mimics the initial configuration of the experiment. Additional faults are added so that each model captures the active faults for the simulated snapshot at that time.

At each stage of deformation, a snapshot model simulates the active deformation from the included active fault geometry at that stage. Building the fault surfaces involves a two-step process. First I input the three-dimensional laser scans of the fault geometry into Move, a structural software for building geomechanical models. The exposed footwalls documented by laser scans constrain the dip of the fault surfaces. For the propagating fault above the stationary plate, the trace of the propagating fault from the laser scans provides the fault strike and these traced lines projected with depth at a specific dip angle replicate the fault geometry from the analog experiment. Above the moving plate, the geometry of the propagating fault distorts when reversing the moving plate.
back to its original position in order to expose the footwall of the fault. To capture the geometry for the propagating fault above the moving plate, I input a shear strain map at stage $d_5$ (Figure 5f) into Move and trace the propagating fault that is above the moving plate. The traced fault is projected at depth at a dip angle that is observed from the laser scans.

1.4.4.1 Displacement boundary conditions

To numerically simulate a snapshot of deformation within the analog experiment, the modeled moving plate simulates 0.25 mm of rightward displacement (Figure 6). In Poly3D, the prescribed boundary conditions constrain slip vectors rather than displacement vectors (Figure 7). To provide displacement for the base of the model within 0.002 mm of 0.25 mm, I calculate the required slip for each element to displace 0.25 mm along the outer region of the plate (light blue region in Figure 6). Although, the desired displacement of 0.25 mm along the upper basal plate mimics the steel plates from the analog experiment, calculating the required slip for each element minimizes the deviation from 0.25 mm.

The displacement components in Poly3D comprise the Burger’s vector acting on each element. The Burger’s vector (b) is the difference between displacement from the positive $D_{(+)}$ face and negative $D_{(-)}$ face of the fracture (Equation 5). The positive and negative side is defined by the direction of the normal vectors when creating a mesh (Figure 7).

\[ b = D_{(+)} - D_{(-)} \]  

(5)
Figure 1.7 Schematic drawing of a crack
A schematic drawing shows how a crack, with crack length of 2a, has two boundaries. For each boundary, there is a positive $D_+$(+ ) face and negative $D_-(\cdot)$ face where for each boundary sums to a prescribed slip. When I apply a slip vector along an element in Poly3D, the element does not distribute the displacements equally and the absolute value of $D_+(+)$ does not equal the absolute value of $D_-(\cdot)$ (Figure taken from Fric2D documentation).

For Poly3D, if I impose 0.25 mm slip along a fault element, the fault element does not displace equally on either side of the element. While the displacement sums to 0.25 mm, one side of the element may slip more than the other if, for example, the element is closer to the surface in a one-half space. For example, if I apply 0.25 mm slip along the basal crack, the negative face of the boundary may displace -0.12 mm and the positive face of the boundary displaces 0.13 which sums to the applied slip, 0.25 mm (Equation 5).

$$0.25 = 0.13 - (-0.12)$$

When I prescribe 0.32 mm of slip along the outer plate of the numerical model, the median displacement at the base of the model is 0.25 mm. However the displacement in the x-direction ranges between 0.242 mm – 0.256 mm (Figure 8a). To provide a more uniform displacement along the base of the model, I impose a unique slip vector for each element. The output file from the
initial model with uniform slip provides the displacements that guide how I should adjust the prescribed slip in order to have 0.25 mm displacement on each element. To calculate the imposed slip for each element, I use the ratio:

\[
\frac{U_1^+}{B_1} = \frac{0.25 \text{ mm}}{B_2}
\]  \hspace{1cm} (6)

Where \( B_1 \) is the slip prescribed in an initial model i.e. 0.32 and \( U \) is the displacement component on the positive face of the boundary from an initial model. For this study, the positive face is the side of the boundary that simulates the base of the numerical claybox model. \( B \) is the required element displacement, of 0.25 mm. \( B_2 \) is the imposed slip that is needed to for each element to achieve a displacement of 0.25 mm along the positive face of the boundary. Below is an example of how I solve for the necessary slip (\( \epsilon \)) for an element after running an initial model.

The scaling of the prescribed slip can be applied iteratively until the resulting displacements are suitably uniform. The displacement gradient from a first iteration of calculated slip ranges from 0.244 mm - 0.256 mm (Figure 8b). A second iteration decreases the range of displacements along the outer plate to 0.248 mm – 0.252 mm (Figure 8c). While a third and fourth iteration for scaling the prescribed slip along each element will minimize the displacement gradient even further. A range 0.248 mm – 0.252 mm plate displacement meets the requirements of our study.

This method of successive iterations of boundary condition refinement in order to achieve uniform plate displacement may be particularly useful for simulations of crustal deformation and fault interaction over multiple earthquake

While these models are validated from comparing slip-rates along the modeled faults with geodetic and geologic slip-rates, applying a unique slip to each element in order to achieve an approximately uniform displacement may be a more accurate approach when modeling complex fault geometries such as the San Andreas fault.
Figure 1.8 The displacement gradient along a boundary

Displacement distribution in map view along the positive face of the outer plate boundary with prescribed slip is applied to each element. I first run an initial model A) where I apply a uniform slip of 0.32 mm along the boundary for this boundary condition the range of displacement along the outer plate is between 0.42 mm – 0.256 mm. After the first iteration of refinement of the displacements along the boundary have a smaller range of 0.244 mm – 0.246 mm. A second iteration minimizes the range of outer boundary plate displacements 0.248 mm – 0.252 mm.
1.4.4.2 Discretization and mesh assessment

A discretization analysis helps to determine the appropriate mesh size. A fully decoupled model of d₁ is run with an element length of 1 cm, and another fully decoupled model is run with a mesh comprised of 0.66 cm length elements. Within 1.4.6 Calibration, I describe in further detail the model setup for a fully decoupled model. When the element size is less than 0.66 cm, memory constraints prevent running the model with the command line code. While the Poly3D GUI is capable of running this model, the solution would be calculated with the iterative solver rather than the direct solver. The iterative solver approximates a solution with an initial guess and subsequently improves the solution for each iterative model. Iterative solvers help reduce run time and use a nonlinear equation approach but the error is larger than direct solvers. The direct solvers use linear equations to calculate an exact solution. Limiting the minimum element length to 0.66 cm for the numerical claybox models allows taking advantage of the direct solver. A plot of strike-slip at the surface of the claybox along the fault trace of the d₁ model indicates the discrepancies of the two models (Figure 9). The blue dotted line is the strike-slip for the finer mesh with a 0.66 cm element length and the pink dotted line is the strike-slip for the coarser mesh with a 1 cm element length. The local increase and decrease in slip, is due to irregularities of the element mesh.
Figure 1.9 Comparing two meshes with different element lengths

The strike-slip near the surface of the claybox is plotted along the x-axis of the fault plane. The pink dotted line is the strike-slip from the model with a mesh length of 1 cm and the blue line is the strike-slip from the model with a mesh length of 0.66 cm. The unusual sharp increase or decrease in slip is due to an irregularity in the mesh, which can be improved with a remesh of the fault. Overall the strike-slip trend for both models is similar.

To fix the irregular elements, the mesh is edited until a satisfactory mesh is met. The difficulty in removing the irregular elements in a finer mesh causes the irregular slip for a model with a 0.66 mm element length and is not satisfactory unless the mesh is edited until the model provides reliable slip. While the strike-slip from a model with a 0.66 mm element length has an irregular mesh, the strike-slip trend is similar to the strike-slip with a model with a 1 cm mesh length. This is noticeable between 0 cm to 25 cm along the x-axis and -15 cm to -25 cm along the x-axis. This suggests that the finer mesh with reliable element shapes produce a more accurate result, however the difference in strike-slip between a mesh with 0.66 cm and 1 cm for the numerical claybox experiment is not large. Therefore I use a mesh that is 1 cm in length because
there is more control over fixing the irregular elements with a 1 cm element length then with a 0.66 cm element length.

![Graph](image)

**Figure 1.10 Determining the error of the numerical model**

A plot of strike-slip along the x-axis of the restraining bend at the surface of the model shows the difference of strike-slip between two models with different meshes with the same size element length. I determine an error of strike-slip of < 3 %, which is the percent difference of slip between the two models.

Using the Poly3D GUI to remesh the fault geometry ensures all the elements share the same element length. When the faults are remeshed in Poly3D GUI, the software will produce a different mesh every time even with the same prescribed element length. I estimate the meshing error of the claybox numerical model with a model at snapshot d1 by repeating the simulation with two different meshes of identical element size and comparing the strike-slip along the restraining bend at the surface of the model (Figure 10). Reassuringly both models produce similar strike-slip along the restraining bend. The mesh error of the models is the percent difference in strike-slip thus < 3%. A model with a mesh error of <3% produces reliable results confirming that the mesh from our model is satisfactory for simulating the numerical claybox model.
1.4.5 Calibration

1.4.5.1 Calibration of degree of decoupling

Observations from the claybox experiment suggest that the clay may at least be partially decoupled from the basal plates (Figure 11). While the imposed displacement of the basal plate is 0.25 mm, the surface of the clay displaces 0.2 mm in the positive x-direction. Above the stationary plate, the displacement in the x-direction is about 0.05 mm near the bend. The difference in the imposed and observed displacement suggests that the clay may be partially decoupled from the basal plates. To investigate this, varying the degree of coupling between the clay and the basal plates provide four model setups to test a fully coupled model (Figure 12a), two partially decoupled models (Figure 12b,c), and a fully decoupled plate model (Figure 12d).

![Figure 1.11 Surface displacement (x) from the analog experiment](image)

A mapview of surface displacements in the x-direction with an overlay of the displacement vectors along the surface of the analog model showing the clay above the moving plate displaces 0.2 mm and decreases near the bend while along the clay above the stationary plate displaces near or less than zero and increase in displacements near the bend.
Figure 1.12 Model setup for four variations coupling

The moving plate (light blue region) displaces 0.25 mm in the x-direction. The partially decoupled plate (dark blue region) has zero shear traction. The shape of the decoupled plate mimics the region of off-fault deformation. The fault-end patches (magenta) are prescribed 0.25 mm slip while the fault (green) slides freely. The four varying coupled clay to plate models are used to determine which best represents the analog experiment.
For the coupled model (Figure 12a) I apply 0.25 mm displacement towards the right along the moving plate (light blue) and keep the stationary plate locked (grey region). For the three decoupled models, I impose 0.25 mm displacement along the light blue regions in Figure 12 that surrounds the decoupled portions of the plate (dark blue). The decoupled plates slide freely in the positive x-direction and are locked in the y and z directions. For the partially decoupled model (Figure 12b) the decoupled area is similar to the region of off-fault deformation observed in the analog experiment (Figure 11). For all four models, the faults can displace parallel to the fault surface while not allowing perpendicular displacement to the fault plane (no opening), as well zero friction is prescribed on the numerical faults. For the fault-end patches at the edge of the model (magenta, Figure 12), I apply 0.25 mm slip.

Comparing the slip in the x-direction along the restraining bend at the surface of the models helps determine which of the four varying coupling models best simulates the analog experiment (Figure 13). The slip in the x-direction, from the numerical model, is calculated from the strike-slip along the surface trace of the fault and from the fault strike. In the analog experiment, the slip in the x-direction along the faults is calculated from the change in displacement across the fault. In the analog experiment at the edges of the measured region the fault has 0.22 mm of slip and decreases to about 0.12 mm within the restraining bend. The fault slip from the analog experiment does not extend from -25 cm to 25 cm along the x-axis because the camera cannot capture the entire region of the claybox experiment.
Figure 1.13 Incremental slip from four decoupling basal plates

Slip in the x-direction distribution for four variations of decoupling basal plates compared to the physical experiment (black line). The dashed lines outline the region of the restraining bend where fault slip decreases. The fully decoupled plate provides the closest match to observations and will be used in subsequent models.

The incremental slip in the x-direction from the coupled model (green line) is larger than the applied displacement (0.25 mm) and decreases to 0.248 mm along the bend. For the fully coupled plate, the slip away from the bend is initially larger than applied displacement even after applying two successive iterations of the boundary conditions in order to reduce the range in plate displacement.

Figure 14 compares the incremental slip for three models in which two of the models include the calculated slip for each element. The first model (black line) is from applying uniform slip along the moving boundary and thus has the largest displacement gradient, the second model (red line) is after one iteration so that a calculated slip is prescribed to each element, and the third model (green line) is after a second iteration and thus the plate displacement gradient is minimized.

While applying a calculated prescribed slip for each element for a coupled model decreases the slip to be nearer to 0.25 mm, the coupled model with these boundary conditions do not produce reliable results.
Figure 1.14 Incremental slip for each successive iteration

Comparing incremental slip in the x-direction along the trace of the fault at snapshot $d_1$ for a coupled model. The black line is surface slip when applying uniform slip along the moving boundary. The red line is the surface slip after applying a calculated prescribed slip for each element to minimize the range in plate displacement. The green line is the surface slip from a coupled model after a second iteration.

While the coupled model produces slip along the fault that is larger than the applied displacement, in the fully decoupled model (red line, Figure 13) the fault slip decreases from 0.25 mm to 0.17 mm. For all four numerical models with varying degrees of coupling of the plate, the incremental slip distribution within the bend does not match the slip observed in the analog experiment. However, as the area of decoupling increases, the slip within the bend decreases and better matches the observations. The simulations of a decoupled plate captures the effects of less displacement that is observed at the surface of the analog experiment shown earlier from Figure 11. The relatively good fit of the decoupled numerical model suggests that the clay is decoupled from the plate in the physical experiments.
The difference in slip from the numerical model to the analog experiment may be due to the rheology. The linear elastic behavior in the numerical model allows the fault to be more efficient than the kaolin viscoelastic material used in the analog experiments. The viscous rheology of the kaolin allows stresses to dissipate by flow within the clay and produce greater off-fault deformation than the elastic numerical model.

1.4.5.2 Calibrating fault geometry from uplift patterns

Laser scans can determine the fault dip from the analog experiment, but the growing fault above the moving plate is distorted and therefore the fault dip is unclear. To determine the dip of the active faults that best simulates the claybox, two numerical models simulate $d_5$ with different fault geometries of the fault above the moving plate. One model includes a fault that is continuously vertical and a second model includes a vertical fault that transitions to a 60° dip near the left tip of the fault. A 60° dip for the left end of the fault above the moving plate may provide a smaller uplift than the 30° dipping fault above the stationary plate.

In the analog experiment, the uplift accumulates 5 mm of plate displacement (Figure 15c) while the numerical models accumulate uplift over 0.25 mm displacement (Figure 15a,b). While photographs are taken every 0.25 mm plate displacement during the claybox experiment, the stereopair analysis is from an increment of 5 mm plate displacement to resolve the change in uplift.

Although the analog experiment and numerical model captures different increments of uplift, the ratio of maximum uplift to plate displacement for the analog experiment is 0.36 (1.8mm/5mm) while for the numerical model the ratio
is significantly smaller, 0.14 (0.035 mm/0.25 mm). Suggesting that the rate of uplift to plate displacement from the numerical model does not scale to the analog experiment. Therefore I compare uplift patterns rather than incremental uplift values to determine the active fault geometry.

From the analog experiment at $d_5$, the majority of uplift is above the stationary plate and the highest region of uplift is towards the right side of the uplifted region (Figure 15c). Towards the right, the fault transitions from a vertical fault to a dipping 30° fault where uplift is greatest in that region. In the analog experiment, the uplift region above the moving plate is not as elevated as the uplift above the stationary plate. Above the moving plate, uplift is greatest towards the left edge of the bend. If the uplift correlates to the fault dip, then I can infer that the fault over the moving plate dips toward the stationary plate at its left most extent. The model with active fault above the moving plate that transitions from vertical to 60° dip at left edge of the fault (Figure 15b) shows greater uplift near the left end of the fault than the model with the vertical fault (Figure 15a). The greater uplift pattern from Figure 15b is more similar to the uplift from the analog experiment suggesting that the model of a fault with variable dip is a reliable representation for the analog experiment.

The numerical models share similarities and differences from the analog experiment. The numerical model is successful in simulating maximum uplift above the stationary plate towards the right edge. While outside the region of the bend, small uplift develops in the numerical model and in the analog experiment elevation is zero outside the region of the bend.
Figure 1.15 Comparison of uplift at stage 5

Two models of $d_5$ with different fault geometries, one model a) includes a vertical fault above the moving plate the other model b) includes a vertical fault that transitions into a dipping fault at the right end of fault. Comparisons of uplift patterns for these models with the uplift patterns from the c) analog experiment suggests that the dipping fault model better fits the observations.
1.5 Results

1.5.1 Uplift for five stages of fault growth

I compare incremental uplift patterns from the numerical model to the analog experiment at the five stages of deformation (Figure 16). At $d_1$ (Figure 16a), the numerical model is successful in modeling a region of uplift around the outer kinks of the bend and simulates the pattern of small uplift away from the bend and no uplift above the stationary plate near the left-most fault and above the moving plate near the right-most of the fault. For the analog experiment a larger region of uplift is present above the stationary plate towards the right end of the bend compared to the region of uplift on the left end of the bend above the moving plate the asymmetry is from the moving plate overriding the stationary plate which promotes a higher concentration of stress above the stationary plate (Hatem et al., 2015). Simulating this effect is difficult in Poly3D because the plates are level with each other.

The incremental uplift at $d_3$ in the analog experiment (Figure 16c) shows a sharp gradient of uplift above the stationary plate that extends further from the uplift in the numerical model. In the numerical model and the analog experiment, the uplift is bounded by the growing faults. For example the model of active faults above the stationary plate at later stages such as $d_4$ (Figure 16d) or $d_5$ (Figure 16e) show a similar uplift pattern to the analog experiment where a sharp gradient of uplift extends along the length of both faults above the stationary and moving plate. The lack of a sharp gradient of uplift at $d_3$ in the numerical model observed in the analog experiment, suggests that the fault above the stationary
plate may be below the surface of the clay and extend further than the visible surface trace. This blind fault propagating upward from the base of the clay would produce uplift before the trace propagates to the surface. Therefore the uplift patterns show that in this analog experiment the fault above the stationary plate initiates at depth and as the oblique-slip fault propagates towards the surface, the surface is uplifted before the fault reaches the surface.

Figure 1.16 Uplift at five stages of fault growth
The normalized incremental uplift patterns from the numerical model and from the analog experiment at stage a) d₁, b) d₂, c) d₃, d) d₄, and e) d₅.
1.5.2 Incremental slip

To further compare the numerical models with the analog experiment, Figure 17 plots the total incremental slip in the x-direction at the surface of the claybox along all faults at the five stages of fault growth. For a numerical simulation at \( d_1 \), the incremental slip at the edge of the fault correlates well to the analog experiment, however, towards the bend the slip from the numerical model is greater suggesting that the fault within the numerical model accommodates slip more efficiently than the restraining bend of the claybox experiment. This also agrees with the uplift patterns observed in Figure 15 where the uplift rate in the analog experiment is larger than the uplift rate in the numerical model. Because the slip from the numerical model is larger, the numerical model underestimates the off fault deformation present in the claybox experiment and thus produces less uplift.

For later stages of deformation (Figure 17b-17e), the incremental slip in the x-direction is summed across all active faults. The numerical simulation of \( d_2 \) (Figure 17b) captures the sharp decrease in slip at \( x = -5 \) and \( x = 5 \) along the x-axis; however, similar to the simulation at \( d_1 \) the slip from the numerical model underestimates off fault deformation in the analog experiment. The incremental slip from the numerical model is consistently higher than the incremental slip from the analog experiment along the bend suggesting that the numerical model is more efficient for all 5 models simulating different stages of fault growth.
Figure 1.17 Incremental slip for five stages of fault growth

The incremental slip in the x-direction at the surface of the claybox from the analog model (black dotted line) is a good proxy for comparing with the incremental slip in the x-direction with the numerical models (red dotted line). Each model replicates a stage further along the experiment. The grey shaded region shows the region of the restraining bend.
1.5.3 Kinematic efficiency compared with external work

To further compare the deformation from the numerical model with the experimental data, I compare the kinematic efficiency at the 5 stages of fault growth. Kinematic efficiency is calculated from the total incremental slip in the x-direction along the surface of all faults. From the analog experiment the kinematic efficiency is calculated from the surface slip that is confined by the region of the camera. To compare the kinematic efficiency with the numerical models, I calculate kinematic efficiency in the numerical model by only including surface slip that is within the same region of the claybox as obtained from the two cameras in the analog experiment.

From the analog experiment the maximum kinematic efficiency is at stage $d_2$ of fault growth. After stage $d_4$ the kinematic efficiency reaches a steady-state of about 0.72, showing that the kinematic efficiency of a restraining bend fault system reaches a steady-state as faults continue to grow (Figure 18a). The kinematic efficiency from numerical models show a successive increase with each stage of fault growth and reaches a steady-state in kinematic efficiency consistent with the data from the analog experiment. At stage $d_1$ kinematic efficiency from the numerical model is 11% greater than the fault system from the analog experiment. For each stage of fault growth, the fault system from the numerical models are increasingly more efficient than the fault system from analog experiment. By stage $d_5$ the fault system from the numerical model is 18% more efficient than from the analog experiment (Table 1). In the numerical model, the kinematic efficiency reaches a steady-state of about 0.9 while for the
analog experiment the kinematic efficiency reaches a steady state of about 0.72. A higher kinematic efficiency from the numerical models agrees with the previous conclusions that the numerical model has less off fault deformation than the analog experiment.

Figure 1.18 Kinematic efficiency and external work
A) I compare the kinematic efficiency from the numerical models with the analog experiment. The blue diamond shapes are the kinematic efficiency at each stage of fault growth from the analog experiment ranging 0 – 80 mm plate displacement. The black dots are the kinematic efficiency for the entire duration of the experiment. B) The second figure is the calculated external work (J) from every numerical model.

From the numerical models I calculate the external work for each stage of fault growth and compare the external work with the kinematic efficiency (Figure 18b). The external work is calculated from the stresses and strains along the boundaries with applied displacement. The external work agrees with the kinematic efficiency from the numerical and analog in that as the fault system
becomes more efficient with each stage of fault growth, the boundaries with applied displacement uses less external work. At \( d_1 \) the external work from the numerical model is 82.1 \( \mu \)J and decreases to 81.2 \( \mu \)J by stage \( d_5 \). The calculated external work from the numerical models is consistent with the analog experiment in that the fault system reaches a steady-state as faults continue to grow. The external work from the numerical models decreases by 1\% from \( d_1 \) to \( d_5 \) while the kinematic efficiency from the numerical models increases by 14\% from \( d_1 \) to \( d_5 \). The larger change in kinematic efficiency compared with the external work is because the external work is calculated for the entire fault system where as the calculated kinematic efficiency is only from surface slip. This suggests that at the surface of the model the fault is less efficient than near the base because the fault near the base is affected by the applied displacement from the plate than the fault near the surface.

<table>
<thead>
<tr>
<th></th>
<th>( d_1 )</th>
<th>( d_2 )</th>
<th>( d_3 )</th>
<th>( d_4 )</th>
<th>( d_5 )</th>
</tr>
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<tbody>
<tr>
<td><strong>kinematic efficiency</strong> (analog)</td>
<td>0.677</td>
<td>0.734</td>
<td>0.691</td>
<td>0.720</td>
<td>0.721</td>
</tr>
<tr>
<td><strong>kinematic efficiency</strong> (numerical)</td>
<td>0.787</td>
<td>0.839</td>
<td>0.853</td>
<td>0.874</td>
<td>0.909</td>
</tr>
<tr>
<td><strong>External work (( \mu )J)</strong></td>
<td>82.1</td>
<td>81.8</td>
<td>81.6</td>
<td>81.3</td>
<td>81.2</td>
</tr>
</tbody>
</table>

**Table 1.1 Kinematic efficiency and external work**

For each stage of fault growth (\( d_1, d_2, d_3, d_4, d_5 \)) the kinematic efficiency from the analog experiment and numerical models are calculated, as well as the external work from the numerical models.
1.5.4 Coulomb stress

Coulomb stress is a failure criterion used to predict crack growth (e.g., Hussain, M.A. et al., 1974; Du and Aydin, 1993; Lawn, 1993; Lockner and David, 1995; Olson and Cooke, 2005). Because Poly3D computes stresses, numerical claybox models can be useful to predict fault growth by solving for coulomb stress. In a 15° analog experiment, a new obliquely dipping fault initiates and propagates above the stationary plate and a new vertical fault initiates and propagates above the moving plate. From the five stages of deformation that are modeled, I calculate coulomb stress to investigate whether areas of high coulomb stress correlate with regions of fault growth in the analog experiment (Figure 19). At $d_1$, high coulomb stress is concentrated around the kinks of the bend similar to where faults grow in the next stage of the experiment, predicting that a fault may grow from both ends of the bend (Figure 19a). While faults do propagate from either end of the bend within the analog experiment, the first fault initiates above the stationary plate due to the increased stresses from the overriding moving plate. The high regions of coulomb stress of the numerical model do not indicate preference for one side or to the other.

At $d_2$ (Figure 19b) high lobes of coulomb stress are present near the tips of the propagating faults (black solid line) and within the regions where faults will propagate (black dashed line). With fault growth from $d_2$, the coulomb stress decreases near the kinks from $d_1$ but is still present showing that the region can potentially grow new faults from the kinks. As the faults grow in later stages (Figure 19d) the coulomb stress near the kinks decrease and the potential for a new propagating fault to initiate at the kinks is eliminated.
From stages $d_1$ to $d_4$, the coulomb stress above the moving plate decreases towards the left of the bend. By stage $d_4$ (Figure 19d) the region of coulomb stress above the moving plate does not connect to the strike-slip fault towards the left of the bend showing that the fault above the moving plate will not continue to propagate. This is consistent with the analog experiment, where the fault above the moving plate does not link to the restraining bend by the end of the experiment.

In $d_3$ (Figure 19c) the coulomb stress is localized around the fault tips and accurately predicts fault growth for the fault above the moving plate. However above the stationary plate, the region of coulomb stress, within the traced white line, barely observes the fault path in later stages of the experiment (black dashed line). Observations from uplift patterns at $d_3$ suggest that the propagating fault above the stationary plate is present below the surface in the analog experiment, which is exposed at later stages. While the highest region of coulomb stress is not within the region of fault growth for later stages, coulomb stress is present within the region where the fault grows (black dashed line). Showing that the propagating fault can be located further along the stationary plate at depth as the coulomb stress indicates a region of failure.
Figure 1.19 Coulomb stress at five stages of fault growth

Map view of high regions of coulomb stress indicate potential fault growth at the surface from a numerical a) model at $d_1$, b) model at $d_2$, c) model at $d_3$, and d) model at $d_4$. The black solid line indicates the fault present in the model while the black dashed line indicates where the fault will grow for the next model. At each stage of fault propagation, the high coulomb stress develops in regions where the fault will grow. The exception is for c) where the lobe of coulomb stress (traced by the white line) above the stationary plate barely intersects with the location of the fault at $d_4$. 
To further investigate whether faults propagate at depth, I compare the coulomb stress distribution at stage $d_3$ (Figure 20) a) at the surface of the numerical model, b) at 1 cm in depth, and c) at 2 cm in depth. At lower depths within the model, the region of high coulomb stress is present. At 1 cm depth (Figure 20b), the region of coulomb stress of 1 MPa surrounds the bend. The higher region of coulomb stress (2 MPa) is similar to at the surface in that the region of high coulomb stress is present near the tips of the fault. Above the stationary plate in Figure 20b the region of high coulomb stress is not located near the fault tip at the surface (black line) because the growing fault above the stationary plate dips towards the positive y-direction and propagates towards the bend at depth. The white line indicates the location of the fault at 1 cm. At 2 cm depth (Figure 20c), the coulomb stress is largest at the fault tips and around the bend. The high coulomb stress around the bend is most likely an artifact because shear stress at 2 cm is low around the bend and largest around the tips of the fault. The higher regions of coulomb stress present at depth demonstrate that faults can propagate at depth during the analog experiment.
**Figure 1.20 Coulomb stress at depth**

In map view, the distribution of coulomb stress at stage $d_3$ at a) the surface of the model, b) at 1 cm of depth, and c) at 2 cm of depth where the total depth of the model is 2.5 cm. The white line in b) shows where the fault is located at depth 1 cm and in c) where the fault is located at depth 2 cm.

### 1.6 Discussion

Simulating a restraining bend from numerical models and analog claybox experiments is beneficial for gaining insight into the mechanics of a restraining bend. The numerical models of the claybox experiment show that a restraining bend fault system becomes more efficient and the external work is minimized with fault growth. Observations of fault growth from the analog experiment are similarly observed from restraining bend fault systems found in the Earth’s crust such as that the southern San Andreas fault (Matti and Mortin, 1993), the Lebanon fault (Gomez et al., 2007), and the Akato Tagh fault (Cowgill et al., 2004). Before an analog experiment is simulated, the shear strength of the wet
kaolin clay is scaled to the Earth’s crust so that the claybox experiment accurately simulates crustal deformation. While scaling of the clay makes a good proxy for simulating fault growth, it is unclear whether the timespan of fault growth within the analog experiment correlates to a timespan observed in the crust. To determine this, I compare the timing of fault growth along the southern San Andreas fault with the timing of fault growth in the analog experiment.

The plate velocity from the analog experiment is 0.5 mm/min and the plate velocity from the North American plate is 45 – 50 mm/yr (Fialko, 2006). The height of the claybox is 2.5 cm, which corresponds to 1.9 km – 3.5 km from the Earth’s crust (Cooke and Dair, 2012, Hatem et al., 2015). The analog experiment from this study runs for a time length that spans 3 hours and 20 minutes simulating 152,000 – 311,000 years of deformation within the Earth’s crust. From the 15° restraining bend experiment, a fault initiates from both kinks of the bend at about 16 mm plate displacement corresponding to 26,000 – 62,000 years of fault slip. The growing fault above the stationary plate links to the strike-slip fault at 27 mm displacement corresponding to 41,000 – 84,000 years and the fault above the moving plate completes propagation at about 78 mm displacement corresponding to 118,000 – 242,000 years. The total duration of fault growth ranges from 15,000 - 22,000 years above the moving plate and 92,000 – 180,000 above the stationary plate. The fault above the stationary plate initiates first and grows at a faster rate than the growing fault above the moving plate because the moving steel plate overrides the stationary steel plate. Hatem et al. 2015 shows that the initial fault consistently grows above the underriding plate in the analog
claybox experiments due to the irregularities present above the underriding plate causing a stress concentration promoting fault growth.

The present day fault geometry of the San Gorgonio Pass region includes the Garnet Hill strand. The Garnet hill strand is a fault strand that grows from the left-stepping restraining bend along the southern San Andreas fault and links to the bend. The evolution of the Garnet Hill strand has developed in the last 120,000 years. This timespan is within the range of timing of fault growth that is observed in the analog experiment.

The discrepancies from the numerical model with the analog experiment occur due to the contrast in rheology. To ensure which simulation best mimics crustal deformation; I consider the kinematic efficiency and uplift rate. The linear elastic numerical models consistently simulate less deformation than observed from the viscoelastic wet kaolin claybox experiment. The southern San Andreas fault slips 16 mm/yr (Keller, 1982) and accommodates 32% – 35% of plate motion therefore the southern San Andreas fault is 68-65% efficient. The numerical models simulated a restraining bend fault system that is 79 – 90% kinematically efficient, while the analog experiment simulated a fault system that is 68% - 72% kinematically efficient. The lower kinematic efficiency observed in the analog experiment is a more accurate representation of the southern San Andreas fault. As well, Hatem et al. 2015 simulated the Denali fault in Alaska with a claybox experiment and successfully simulated uplift that mimics the uplift present in Alaska formed by the Denali fault. The analog experiment has a higher uplift rate than the uplift rate from the numerical model by 0.22 mm/min. Because
the uplift from the analog experiment agrees with uplift in the crust, and the calculated kinematic efficiency from the analog experiment is reasonable to the efficiency calculated in crustal fault systems, the analog experiment better accurately simulates the crust than the numerical models. Simulating a numerical model that captures the deformation present in the analog experiment will as well capture the deformation observed in the crust.

1.7 Summary

I numerically simulate five stages of fault growth from an analog experiment of a 15° restraining bend. This approach provides a detail calibration, which includes a method for achieving a uniform plate displacement by applying successive iterations of the boundary conditions. Two iterations, reduces the range of displacement from +- 0.012 mm to +-0.004 mm. Calculating the required slip for each element along a boundary may be useful for other numerical models that use Poly3D such as simulations of crustal deformation. The calibration process as well includes simulating two numerical models with a coarser element length of 1 cm and a finer element length of 0.66 cm. The model with element length of 1 cm provides similar results to the model with a mesh of 0.66. The model with a finer mesh produces elements that contribute to a larger error. Therefore I use an element length of 1 cm for accurate results and I determine the error of the model to be < 3 %.

I also take into account the decoupling of the clay from the base plate. I simulate 4 models with varying regions of coupling and compare surface incremental slip in the x-direction from the numerical models with the analog
experiment for a model at $d_1$. When decreasing the effect of coupling, the incremental slip from the numerical model decreases towards the bend and better matches the slip from the analog experiment. While the fully decoupled region best simulates the analog experiment, the off-fault deformation present in the analog experiment cannot be completely simulated due to the rheology contrast of the viscoelastic clay and linear elastic material in Poly3D.

I compare uplift patterns, incremental slip in the x-direction, and kinematic efficiency from the numerical model with the analog experiment. Uplift patterns from stage $d_3$ show that a sharp uplift gradient above the stationary plate prior to observations of a fault trace at the surface. This suggests that the fault above the stationary plate grows from depth. Uplift is also used to help determine the dip of a fault. The dip of the growing fault above the moving plate is unclear, therefore I simulate two models in which one model includes a fault above the moving plate that is continuously vertical and a second model that includes a fault above the moving plate that is initially vertical and transitions to a 60° dipping fault towards the propagating tip. The model with a fault that dips at the tip of the fault shows a more consistent uplift pattern with the analog experiment than the uplift from the model with a continuously vertical fault.

For all five stages of fault growth, the incremental slip from the numerical model is higher than the incremental slip from the analog experiment, as well, the numerical models continue to be more kinematically efficient than the analog experiment. At $d_1$, the numerical model has a kinematic efficiency of 0.76 and the analog experiment has a kinematic efficiency of 0.67. In the numerical model, the
calculated external work shows that as faults grow to be more efficient, the external work in the system decreases as expected. The external work reaches a steady-state similar to the kinematic efficiency showing that the external work is constant in later stages of fault growth.

The numerical models provide the stress component to determine the coulomb stress, which predicts fault growth from the analog experiment. High lobes of coulomb stress are present in regions where faults grow in later stages of deformation. At stage d3, the coulomb stress indicates that the region where a fault may be growing at depth is in failure and thus agrees with the observations made from the uplift patterns.

Due to the constraint of obtaining only surface displacements in the analog claybox experiment, numerical models of analog experiments are beneficial. While using Poly3D is useful in numerically modeling complex fault systems, the rheology of the linear elastic model inhibits the accuracy of simulating off-fault deformation that is present in the analog experiment. To further numerically simulate analog claybox experiments, incorporating a modeling software that captures the viscoelastic rheology from the wet kaolin clay may provide another approach that may be more consistent with the slip and uplift rates from the analog experiment.
1.8 References


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CHAPTER 2
CALCULATING ABSOLUTE STRESS IN THE SAN GORGONIO PASS REGION THAT INCORPORATES FAULT INTERACTION

Aviel Stern, Michele Cooke, and Jennifer Beyer

2.1 Abstract

In order to incorporate fault interaction into estimates of absolute stresses along the southern San Andreas fault, we use a three-dimensional quasi-static mechanical model, Poly3D, to simulate both the stresses over multiple earthquake cycles and the interseismic loading of the fault system using deep slip rates determined from the multi-cycle model. To estimate the absolute shear tractions along the faults, we assume complete coseismic shear stress drop and then use the time since the last ground-rupturing event from the paleoseismic record for each segment and the stressing rates from the interseismic model. For the normal tractions, the distribution of normal stressing rates from the multi-cycle model will be scaled for the dynamic rupture models to provide ripe conditions for earthquake rupture initiation. We compare our interseismic stressing rates to shear tractions resolved from a uniform remote stress tensor used in the dynamic rupture models. Shear stressing rates from the interseismic model differ from the resolved shear tractions indicating that fault interaction within the quasi-static impacts the stress distribution. We also simulate the 1992 Landers earthquake in order to assess the impact of this rupture on the stress distribution. Calculated absolute shear stress from the Landers earthquake rupture differs from the absolute shear stress from a model without the impact of the Landers earthquake by < 10%. Consequently, including nearby earthquake
ruptures varies the distribution of stresses and may provide a more accurate stress distribution along the San Andreas fault. We conclude that incorporating fault interaction, time since last earthquake, and nearby earthquake ruptures in the stress distribution along faults influences fault tractions that may improve accuracy in dynamic rupture models earthquake simulations.

2.2 Introduction

The San Andreas fault is a multi-segmented strike-slip fault system where distribution of stress depends on tectonic loading and interaction among nearby active faults. The principal stresses can reorient due to nearby earthquake ruptures and evolution of faults such as the presence of new growing faults and dip rotation of current faults (e.g. Harris and Simpson, 1992). Complex fault geometries such as compressional bends where fault strike diverges from plate motion can produce local reductions in shear stress within the bend accompanied with increased local compression, which suppresses strike-slip. Physical experiments show such strike-slip reductions within the restraining bends (Cooke et al., 2014; Hatem and Cooke, 2015; Chapter 1). Furthermore, dynamic rupture models show that strike-slip restraining bends can act as a barrier to earthquake propagation (Harris, 2004, Kase and Kuge, 2001, Oglesby, 2005). Compilations of earthquake rupture across releasing and restraining step overs show that while fault geometry has a first-order effect on the ability for ruptures to pass through restraining steps, the data shows significant scatter (e.g. Wesnousky, 2006). The ability for a rupture to pass through restraining bends may depend on fault geometry and also on the stress state along the
restraining bend (e.g. Nielson and Olsen, 2000; Harris et al., 2002 Kame et al., 2003; Duan and Oglesby, 2005; Kase and Day, 2006; Lozos et al., 2011).

Along the southern San Andreas fault (sSAF), a left stepping bend, known as the San Gorgonio Pass region (SPGr), is located along the southwestern edge of the San Bernardino Mountains. The active faults of the SAF that make up the bend are the San Bernardino strand, Banning strand, the Garnet Hill strand, the San Gorgonio Pass thrust, and the Mission Creek strand, and the Coachella segment of the SAF (Figure 1). The San Bernardino strand intersects the San Gorgonio Pass thrust north of the bend and the Coachella segment of the SAF intersects the Mission Creek and Banning strands south of the bend (Figure 1). Recent paleoseismic data within the SGPr suggest that previous large earthquakes have a recurrence interval of 700 - 1000 years, with the most recent earthquake rupture through the San Gorgonio Pass region occurring in 1400 AD (Yule et al., 2014). Earthquakes along the San Bernardino strand (north of the bend) and Coachella segment (south of the bend) occur more frequently with recurrence intervals of 100 - 200 years (e.g. Field, E.H. et al., 2013). The lack of paleoseismic evidence for ground rupturing earthquakes in the San Gorgonio pass within the past 1400 years suggests that previous earthquakes that have ruptured along the San Bernardino and Coachella segment terminated at the restraining bend. While paleoseismic data provides time estimates on earthquake ruptures, it does not provide information about the rupture path. Therefore it is unclear whether the 1400 AD event, a through-going rupture, initiated within or outside of the restraining bend.
The capability for an earthquake to rupture through multiple fault segments and through complex fault geometries became evident from the 2012 Mw 8.6 Indian Ocean earthquake. The earthquake ruptured 4 subparallel and conjugate strike-slip faults 100 – 200 km west from the Sumatra subduction zone in less than 200 seconds and the seismicity extended 10,000 – 20,000 km from the epicenter (Pollitz et al., 2012, Yue et al. 2012). Although dynamic rupture models show that segmented fault systems with a bend more readily terminate rupture at the bend rather than promote a through-going rupture (e.i. Kase and Kuge (2001), Sibson, 1986), predicting the capability for the extent of an earthquake rupture path along a multi-segmented fault system such as the restraining bend of the southern San Andreas fault will give insight into the earthquake hazard for the Los Angeles region.

Figure 2.1 Map view of San Gorgonio Pass region
Map of the southern San Andreas fault shows the left-stepping restraining bend south of the San Bernardino Mountains. The San Bernardino strand, Coachella segment, Banning strand, Garnet Hill strand, Mission Creek strand, and San Gorgonio Pass thrust make up the San Gorgonio Pass region (SGPr) of the San Andreas fault.
To simulate earthquake events, dynamic rupture models require fault geometry, initial shear and normal tractions on faults, the material properties surrounding the fault, and friction laws (e.g. Harris, 2004). The models typically prescribe initial shear and normal stresses by resolving the remote stress tensor, constrained from focal mechanism inversions, onto individual fault elements (e.g. Dreger et al., 2004, Oglesby and Martin, 2012). This approach provides spatially variable stresses that capture the first-order loading of the faults, but does not take into account the interaction between faults. Not only can individual earthquake events change stresses along nearby faults (e.g. Stein, 1999; Duan and Oglesby, 2005), interaction among active faults influences the long-term slip rate and stressing rates on the faults (Hurd and Zoback, 2012; Maerten et al., 2000; Maerten et al., 1999; Willemse et al. 1998). The initial normal and shear stresses control the nature of rupture propagation (e.g. Lozos et al. 2015; Duan and Oglesby, 2005) so the better constraints on stress state along active faults will provide more accurate rupture simulations.

In order to account for fault interaction we simulate crustal deformation using forward models that provide stressing rates over both multiple earthquake cycles and between earthquake events. The interseismic shear stressing rates along with information about time since last earthquake event can be used to estimate absolute shear stress through the SGPr. Estimating shear stress from this approach differs from resolving remote stresses onto faults in that our models explicitly include fault interaction. The normal stress distribution is constrained from the multi-cycle models to show the long-term interaction
between different fault strands and the magnitudes are scaled to provide ripe conditions for earthquake genesis. Such conditions are consistent with the region being late in the earthquake cycle as the time since last event on nearly all fault strands of the southern San Andreas exceeds the recurrence interval (Field et al., 2013). Using stress values that incorporate fault interaction may enhance the accuracy of dynamic rupture models. We hope that by using a numerical model for estimating absolute shear stress and normal stress distribution, dynamic rupture models of David Oglesby from University of California, Riverside will utilize our stresses that incorporate fault interaction and time since last rupture to gain insight into the nature of earthquake rupture propagation due to stress accumulation along the San Gorgonio Pass region.

2.3 Methods

To calculate stressing rates, we use Poly3D, a quasi-static linear elastic Boundary Element Method code, to simulate deformation along the southern San Andreas Fault system. Poly3D discretizes the boundaries and faults into triangular elements with constant displacement discontinuity and uses continuum mechanics to calculate for stresses, and displacements throughout the model. Poly3D is beneficial in that it uses a triangulated mesh to model complicated 3D geometries. Our models simulate the active fault geometry of the southern San Andreas fault in California, the San Jacinto fault and Eastern California Shear Zone based on the Community Fault model version 4.0 (CFM) with modifications from Cooke and Dair (2011), Herbert and Cooke (2012), Herbert et al. (2014), and Fattaruso (2014). The results from these models match geologic strike slip-
rates within the San Gorgonio Pass region and Eastern California Shear Zone (Cooke and Dair, 2011, Herbert et al., 2012; Herbert et al., 2014) and match uplift patterns within the San Bernardino Mountains and Coachella Valley (Cooke and Dair, 2011; Fattaruso et al., 2014). The good match of the model results and geologic data serves to validate the models. While the homogenous and elastic models do not incorporate the spatially variable and non-linear host rock rheology of the region, the complex fault geometries used in the model adequately capture the behavior of the southern San Andreas fault.

We use a two-step modeling approach to estimate the stressing rates along the southern San Andreas fault. The first model simulates deformation over many earthquake cycles providing slip-rate information to an interseismic model that simulates the stress build up between earthquakes. In the multiple earthquake model, tectonic loading is prescribed at the boundaries while leaving the faults in the system free to slip in response to both tectonic loading and fault interaction (Figure 2). Uncertainties in the tectonic loading are considered by testing four models with a range in plate velocity from 45 mm/yr to 50 mm/yr and a range in plate motion orientation from 320° to 325° following Herbert and Cooke (2012). This range in plate motion and velocity produce strike-slip rates that vary up to 1.8 mm/yr along the six active faults that comprise the SAF within the San Gorgonio Pass region.

The distribution of strike-slip rates from the four multi-cycle models are prescribed to fault surfaces below 25 km within the interseismic model where faults are locked above 25 km depth. This condition simulates the deep
deformation that occurs between earthquake events. The depth of 25 km ensures that we produce reliable fault stress to about 20 km depth that can be used within the dynamic rupture models of our University of California, Riverside collaborators. Because the locking depth produces an abrupt transition from locked to slipping, stresses within 5 km of this transition are unreliable because the crust likely has a more gradual transition in fault behavior. In order to analyze the shear and normal stressing rates and calculate absolute stress from the range of variable tectonic loading, we use the mean stressing rates from the four multi-scale and interseismic models.

Figure 2.2 Model setup of the southern San Andreas fault
A schematic drawing of the fault geometry based on the Southern California Earthquake Center CFM. Tectonic loading is prescribed on the edges of the basal plates, while letting the rest of the faults slip freely in response to fault interaction and loading.
The interseismic model determines stressing rates due to deep movement along active faults, which are used to calculate absolute shear stress along San Bernardino strand, Banning strand, Garnet Hill strand, San Gorgonio Pass thrust, Mission Creek strand and the Coachella segment of the SAF. To estimate absolute shear tractions on the fault, we assume complete coseismic stress drop and use the stressing rate information from the interseismic model and time since the last earthquake for each fault in manner similar to that used by Smith-Konter and Sandwell (2009). In this approach, only large ground surface rupturing events that are likely to be preserved in the paleoseismic record are considered. The calculations of absolute shear tractions rely on the assumption that a complete shear stress drop occurs during these ground-rupturing events (Figure 3A/3C).

**Figure 2.3 Three shear stress evolution scenarios**

A) A simplified version where only large earthquakes, such as those that would produce ground surface rupture, are considered. Stress drop, $\Delta t$, is the same between each earthquake. B) Hypothetical shear stress evolution over several earthquake events. The time between two earthquakes differs, and stress drop differs with each earthquake. C) A simplified version from B) where the recurrence interval differs between earthquakes while the shear stress drop is complete after each earthquake. We use this simplified representative model to calculate absolute shear stress with consideration that only large ground rupturing events will be detected in the paleoseismic record.
Complete stress drop for each earthquake is consistent with recent field measurements of low temperatures along a ruptured fault surface after a large earthquake, a result of a very low dynamic friction (e.g. Carpenter, 2012, Fulton et al., 2013, Li et al., 2015). The associate shear stress at any time in the earthquake cycle is

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

(1)

where \( \tau \) is the absolute shear stress, \( \dot{\tau} \) is the shear stressing rate and \( t \) is time since last event. While we use this assumption to estimate absolute shear stress, we acknowledge that the shear stress evolution over several earthquake events is much more complex (e.g. Matthews et al. 2002; Ellsworth et al. 1999; Molnar, 1979) and not all events have complete stress drop (Figure 3B). While the approach to calculate absolute stress is simplified, the distribution of shear stresses may affect dynamic rupture models and may provide more accurate initial conditions than resolving the remove loading onto the faults.

2.4 Normal Stressing Rates

Unlike shear stresses, which can be relieved with earthquake ruptures, normal tractions on the fault surfaces may accumulate both during the interseismic period between earthquakes and across multiple earthquake cycles. We examine the normal stressing rates along the faults from both the interseismic and multi-cycle models to provide insight into the accumulation of normal stresses at different time scales. The results presented here do not consider lithostatic loading, which can be superposed on the tectonic stressing patterns.
Figure 2.4 The interseismic normal stressing rates along the SGPr

Normal stressing rates along the San Andreas fault south from Cajon Pass. A) Map trace of active strands of the southern San Andreas fault through the SGPr. The grey shaded region shows the extent of the restraining bend. B) Interseismic normal stressing rate where saturation of the symbol fill indicates the magnitude of the stressing rate. Tension is positive so that the blue and red filled dots show compressive and tensile stressing rates respectively. The black curve is the running average interseismic normal stressing rates along the San Andreas fault. The interseismic normal stressing rates are predominantly compressive, within the restraining bend.

During the interseismic period, we expect compressional stresses (negative in this study) to accrue along the restraining bend of the San Gorgonio Pass region. Figure 4 shows that the interseismic normal stressing rates along the San Andreas fault surfaces within the San Gorgonio Pass ranging from -4.6 kPa/yr to 1.4 kPa/yr. The overall compressive interseismic stressing rate is consistent with local transpression of the San Andreas fault within the restraining bend.
The three-dimensional distribution of interseismic normal stressing rates in Figure 5A shows that compressive stressing rates increase towards the bend and largest along the San Gorgonio Pass thrust. Local regions of tensile stressing rates arise within regions of complex fault intersections (Figure 5A). Such tensile stressing rates develop 1) along the southern end of the San Bernardino strand where this fault intersects the San Gorgonio Pass thrust, 2) along the southern end of the Banning strand of the SAF where this fault intersects the Coachella segment of the SAF, and 3) along the southern end of the Garnet Hill strand of the SAF. The combination of deep reverse slip along the San Gorgonio Pass thrust and increased rate of right-lateral slip northward from the southern tip of the San Bernardino strand of the SAF produce tensile stresses along the southern end of this fault (region 1 on Figure 5). The regions marked 2 and 3 on Figure 5A develop tensile stressing rates slip along the Garnet Hill and Banning strands near where these faults intersect the Coachella segment where the interaction of these three faults pulls regions of the faults into tension. The tensile stressing rates at locations 2 and 3 are close to the application of deep slip that drives this tension.

The models of multiple earthquake cycles allow slip at all depths along the fault surfaces and the first order distribution of normal stresses is similar to the interseismic pattern. Compressive stresses are greatest within the restraining bend along the San Gorgonio Pass thrust and the Garnet Hill strand of the SAF. Because small variations of fault geometry have a large impact on local normal stressing rate, the multi-cycle normal stressing rates have been smoothed to
remove the local influence of small changes in element orientation. The non-zero value of the normal stressing rates along the faults confirms that, the compression that accumulates between earthquakes within the restraining bend is not relieved from earthquake events.

Figure 2.5 The normal stressing rates along the SGPr
The distribution of normal stressing rates along the southern San Andreas fault within the San Gorgonio Pass region from the A) interseismic model and B) multi-cycle model. Tensile stressing rates are positive. SGPT = San Gorgonio Pass thrust. GH = Garnet Hill strand of the SAF. Most of the restraining bend experiences compressive loading between earthquakes except for small regions of tensile stressing rates near complex intersections of the fault strands. The normal stressing pattern across multiple earthquake cycles shows the strong influence of fault geometry to produce local variations in tension and compression.
The results from the multiple earthquake cycle model show that slip events may strengthen tensile stressing rates at fault intersections. Regions of local tensile stressing rate due to fault interaction within the interseismic model (1-3 on Figure 5A) have even stronger tensile signal within the multi-cycle model. While the interseismic normal stresses rate pattern shows the influence of deep slip on the shallower fault surfaces, the multi-cycle model pattern reflects nearby slip along the fault elements. Consequently, tension at the intersection of the Garnet Hill and Banning strands with the Coachella segment of the SAF within the multi-cycle model are both stronger and occur at shallower depths on the fault surfaces than within the interseismic model (Regions 2 & 3 Figure 5). The concave shape of the faults to the west of this region (between locations 4 & 5) produce gradients in strike-slip rate that lead to local patches of tensile and compressive stressing rate.

The shallow fault slip within the multi-cycle model produces three additional regions of tensile stressing rate not evident in the deep-slip interseismic model (regions 4-6 Figure 5B). A region of tensile stressing rate develops along the San Bernardino strand of the SAF at location 4 in response to both a small change in strike of the fault and tension due to reverse slip along the San Gorgonio Pass thrust (Figure 5B). This thrusting along the SGPT unclamps the vertical San Bernardino strand that sits in the hanging wall of the thrust in a similar manner to the unclamping of strike-slip faults by shallow slip along subduction zones (e.g. ten Brink and Lin, 2004). Tensile stressing rates also develop along the San Gorgonio Pass thrust to the west of its intersection with
the San Bernardino strand of the SAF (‘5’ on Figure 4B). This band of tension that occurs at all depths develops in response to right-lateral slip along the San Bernardino strand. A similar mechanism of fault interaction accounts for the region with relatively high compression that develops east of the fault intersection. At location 6, a region of tensile stressing rate develops on the Coachella segment of the SAF south of its merger with the Garnet Hill and Banning strands due to strike-slip along those branches of the SAF system (Figure 5). This and the adjacent compressive stressing rate patch to the north are similar to the normal stress pattern around bends along slipping faults (e.g. Duan and Oglesby, 2005). All of these local regions of tensile stressing rate demonstrate the impact of interactions between active faults on normal stressing rates within the multi-cycle model. For systems with complex, curving and branching fault geometry the resulting distribution of normal stressing rates contains abundant variations. Some of the overall compressive stress within the restraining bend that accumulates due to local transpression between earthquakes is relieved by slip events but these same slip events produce locally high patches of tensile and compressive stressing rate and compressive stressing rate.

Three hypothetical scenarios demonstrate different types of normal stressing rate accumulation where the hypothetical stressing rates are plotted with a positive slope (Figure 6). For some regions of the fault system, the accumulated normal stress between earthquakes is partially reduced during slip events to produce multi-cycle normal stressing rates that are lower than the
interseismic rate (Figure 6A). In other areas of the fault system, the multi-cycle stressing rates have the opposite sign of the interseismic stressing rate due to the large changes in normal stress associated with earthquakes (Figure 6B). A third alternative is that the normal stressing rates over multiple earthquake cycles exceed that between earthquakes because the coseismic events increase the normal stress (Figure 6C). For the regions where the long-term geologic stressing rate is non-zero, deformation mechanisms along the faults and within the host rock must dissipate the normal stress within the crust. These mechanisms may include folding, fracturing, cleavage development, secondary faulting etc. (e.g. Bahat, 1980, Engelder, 1987, Savage and Cooke, 2003).

Figure 2.6 Normal stressing rates scenarios over several earthquakes

Three schematic diagrams show the rates of normal stressing over several earthquakes. A) Normal stresses can increase over time because not all of the accumulated normal stress is relieved with earthquakes. B) Normal stresses can decrease over time due to large drops in normal stresses associated with earthquake events. C) Normal stresses can increase over time if earthquake events increase the normal stress beyond the accumulated interseismic stress.

We map the three scenarios of normal stress accumulation outlined in Figure 6 onto the southern San Andreas fault through the San Gorgonio Pass region (Figure 7). The blue elements along the fault accumulate normal stresses at larger rates over multiple earthquake cycles than between earthquakes (corresponding to Figure 6C), the red elements along the fault accumulate...
normal stresses at larger rates between earthquakes than over multiple earthquake cycles due to coseismic unloading (corresponding to Figure 6A), and the green elements have opposing normal stress accumulation between earthquakes and over multiple earthquake cycles (corresponding to Figure 6B).

Most of the surfaces along the San Gorgonio Pass thrust and the Garnet Hill strand of the SAF show long term stressing rate that is lower than the interseismic rate (red on Figure 7). This suggests that earthquakes along the SAF fault system reduce the local compression along these faults. In contrast, small portions of the San Bernardino strand, Banning strand and Coachella segment of the SAF show regions were the multi-cycle stressing rate is higher than the interseismic stressing rate (blue on Figure 7) suggesting that slip events accentuate the local normal stresses. The regions in green along Figure 7 show where the multi-cycle stressing rates have opposite sign of the interseismic rates due to the strong influence of slip along nearby elements on normal stress.

**Figure 2.7 Location of non-zero normal stressing rates**

View to the northeast shows where normal stressing rates on San Andreas fault are larger over multiple earthquake cycles than between earthquakes (blue) and where normal stressing rates between earthquakes are larger than over multiple earthquake cycles (red). The green elements have opposing interseismic and multi-cycle normal stress accumulation rate (tension versus compression). SGPT = San Gorgonio Pass thrust. GH = Garnet Hill strand of the SAF.
For the dynamic rupture models, we want the distribution of normal stresses to be guided by the strong influence of nearby slip on normal stress. Because stress dissipation rates depend on the details of rock rheology (e.g. Moore et al., 2007, Marone and Scholz, 1988, Ikari et al., 2009) and fluid flow systems (Fulton et al., 2009; Byerlee, 1993; Sibson, 1994) that are unknown, we will use the distribution of normal stressing rate from the multicycle model to guide the pattern of normal stress. The values will be scaled and added to lithostatic stresses to ensure reasonable behavior rupture along the faults.

2.5 Strike-Shear Stressing Rates

Fault interaction redistributes both normal stresses and shear stresses along faults. Because shear stress drives slip along the faults, the impact of fault interaction can be revealed from distributions of fault slip rates. Figure 8 displays strike-slip rates (mm/yr) along the southern San Andreas fault and the San Jacinto fault (SJF). The San Bernardino strand and the Coachella segment of the SAF strike parallel to the modeled plate motion direction (approximately 320°) and have the largest strike-slip rates (~20 mm/yr). In contrast, the San Andreas fault within the restraining bend strikes obliquely to the plate velocity and has slower slip rate (0 - 5 mm/yr). This first-order pattern of slip rate along the SAF corresponds to the obliquity of each fault segment relative to the applied plate velocity. The secondary impact of fault interaction is evident in the difference in slip rate between the San Jacinto fault and Coachella segment of the SAF, which have similar strike. Resolution of the tectonic loading onto the faults would predict similar strike-slip rate for the San Jacinto fault and Coachella segment of
the SAF. The difference in strike-slip rates along these faults suggests that fault interaction affects stress distribution along faults.

![Map view of strike-slip rates](image)

**Figure 2.8 Map view of strike-slip rates**

Map view of strike-slip rates. Although the San Jacinto Fault (SJF) strikes similarly to the Coachella segment of the SAF, the SJF has slower strike-slip rates due to fault interaction.

Fault interaction is not considered in many dynamic rupture models where initial tractions along the faults are resolved from a uniform remote stress tensor. This approach does not consider local stress variations due to fault interaction. To further investigate the influence of fault interaction, we compare the interseismic shear stressing rates from our models with resolved tractions from a remote stress tensor used by our colleagues at the University of California, Riverside for their dynamic rupture models. The following stress tensor is used, where tension is positive, $x_2$ is parallel to the San Bernardino strand of the SAF and $x_3$ is vertical (Tarnowski, pers com).

$$
\begin{bmatrix}
-31 & -11 & 0 \\
-11 & -31 & 0 \\
0 & 0 & 53
\end{bmatrix}
$$
Since the maximum horizontal compression is oriented at 350˚, transforming this tensor to north-south reference frame (x₁ is East and x₂ is north) gives

\[
\begin{bmatrix}
-20.66 & -3.76 & 0 \\
-3.76 & -41.3 & 0 \\
0 & 0 & -53 \\
\end{bmatrix}
\]

Within our interseismic models, we expect maximum shear stressing rates where fault strike parallels the average plate motion of 322.5˚. To calculate shear stress we use the stress transformation equation

\[
\tau = \tau_{\text{max}} \sin 2\theta = 11 \sin 2\theta \text{ MPa}
\] (2)

where \(\tau\) is the strike-shear stress at a range of fault strike orientations, \(\theta\) is measured from the principal stresses, and \(\tau_{\text{max}}\) is the maximum shear stress determined as one half of the differential stress of the stress tensor in the x₁-x₂ plane. The interseismic shear stress will be zero at the surface and increase with depth on the fault to reach a maximum at 20 km near the deep interseismic loading of the fault system. We add a linear increase of shear stress with depth to Equation (2) and formulate, \(\theta\), the orientation relative to the principal stress, in terms of fault strike to get

\[
\tau = 11 \sin(2|305^\circ-\text{strike}| + 45^\circ)| \text{ d/20 MPa/km}
\] (3)

where \(d\) is depth in km and 305˚ is the orientation of maximum shear that is 45˚ from the principal stress orientation (350˚). This relationship of resolved shear stress and fault strike is plotted for in Figure 9 with deeper depths curves in warmer colors.
Figure 2.9 Strike-shear stressing and resolved shear stress

Strike-shear stressing rates versus fault strike of A) southern San Andreas fault and B) San Jacinto fault. Colors of symbol fill indicate depths of fault element and curves show the resolved shear stress scaled for linearly increasing depths. Shear stressing rates decrease away from the orientations of 305°-310° and increases with depth.

The interseismic right-lateral shear stressing rates and the resolved shear tractions along the San Andreas fault show maximum around 305°-315° with decreasing strike-shear stress as fault strike deviates from the orientation of maximum shear (Figure 9A). Fault elements that strike more westerly than 260° display left-lateral shear. Patches of left-lateral shear develop on the San Gorgonio Pass thrust. The resolved shear traction curves on Figure 9 are scaled to match the interseismic strike-shear stressing rates and show linearly increasing shear stress with depth. Small deviations of the interseismic strike-shear stressing rates from the linear increase of resolved shear traction with...
depth plotted indicate that the increase of modeled stressing rates with depth has some degree of non-linearity. The relatively small variation in strike-shear stressing rates along the San Jacinto fault owes to the small variation in fault strikes, which primarily parallel plate motion (Figure 9B).

The increase of strike-shear stressing rate with depth is less consistent for the San Jacinto fault than for the San Andreas fault. The strike-slip stresses along elements of the San Jacinto fault have lesser value than elements of equivalent depth and strike along the San Andreas fault. For example, the red symbols are close to the red curves on Figure 9A and fall below the red curve for the San Jacinto plot. This difference shows that resolving the strike-shear tractions from a uniform remote stress tensor will not provide the same distribution of shear stress as a model that considers fault interaction. We further demonstrate the difference in interseismic strike-shear stressing on similar striking portions of the San Andreas and San Jacinto faults by comparing the best-fitting surfaces through the data points between fault strikes of 290˚ and 320˚.
Figure 2.10 A gridded surface fit of right-lateral stressing rates

A gridded surface fit through the data points illustrates the different right-lateral stressing rates along the San Andreas fault (A) and San Jacinto fault (B). For similar fault strike and depth, the San Jacinto fault has lower stressing rates.

Figure 10 shows the strike-shear stressing rate with depth and strike for the two faults. For similar fault strike and depth, the San Jacinto fault has lower right-lateral shear stressing rates than the San Andreas fault. This difference in strike-shear stressing rates owes to the interaction between faults within the interseismic model. Estimating initial fault tractions using remote stress tensor cannot capture such fault interactions.

Maps of shear stressing rate along the southern San Andreas show how the fault geometry controls the stressing rate distribution. As expected along the primarily strike-slip San Andreas fault, right-lateral shear stressing rates are larger (maximum 12 kPa/yr) than the reverse-shear stressing rates (maximum ~3 kPa/yr).
Figure 2.11 Right-lateral and reverse shear stressing rates

Shear stressing rates along modeled surfaces representing the southern San Andreas fault through the San Gorgonio Pass region. A) right-lateral shear stressing rates (kPa/yr). B) Reverse shear stressing rates (kPa/yr).

Right-lateral shear stressing rates are largest along the San Bernardino and Mission Creek strands of the SAF and decrease within the restraining bend of the San Gorgonio Pass region (Figure 11A). The San Gorgonio Pass thrust has an undulating strike and small left-lateral shear stressing rates occur along some regions of the western San Gorgonio Pass thrust where the strike is less than ~265°. As with strike-shear stressing rates, the reverse shear stressing rates increase with depth because deeper elements are closer to the deep slip that is applied to the interseismic model. The reverse-shear stressing rates are near to zero outside the bend and increase within the bend along north-dipping fault strands that strike obliquely to the plate motion and accommodate uplift (Figure 11B).
2.6 Estimating absolute shear and normal tractions

2.6.1 Right lateral and reverse shear tractions

To estimate the absolute shear tractions along the southern San Andreas fault from the shear stressing rates provided by the interseismic model, we consider the time since last earthquake rupture along each fault strand. To determine absolute shear traction we multiply the shear stressing rates from our interseismic model with the time since the last ground-rupturing event, which are likely to be preserved in the paleoseismic record (Equation 1). The assumption of this equation is that the large ground-rupturing events have complete stress drop so that the present-day stresses are those that have accumulated since the last event. This approach has been used to estimate stresses from stressing rate (e.g. Smith and Sandwell, 2006).

Paleoseismic data provide bounds for the earthquake rupture years for each individual fault segment (e.g., Biasi et al., 2009). We use Biasi et al. (2009) most recent earthquake years for each paleoseismic site as input for the time since last event. Paleoseismic sites at Pitman Canyon, Plunge Creek, and Wrightwood provide a mean age of 204 years for the most recent earthquake year for the San Bernardino segment. The Thousand Palms Oasis and site is used for Mission Creek strand and the Indio site for the Coachella segment. For the San Gorgonio Pass thrust, Banning, and Garnet Hill strands of the SAF we use an earthquake rupture year of 1400 (Heermannce et al., 2014, Yule et al., 2014).
While paleoseismic evidence suggests that earthquakes rupture through restraining bends along strike-slip faults, the earthquakes can be infrequent resulting in long recurrence intervals, such as along the southern San Andreas fault’s restraining bend within the San Gorgonio Pass (e.g. Yule et al., 2014). Due to the variable time since last earthquake event across faults of the SGPr, the shear traction distribution along the fault surfaces (Figure 12) differs from the shear stressing rate distributions (Figure 11). Whereas strike-shear stressing rates were lower along the north-dipping fault surfaces within the SGPr restraining bend than on fault surfaces outside of the bend, the longer time since the last event along the north-dipping thrust faults increases the total right-lateral shear traction compared to other faults. Although the San Bernardino strand and the Coachella segment of the SAF have greater right-lateral stressing rates, these shear stresses are presumed to have been relieved in the earthquakes of 1680 and 1812, which did not rupture through the restraining bend (Table 1).

<table>
<thead>
<tr>
<th>Fault</th>
<th>Paleoseismic Site</th>
<th>Most recent EQ year</th>
<th>Time since last event (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Bernardino segment</td>
<td>Pitman Canyon/ Plunge Creek/Wrightwood</td>
<td>1812</td>
<td>204</td>
</tr>
<tr>
<td>Banning strand</td>
<td>Millard Canyon</td>
<td>1400</td>
<td>616</td>
</tr>
<tr>
<td>Garnet Hill strand</td>
<td>Millard Canyon</td>
<td>1400</td>
<td>616</td>
</tr>
<tr>
<td>San Gorgonio thrust</td>
<td>Millard Canyon</td>
<td>1400</td>
<td>616</td>
</tr>
<tr>
<td>Mission Creek strand</td>
<td>1000 palms</td>
<td>1680</td>
<td>336</td>
</tr>
<tr>
<td>Coachella segment</td>
<td>Indio</td>
<td>1680</td>
<td>336</td>
</tr>
</tbody>
</table>

Table 2.1 Paleoseismic record
For each fault strand along the SGP thrust region, a time since last event is used to calculate absolute stress. For the San Gorgonio pass thrust, Banning strand, and Garnet Hill Strand of the San Andreas Fault we use a compilation of paleoseismic data not yet published (Yule, pers. Comment).
Consequently, the largest right-lateral shear tractions arise along the Banning and Garnet Hill strands of the SAF near the juncture with the Coachella segment of the SAF (Figure 12A). Regions of large right-lateral shear traction also arise along portions of the San Gorgonio Pass thrust. The reverse shear tractions are greatest along the San Gorgonio Pass thrust within the restraining bend (Figure 12B).

**Figure 2.12 Right-lateral and reverse shear stress**
A) Right-lateral shear stress and B) reverse shear stress along modeled surfaces of the San Andreas fault through the San Gorgonio Pass region.
The distribution of strike-shear traction that considers both fault interaction and time since last event differs from that predicted by resolving the tectonic load onto the faults. We compare the right-lateral shear traction with the resolved strike-shear traction of equation 3 (Figure 13). The resolved remote stress tensor produces larger shear tractions on the San Bernardino strand of the SAF. While the larger right-lateral tractions are largest along the Garnet Hill strand where the Garnet Hill strand intersects with the Coachella segment. The resolved tractions do not consider the shear stress reducing influence of the 1812 earthquake along the San Bernardino strand of the SAF.

Figure 2.13 Compared resolved right-lateral shear tractions
A) Absolute right-lateral shear tractions considering time since last event and fault interaction from interseismic stressing rates. B) Resolved right-lateral shear traction from the remote stress tensor.
2.6.2 Normal tractions

For the normal tractions on the San Andreas fault through the San Gorgonio Pass region, we use the pattern of normal stressing rate from the multi-cycle model, which incorporates the important effects of fault interaction. We superpose lithostatic loading and scale the normal stressing rate distribution so that portions of the fault are ripe for failure. Failure occurs along the fault where the shear stress exceeds the static strength of the fault. Assuming zero cohesion and using tension positive the failure conditions is expressed as

\[ |\tau| = -\mu (\sigma^e + A\sigma_n) \] (4)

where \( \tau \) is the absolute value of shear traction on the fault, \( \mu \) is the static friction, \( \sigma^e \) is the effective lithostatic stress, \( \sigma_n \) is the normalized normal traction of this study, and \( A \) is the scaling factor that can be used to adjust the normalized normal traction. The effective lithostatic stress considers the contribution of hydrostatic pressure. Here we increase effective lithostatic compression with depth to a maximum value of 30 MPa. Using static friction of 0.6 we can solve for the values of scaling factor, \( A \), needed to produce failure.

\[ A = -\left(\frac{\mu}{0.6} + \sigma^e\right) \frac{1}{\sigma_n} \] (5)
The resulting distribution of the scaling factor, $A$, highlights regions that are close to failure (Figure 14). Regions with low positive scale factor, warm bright regions on Figure 14, are closest to failure. Regions with negative scale factor (blue regions on Figure 14) are unlikely spots for failure and subsequent earthquake initiation.

![Figure 2.14 Normal traction scale factor](image)

**Figure 2.14 Normal traction scale factor**

A map of the normal traction scaling factor (Eq 5) reveals which portions of the faults through the San Gorgonio Pass region are closest to failure.

### 2.7 Impact of stresses from Landers Earthquake

The shear stresses do not take into account recent nearby earthquakes that may impact the accumulated stresses. Numerical models and GPS data suggests that ground-rupturing earthquakes alter the nearby stresses (e.g. Harris and Simpson, 1992, Stein et al., 1992, Freed et al., 2007). We numerically simulate the 1992 Landers earthquake to assess its impact on the stresses along the San Andreas fault within the San Gorgonio Pass region. The calculated stresses are added to our stress accumulation estimates.
The right-lateral Landers earthquake (M7.3) ruptured five fault segments, striking northwest-southeast, in the Eastern California Shear Zone on June 28, 1992. The epicenter was located on the south portion of the Johnson Valley Fault, and the rupture traveled northward along the Landers-Kickapoo Fault, Homestead Valley Fault, Emerson Fault, and Camp Rock Fault, crossing two extensional stepovers, and one compressional stepover (e.g., Madden and Pollard, 2012). A maximum right-lateral slip of approximately 6 meters occurred on the North Emerson Fault (Bryant, 1994; Wald and Heaton, 1994).

2.7.1 Methods

We prescribe slip associated with the Landers earthquake (Bryant, 1992; Bryant, 1994; Madden and Pollard, 2012) on faults surfaces within the model representing the rupture path. The faults are manually segmented into multiple vertical segments to prescribe a slip gradient along the length of each fault. All other faults in the model simulation of the Landers earthquake are locked.

We first validate our model by calculating the coseismic change in Coulomb stress following the methods outlined by King et al. (1994) (Figure 15). Using a tension positive convention, the orientation of the optimal failure plane can be defined as the orientation of failure plane to, , the orientation of the failure plane to the x-coordinate (east in this case).

$$\psi = \theta \pm \beta$$  \hspace{1cm} (6)

$$\theta = \frac{1}{2} \tan^{-1} \left( \frac{2 \sigma_{xy}}{\sigma_{xx} - \sigma_{yy}} \right) + \frac{\pi}{2}$$  \hspace{1cm} (7)

$$\beta = \frac{1}{2} \tan^{-1} \left( \frac{1}{\mu} \right)$$  \hspace{1cm} (8)
For this comparison with King et al., (1994), we calculate the Coulomb stress at the Earth’s surface around the rupture. Coulomb stress \( (\sigma_c) \) is calculated from the summation of shear stress \( (\tau) \) and normal stress \( (\sigma_n) \). Using the stress components from the output file from the model, we can use equation 10 and equation 11 to solve for shear and normal stress.

\[
\sigma_c = \tau + \mu \sigma_n \quad (9)
\]
\[
\tau = \frac{1}{2}(\sigma_{yy} - \sigma_{xx}) \sin 2\psi + \sigma_{xy} \cos 2\psi \quad (10)
\]
\[
\sigma_n = \sigma_{xx} \sin^2 \psi - 2\sigma_{xy} \sin \psi \cos \psi + \sigma_{yy} \cos^2 \psi \quad (11)
\]

![Figure 2.15 Coulomb stress failure plane](image)

The coordinate system for calculating Coulomb stress on the failure plane. Our coordinate system differs from King et al. 1994 in that we use tension positive rather than compression positive therefore the orientation of principal stresses are switched from King et al. 1994.

### 2.7.2 Results

To validate that our coseismic model of the Landers earthquake produces a reliable distribution of stresses, we compare the Coulomb stress distribution on ideally oriented planes (Figure 16a) with calculated Coulomb stress distribution from a simulated Landers earthquake from King et al. (1994) (Figure 16b). The
first order patterns of our Coulomb stress distribution match the results of King et al. (1994). Our models show concentrated increase in coulomb stress near the tips of the rupturing segments and in the region of the Big Bear rupture. The models also show negative coulomb stress concentrations North-East of the multi-fault rupture path and South-West of the fault rupture. The discrepancies between the two models Coulomb stress patterns are due to the detailed rupture fault geometry and slip distribution used in our simulation that have been constrained since King et al. (1994) performed their analysis. Furthermore, we did not consider the effect of tectonic loading in our calculations due to the short rupture time. Considering these differences, our results provide a good match, and thus we evaluate the change in stresses along the San Andreas fault surfaces within the San Gorgonio Pass region.

Figure 2.16 A mapview of coulomb stress from Lander’s earthquake

A plot of coulomb stress in mapview from the Lander’s earthquake rupture showing that even with discrepancies from our models to the calculations of King et al. 1994 that the pattern of coulomb stress produced with our fault geometry and calculations A) are similar to the B) coulomb stress distribution produced by the Lander’s earthquake taken from King et al. 1994.
To investigate the impact of the Landers earthquake on the San Andreas Fault surfaces, we examine the shear and normal tractions resolved along each modeled fault surface. Along the southern San Andreas fault, the Landers earthquake has the greatest impact within the restraining bend in the SGP region (Figure 17). The strike-shear stresses are right-lateral with a maximum of ~0.3 MPa, along the San Gorgonio Pass thrust and left-lateral (negative) on the southern Garnet Hill and the Mission Creek strands of the SAF (Figure 17). Because all of these faults are loaded during the interseismic period with right-lateral shear stress, the Lander’s rupture reduces the Garnet Hill and Mission Creek strands and increases the right-lateral shear stress accumulated on the San Gorgonio Pass thrust, presumably bringing this fault closer to failure. The Garnet Hill strand lies in the extensional quadrant of the Landers double-couple so that the earthquake reduces the reverse shear stress on that fault by up to 0.3 MPa. The faults within the extensional quadrant also see increased normal tensile stress (tension positive) by as much as 0.5 MPa.
Figure 2.17 Static stress change

Static stress change along the San Andreas fault due to the simulated Landers rupture. A) Right-lateral shear stresses show unloading of right-lateral shear on the Mission Creek and Garnet Hill strands of the SAF. B) Reverse shear stresses show unloading of the Garnet Hill strand of the SAF. C) Normal tensile stress change is larger than the shear stress changes as the Landers earthquake unclamps the Garnet Hill strand of the SAF.

Whereas the normal stressing rates along faults within the SGPr restraining bend are compressive at 1-5 kPa/yr, we show that the Landers earthquake may have unclamped portions of the Garnet Hill strand. This change in stress distribution may impact rupture propagation. The regions of the restraining bend that are unclamped by the Landers rupture may have different slip behavior when
these stresses are considered. Rupture behavior is sensitive to the initial stresses resolved on the faults prior to rupture propagation. By including the impact earthquakes have on the stress state of faults, we can better inform dynamic rupture modelers and more accurately determine the seismic hazard potential in the region.

2.8 Conclusion

We conclude from our interseismic and multi-cycle models that including fault interaction, time since last earthquake rupture, and stress redistribution from nearby earthquakes are significant in determining the stress state along the southern San Andreas fault. Due to fault interaction, fault geometry, and deep slip driving stresses, local tensile stressing rates appear present along the southern edge of the San Bernardino segment and portions of the San Gorgonio Pass thrust. While shear stresses are completely relieved from a multi-cycle model, this is not the case for the normal stresses. Along the San Gorgonio Pass thrust and Garnet Hill strand the normal stresses are reduced after multiple earthquake cycles while along the San Bernardino segment, Banning strand, and Coachella segment the normal stresses accrue. In order to include the normal stresses that incorporate fault interaction for dynamic rupture models, we provide the distribution of normal stressing rates with the addition of lithostatic load and we scale the normal stresses to be suitable for failure. Even though the San Gorgonio Pass is a region where stresses are in compression, the normal traction scaling factor reveals that portions of the fault along the bend is prime for failure due to local tensile stresses caused by fault interaction.
At shallow depths fault interaction impacts the shear stressing rate distribution along the San Andreas fault when fault strike diverges from plate motion while near the base the shear stressing rates are not as affected indicating that the role of fault interaction is more dominant near the base due to interaction from the plate velocity. Along the San Jacinto fault small deviations of strike-shear stressing is apparent where stressing rates are lower at depths compared to the stressing rates along the San Andreas fault. As well, including time since last earthquake event for calculating shear tractions redistributes the shear tractions so that the right-lateral shear tractions are smaller than the resolved shear tractions along the San Bernardino and Coachella segment due to the variable recurrence interval along the San Gorgonio Pass region.

A simulation of a coseismic event from the Landers earthquake shows that the earthquake rupture reduces the shear tractions along the Garnet Hill and Mission Creek strands and increases the shear tractions along the San Gorgonio Pass thrust suggesting that the Landers earthquake enhances the chance for failure along the San Gorgonio Pass thrust.

We provide our calculated absolute shear tractions and scaled normal tractions that incorporate fault interaction to our collaborators from University of California, Riverside. Dynamic rupture simulations that incorporate initial stresses from our models provides a method that may enhance our knowledge for the seismic potential in a region where the fault geometry is complicated and the earthquake history is unclear, specifically for the San Gorgonio pass region.
2.9 REFERENCES


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