Dynamic Rupture Modeling to Investigate the Role of Fault Geometry in Jumping
Rupture Between Parallel-Trace Thrust Faults

A thesis submitted in partial fulfillment of the requirements
For the degree of Master of Science in Geology - Geophysics

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Dedication

This thesis is dedicated to my wife.

I only got this far thanks to you. I love you forever.
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Abstract

Dynamic Rupture Modeling to Investigate the Role of Fault Geometry in Jumping Rupture Between Parallel-Trace Thrust Faults

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Fold and thrust belts (such as those found in California Transverse Ranges or Iran Zagros Mountains) consist of many neighboring thrust faults in a variety of geometries. Active thrusts within these areas individually contribute to regional seismic hazard, but there is also possibility of multi-fault rupture in a single event. Investigations of historic thrust surface traces suggest that within a single event rupture can jump from one fault to a separate fault up to 8 km away. There is also observational data of jumps occurring between thrust faults ~50 km apart. In contrast, previous modeling studies of thrust faults find a maximum jumping rupture distance of merely 0.2 km. Here, we present a new dynamic rupture modeling parameter study that attempts to reconcile these differences and determine which geometric and stress conditions promote jumping rupture. We use a community-verified 3D finite element method to model rupture on pairs of thrust faults.
with parallel surface traces and opposite dip orientations. We vary stress drop and the
dimensionless strength ratio to determine which conditions produce jumping rupture at
different dip angles and different minimum distance between faults. We find that
geometry plays an essential role in determining whether or not rupture will jump to a
neighboring thrust fault. Rupture is more likely to jump in faults oriented dipping toward
one another at steeper angles, and the behavior tapers down to no rupture jump in shallow
dip cases. Our variations of stress parameters emphasize these toward-orientation results.
Rupture jump in faults dipping away from one another is complicated by variations of
stress conditions, but the most prominent consistency is that for mid-dip angle faults
rupture rarely jumps. In most of our models, rupture does not jump beyond 3 km, while
some reach 5 km, and in one unique dipping away case rupture jumps beyond 20 km
(potentially much farther). If initial stress conditions are such that they are already close
to failure the possibility of a long distance jump increases. Our models call attention to
specific geometric and stress conditions where the dynamic rupture front is most
important to potential for jump. However, our models also highlight the importance of
near-field stress changes due to slip. According to our modeling, the potential for rupture
to jump is strongly dependent on both dip angle and orientation of faults.
(1) Introduction

Compressional continental tectonic regions, such as the California Transverse Ranges, Japan Hidaka Range, Siberia Verkhoyansk Range, or Iran Zagros Mountains, are defined and surrounded by faults which accommodate compressional strain from the collision of two lithospheric plates (Fuis et al., 2003; Ita, 2000; Khudoley and Prokopiev, 2007; McQuarrie, 2004). The ruptures of the 1971 San Fernando and 1994 Northridge earthquakes occurred on separate thrust faults in the California Transverse Ranges, and they were some of the most destructive earthquakes in North America, causing total unadjusted damage estimates of $500 million and $40 billion, respectively (Stover and Coffman, 1993; Petak and Elahi, 2001).

Throughout this paper, faults in compressional stress conditions are referred to as thrust faults. We note that from a structural perspective these faults are often defined such that "reverse faults" refers to faults with high dip angle, while "thrust faults" relates to faults at low dip angle. We use the term thrust faults in this paper for both, as a convenience, because our study looks at a range of dip angles crossing definitions of both terms (Appendix A goes into further theoretical detail).

Rupture can initiate on one fault and cause slip to occur on a second. We refer to this as jumping rupture. If sufficient slip occurs on the second fault, rupture can renucleate, adding to the overall magnitude of the earthquake. An earthquake with nucleation on two separate faults is often called a doublet. We consider triggered slip evidence of a rupture jump, whether or not renucleation occurs on our second fault.
Heaton (1982) found that the 1971 San Fernando mainshock could have involved two separate faults (Fig. 1). According Heaton's model, the rupture started on the Sierra Madre Fault at 13 km depth, and then a second nucleation initiated at 8 km depth on the San Fernando Fault. This is an example of jumping rupture with renucleation on the second fault. The epicenters of the San Fernando and Northridge earthquakes were ~27 km apart (via earthquake.usgs.gov), although since the faults are dipping away from one another, the distance between them at shallower depths is much less. The cross-section from Stein et al. (1994) suggests the fault planes from these two ruptures were about 10 km apart around 6 km depth (Fig. 2). However, Carena and Suppe (2002) used aftershocks to delineate the Northridge Thrust at depth, and their analysis suggests the minimum distance between the two fault planes is potentially only 2 to 3 km (Fig. 3).

Stein et al. (1994) presented evidence that the 1971 San Fernando rupture caused static stress changes favorable to the 1994 Northridge rupture (Fig. 2), potentially bringing the Northridge Thrust closer to rupture by 20 years. Although this was not enough to cause a rupture jump between the faults, the proximity of these faults does suggest such a jump could be possible.

In 1997, a $M_w$ 7.1 blind thrust fault ruptured in the Harnai district of Pakistan dynamically triggering a $M_w$ 6.8 earthquake on a separate blind thrust fault ~19 sec later, at a distance of ~50 km (Nissen et al., 2016). These rupture planes were potentially both dipping northeast, offset, and slightly off parallel (Fig. 4). Faults in the near-field (1-5 rupture lengths) are potentially affected by both static stress changes and dynamic triggering (Parsons and Velasco, 2009), but Kilb et al. (2002) point out that dynamic
stress changes are much greater than static changes. Stress in the crust is still only roughly estimated, so we do not know the initial, nor final conditions on either of the faults. However, we can investigate the physics of how geometry might affect the potential for rupture to jump between thrust faults.

Figure 1. Cross-section showing potential geometry of two faults involved in the 1971 San Fernando earthquake (Heaton, 1982). Note the two separate hypocenters; this is an example of jumping rupture that led to re nucleation.

Figure 2. Coulomb stress change cross-section, showing the locations of the rupture planes of 1971 San Fernando and 1994 Northridge (Stein et al., 1994). Stress changes in red promote rupture on receivers in the orientation of the Northridge rupture surface.
Figure 3. Cross-section of the 1971 San Fernando and 1994 Northridge fault planes estimated from aftershock distribution (Carena and Suppe, 2002).

Figure 4. 3D diagram of 1997 Harnai doublet slip planes as estimated from InSAR inversions. This is an example of jumping rupture (Nissen et al., 2016).
The Uniform California Earthquake Rupture Forecast v.3 (UCERF3) was developed to assist in estimating earthquake probabilities throughout the complex California fault systems (Field et al., 2014). One of the key restrictions on rupture propagation integrated into UCERF3 is that ruptures will not jump beyond 5 km. This limitation is well documented in historical investigation of strike-slip surface ruptures (Wesnousky, 2008; Biasi and Wesnousky, 2016) and supported by dynamic models of strike-slip ruptures (Harris and Day, 1993). However, this limitation seems to be inaccurate in regards to dip-slip faults. Biasi and Wesnousky (2016) present evidence of 4 thrust earthquakes in which rupture jumped beyond 5 km. The largest of these had a maximum jump distance of 8 km, but it is important to point out they were only looking at surface traces, so the minimum distance between faults could be less at depth. Such datasets continue to grow, but given the difficulty in finding preserved dip-slip ruptures we must use computer modeling to make up for a sparse real-world dataset.

Much of the dynamic rupture modeling research on jumping rupture focuses on strike-slip faults (Harris and Day, 1993; Ryan and Oglesby, 2014; Lozos, 2016). Previous research is limited for thrust faults because high resolution meshing is very restrictive in both mesh generation and computation runtime. Using finite difference Magistrale and Day (1999) modeled parallel plane blind thrust rupture at a single dip angle, and found it would not jump beyond 200 m, but an interconnecting tear fault would allow rupture propagation up to 2 km apart. They varied stress drop from 5 to 10 MPa while using dimensionless strength ratio values of 1.5 and 3 (defined in Methods). Oglesby et al. (2000) used the 3D finite element method (FEM) to investigate how slip direction and dip
angle affected surface motion in dip-slip faults. They found that thrust faults produce more slip and ground motion than normal faults due to feedback from surface interactions. These findings supported the previous 2D research, as well as observational evidence.

To better inform rupture forecast modeling and prepare for potential hazards we use current modeling techniques on generally more destructive thrust ruptures, attempting to explore this sparse area of investigation. We use the 3D finite element method to model thrust faults with aligned, parallel traces, varying geometry and stress conditions. We vary the geometric parameters of dip angle, minimum distance between faults, and orientation of the faults to one another, while also changing the stress parameters of stress drop and dimensionless strength ratio. While the geometries of our faults are very simple, they do reflect real-world cases to varying degrees of similarity. This parameter study helps to clarify basic unexplored fault interactions, and therefore will help to inform many real-world cases.
(2) Methods

We use the Southern California Earthquake Center (SCEC)/USGS community-verified (Harris et al., 2009) 3D FEM software FaultMod (Barall, 2009) to conduct a parameter study of dynamic rupture on pairs of planar thrust faults as computed using slip weakening friction and Coulomb failure criterion (Ida, 1972; Andrews, 1976) in a perfectly elastic, isotropic, homogeneous half-space. Our principal goal is to search for any potential relationship between geometry and the ability of rupture to jump between thrust faults. Our geometric parameters are minimum distance between faults ($dm$) and equal dip angle of both faults ($\theta$). We also vary stress parameters of stress drop ($\Delta \tau$) and dimensionless strength ratio ($S$) (Das and Aki, 1977; Day, 1982). The faults we create have aligned parallel surface traces and either dip toward each other (V-faults) or away from each other (A-faults) (Fig. 5). We use the terms V-faults and A-faults because the letters represent the geometry of two faults dipping toward or away from each other. We nucleate rupture on the first fault, looking for any slip on the second fault. We consider any slip on the second fault a rupture jump, whether or not renucleation occurs.

Figure 5. Cross-section perpendicular to strike of our two fault orientations. Dipping toward (V-faults), left. Dipping away (A-faults), right.
We initiate rupture on the first fault by increasing shear stress above the yield stress in a forced nucleation patch greater than the critical nucleation radius (Day, 1982). If the second fault slips, it is due to the physics of the rupture. Tables 1 and 2 show our physical and computational parameters.

**Table 1: Constant physical and computational parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static friction coefficient, μ₀</td>
<td>0.6</td>
</tr>
<tr>
<td>Dynamic friction coefficient, μₐ</td>
<td>0.2</td>
</tr>
<tr>
<td>Slip weakening distance, dₒ</td>
<td>0.4 m</td>
</tr>
<tr>
<td>Vₚ (P wave velocity)</td>
<td>6000 m/s</td>
</tr>
<tr>
<td>Vₛ (S wave velocity)</td>
<td>3464 m/s</td>
</tr>
<tr>
<td>Density</td>
<td>2700 kg/m³</td>
</tr>
<tr>
<td>Radius of forced nucleation</td>
<td>2000 m</td>
</tr>
</tbody>
</table>

**Table 2: Varied physical and computational parameters.**

<table>
<thead>
<tr>
<th>S (Strength, dimensionless)</th>
<th>Δτ (stress drop, MPa)</th>
<th>τᵢ (initial shear stress, MPa)</th>
<th>σₙ (initial normal stress, MPa)</th>
<th>τᵣ (yield stress, MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>5.00</td>
<td>11.25</td>
<td>31.25</td>
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</tr>
<tr>
<td>1.5</td>
<td>10.00</td>
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<td>37.50</td>
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<td>125.00</td>
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</tr>
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<td>10.00</td>
<td>25.00</td>
<td>75.00</td>
<td>45.00</td>
</tr>
</tbody>
</table>

We generate finite element meshes of our fault geometry using the commercial software Cubit. We implement tetrahedral elements with edge-length of 200 m for the fault planes, the space between faults, and 2 km buffers parallel to strike outside of the faults. We use element edge-lengths of 600 m in 10 km blocks beyond the endpoints and
base of faults. We vary \(dm\) in increments of 200 m, increasing until rupture does not jump and/or decreasing until the second fault renucleates. The smallest value of \(dm\) we test is 600 m; this allows three full-size elements between faults at minimum. For A-faults, we measure \(dm\) at the surface, while \(dm\) of V-faults is measured at the base of faults (Fig. 5). Fault basal depth and along-strike length are constant for all models at 15 km and 20 km, respectively. Dip angle is equal for both faults and varies from 20° to 60°, at increments of 10°. Changing dip angle while keeping basal depth at 15 km means that the area of each fault ranges from \(\sim 370\) to \(935\) km\(^2\). The center of the forced nucleation patch on the first fault is \(\sim 12\) km depth for all models, and \(\sim 3\) km in from the edge.

Our stress parameters of \(\Delta \tau\) and \(S\) are relationships of defined stresses in the system. \(\Delta \tau\) is a measurable physical property, while \(S\) is a computational index. Initial normal and shear stresses are uniformly applied to both faults. Stress drop is defined as,

\[
\Delta \tau = \tau_i - \tau_f, \tag{1}
\]

where \(\tau_i\) is initial shear stress, and \(\tau_f\) (final shear stress) is initial normal stress \(\sigma_n\) multiplied by the dynamic friction coefficient \(\mu_d\). While \(S\) is,

\[
S = (\tau_y - \tau_i) / \Delta \tau, \tag{2}
\]

where \(\tau_y\) (yield stress) is \(\sigma_n\) multiplied by the static coefficient of friction \(\mu_s\) (Das and Aki, 1977; Day, 1982). Day describes \(S\) as relation of how close the initial stresses are to failure. These two stress parameters relate to the critical patch size for nucleation \(r_c\) through,

\[
r_c = \frac{7\pi}{24} \frac{\mu (S + 1) d_o}{\Delta \tau}, \tag{3}
\]
where $\mu$ is the Lamé parameter for rigidity (shear modulus), and $d_o$ is the slip weakening distance (Day, 1982). The value of $d_o$ relates to the distance at which friction changes from a static to a dynamic condition. We choose a community accepted value of $d_o$, but Lozos et al. (2014) pointed out that changing $d_o$ has a strong effect on jumping rupture.

We modeled ruptures on each geometry with $\Delta\tau$ of 5, 10, 20, and 40 MPa, given $S = 1.5$. We also varied $S$ at 1, 1.5, and 2, with a $\Delta\tau$ value of 10 MPa. Real-world estimates of $\Delta\tau$ vary greatly depending on method, and it also varies locally on a fault within a single event. $S$ cannot be estimated because we do not know initial or final stress conditions. Trifunac (1972) found that the 1971 San Fernando main shock had a $\Delta\tau$ of 6 MPa, while McCowan et al. (1977) found an average $\Delta\tau$ of 29 MPa with a maximum of 65 MPa. Allmann and Shearer (2009) completed a comprehensive, worldwide investigation of $\Delta\tau$ and found a range from less than 1 to more than 100 MPa (for more information see Appendix B). We ran all models for 30 seconds of rupture, outputting details of rupture conditions every second. These details included cumulative slip, active slip, as well as normal and shear stress values calculated at every node on the fault.
(3) Results

We ran over 200 individual dynamic rupture models, and found three general behaviors of rupture for both orientations. The first fault always completely ruptures. The second fault either has no slip, small magnitude localized slip, or complete rupture from renucleation (Fig. 6). We call these cases no jump, triggered slip, and full renucleation, respectively. Whether the second fault has triggered slip or full renucleation is based on stress parameters and the amount of triggered slip through the critical patch size (Eqn. 3). Triggered slip on the second fault varies from a minimum of ~1 mm at a single node, to a maximum of ~50 cm over several square kilometers. The maximum slip on either fault always occurs at the surface, no matter the orientation, and the slip magnitude ranges from ~5 to ~70 m. Please note the extreme upper value of this range. We recognize such slip values are nonphysical for this type of tectonic system, but our variations of Δτ highlight the similarities in scaling relations. It is worth noting that the highest slip values come from the largest Δτ, and our initial stress conditions lead to an evenly distributed stress drop, which diverges from reality (refer to Appendix B for more on real-world Δτ values).

While most of our slip values are unrealistically large, it is also important to point out that any fault with nucleation always completely ruptures, unlike real world faults. This is particularly important because our initial stress values are uniform across the entire planar faults, thus our models lack the localized variations of stress and geometry of real-world faults. Such stress variations lead to Δτ variations and decrease overall earthquake energy release.
Figure 6a. V-faults full renucleation.

Figure 6b. V-faults triggered slip.

Figure 6c. V-faults no jump.

Figure 6d. A-faults full renucleation.

Figure 6e. A-faults triggered slip.

Figure 6f. A-faults no jump.

Caption and scale bars on next page.
First, we review V-faults results with S constant at 1.5 and Δτ varied from 5 to 40 MPa (Fig. 7). For all Δτ, ruptures on low dip angle faults do not jump, while those on steep dip angle faults jump the farthest. Triggered slip always occurs at the base of the second fault, at dm, approximately centered on the fault. Full renucleation is most likely at steep dip angles. The farthest full renucleation of 2600 m occurs on 60° models at Δτ of 40 MPa, but the farthest jump (triggered slip without renucleation) is actually 2800 m, at Δτ of 10 MPa. Increasing Δτ increases renucleation for dip angles 40°-60°, while only showing slight variation at 30°, and never altering 20° model behavior.

Next, we review A-faults results with S constant at 1.5 and Δτ varied from 5 to 40 MPa (Fig. 8). For all Δτ, ruptures on 30° & 40° faults never jump, and those on 60° faults always jump. Faults at 20° are the most inconsistent, showing significant variation in rupture behavior across all Δτ values. The farthest jump occurs in 20° models at a large distance of 9 km, while not jumping whatsoever at high Δτ. Triggered slip always occurs at the surface, at dm, while also at different places along strike for shallow or steep dip angle. The triggered slip for steep A-faults generally occurs along strike (Fig. 6e and 9) from the forced nucleation patch, while shallow models trigger at many locations along
strike (Fig. 10). The farthest full renucleation occurs at 2.4 km in both the 20° & 60° models at different $\Delta \tau$ of 10 and 20 MPa, respectively. Increasing $\Delta \tau$ from 10 to 20 MPa, 20° models go from 2.4 km to no jump at any distance. Alternatively, increasing $\Delta \tau$ from 10 to 20 MPa, 60° models at all separations up to 2.4 km go from triggered slip to full renucleation. At $\Delta \tau$ of 40 MPa, 60° models maximum jump distance is significantly decreased from 3 to 1.6 km. Overall, while keeping $S$ constant, the two orientations show two distinct behavior patterns due to increases in $\Delta \tau$. The pattern of the A-faults is much more complicated as to which dip angles and what separations are prone to rupture jump.

The last set of results graphs (Fig. 11) show both orientations, with $\Delta \tau$ constant at 10 MPa while varying $S$ to 1, 1.5, and 2. The $S = 1.5$ results are the same as seen in Fig. 7 & 8, but re-presented here with different dm axes to allow comparison to the data of $S$ at 1 & 2. For both orientations, lower $S$ results in more full renucleations and farther jumps, while higher $S$ equates to no full renucleations and shorter jumps. V-faults at 20° and A-faults at 40° never result in jumping rupture, echoing results of varied $\Delta \tau$. Varying $S$ for V-faults does not alter the overall pattern seen with varied $\Delta \tau$. The pattern of behaviors in the A-faults is much more consistent with varied $S$ than $\Delta \tau$, showing a similar pattern within these results.
Figure 7. V-faults result graphs for $S = 1.5$. In order to visualize the variations in rupture behavior across geometric parameters we present our results using graphs of $d_m$ vs dip angle, with inferred approximate delineations of rupture behavior boundaries. Individual model results are marked with a symbol relating to type of behavior. Models with no jump are marked by dark colored circles, triggered slip by lighter color triangles, and full renucleations by lightest color squares. Regions between boundaries are relatedly colored to make differences across result graphs more apparent.
Figure 8. A-faults result graphs for $S = 1.5$. Individual model results are marked with a symbol relating to type of behavior. Models with no jump are marked by dark colored circles, triggered slip by lighter color triangles, and full renucleations by lightest color squares. Regions between boundaries are relatedly colored to make differences across result graphs more apparent.
Figure 9. 3D diagram of 60° A-faults, showing triggered slip only along strike from forced patch of nucleation on the first fault (black circle). Scale set to saturation to highlight slip on second fault.

Figure 10. 3D diagram of 20° A-faults, showing locations of triggered slip all along strike. Scale set to saturation to highlight slip on second fault, using same scale as Fig. 9.
Figure 11. V-faults, left column (a, b, c), A-faults, right column (d, e, f). Result graphs for both orientations at S of 1, 1.5, & 2, with constant $\Delta r$ at 10 MPa.
(4) Discussion

Our dynamic rupture models show that dip angle and orientation are strongly controlling factors in rupture jump distance between two aligned, parallel-strike faults. Dip angle affects overall rupture jump inhibition more than initial stress conditions do. Our variations of stress parameters act as confirmation and support for dip angle as a primary factor in rupture jump. Real-world conditions are much more complex in both geometry and stress conditions than our simplified scenarios, but these models shed light on an aspect of thrust fault rupture dynamics previously unexplored using finite element modeling.

In order to better examine our results we present 3D normal and shear stress change snapshots (1 s before slip first occurs on the second fault, unless otherwise noted) with varied dm and at $\Delta \tau$ chosen to best highlight variations. Due to the relatively straightforward pattern of the V-faults results we only present selected 60° and 20° dip models (Fig. 12 and 13, respectively). For the A-faults, we present 60° and 20° dip models (Fig. 14 and 15, respectively), and also include 40° models (Fig. 16) to better explore additional complexities of the rupture jump pattern.

In all our models, the largest magnitude slip occurs at the ground surface, and our stress diagrams show that the largest normal stress decrease occurs at the surface of a ruptured thrust fault. These results relate well to Brune (1996), which used rubber foam models to show strong detachment at the surface of thrust faults. Although the 1996 paper focused on low dip angle subduction zone thrust faults, Brune (2001) found
real-world examples of non-subduction zone thrust faults (such as the rupture of 1971 San Fernando) consistent with the foam models.

(4.1) V-faults

First, we discuss the V-faults (Fig. 7 and 11a-c). For all S and Δτ values in the V-faults, rupture jumps farthest at 60° dip, while rupture never jumps in 20° models. For the 60° dip cases at S of 1.5, the maximum jump distance is about the same for all Δτ, but the low Δτ models show the least renucleations, while the highest Δτ has the most (and farthest) renucleations. This is well explained by the inverse relationship between critical patch size and Δτ (eqn. 3); with larger Δτ, the necessary patch required for nucleation is smaller. This means that the minimum amount of triggered slip required to nucleate rupture at higher Δτ, is not enough at lower Δτ. The overall distance of jump seems more related to geometry and S, rather than Δτ.

For the V-faults at steep dip angle, full renucleation occurs at small dm (Fig. 12 a and b) because normal stress decreases and shear stress increases at the base of the second fault. Both normal and shear stress changes promote rupture in this geometry. These stress changes are seen in the mid (Fig. 12 c and d) and far (Fig. 12 e and f) dm as well, but the mid only has triggered slip and the far has no jump. The stress changes provide for triggered slip out to an apparent maximum, which varied depending on dip angle, but the relationship between critical patch size and Δτ dictates when renucleation occurs on the second fault. Since all stress changes in the 60° dip cases promote rupture, either the dynamic stresses of the rupture front or the slight variations of stress change at
farther distances define the longest jump distance. We will further explore this in section 4.3.

The 20° V-faults (Fig. 13) also show decreased normal stress at the base of the second fault, but the difference is that the shear stress decreases, which counters the normal stress. The decrease in shear shear stress also affects the dynamic rupture front, decreasing the potential for rupture jump. This implies that dip angle has a dramatic influence on the stress change. Despite a potentially strong dynamic rupture front, the overall stress changes have a significant effect in the near field.
Figure 12. V-faults 3D normal and shear stress change plots for 60° dip, \( \Delta\tau = 5 \) MPa, and varied \( dm \). Snapshot before slip occurs on second fault, a and b: small \( dm \), full renucleation; c and d: mid-\( dm \), triggered slip; snapshot at maximum stress, e and f: far \( dm \), no jump. All plots use the same scale (g). Black circle represents forced nucleation patch on the first fault. Black star represents the first location of triggered slip, and the black patch on second fault is the area of triggered slip.
Figure 13. V-faults 3D normal and shear stress change plots for 20° dip, $\Delta \tau = 5 \text{ MPa}$, and $dm = 600 \text{ m}$, at 13 s (a and b), and 30 s (c and d). All plots use the same scale (e).
(4.2) A-faults

Next, we discuss the A-faults (referencing Fig. 8 and 11d-f). The A-faults express some of the pattern seen in the V-faults, in that the farthest jumps occur at lowest S. However, variations of dip angle and $\Delta \tau$ show much greater complexity in the A-faults. Rupture jump in all the A-faults is affected by $\Delta \tau$ in a less straightforward pattern than in the V-faults. A-faults at 60° show the shortest rupture jumps at high $\Delta \tau$, while 20° models go from an extreme maximum jump distance of 9 km at $\Delta \tau$ of 10 MPa, to no jump at 20 or 40 MPa. This is in stark contrast to the straightforward pattern seen in the V-faults, in which 60° always have the farthest jump and the 20° models never jump. In the case of the steep A-faults, the farthest rupture jump occurs at S of 1.0 and $\Delta \tau$ of 10 MPa, but the second farthest occurs at S of 1.5 and 20 MPa. This is another example of the increased complexity of the rupture jump pattern seen in the A-faults, but the most dramatic difference is the lack of any rupture jump at 40°.

For the 60° A-faults, Fig. 14 shows that as the rupture front reaches the surface of the first fault, high magnitude stress changes occur on the second fault in a focused radial pattern mirroring the rupture front on the first. We refer to this as the stress front. Our 3D diagrams represent the combination of the stress changes due to the dynamic rupture front in addition to the static stress changes due to slip on the first fault. Fig. 14 shows the stress changes of close (a and b), medium (c and d), and far dm (e and f), 1 s before triggered slip occurs on the second fault, or mid-rupture in the no jump far case. After rupture reaches the surface on the first fault there is a large decrease in both shear and normal stresses on the second fault (Fig. 14, a and b, profile line A-A'). Although, as the
rupture front approaches the surface of the first fault, and as it moves along strike from
the forced patch of nucleation, an increased stress front moves with it on the second fault
(Fig. 14, a and b, profile line B-B'). For these steep dip cases, triggered slip always occurs
as the stress front moves along strike on the second fault (Fig. 14, a - d). This suggests
that the rupture front prominently affects the potential for rupture jump in the steep
A-faults, and since the stress front is increasing for both normal and shear stress, we
contend that shear stress changes are the dominating factor for triggered slip. The stress
changes ahead of the rupture front are maxed out and saturated in our diagrams. The
down-dip stress changes reach 3.5 times stress drop. Stress changes ahead of the rupture
front seem to dominate the potential for rupture jump between A-faults at 20° as well.
However, they show a different type of stress fronts, and these two types of stress front
also lead to an explanation for the lack of rupture jump in the 40° cases.

In the A-faults, there are two types of stress fronts seen on the second fault
induced by the rupture front on the first fault. The first is the stress front seen along strike
as the rupture propagates along the first fault in steep dip cases, this could be considered
both an effect of slip and of the rupture front (we discuss this possibility in section 4.3).
The second type of stress front is best seen in the 20° models (although it is present in all,
in lower magnitude), where a front of high magnitude stress change propagates down-dip
of the second fault. The multiple locations of triggered slip seen in Fig. 15 (a-d) illustrate
the importance of this down-dip stress front. It is also worth noting that due to the length
of the 20° models, the rupture front on the first fault arrives at the surface along strike in
a much smaller time window, thereby eliminating the same type of along strike rupture as seen in the 60° models.

The down-dip stress front is best explained by the geometry of the shallow dipping A-faults. It is partially due to the fact that the shallower faults have greater area, so the magnitude of energy is much greater by the time the rupture reaches the surface. Although it is also due to increased directivity, because the geometry of two shallow A-faults better align their fault planes, so energy moving up the first fault will more easily continue propagating in the direction of rupture onto the second. Proximity of the faults down-dip would also have an effect; if the faults are closer at depth, the rupture front on the first fault will create a stronger stress front on the second. In the 40° A-faults there are both along strike and down-dip stress fronts (Fig. 16), but even at our lowest value of S, neither are enough to initiate rupture on the second fault. The lack of rupture jump in these models suggests that dip angle strongly affects the different stress fronts' potential to initiate slip on the second fault.

Regarding the models with varied S from 1 to 2 (Fig. 11), due to the relationship of stresses in S (Eqn. 2), if we keep Δ𝜏 constant, changes in S are directly proportional to τ_y, and to a lesser degree τ_i. This means a change in S relates to a large proportional change in yield stress. This explains why lower S has the farthest triggered slip, and why higher S restricts jump distance significantly. The overall pattern of stress distribution is the same given changes in S. This reinforces the point that geometry is a significant factor in whether or not rupture can jump, in addition to how far it can jump.
Figure 14. A-faults 3D normal and shear stress change plots for 60° dip, $\Delta \tau = 5$ MPa, and varied $dm$. a and b: small $dm$, triggered slip. c and d: mid-$dm$, triggered slip. e and f: far $dm$, no jump.

All plots use the same scale (g). Black circle represents force nucleation patch on the first fault. Black star represents triggered slip location.
a

Normal Stress

@ 12 s  \( dm = 1 \) km  
\( \theta = 20^\circ \)  \( \Delta r = 10 \) MPa

b

Shear Stress

@ 12 s  \( dm = 1 \) km  
\( \theta = 20^\circ \)  \( \Delta r = 10 \) MPa

c

Normal Stress

@ 13 s  \( dm = 4 \) km  
\( \theta = 20^\circ \)  \( \Delta r = 10 \) MPa

d

Shear Stress

@ 13 s  \( dm = 4 \) km  
\( \theta = 20^\circ \)  \( \Delta r = 10 \) MPa

e

Stress Change (MPa)

Initial Normal (zero) = 62.5 MPa
Initial Shear (zero) = 22.5 MPa
Figure 15 (this and previous page). A-faults 3D normal and shear stress change plots for 20° dip, $\Delta \tau = 10$ MPa, and varied $dm$. a and b: small $dm$, renucleation. c and d: mid-$dm$, triggered slip. f and g: far $dm$, no jump. All plots use the same scale (e and h), note that this scale is different from previous figure (20 MPa max versus 10 MPa max). Black circle represents force nucleation patch on the first fault. Black stars represent triggered slip locations.
(4.3) Stress Change Causes

Finally, we use 2D cross-section diagrams created with Coulomb software for Matlab (Toda, et al., 2005; Lin and Stein, 2004) to help delineate where the stress
changes on the second fault are due to slip on the first fault, in contrast to those due to the rupture front. These cross-sections are only examples of stress changes due to uniform slip on the first fault, they do not directly relate to our FEM models. We recreate our fault geometries, assign average slip to the first fault, and then the Coulomb software calculates stress changes due to that slip on receivers of our second fault orientation. Stress changes due to slip show characteristic lobes of increased or decreased stress, and the lobe orientations are dependent on both the orientation of the source and receiver faults. This means the lobes shown in our cross-sections only represent stress changes on faults with the dip angle and orientation of the second fault. These cross-sections were created using Coulomb software because the setup and running of FEM calculations to create such cross-sections would have been prohibitively long for this project. These simple calculations from the Coulomb software do not highlight where slip occurs on the second fault, nor do they include effects from the dynamic rupture front.

Examining the V-faults (Fig. 17 and 18), we see that the stress changes at the base of the second fault are fairly well explained by slip on the first fault. In our FEM 3D diagrams for the 60° models (Fig 17, a and b) there is a decrease in normal stress and a slight increase in shear stress at the base of the second fault. Looking at the cross-sections (Fig. 17, c and d) we see that stress lobes due to slip on the first fault generally coordinate with the stress changes seen in the FEM models. In the 20° models (Fig. 18), the cross-sections again coordinate with the 3D diagrams. The normal stress is decreased, promoting rupture, but due to the geometry of the 20° faults, the second fault is now positioned in the decreased shear stress lobe, thus inhibiting rupture. This suggests a
strong explanation for the variations of rupture jump potential as dip angle changes in the V-faults.

Figure 17. V-faults @ 60° dip, $\Delta \tau = 5$ MPa. Mid-rupture FEM-generated 3D normal (a) and shear (b) stress change plots. Matlab-generated approximate 2D cross-sections of normal (c) and shear (d) static stress changes due to average uniform slip on the first fault. All plots use the same scale (e).
Figure 18. V-faults @ 20° dip, Δτ = 5 MPa. End-of-rupture FEM-generated 3D normal (a) and shear (c) stress change plots. Matlab-generated approximate 2D cross-sections of normal (b) and shear (d) static stress changes due to uniform slip on the first fault. All plots use the same scale (e).
In the case of the A-faults (Fig 19 - 21), the along strike stress front seen in the steep FEM models is fairly consistent with the stress changes due to slip, but the down-dip stress front of the shallow models is best explained by the dynamic rupture front. In the 60° V-faults, the FEM 3D diagrams are presented at 1 s before triggered slip occurs on the second fault (Fig. 19, a and b), with profile lines A-A' and B-B' corresponding to stress change cross-sections for normal (Fig. 19, c and e, respectively) and shear (Fig. 19, d and f, respectively). The cross-sections of profile line A-A' show stress changes due to uniform slip on the first fault after rupture arrival at the surface, while the cross-sections of B-B' show stress changes due to uniform slip before rupture reaches the surface. The decrease in stress seen on the second fault after slip occurs at the surface of the first fault (profile A-A') presents in both the FEM 3D diagrams and the cross-sections. The 3D diagram and cross-section also generally correspond when the slip on the first fault is ~1 km from reaching the surface (profile B-B'). This suggests that in the steeply A-faults, stress changes due to slip are dominant.

In contrast, for the 20° A-faults (Fig. 20), stress changes are dominated by the dynamic rupture front, since neither of the cross-sections relate to their corresponding profile lines in the FEM 3D diagrams. This strengthens the argument for distinction between the along strike and down-dip stress fronts. In the 40° A-faults (Fig. 21) which never jump in any of our models, we see both the along strike and down-dip stress fronts. The difference is that the magnitude of stress change is smaller than those found in the 60° and 20° models, just enough to inhibit triggered slip.
Figure 19. A-faults @ 60° dip, $\Delta \tau = 5$ MPa. Mid-rupture FEM-generated 3D normal (a) and shear (b) stress change plots. Matlab-generated approximate 2D cross-sections of normal (c, e) and shear (d, f) stress changes due to uniform slip on the first fault. (c, d) represent changes after first fault completely ruptures, while (e, f) show changes before the rupture reaches the surface of the first fault. All plots use the same scale (g).
Figure 20 (this and next page). A-faults @ 20° dip, $\Delta \tau = 10$ MPa. Mid-rupture FEM-generated 3D normal (a) and shear (e) stress change plots. Matlab-generated approximate 2D cross-sections of normal (b, c) and shear (f, g) stress changes due to uniform slip on the first fault. (b, f) represent changes after first fault completely ruptures, while (c, g) shows changes before the rupture reaches the surface of the first fault. All plots use the same scale (d and h), note that this scale is different from previous figures (20 MPa max versus 10 MPa max).
Figure 20 continued from previous page.
Refer to caption on previous page for explanation of Figure 20e-h.
Figure 21. A-faults @ 40° dip, $\Delta\tau = 5$ MPa. Mid-rupture FEM-generated 3D normal (a) and shear (b) stress change plots. Matlab-generated approximate 2D cross-sections of normal (c, e) and shear (d, f) stress changes due to uniform slip on the first fault. (c, d) represent changes before the rupture reaches the surface of the first fault, while (e, f) rupture reaches the surface of the first fault. All plots use the same scale (g).

(4.4) Future Directions

Our results should help inform future rupture forecast systems, such as UCERF4, but given the simplified nature of these models, further research is needed to best relate these results directly to reality. One major simplification is the use of perfectly aligned planar faults with the same dip angles. Localized variations of initial stresses, with depth
and along a fault, are more realistic, and such complexity could prove key to future research. Additionally, the initial stress conditions of our models are applied uniformly to both faults, but considering the fault orientations, it is reasonable that on-fault stresses should relate to some regional stress pattern. A realistic regional compression would apply stresses to both faults differently, so the normal and shear stress components would not be the same for our oppositely dipping faults. Use of a velocity model such as PREM or ak135 may have significant effects. Seismic velocities often decrease significantly near the surface (this is especially true in basins), and given how influential the surface is in our results, variations of velocity with depth could also help to make future studies of this nature more realistic. Beyond changing dip angle or strike of one fault to the other, there is also the need to investigate blind thrusts, especially considering the strong surface effects seen in all models.

(4.5) Final Thoughts

Looking back at the 1971 San Fernando and 1994 Northridge rupture planes, if we use Carrena and Suppe's geometry for faults at depth (Fig. 3), we can approximately compare them to our 50° A-faults at Δτ of 20 MPa, with a separation of about 2.5 km. In this respect our dynamic rupture models support the lack of rupture jump between the 1971 and 1994 faults. While the fault geometry of our models does not represent that of 1997 Harnai, the long distance rupture jump of that event seems likely to correspond to initial stresses that were already close to rupture.

This parameter study provides important guidance to both future research and earthquake forecasting. Our parameter study investigates key interactions between faults
and we hope it will inspire further research of this type. While this research begins to answer questions of rupture jump, there remain large gaps in our understanding. This type of research is essential to explore the physics of rupture, especially considering our miniscule collection of real-world events. Public and private sectors alike are desperate for more capability in the realm of understanding earthquakes. Forecasting systems provide some alleviation of this hunger, but we are always in need of more data to better inform such systems. Earthquake forecasting requires better understanding of conditions that promote or inhibit rupture jump. UCERF4 is the next iteration of the California forecast system. Our results highlight details of rupture jump, or the lack thereof, which directly informs such future forecasts. The usefulness of this research to such systems is directly dependent on estimates and accuracies of fault geometry at depth.
(5) Conclusions

Our models highlight the importance of dip angle in jumping rupture distance between thrust faults. The dip orientation of one fault relative to another also affects the pattern of rupture jump distance, leading to inhibited or maximum rupture jump at different dip angles. Variations in S do not change the dip angle jump pattern (given the same stress drop) for either orientation, but it does increase rupture jump distance at lower values, and decrease rupture jump distance at higher value.

For V-faults, increased stress drop does not change maximum jump distance by much (from 2.6 to 2.8 km), but it does increase maximum distance of full renucleations (from 1.6 to 2.6 km). Maximum jump in the V-faults occurred at 60°, with an S of 1.0, at a distance of 4.8 km. While rupture never jumped in the 20° V-faults. Alternatively, for the A-faults, rupture never jumped at 40° In addition, the maximum rupture jump resulted in a full renucleation which occurred in the 20° models somewhere beyond dm of 30 km at S of 1.0. A stress drop increase from 10 to 20 MPa completely shuts down the potential for rupture to jump at 20°. As further contrast, in the 60° A-faults, increased stress drop from 20 to 40 MPa, maximum rupture jump distance is decreased from 3.0 to 1.6 km.

The V-faults and A-faults have different behaviors due to the differences in what causes rupture jump to the second fault. In the V-faults, triggered slip usually occurs on the second fault after the rupture front has passed. This suggests that in the V-faults stress changes due to slip have a greater effect than the peak stress changes due to the passing rupture front. This may relate to the fact that dm is in close proximity to the forced patch of nucleation on the first fault. In contrast, the A-faults are positioned such that the
rupture front always has maximum energy when it reaches \( dm \) at the ground surface. Rupture jumps in the A-faults coincide with the passing of the rupture front. The steep A-faults are triggered by an along-strike stress front, while the shallow A-faults are triggered by a down-dip stress front.

These results are important to rupture forecast models, and they point to the need for further investigation along many different lines of inquiry, including but not limited to: depth-dependent stress, independently varied dip angles, non-parallel strike, offset traces, and burial depth (blind faults). This parameter study fills a gap in the scope of dynamic rupture modeling. It demonstrates the importance of dip angle on rupture jump and potential of a large earthquake to include multiple faults in complex compressional tectonic systems, especially those akin to the fault geometries around the San Fernando Valley, California, USA.
References


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Appendix A - EQ Basics, Fault Terminology, and Concerning Curiosities

Earthquakes are often thought of as ground shake, but from a geoscience perspective, the shake is a representation of a break. These breaks (ruptures) often occur on previously-developed fractures (faults). While friction holds faults closed most of the time, if pressure along a surface (shear stress) overcomes friction, energy is released as a rupture that propagates through the Earth, emitting seismic waves in frequencies that vibrate the ground beneath us. There are three distinct types of faults, and each type relates to specific three-dimensional stress conditions. Shear stress describes the sliding force applied to a surface, while normal stress refers to a force which either pulls a surface apart (tension) or pushes it together (compression). Faults in primarily shear stress conditions are referred to as transform faults, while faults in tensional stress conditions are dubbed normal faults. Faults in compressional stress conditions are called reverse or thrust faults, and these are the focus of our study.

The USGS defines faults in compressional systems with dip angles less than 45° as "thrust faults", while "reverse faults" are those greater than 45° (Dip-slip [Def.], n.d.). However, there are many geoscientists that define the boundary at 30°. Although this seems only a matter of terminology, important discontinuities seem apparent in geoscience beyond the nomenclature. The USGS definition relates well to the two possible fault planes of earthquake focal mechanisms, which orients the compressional stress axis ($\sigma_1$) 45° from the fault plane. Structural geology describes how the static friction coefficient ($\mu_s$) relates to fault angles through Coulomb failure criterion at approximately 30° from $\sigma_1$ (Davis and Reynolds, 1996). Von Mises failure criterion
describes $\sigma_1$ at 45° from the fault plane, but it refers to ductile failure (Davis and Reynolds, 1996), which does not apply to our investigation. This apparent discontinuity is important to our study because our models employ Coulomb failure criterion while corresponding to focal mechanism relationships.
Appendix B - Stress Parameters and Reality

Real world estimates of $\Delta \tau$ are calculated using estimates of magnitude, average slip, and rupture area (Trifunac, 1972), or via data inversions to create more detailed plots. The inversion calculations are complicated by path effects and are very dependent on initial models (Allmann and Shearer, 2009). Inversion estimates for $\Delta \tau$ often have a wide range of values within a single event, and $\Delta \tau$ calculated for a wide variety of events also shows high variability. Nielsen and Olsen (2000) used 3D finite difference inversions for 1994 Northridge, finding $\Delta \tau$ of 3.5 MPa as the average, with a localized maximum of 18 MPa. Allmann and Shearer (2009) found that continental collision systems had a median $\Delta \tau$ of ~2.5 MPa, although they also found several events with maximum $\Delta \tau$ values over 100 MPa.

Although S is a computational index, as our technology improves and our understanding of real-world stress conditions grows, real-world estimates of S might be possible. Earthquake forecasting could improve immensely if we understand and can estimate initial and final stress values in the Earth. Such capability would also offer the potential to estimate S of real-world events and assist to create more informed dynamic rupture models.
Since the 1994 Northridge event occurred on a blind thrust with no surface rupture, the distances between faults beneath the surface is estimated by data inversions or plane-fitting to aftershock distributions. Stein et al. (1994) used inversions from other publications to map the rupture planes, showing a minimum distance between faults of about 10 km. Alternatively, Carena and Suppe (2002) use the aftershock method which shows more alignment between the potential faults at depth while bringing the minimum distance between them around 2 to 6 km. These two methods provide greatly varied estimates of approximate rupture plane, but in either case, highlight two faults in relatively close proximity to one another.

Fault geometry at depth is difficult to define. The best understanding of fault geometries comes from earthquake data, but for faults without modern ruptures various techniques are used to extrapolate specifics. Close to the surface, field mapping works well, but stratigraphic records only provide extrapolations beyond the first few kilometers of depth. Active reflection seismology is used to find patterns down to 30 km (Fuis et al., 2003), but resolution decreases with depth and underlying complexity. Wells are particularly helpful to exploring faults at depth, but the average oil well depth in California is only ~2 km, while the maximum is ~7.5 km (Miller, 2009). Thus, most fault geometry estimates at depths greater than 2 km are low resolution.

SCEC publishes a comprehensive 3D model of California faults (Plesch et al., 2007, Nicholson et al., 2017) using a broad range of constraints for these geometries. Real-world approximations of our A-faults are present in some places (such as the San
Fernando Valley) but the V-faults are rarely seen as we model them. V-faults do occur, but frequently one fault will extend to greater depth beneath the other, with a potential intersection. Although our models are greatly simplified, they provide a starting point to understand potential broad relationships.
Appendix D - Technical Details

FEM calculations are performed at every node, accounting for elastic changes to friction, stress, motion, and wave propagation. Elastic properties are calculated using inputs of friction coefficients, seismic velocities, initial stresses, and density.

The color bars of our figures all show increased stress in red and decreased stress in blue. This concept is important because normal and shear stress changes are opposite in potential to initiate rupture. Decreasing normal stress promotes rupture via lowering of the yield stress, while increasing shear stress promotes rupture by bringing it closer to yield stress. Similarly, increased normal stress inhibits rupture and decreased shear stress promotes rupture. Whether decreasing or increasing, changes in shear stress have a proportionally higher effect, since yield stress is defined as normal stress multiplied by the static coefficient of friction. This means that a 5 MPa normal stress change only changes the yield stress by 3 MPa, whereas a 5 MPa shear stress change brings the shear stress either 5 MPa closer to, or further from yield stress. We focus on the overall behavior while highlighting the general stress changes and their potential for inhibiting or promoting rupture on the second fault.

The magnitude of an earthquake is directly proportional to the area of fault which ruptures, so more fault breaking equates to a larger earthquake. If 1971 San Fernando set off the faults of 1994 Northridge, 1971 total magnitude would still be less than $M_w$ 7.0. The earthquake magnitude range of our models is $M_w$ 7.0 to 7.9. The largest $M_w$ occurs in the shallowest dipping model (largest surface area) at the highest $\Delta \sigma$, with no jump to the
second fault. The lowest $M_w$ occurs at the lowest $\Delta r$ on the steepest dip angle, with no jump to the second fault.