Dynamic Rupture Modeling of Coseismic Interactions on Orthogonal Strike-Slip Faults

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Introduction and Motivation

The San Andreas Fault System is dominated by right-lateral strike-slip faulting. However, a large number of smaller orthogonal left-lateral structures also exist. Some, such as the Garlock Fault or Pinto Mountain Fault, are large enough to be mapped without having had a historic earthquake. However, the existence of other smaller orthogonal structures is often highlighted only when they rupture in conjunction or sequence with a larger mapped fault. The 2019 Ridgecrest sequence, which included a M6.4 rupture on a left-lateral fault followed 34 hours later by a M7.1 earthquake on an orthogonal right-lateral fault, exemplifies this. The Ridgecrest example raises questions as to what conditions led to the source faults rupturing in two closely-spaced earthquakes as opposed to one single larger event. That extends to broader questions about general behaviors of orthogonal strike-slip faults as earthquake gates: what conditions might make them rupture together versus separately, how likely is a rupture on one fault to activate a large cross-fault, and is this persistent behavior versus something changes over multiple earthquake cycles? Here, I use the 3D finite element method to simulate dynamic ruptures on orthogonal strike-slip fault systems with several geometrical configurations.

Methods and Model Setup

I use the 3D finite element software FaultMod (Barall, 2009) to conduct my dynamic rupture simulations. I implement linear slip-weakening friction in a homogeneous fully-elastic half space. I nucleate my ruptures by raising the shear stress to over the yield stress at a chosen hypocenter, then forcing propagation over an area larger than the critical patch size required for self-sustaining rupture.

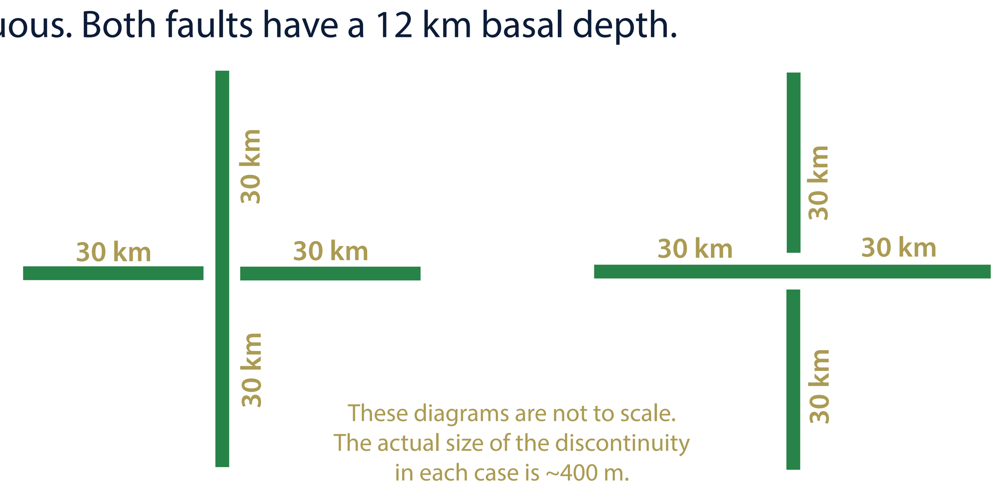
I chose stress and material parameters consistent with other dynamic rupture modeling fault geometry parameter studies (e.g. Harris and Day, 1993; Lozos et al., 2013).

Along-strike shear stress	40.0 MPa (high stress); 12.0 MPa (low stress)
Down-dip shear stress	0 MPa
Normal stress	66.6 MPa (high stress); 19.98 MPa (low stress)
Principal stresses (high stress)	σ_V = 67.8 MPa; σ_{NS} = 108.4 MPa; σ_{EW} = 27.2 MPa
Principal stresses (low stress)	σ_V = 20 MPa; σ_{NS} = 32 MPa; σ_{EW} = 8 MPa
Static coefficient of friction	0.75
Dynamic coefficient of friction	0.51 (high stress); 0.3 (low stress)
Slip weakening parameter	0.4 m
Vp	6000 m/s
Vs	3464 m/s
Density	2700 kg/m3
Hexahedral element size	200 m in near field, 600 m in far field
Radius of forced nucleation zone	3000 m

I generated my fault meshes using the commercial software Trelis.

I created two T-shaped fault geometries: both with one 60 km-long vertically-oriented vertical strike-slip fault, one with a 30 km-long horizontally-oriented vertical strike-slip fault on the left, and other with the horizontal fault on the right. Both faults have a 12 km basal depth.

Trelis and FaultMod do not accommotate geometries with two mutually crossing continuous faults. One fault is always considered throughgoing, but the other is considered discontinuous at the exact point of intersection. I thererfore also created two +-shaped geometries, each with two 60 km-long vertical strike-slip faults: one in which the vertically-oriented fault is continuous and the horizontally-oriented one is discontinuous at the junction, and one in which the horizontal fault is continuous and the vertical one is discontinuous. Both faults have a 12 km basal depth.



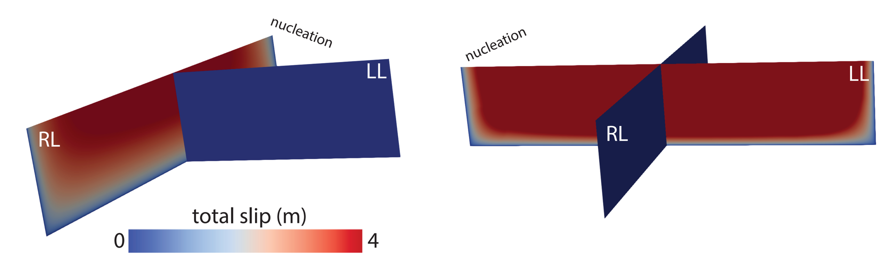
Here, I show cases in which the vertically-oriented fault is right-lateral and the horizontally-oriented fault is left-lateral. I also tested the opposite configuration, and the results were a mirror image. I do not show those models here for the sake of space. I also tested nucleation points at the far end of each branch of the fault system.

Results: Rupture Behaviors

My models produce fivetypes of slip distribution, three which correspond with the three types of rupture behavior through an orthogonal fault system that I discuss in the introduction.

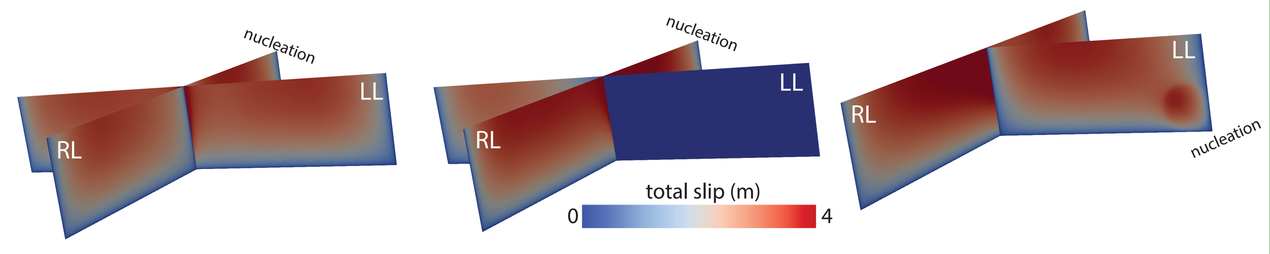
Single-Fault Rupture

Rupture stays on the nucleation fault. The second fault does not respond at all. Possibly corresponds to real cases of rupture passing through a cross fault without activating it (e.g. the M7.3 1992 Landers earthquake).



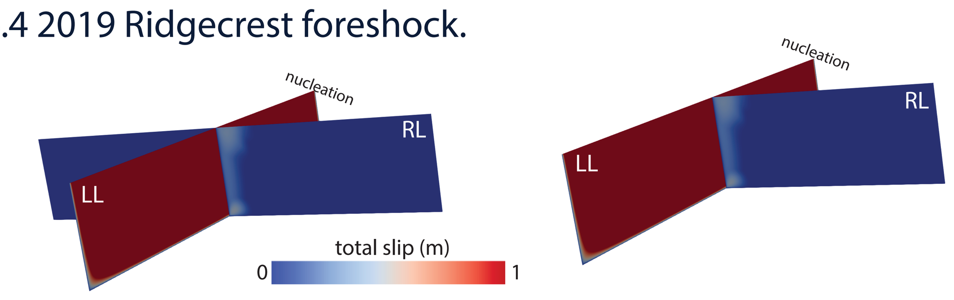
Multi-Fault Rupture

Rupture propagates through the entire nucleation fault and at least part of the cross fault. Corresponds to multi-fault events such as the M8.6 2012 Off-Sumatra earthquake.



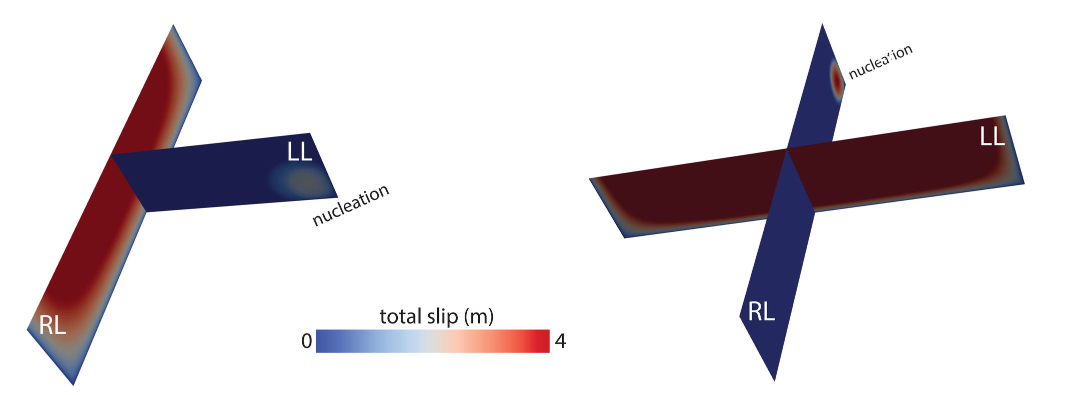
Triggered Slip on Second Fault

Only the nucleation fault hosts a propagating rupture front, but the cross fault has a small patch of triggered slip near the junction. Comparable to the M6.4 2019 Ridgecrest foreshock.



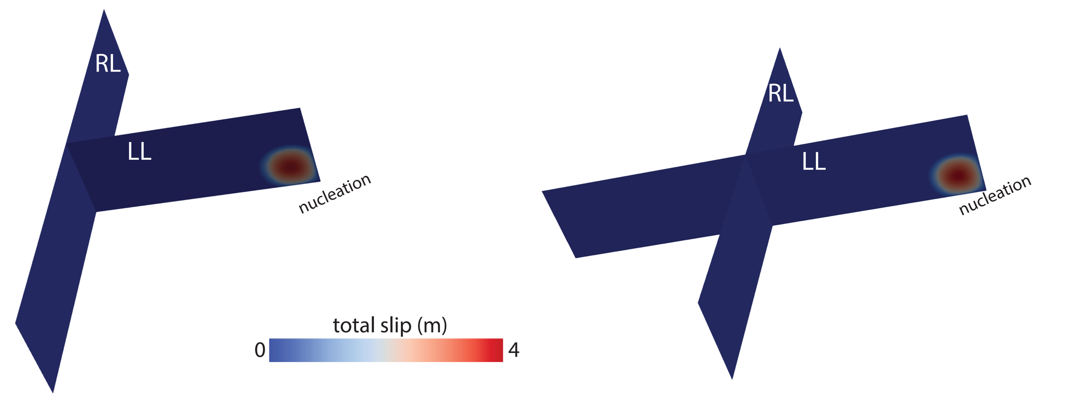
Triggered Nucleation

In these cases, the forced nucleation fault is too unfavorable to host propagating rupture. However, the cross fault is so favorable that stress changes even from the failed forced nucleation are enough to nucleate a full dynamic rupture on the cross fault. This is comparable to a smaller earthquake triggering a larger earthquake on a nearby fault.



Failed Nucleation

Here, the forced nucleation fault is also too unfavorable to host a propagating rupture, and the sense of slip does not unclamp the cross fault enough to nucleate a second rupture. The closest analogue here is just a small earthquake, where rupture is confined by unfavorable conditions.

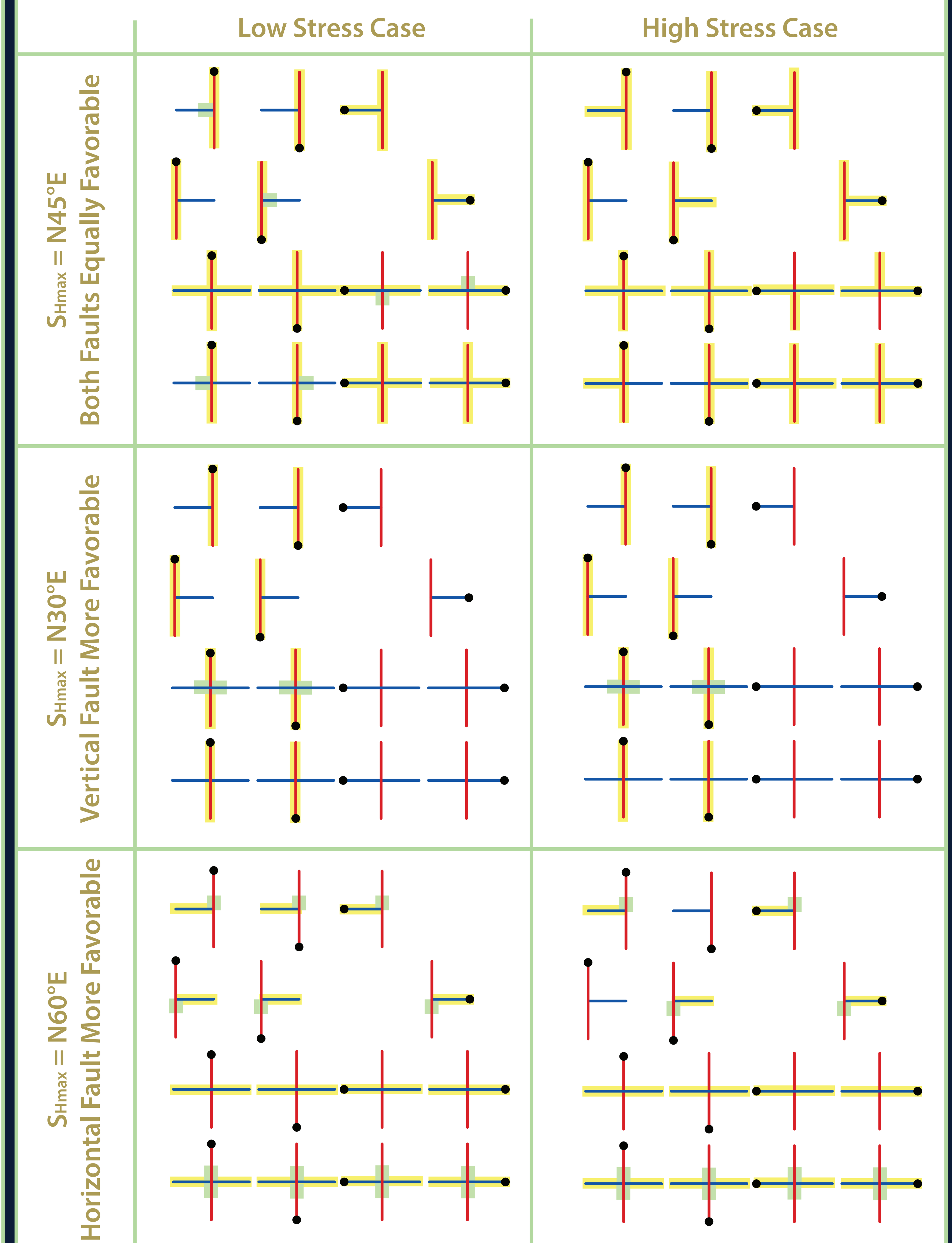


Results: Orthogonal Faults in a Regional Stress Field

In these simulations, I impose a regional stress field on the fault system, where tractions on each fault are controlled by how the angle of the maximum horizontal compressive stress (S_{Hmax}) resolves onto the angle of the fault. This stress orientation also controls the sense of slip on each fault.

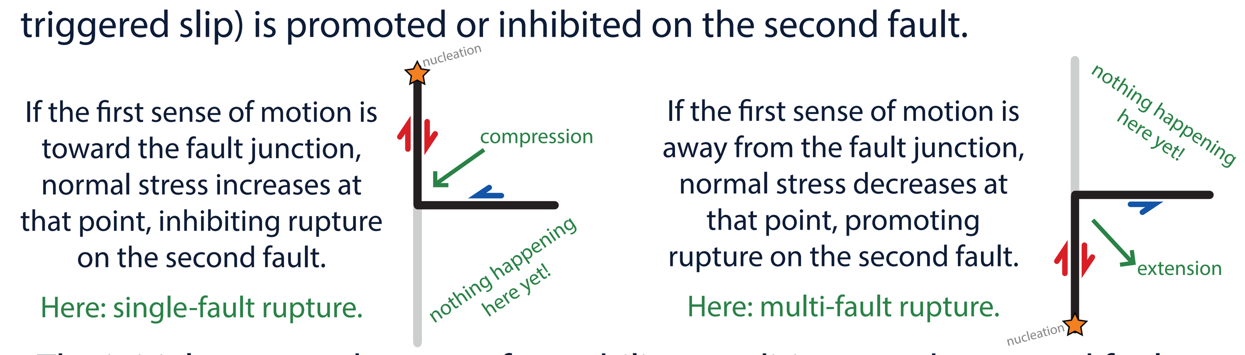
Below, I show results from S_{Hmax} = 45° (exactly between the faults), and from rotating S_{Hmax} to 30° away from one fault or the other: the angle which should produce conjugate (but not orthogonal) strike-slip faults according to Andersonian faulting and Mohr-Coulomb friction. This makes one fault significantly more favorable for rupture than the other, which in turn prevents multi-fault ruptures.

I show the resulting slip patterns from these models using simple schematic diagrams. Right-lateral faults are colored red, and left-lateral faults are colored blue. Yellow highlighting indicates the path of propagating rupture, while green highlighting indicates patches of triggered slip. The black dot shows the nucleation site.



Discussion: Rupture Patterns

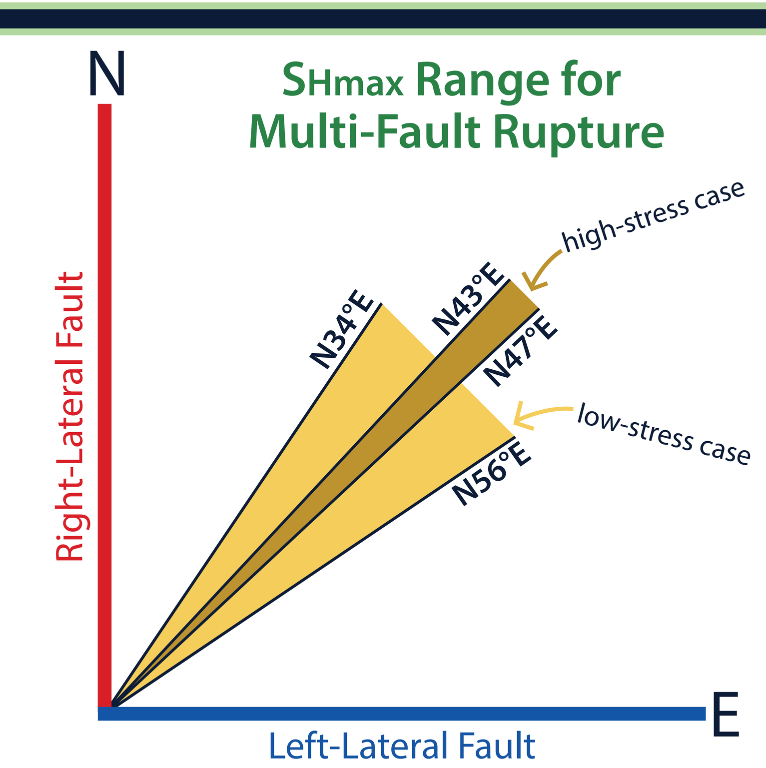
- The first direction of slip on the first fault affects whether rupture (or triggered slip) is promoted or inhibited on the second fault.



- The initial stress and rupture favorability conditions on the second fault control whether it actually ruptures.
- The high-shear-stress stopping phase from rupture hitting the end of one fault promotes rupture or triggered slip. If the first fault terminates at its junction with the second fault, the second fault is more likely to rupture.

Discussion: Stress Orientations

- If one fault is optimally oriented for failure according to Mohr-Coulomb friction and Andersoninan faulting, the other fault is extremely unfavorable for rupture.
- Only a narrow range of S_{Hmax} orientations allow multi-fault rupture through a pair of orthogonal strike-slip faults. (See figure to the right.)
- A wider range of S_{Hmax} angles allows multi-fault rupture in the low-stress case, since there is less normal stress clamping the less-favorable fault shut - and therefore a lower yield stress than in the high-stress case.
- Can the presence of orthogonal strike-slip faults, as opposed to Andersonian conjugate pairs, tell us about the regional stress conditions under which the faults formed?



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- Harris, R. A., & Day, S. M. (1993). Dynamics of fault interaction: Parallel strike-slip faults. Journal of Geophysical Research: Solid Earth, 98(B3), 4461-4472.
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Acknowledgments

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