The effect of along-strike variation in dip on rupture propagation on strike-slip faults

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ABSTRACT

Strike-slip faults can be nonplanar in both their strike and dip dimensions. While a large body of work has investigated the effects of changes in strike on earthquake rupture and arrest, no previous studies have investigated the role of along-strike variations in dip on strike-slip ruptures. Here, I use the three-dimensional finite-element method to conduct dynamic simulations of ruptures on strike-slip faults with linear surface traces and changes in dip along strike. I experiment with the amount of dip change as well as the abruptness of that change under a variety of initial stress conditions. In all of my initial stress cases, I find that a change in dip along strike can cause rupture to stop, and that larger dip changes over shorter distances are more likely to do so. This is largely due to the change in strike at depth that inherently comes from changing the dip; the majority of these behaviors are a result of the rupture front being forced to change direction mid-rupture. While some dip-slip movement does occur on the nonvertical parts of the model fault, it does not have a significant effect on rupture extent. However, linear-surface-trace, nonvertical-dip faults do produce different surface slip, stress, and ground motion patterns compared to corresponding nonlinear-strike, vertical-dip faults. Together, my results show that changes in dip along strike-slip faults do considerably impact the rupture process, suggesting that this type of geometrical complexity should be considered in rupture forecasts and hazard assessments.

INTRODUCTION

Geometrical complexities along strike-slip faults commonly become the endpoints for coseismic ruptures. Statistical analyses of historic and recent surface-rupturing strike-slip events show that ~90% of these earthquakes have at least one endpoint at a previously mapped complexity along the source fault (Wesnousky, 2008; Biasi and Wesnousky, 2016). Paleoseismic studies of either side of mapped discontinuities along major strike-slip faults also commonly show different rupture histories (e.g., Fraser et al., 2010, for the North Anatolian fault in Turkey; Howarth et al., 2016, for the Alpine fault in New Zealand; Scharer et al., 2017, for the San Andreas fault in California, USA; Elliott et al., 2018, for the Altyn Tagh fault in China). There is also a large body of rupture-modeling literature, spanning several decades, which probes the physics of how stepovers (e.g., Harris and Day, 1993; Oglesby, 2008; Lozos et al., 2012; Wang et al., 2020), bends (e.g., Oglesby, 2005; Lozos et al., 2011), gaps (e.g., Kase and Kuge, 2001; Aochi, 2003; Oglesby, 2020), and splays (e.g., Aochi et al., 2000; Kame et al., 2003; Fliss et al., 2008) can affect and stop rupture propagation. The combined results of these empirical, observational, and numerical studies have led to geometry-based rules for excluding certain large-stepover or extreme-angle rupture patterns from earthquake rupture forecasts (e.g., Field et al., 2014).

Strike-slip faults can also have nonvertical dip, however, or may change dip along their strike—though this is more difficult to observe than nonlinearity along a fault’s surface trace. The 2016 Kumamoto, Japan, earthquakes occurred on a bent fault system with near-vertical dip on one side of the bend and northwestward dip on the other side; this inflection point represented the boundary between rupture in the M6.2 foreshock and the M7.0 mainshock (e.g., Asano and Iwata, 2016; Fukahata and Hashimoto, 2016). The M7.8 2016 Kaikoura, New Zealand, rupture propagated through a predominantly strike-slip fault system with different dips on different component faults (e.g., Hollingsworth et al., 2017; Litchfield et al., 2018). The San Andreas fault in southeastern California changes from a southwestward dip through the Carrizo Plain and Big Bend to a northeastward dip through the San Bernardino Mountains and San Gorgonio Pass (e.g., Fuis et al., 2012; Nicholson et al., 2015)—a section of the fault with a relatively linear surface trace—and the southern endpoint of the M7.9 1857 earthquake (Wallace, 1970) corresponds with one of the inflection points in dip (Fuis et al., 2012). These earthquakes and geometries suggest that changes in dip along strike can also influence rupture behavior and may even account for some rupture endpoints that do not correspond with mapped discontinuities along strike (e.g., Wesnousky, 2008; Biasi and Wesnousky, 2016).

Despite the potential role of geometrical complexity in the dip direction in rupture dynamics and arrest, I am not aware of any previous studies that investigate that role and the physical processes behind it. Here, I use three-dimensional (3-D) dynamic rupture simulations on strike-slip faults with linear strikes and changes in dip along strike to address how dip-related geometrical complexities can influence the rupture process and the size of earthquakes.
**METHODS**

I use the 3-D finite element software FaultMod (Barall, 2009), which has performed consistently in validation benchmarks against other dynamic rupture codes (Harris et al., 2009; Harris et al., 2018), to conduct models of dynamic ruptures on strike-slip faults with linear surface traces and along-strike variation in dip. My geometrical parameter space requires a total of 36 fault meshes, which I generated using the commercial software Trelis; I describe the geometry of these meshes in more depth below. The faults are embedded in an 84-km-long, 90-km-wide, 30-km-deep homogeneous fully elastic half space with no velocity or stiffness gradient, with linear slip-weakening friction implemented on the fault planes (Ida, 1972; Andrews, 1976). The material properties of the half space and the frictional properties on the fault plane are listed in Table 1. Nucleation is not spontaneous in these models; I force nucleation by raising the shear stress over the yield stress for an area larger than the critical patch size required for self-sustaining rupture (Day, 1982). This nucleation zone is at the lower left corner of the fault, as far as possible from the change in dip, in order to maximize the effects of rupture directivity and make the rupture front most likely to be able to negotiate the geometrical complexity.

All of my model faults are 60 km long and have a 15 km basal depth. The leftmost 30 km of the fault is vertical in all models. I test 10°, 20°, 30°, 40°, 50°, and 60° variation from vertical dip over the rightmost 30 km of the fault. Along these nonvertical fault sections, I linearly increase the dip from vertical to its final value over a given along-strike distance and stay at the final value over the entire right half of the fault (Fig. 2, top); in the case of 20 km transition distance, the dip changes to its final value over 20 km of along-strike distance and stays at the final value for the last 10 km (Fig. 2, center); and in the case of 10 km transition distance, the dip changes to its final value over 10 km of along-strike distance and stays at the final value for the last 20 km (Fig. 2, bottom).

Despite the linear strike of the surface trace in all of my model faults, the change in dip inherently produces changes in strike along the fault at depth. The at-depth strike of my model faults approximates a simple fault bend in the 30 km transition case, and a double-bend or linked stepover in the 20 km and 10 km transition cases. This deviation from the linear surface strike is smaller toward the surface and most extreme at the base. Table 2 shows the angles of bends in the basal strike of the fault that result from changes to different dip angles over different transition distances.

In all of my model geometries, the direction of the dip change and the resulting nonplanarity lead to dynamic rupture either reducing or increasing normal stress within the zone of geometrical complexity, much like in an extensional or compressional bend, respectively, in a vertical fault (e.g., Kame et al., 2003; Oglesby, 2005; Lozos et al., 2011). The direction of the dip change also affects whether the nonvertical section of the fault experiences static compression or extension under a given regional stress orientation. I chose to implement compression and extension in my models by switching the direction of the dip change, rather than by changing the sign of the shear stress.

I implement a regional stress direction in my models so I can test how overall fault strike, in addition to the change in dip, affects rupture propagation and extent. Because these models require that stresses be assigned directly to the fault, rather than loaded remotely from the mesh, I set up the stress field by rotating a set of principal stresses to a given maximum horizontal compressive stress ($S_{max}$) angle then resolving this onto the fault plane to produce the initial on-fault tractions for the dynamic rupture simulations. My baseline stress case treats the faults as N45°W-striking right-lateral strike-slip faults in a stress regime with maximum horizontal compressive stress oriented N7°E. This is based on the strike of the San Andreas fault, which is favorably oriented for rupture within the average regional stress orientation for southern California (Yang and Hauksson, 2013). To test how the angle between the fault and $S_{max}$ affects rupture propagation, I also model the faults as striking N28°W and N62°W (see Fig. 1B). The N62°W orientation emulates the strongly compressional Big Bend in the San Andreas fault; the N28°W case is also a 17° change in strike, just in the opposite, more extensional direction. Although I designate my faults as strike-slip and choose initial stresses to support this, the model does allow dip-slip motion as driven by rupture dynamics.

Within these different fault and $S_{max}$ orientations, I also test the effect of varying initial stress amplitudes and fault strength. Higher static stress drop ($\Delta \tau$), defined as the difference between the initial and final shear stress on the fault, produces more energetic rupture, which may allow the rupture front to propagate further into unfavorable

| Parameter                      | Value |
|-------------------------------|-------|
| Static coefficient of friction ($\mu_s$) | 0.6   |
| Dynamic coefficient of friction ($\mu_d$) | 0.2   |
| Slip weakening parameter ($d$) | 0.4 m |
| P-wave velocity ($V_p$)        | 6000 m/s |
| S-wave velocity ($V_s$)        | 3484 m/s |
| Density ($\rho$)               | 2700 kg/m$^3$ |
| Tetrahedral element size       | ~200 m near field, ~600 m far field |
| Forced nucleation zone radius  | 3000 m |
| Initial stresses               | See Table 3 |

**TABLE 1. PHYSICAL AND COMPUTATIONAL PARAMETERS**

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Lozos | Rupture on variable-dip strike-slip faults

GEOSPHERE

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Figure 1. Model setup. (A) Basic model geometry, as viewed from above (left) and in cross section (right). The vertical section of the fault is shown in light blue, and the nonvertical section in dark blue. The linear surface strike is shown in light green, and the bent basal strike in dark green. The fault system itself is shown to scale, but the homogeneous half space surrounding is shown smaller here for the sake of highlighting the features of the fault itself. (B) Model geometry compared to regional stress orientation. The maximum horizontal compressive stress ($S_{Hmax}$), shown in red, is fixed at N7°E. I test three different strikes for my fault system; I show the linear surface strike in blue.
stress and/or geometrical conditions on the fault. Fault strength \( S = (\tau_y - \tau_i) / \Delta \tau \), where \( \tau_y \) is yield stress (defined as initial normal stress multiplied by the static coefficient of friction) and \( \tau_i \) is final post-rupture shear stress (Das and Aki, 1977; Day, 1982). A lower \( S \) value means the shear stress accumulated on the fault is closer to exceeding the strength of the material on the fault. This means both that it is easier for a rupture to begin on a low-\( S \) fault and that the rupture is more energetic because there is less resistance to the stress dropping as the rupture propagates. This energy in the rupture front then dynamically raises the shear stress ahead of the rupture even further, which results in even larger dynamic stress drops and even more energy as the rupture propagates. Both \( \Delta \tau \) and \( S \) are commonly used in dynamic rupture modeling geometrical parameter studies to modulate the energy of the rupture front (e.g., Harris and Day, 1993; Oglesby, 2005; Lozos et al., 2011; Peshette et al., 2019; Ulloa and Lozos, 2020). Here, I test \( S \) values of 1.2, 1.7, and 2.2 with a fixed \( \Delta \tau \) of 5 MPa, and \( \Delta \tau \) values of 2.5, 5, and 10 MPa with a fixed \( S \) of 1.7, for the N45°W-striking fault case. These values apply to the vertical left segment of the fault but vary according to geometry on the nonvertical right segment. Table 3 lists the specific stress values for each of these cases.

### RESULTS

#### Rupture Kinematics

Regardless of whether the dip change—and resulting change to the fault’s strike at depth—is compressional or extensional, the rupture progression in all of my models was very similar (Fig. 3 shows representative examples). Rupture propagates uniformly updip and along strike from the forced nucleation point in the lower left corner of the planar half of the fault. When the rupture front reaches the second half of the fault, where the dip begins to change, it propagates faster along the top edge of the fault, where the strike is closer to linear, and slower toward the base, as the fault deviates further from the surface strike.

Three main effects control why the rupture front takes more time to propagate along the base of the fault than it does toward the free surface. First is rupture directivity, an effect in which seismic energy and shear stress build up in line with and in front of a propagating rupture front. As long as the rupture front continues in the same direction, it propagates into this high-energy, high-shear-stress zone, which leads to a higher dynamic stress drop and an even more energetic rupture. This effect compounds itself the longer the rupture front continues in the same direction but is interrupted as soon as the rupture front is forced to change direction and propagate out of the zone of increased energy. On the fault geometry in this study, the rupture front toward the base of the fault propagates through a larger change in strike than it does.

### TABLE 2. BASAL STRIKE BEND ANGLES

| Dip | 30 km transition | 20 km transition | 10 km transition |
|-----|------------------|------------------|------------------|
| 80° | 5.0°             | 7.5°             | 14.8°            |
| 70° | 10.3°            | 15.3°            | 28.6°            |
| 60° | 16.1°            | 23.4°            | 40.9°            |
| 50° | 22.8°            | 32.2°            | 51.5°            |
| 40° | 30.8°            | 41.8°            | 60.8°            |
| 30° | 40.9°            | 52.4°            | 69.0°            |

### TABLE 3. INITIAL STRESS CASES

| Stress drop (\( \Delta \tau \)) | Strength (\( S \)) | \( \sigma_v \) (MPa) | \( \sigma_{ns} \) (MPa) | \( \sigma_{ew} \) (MPa) |
|-------------------------------|---------------------|-----------------------|------------------------|------------------------|
| 5 MPa                         | 1.2                 | 25                    | 35.6                   | 14                     |
| 5 MPa                         | 1.7                 | 30                    | 42.9                   | 18.7                   |
| 5 MPa                         | 2.2                 | 35                    | 50.05                  | 23.3                   |
| 2.5 MPa                       | 1.7                 | 15                    | 21.55                  | 9.4                    |
| 10 MPa                        | 1.7                 | 60                    | 86.0                   | 37.5                   |

\( \sigma_v \)—vertical principal stress; \( \sigma_{ns} \)—north-south principal stress; \( \sigma_{ew} \)—east-west principal stress.
Figure 3. Snapshots of coseismic slip rate, showing how the rupture front negotiates a change in dip from vertical to 60° over a 30 km transition length (A) and a 20 km transition length (B). The dashed black circles indicate the forced nucleation zone. Notice how the rupture front propagates faster closer to the top of the fault and slower toward the bottom; in B, rupture propagates downdip through the rightmost section of the fault before along-strike rupture reaches that segment from the bottom. Rupture behavior for the 10 km transition length case is comparable to that for the 20 km case. Although both of these examples represent compressional geometries, I see the same general rupture behaviors in extensional cases. I therefore chose to show only compressional cases and no 10 km transition length case for conciseness.
toward the surface. It therefore experiences a more significant break in rupture directivity toward the base of the fault. The rupture front toward the surface is able to build on its previous directivity as it continues relatively straight and is therefore able to keep moving quickly, while the rupture front at the base slows down and needs to rebuild its energy after changing direction.

Second, the parts of the fault closer to the surface, and therefore more closely aligned with the vertical section of the fault, have nearly the same favorability for rupture within the stress field as the vertical segment. However, as the fault deviates more from the vertical surface at depth, it may become significantly worse or better aligned within the stress field, affecting the amount of stress drop available on this part of the fault and therefore also affecting the rupture velocity. Even in models where the bent portion of the fault is more favorable within the stress field, however, rupture slows down toward the base of the fault on bent sections, suggesting that the break in directivity is the dominant effect on rupture progression here.

Third, due to the change in dip and resulting change in strike, the basal edge of the fault is longer than the surface edge, especially in cases where the final dip is shallow. Rupture therefore has a longer distance to travel in order to propagate through the entire base of the fault. This compounds the effect of rupture propagating more slowly across the larger geometrical complexities at depth.

In the cases where the dip continues to change along the full second half of the fault (and the basal strike is a simple bend, as in Fig. 3A), rupture reaches the end of the fault toward the free surface first and at the bottom right corner last. In cases where the dip change occurs over only 10 or 20 km (and the basal strike is a double bend, as in Fig. 3B), similar behavior occurs on the middle section of the fault where the dip change occurs. This slows the rupture down enough at depth that rupture propagates downward from the surface through the rightmost segment of the fault before the rupture front at the base of the fault can catch up, comparable to how rupture fronts wrap around other types of on-fault barriers to rupture (e.g., Day, 1982; Das and Kostrov, 1983; Lozos, 2013). For a given transition distance and dip angle, it takes longer for rupture to propagate through faults with a 10 km or 20 km transition distance than ones where the dip change occurs over 30 km, for all three reasons described above. These cases have two inflections in dip, and therefore two breaks in rupture directivity along the fault’s basal strike, rather than only one in the 30 km transition case. Additionally, the change in the basal strike is sharper for smaller transition distances (see Table 2), producing a more significant break in rupture directivity and larger energy loss in the rupture front at the base of the fault. Finally, the fault has more area at its base than at its surface, so the slowed-down rupture front also has to travel a larger distance to reach the end of the fault.

This rupture progression produces three categories of final slip distribution, which I use to classify and discuss results throughout the rest of this paper. In complete-rupture cases (as in Fig. 4A), the entire fault has slipped, both at the surface and at depth. In partial-rupture cases (as in Figs. 4B and 4C), the entire fault experiences surface rupture, but some portion of the fault at depth remains unruptured. In stopped-rupture cases (as in Fig. 4D), parts of the fault remain unslipped at all depths; surface slip does not extend along the full length of the fault.
Dip Variations

The transition from vertical to nonvertical dip along a strike-slip fault can stop rupture from propagating through the entire fault, in comparison to a planar fault of the same length. Figure 5 shows the relationship between the change in dip angle, the transition length for that dip change, and the occurrence of throughgoing rupture for both compressional (top) and extensional (bottom) cases.

The first-order pattern of full versus partial versus stopped rupture across my geometrical parameter space is nearly identical for both extensional and compressional cases, suggesting that the magnitude of the change in fault geometry matters more than the direction in which the dip changes and the basal strike bends. In general, larger and more-abrupt dip changes are more likely to stop rupture before it reaches the end of the fault; a change from vertical to 30° dip over only 10 km stops rupture in both extensional and compressional cases, while a change from vertical to 80° over 30 km produces a nearly identical slip distribution to a completely planar fault. Large dip changes over long transition lengths can still produce partial rupture of the fault, though small dip changes still allow throughgoing rupture even over short transition distances.

The difference between compressional and extensional cases is more of a second-order effect, visible in how much surface rupture occurs in the stopped rupture cases. Rupture is able to progress slightly further in compressional cases when compared to extensional ones of the same geometry. However, seemingly in contrast, the extensional case allows complete rupture in one geometry (change to 60° over 10 km) that produces only partial rupture in the compressional case.

Stress Drop ($\Delta \tau$) Variations

The amount of shear stress released during the fault weakening process affects the amount of energy in the rupture front, which, in turn, affect the ability of rupture to propagate through a geometrical discontinuity in a fault (e.g., Andrews, 1976; Day, 1982; Kanamori and Rivera, 2006). This is partly true in my models (see Fig. 6). Halving the static stress drop ($\Delta \tau$) to 2.5 MPa (Fig. 6, left panels) stops rupture in some geometries that previously had partial rupture, and prevents rupture from going as far along strike as it did in $\Delta \tau = 5$ MPa stopped-rupture cases (Fig. 6, center panels). However, doubling $\Delta \tau$ to 10 MPa (Fig. 6, right panels) has very little effect on the distribution of full versus partial versus stopped ruptures when compared to the $\Delta \tau = 5$ MPa stress-drop models, and mostly just allows rupture to progress further along strike in the stopped-rupture cases. This suggests that the fault geometry plays a significant role in controlling rupture propagation regardless of the energy of the rupture front.

Fault Strength ($S$) Variations

Fault strength $S$ affects how a fault weakens; a lower $S$ means the fault weakens more easily and rapidly, producing a faster and more energetic rupture, while a higher $S$ means the fault is more resistant to weakening and rupture propagation (Day, 1982). In my models in which this parameter varies (Fig. 7), $S$ has only a small effect on throughgoing rupture compared to fault geometry. However, the second-order changes to the distance rupture can propagate before stopping in the stopped-rupture cases produces a rather unintuitive pattern. Both lower and higher $S$ produce shorter ruptures compared to the baseline $S = 1.7$ case. However, for compressional geometries, the high-$S$ case has higher slip than the low-$S$ case, while the opposite is true for extensional geometries. This is because the high-$S$ compressional case has more normal stress than the low-$S$ case, which means a higher shear stress must be reached for the high-$S$ compressional fault to rupture. This results in a higher dynamic stress drop, which in turn produces a more energetic rupture front and a larger amount of slip. In contrast, the normal stress in the low-$S$ extensional case is so low that it is very easy for the fault to reach its failure point even under lower shear stress, and the fault is able to slip further because there is so little normal stress resisting movement. Thus, compressional versus extensional changes to the fault’s basal strike do still impact rupture dynamics and stress transfer, even though bend angle and rupture directivity effects dominate where the rupture stops.

Fault Orientation Variations

Rotating the fault such that the linear surface strike is at a different angle relative to the regional stress orientation further emphasizes that compression versus extension does fundamentally...
affect rupture propagation across my geometrical parameter space. Figure 8 shows the results of models that rotate the fault 17° in a more extensional (left panels) or more compressional (right panels) direction. When rotating a compressional geometry into a more compressional orientation, or when rotating an extensional geometry into a more extensional orientation, rupture stops across the majority of my geometrical parameter space, and very few complete ruptures occur. However, rotating compressional geometries into a more extensional orientation, and vice versa, causes only second-order differences in rupture behavior across parameter space compared to faults with optimally oriented surface strikes.

**DISCUSSION**

**Effects of Variable Dip**

Although the purpose of this study is to investigate how variable dip on strike-slip faults affects rupture propagation, ultimately, it is impossible to isolate the effects of along-strike changes in dip from the impacts of nonlinear strike. Along-strike variation in dip inherently produces variation in the basal strike of a fault, even if the surface strike is completely linear (see Fig. 2 and Table 2). Thus, many of the same effects that control rupture propagation and arrest on vertical strike-slip faults with nonlinear strikes also control rupture dynamics and length here.

The linear surface strike of all of my model faults is what allows rupture to propagate along the top portion of the right half of the fault before...
extending further downdip. The closer to planar the fault is, the more the rupture front is able to maintain directivity and build up energy. Even if the change in basal strike is abrupt and large, producing a break in rupture directivity at the bottom of the fault that slows further rupture propagation at depth, ongoing rupture at shallower depths can still affect on-fault stresses enough to allow the rupture front at depth to eventually reach the far end of the fault. In partial- or stopped-rupture cases, however, the remaining unruptured portions along strike or at depth may be possible locations of large aftershocks because they have been stressed by rupture on adjacent parts of the fault.

Given that the surface strike is the same in all of my model faults, the abruptness and angle of the change in dip—and therefore also of the change in basal strike—actually control how far rupture goes. When the dip continues to change over the entire right half of the fault (30 km transition distance), there is only one inflection point in the basal strike and therefore only one break in rupture directivity. The basal strike approximates a simple bend, meaning that the rupture front at all depths has the same distance to build up directivity on both halves of the fault. For a change in dip to 80°, the bend in basal strike is only 10.3°, which is an angle that consistently allowed throughgoing rupture in my previous work on bent faults (Lozos et al., 2011); whereas a change in dip to 30° constitutes a 27.8° change in basal strike, which allowed throughgoing rupture over only very short distances in my previous work (Lozos et al., 2011) and is just barely within the range of easily propagated-through bends in historic surface ruptures (Biasi and Wesnousky, 2017). The linear surface strike allows complete...
surface rupture despite sharp bends in basal strike, but whether rupture is able to reach the opposite end of the fault at depth depends on whether the base of the fault falls within or outside of the lobe of shear stress change produced by rupture hitting the point where the fault geometry at depth deviates from the linear surface strike direction (e.g., Harris and Day, 1993; Kame et al., 2003; Lozos et al., 2014). Smaller changes in dip produce smaller deviations from the surface strike direction (see Table 2), which means the rupture propagation is more in line with those shear stress changes. These less severe breaks in rupture directivity therefore allow longer ruptures.

When the dip changes over a shorter distance (10 km or 20 km transition), the basal geometry approximates a double bend; although the dip is nonvertical past the transition distance, the basal strike is parallel to the surface strike again. Rupture across this geometry experiences two breaks in rupture directivity at the base of the fault (one at each hinge of the double bend). The rupture front loses energy from two breaks in directivity in these cases and therefore slows down; this, along with larger fault area toward the base, is why rupture takes longer to propagate through the entire fault than in cases with a 30 km transition distance. As with the 30 km transition distance (single bend) case, however, the further outside the zone of stress change from one fault segment the next segment is, the more difficult it is for rupture at depth to propagate around the bend. For a given dip angle, geometries with a 20 km transition distance allow

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**Figure 8.** Grids showing how rupture behavior changes across geometrical parameter space with the fault orientation rotated within the regional stress field. Stress drop ($\Delta \tau$) is fixed at 5 MPa and fault strength ($S$) is fixed at 1.7 in these models. Blue represents complete rupture, yellow represents partial rupture, and white represents stopped rupture, with the length of surface rupture in kilometers listed in black. When the fault is rotated to a more compressional angle, there is little effect on rupture behavior for extensional geometries, but nearly all compressional geometries produce stopped ruptures. Similarly, when the fault is rotated to a more extensional angle, compressional ruptures are not strongly affected, but rupture stops on nearly all extensional geometries.
longer ruptures than those with a 10 km transition distance. This is partly because the rupture front has a longer distance over which to build up directivity again before hitting the second bend, but also due in part to the difference in basal strike change for longer and shorter transition distances (see Table 2). A change to 80° dip for the 20 km transition distance produces a 75° bend at depth, while the same dip angle produces a 14.8° bend over a 10 km transition distance. Even at this smallest dip change, the difference in basal strike change—and therefore the misalignment between the stress changes from the first half of the fault and the position of the bent segment—is significant, and it only becomes more pronounced at larger changes in dip. A change to 30° dip over 20 km produces a 52° bend at depth, and a change to 30° over 10 km produces a 68.9° bend. More than 95% of bends through which mapped historic surface ruptures propagated are smaller than these angles (Biasi and Wesnousky, 2017), and neither of these angles allows throughgoing rupture in my previous models of bent faults (Lozos et al., 2011).

These effects of basal strike angle and breaks in rupture directivity at these geometrical inflection points are the dominant effects controlling whether rupture is able to propagate through the entire fault, in both extensional and compressional geometries. However, extension and compression do affect the length of a stopped surface rupture, and they do contribute to how easily rupture is able to resume after breaking directivity at the nonlinearities along the basal strike. Here, both compression and extension are dynamic effects, caused by the sides of the fault in the nonplanar segment moving toward or away from each other. In compressional cases, the sides of the fault move together and increase normal stress, and therefore also yield stress. This could pose a barrier to rupture; however, if shear stress does exceed this higher yield stress, the resulting dynamic stress drop is larger than it would have been without the compressional effect (e.g., larger than static Δτ), which in turn produces a more energetic rupture. In extensional cases, the sides of the fault move apart, lowering normal and yield stresses. While this allows the fault to start weakening and rupturing at a lower shear stress, it also decreases the dynamic stress drop compared to the static Δτ, which results in a less energetic rupture overall (Lozos et al., 2011). This is why ruptures stop further along strike in compressional geometries compared to extensional ones, particularly when the strike of the fault is optimally aligned to rupture. I discuss cases where the faults are misaligned with the regional stress field later in this Discussion section.

Effects of Stress Drop (Δτ) and Fault Strength (S)

Although the extensional and compressional effects discussed above are matters of locally modulating shear and normal stresses, Δτ, the potential pre-rupture stress drop across the whole fault system, which is determined by pre-stress rather than by rupture dynamics, has minimal effect on stopping rupture. This is because the dynamic effects of rupture directivity and stress radiation still occur at all pre-stress levels; geometrical complexity still leads to breaks in rupture directivity at higher or lower Δτ, and a fault segment that is unfavorably aligned relative to stress changes from an adjacent fault segment would be unfavorable regardless of the magnitude of those stress changes. The lower-Δτ case has stopped ruptures over more geometrical parameter space not because of the geometrical complexity in and of itself, but because the rupture energy on even the completely planar first half of the fault is low enough to minimize rupture directivity effects.

Fault strength (S) also has a minimal effect because it is also determined by on-fault stress and friction conditions and does not change any geometrical effects. S on a fault segment can influence whether rupture propagates or jumps onto it from another segment in cases where the geometrical complexity exists at both the surface and base of the fault (e.g., Oglesby, 2005; Lozos et al., 2011, 2014) or when the fault segments are actually discontinuous (e.g., Harris and Day, 1993; Oglesby, 2008; Peshele et al., 2019), but these are all cases of rupture slowing to a stop and restarting. Because of the linear surface strike and relatively smooth surface near the top of my model faults, rupture propagation never slows to a near stop; the question of rupture restarting, where S is most significant, is not a large factor in these simulations.

Effects of Fault Orientation

The reason that compressional geometries inhibit rupture propagation under more compressional regional stresses and that extensional geometries inhibit rupture in more extensional stress fields, but both geometries are comparable to the optimally aligned case when the regional compression or extension is opposite that of the geometry, is related to the balance between (1) static stress effects from how the regional stress orientation resolves onto the fault and (2) dynamic stress effects from slip on the fault and rupture from propagation.

In optimally aligned cases, the regional stress field neither compresses nor extends the fault; all compressional increases or extensional decreases in normal stress come from the sides of the fault moving together or apart along nonplanar sections. As discussed above, this alone has a negligible effect on rupture length when compared to the effects of broken rupture directivity at inflection points along the fault. For a compressional geometry in a compressional stress field, however, the combined high static normal stress and additional coseismic normal stress increase raise the fault’s yield stress to a point where shear stress may not exceed it and the rupture front may stop. Similarly, extensional geometries in extensional stress fields have a lower static yield stress, which is further lowered by coseismic slip to the point where the stress drop from shear stress exceeding that yield is so low that rupture is not able to sustain itself. However, when the geometry and the stress field produce opposite normal stress effects, the static and dynamic effects balance each other out, leading to a pattern of rupture behavior over geometrical parameter space that matches the pattern in the optimally aligned case with no static extension or compression. These results are consistent with previous modeling work on geometrically complex strike-slip faults under different regional stress orientations (e.g., Lozos et al., 2011).
Other Geometrical Effects

Although it is not possible to separate the effects of variable dip from the effects of nonlinear strike in terms of which geometries allow versus arrest throughgoing rupture, the nonvertical dip in my models has effects on other aspects of earthquake behavior.

When compared to comparable vertical strike-slip faults whose surface strike is the same as the basal strike in my variable dip models, the variable dip models produce more vertical slip and in a different distribution. Figure 9 shows examples of final vertical slip, comparing linear strike–variable dip models with nonlinear strike–vertical faults of the same length. The vertical faults experience some vertical slip at the bend hinges, where dynamic compression and extension are strongest, as well as a smaller amount along the bent segment that is misaligned with the regional stress field. In contrast, the nonvertical faults experience much larger vertical motion along the sections where the dip is changing, consistent with the idea that the dip change produces a hanging wall–footwall geometry on these strike-slip faults and that dynamic compression or extension can produce dip-slip movement in this configuration. I suggest that the pattern and ratio of horizontal versus vertical surface slip observed on a strike-slip fault may help infer whether the fault changes dip along its strike. This also implies that the dip of a strike-slip fault may be important to consider when engineering fault-crossing structures and lifelines, which may be offset by both vertical and horizontal motion.

The combination of hanging wall–footwall geometry imposed by the change in dip, along

![Figure 9. Final vertical slip distributions, comparing example faults with a linear surface strike and a nonvertical dip (left) to equivalent vertical faults with nonlinear strike (right). The faults are oriented to show the acute angle (hanging wall) side imposed by the dip change; the forced nucleation zone is shown with the black circle. Red indicates uplift and blue indicates subsidence. Note that vertical slip mostly occurs at bend hinges in the vertical models; it is much larger and deeper in models with nonvertical dip and occurs along longer sections of the fault.](http://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/doi/10.1130/GES02391.1/5455696/ges02391.pdf)
with dynamic compression and extension leading to localized dip-slip movement also affects the distribution and intensity of ground motion. Figure 10 compares examples of low-frequency (~1 Hz) ground-motion distributions for linear strike-variable dip models versus equivalent bent vertical faults. The effects of along-strike rupture directivity and the break in rupture directivity where the fault becomes nonplanar dominate the ground-motion signature for all geometries. However, peak horizontal particle velocity is lower on the nonvertical fault, but peak vertical particle velocity is higher when compared to the vertical fault. This implies that the dip-slip movement on the nonvertical parts of the fault that are either compressed or extended during rupture is enough to produce hanging-wall effects above the fault plane (e.g., Campbell and Bozorgnia, 1994; Shabestari Khosrow and Yamazaki, 2002), even along a predominantly strike-slip fault. While other factors, such as material contrasts and wave velocities, may have larger effects on ground-motion intensities and distributions from ruptures on real-world faults, along-strike changes in dip on strike-slip faults do still fundamentally alter the pattern of ground motion. With this in mind, it is therefore important to identify changes in dip along strike-slip faults in order to properly assess ground motion hazard in addition to rupture hazard.

### CONCLUSIONS

I have shown that a change in dip along a strike-slip fault with a linear surface strike can pose a barrier to rupture, with the sharpness of the deviation (a larger change in dip over a shorter distance) being more likely to prevent rupture from propagating through the entire fault. These geometrical factors remain the dominant control on rupture behavior through a wide range of on-fault initial stress conditions. The primary reason for this, however, is that a change in dip along strike inherently produces nonlinear strike at the base of the fault; thus, the same directivity, compression-extension, and secondary fault segment alignment issues that control rupture behavior and arrest on vertical strike-slip faults with along-strike geometrical complexities are largely

Figure 10. Examples of peak horizontal (left) and vertical (right) particle velocity distributions for models of compressional and extensional changes to 60° dip over a 30 km transition distance, and of vertical strike-slip faults with a strike equivalent to the basal strike of the nonvertical models. The geometrical inflection point, whether along strike or down-dip, is at the center of each panel. The surface strike of each fault is shown with a solid white line. Dashed white lines indicate the position of the fault at depth for nonvertical cases. The black circle shows the forced nucleation location. Note the different color scale for horizontal versus vertical motion. In the nonvertical fault models, vertical ground motion is higher over the fault surface when compared to that in the vertical-dip models, implying that hanging-wall effects occur even on predominantly strike-slip faults. This effect also occurs on the bent sections of the models with 10 km and 20 km transition distance, but it is less pronounced on these shorter sections.
responsible for controlling rupture propagation and arrest in the linear surface strike–variable dip case. These geometrical effects become even more pronounced when the entire fault is misaligned from optimal orientation within its stress field. The basal strike bend angles that stop rupture in these simulations are consistent with bend angles that stop ruptures in empirical data sets (e.g., Biasi and Wesnousky, 2017) as well as in other dynamic rupture modeling studies focused on the effects of fault geometry on rupture propagation (e.g., Kame et al., 2003; Oglesby, 2005; Lozos et al., 2011).

Despite changes in the basal strike of the fault controlling rupture extent, the along-strike rotation to nonvertical dip in these simulations has other impacts on the rupture behavior. The nonvertical dip creates a hanging wall–footwall configuration along these faults. While slip remains predominantly horizontal along fault sections where the basal strike is parallel to the surface strike, along segments where the basal strike deviates, dynamic compression or extension leads to considerable dip-slip motion. This manifests not only in vertical surface offsets, but in signatures of hanging-wall effects in ground-motion distributions.

Based on these results, I suggest that variations in dip should be considered as heavily as variations in strike in determining possible rupture paths and endpoints in rupture hazard calculations for real-world fault systems, and therefore that identifying these variations using various geometrical methods is also an important part of earthquake hazard assessment. I also suggest that it is important to consider possible vertical offsets and hanging-wall-effect ground motions when engineering infrastructure near strike-slip faults with variable dip. These dynamic effects and their resulting displacement patterns may be particularly useful for understanding the rupture history and possible future behaviors and impacts of faults that are known to have variable dip, such as the section of the southern San Andreas fault from Tejon Pass to San Gorgonio Pass.

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