Small intermediate fault segments can either aid or hinder rupture propagation at stepovers

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[1] Large-scale geometrical complexities along faults are known to be likely endpoints for coseismic rupture, as suggested by analysis of historic ruptures and corroborated by models of rupture on bent or discontinuous faults. However, natural faults also include smaller-scale complexities. We use the 3D finite element method to model dynamic ruptures on strike-slip fault stepovers with a smaller intermediate fault between the main strands. We find that such small faults can have a controlling effect on rupture behavior and ground motion intensity and distribution. In particular, the intermediate fault can either aid or prevent rupture propagation across the stepover, depending on its length and basal depth. The results have important implications for hazard assessment of faults with large- and small-scale geometrical complexities, and also suggest that more site-specific modeling studies may be necessary to develop realistic rupture scenarios for individual complex fault systems. **Citation:** Lozos, J. C., D. D. Oglesby, J. N. Brune, and K. B. Olsen (2012), Small intermediate fault segments can either aid or hinder rupture propagation at stepovers, *Geophys. Res. Lett.*, *39*, L18305, doi:10.1029/2012GL053005.

1. Introduction

[2] Natural faults are complex systems, and the details of their geometry can play a controlling role in their rupture behavior and in the ground motion those ruptures produce [*Wald and Heaton*, 1994; *Brune*, 2002; *Lozos*, 2010]. In particular, many historic surface ruptures have stopped at previously-mapped geometrical complexities [*Wesnousky*, 2008]. There have been many modeling studies investigating the ability of rupture to propagate through large-scale discontinuities in the fault trace, including disconnected stepovers between fault segments [*Harris and Day*, 1993; *Kase and Kuge*, 1998; *Oglesby*, 2008], and stepovers with the main strands connected by a linking fault [*Magistrale and Day*, 1999; *Oglesby*, 2005; *Lozos et al.*, 2011]. However, many natural faults include smaller geometrical complexities – such as short breaks and stepovers, slight bends, and additional fault strands that are short in comparison to the main trace – in addition to the types of large-scale features that are well represented by models in the literature. The San Jacinto Fault, and the San Andreas Fault through San Gorgonio Pass both include all of these types of complexity (Figure 1); many further examples exist beyond southern California. Within a fault stepover specifically, there may be many types of smaller-scale complexity, including damage zones, fractures, smaller subsidiary fault strands, variations in strike and dip of each component fault, and flower structures in which the individual fault strands meet at depth, all of which may possibly have an effect on rupture behavior [*Kim et al.*, 2004; *Finzi et al.*, 2009]. In the present study, we investigate the effect of a smaller fault segment positioned between and parallel to the primary segments of a stepover. This geometry is motivated by that of the San Jacinto Fault, but it is not meant to represent the actual fault geometry in detail. We choose to focus on this geometry because a smaller fault segment in the middle of a stepover might be expected to turn the larger stepover into two smaller ones, allowing rupture to more easily “stair-step” their way across the gap, and thus aid through-going rupture. We find that the reality is actually much more complicated.

2. Method

[3] We use FaultMod, a 3D finite element code [*Barall*, 2009], with a slip-weakening Coulomb friction criterion [*Andrews*, 1976] to model earthquakes on a fault system with two planar parallel 50 km long strike-slip faults that overlap by 25 km and are separated by 4 km of stepover width, with a smaller fault of variable length positioned halfway between the two primary faults (Figure 2). The intermediate fault is positioned so that its center is aligned with the point on the second primary segment to which rupture would jump in the absence of the intermediate fault. We test two different basal depths for the intermediate fault: 16 km (consistent with the basal depth of the two primary segments) and 8 km. We model this geometry as both an extensional and compressional system; this is achieved within our imposed regional stress field by switching whether there are right left steps between the faults. We also test two different stress regimes: one in which rupture would jump from one primary segment to the other in the absence of the intermediate segment, and one in which rupture would not jump in the absence of this segment (Table 1). The specific stress values to achieve these states are different between the extensional and compressional cases. In addition, we experimented with implementing depth-dependent stresses that tapered from their ambient value at the base of the seismogenic zone to 10% of that value at 3 km below the free surface, but this did not qualitatively change our results. We did not incorporate pore fluid pressure changes into the present study, though work by *Harris and Day* [1993] suggests that this would reduce the effect of dynamic

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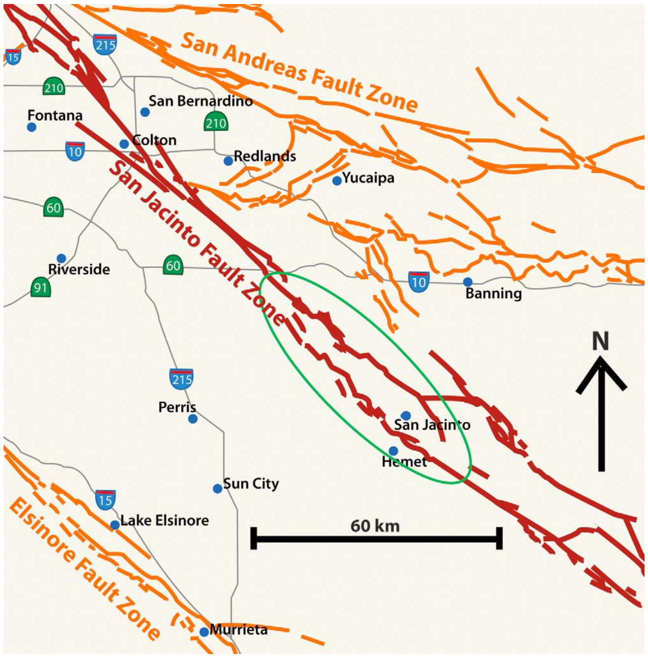

Figure 1. Map of the northern San Jacinto Fault Zone (red) and surrounding faults (orange), southern California. The stepover in the middle of the map, circled in green, includes a small fault segment between the main strands of the fault; this geometry was the basis for the current study. The San Gorgonio Pass area of the San Andreas Fault, in the upper right of this map, is also characterized by extremely complex and discontinuous geometry. Fault geometry based on the USGS Quaternary Fault Database.

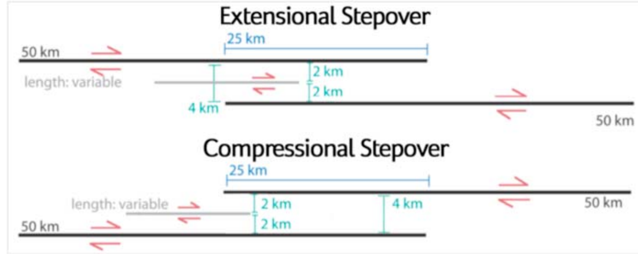

Figure 2. Model geometry. The black lines represent the primary fault segments, which are fixed at 50 km length and 16 km basal depth. The gray lines represent the intermediate fault, which is of variable length, and may have a basal depth of 16 km or 8 km. In both the extensional and compressional case, the intermediate fault is centered on the point to which rupture would re-nucleate on the second fault segment, in the absence of the intermediate fault. In the present study, all ruptures nucleate 3 km from the right end of the right primary segment, at 8 km depth.

unclamping, thereby reducing the distance that rupture can jump. We initially nucleate rupture by raising the shear stress above the yield stress over a designated patch; rupture re-nucleation after a jump occurs naturally based on the model stresses. Other physical and computational parameters are listed in Table 2. Further details of our model setup are presented in the auxiliary material.[1]

[4] Ground motion is one of the calculated outputs of FaultMod models. Due to the grid size of our models, as well as lack of geometric complexity on the fault and small-scale heterogeneity in the surrounding medium, they likely misrepresent some of the higher-frequency motions that may be particularly damaging to structures. As such, we do not consider these outputs as a quantitative description of expected motion from the modeled events, but rather a qualitative evaluation of the pattern of ground motion one might expect from rupture on a fault system with this geometry.

3. Results

3.1. Compressional Stepovers

[5] The compressional stepovers behave in a way that might have been predicted. After rupture termination on the initial segment, rupture always jumps from the nucleating segment to the intermediate segment. For the stress state in which rupture would have jumped to the far segment without this segment, rupture proceeded to jump from the intermediate segment to the far primary segment. For the stress state in which rupture would not have jumped without the intermediate segment, intermediate segments of less than 5 km do not allow the rupture to continue to the far segment, but segments of 7 km and longer allow the rupture to stairstep to the far segment. Changing the basal depth of the intermediate segment has no first-order effect on the rupture behavior, though it may alter the pattern of ground motion. In summary, a small fault segment between the primary segments of a compressional stepover either serves as an aid to rupture propagation or makes no difference; it never serves as a barrier.

3.2. Extensional Stepovers

[6] The results for extensional stepovers are far more sensitive to the details of initial stresses and geometry than the equivalent compressional cases. For the stress state in which rupture would have jumped without the intermediate segment and an intermediate fault that extends to 16 km depth, a short segment (~3 km) increases ground motion compared to a system with no segment, but a 5 km intermediate fault produces the somewhat counter-intuitive result of preventing rupture from jumping to the far primary segment. 7 km and 10 km intermediate segments also arrest rupture, but a 15 km segment allows rupture to stairstep between all three faults once again. The ground motions from these ruptures are shown in Figure 3. In the stress case where rupture would not have jumped in the absence of the intermediate segment, the presence of a segment of any length does not allow jumping. These results change dramatically in a case in which the intermediate fault can slip only to a depth of 8 km: ruptures that would have jumped in

Table 1. Model Stress Cases

Stress Case	Normal Stress	Shear Stress	S
Jumps without intermediate segment	16.65 MPa	10 MPa	0.49
No jump without segment (extensional)	17.8 MPa	10.34 MPa	0.60
No jump without segment (compressional)	20.02 MPa	11.01 MPa	0.80

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL053005.

Table 2. Physical and Computational Parameters

Parameter	Value
P-wave velocity	5000 m/s
S-wave velocity	3100 m/s
Density	2675 kg/m^3
Static coefficient of friction	0.75
Dynamic coefficient of friction	0.3
Slip-weakening parameter	0.4 m
Element size	200 m
Forced nucleation radius	3000 m

the absence of the intermediate fault continue to jump regardless of the length of the segment, and ruptures that would not have jumped in the absence of the intermediate fault can jump if the intermediate segment is greater than 5 km long.

4. Discussion

[7] The results for our test cases can be explained by an interaction between dynamic stress shadowing and directivity. If the intermediate fault is long enough to sustain a continuous, well-localized rupture front, the directivity effect of amplified dynamic waves radiating from the rupture tip in the direction of rupture produces a significant enough dynamic increase in Coulomb stress to trigger secondary rupture on the far primary segment. This effect occurs in spite of the dynamic stress shadowing that the intermediate fault imposes on the far primary segment. However, if the intermediate segment experiences only disconnected patches of slip, rather than a continuous rupture front, that slip does not generate amplified dynamic waves in the way that a continuous rupture front does, so they do not produce enough of an increase in Coulomb stress to overcome the stress shadow, thus preventing re-nucleation on the far fault. Ground motion in the direction of rupture propagation is stronger than in the reverse direction in both along-strike and up-dip directions. In some cases (particularly illustrative are the cases in which the basal depth of the intermediate fault is less than that of the primary faults), stress shadowing from rupture on the intermediate fault forces rupture on the far fault to nucleate closer to the base of the fault, leading to along-strike *and* up-dip directivity, and therefore stronger ground motion.

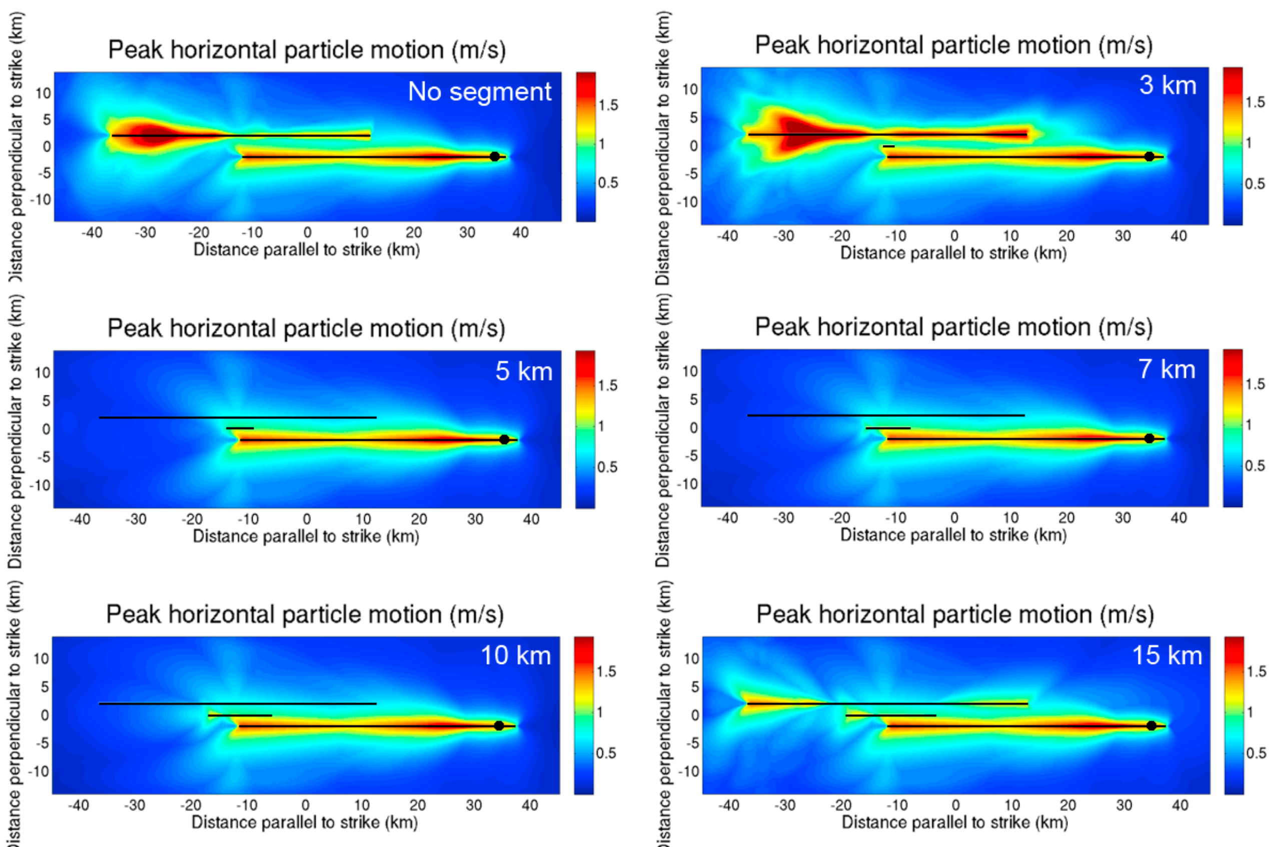

Figure 3. Map view plots of peak horizontal particle motion for models of dynamic rupture through an extensional stepover with an intermediate fault segment of variable length. The faults are shown in black, and the epicenter is marked with a black dot. (top left) No intermediate segment. (top right) 3 km intermediate segment; note the increased peak ground motion relative to a fault system with no intermediate segment. (middle left) 5 km intermediate segment; the intermediate segment prevents rupture from jumping to the far fault segment. (middle right) 7 km intermediate segment; the intermediate segment prevents rupture from jumping, but the intermediate segment shows its own ground motion signature. (bottom left) 10 km intermediate segment; similar to the 7 km case. (bottom right) 15 km intermediate segment; rupture is again able to jump between all three fault segments, but with reduced peak ground motion.

[8] The difference between the more predictable compressional cases and the more variable extensional cases comes from the difference in what happens to the region between the two primary faults. In a compressional strike-slip stepover, the direction of slip leads to an increase in normal stress between the faults. In order for rupture to re-nucleate in these stress conditions, there must be a considerable dynamic shear stress increase. This occurs ahead of the rupture front on the first primary fault, which allows re-nucleation on the intermediate fault. The resulting rupture has a high dynamic stress drop, which makes it energetic enough in most of our test cases to initiate a rupture on the far primary fault. In contrast, the area between the faults in an extensional stepover experiences a decrease in normal stress. While it becomes easier for rupture to re-nucleate on the intermediate fault given this low normal stress, the dynamic stress drop is lower than in the compressional case, which makes sustaining a continuous energetic rupture front, as opposed to unconsolidated patches of slip, more difficult. The auxiliary material includes Figure S1, which depicts normal stress intensities immediately after rupture reaches the end of the first fault. Finally, the observation that a shallower intermediate segment does not pose a barrier to rupture can be explained by the lack of stress shadowing on the farther fault at depth; it is in this deep region that nucleation takes place in such cases.

5. Conclusions

[9] The presence of a small fault segment within a stepover can have a controlling effect on ruptures through that fault system, as well as on the resultant ground motion. A rule of thumb for evaluating the likelihood of jumping rupture at a stepover is to examine the stepover width. It might appear that the presence of an intermediate segment should reduce the stepover width, implying a greater likelihood of through-going rupture propagation. In contrast, our results include the somewhat counter-intuitive effect that in some cases, an intermediate fault in a stepover may hinder rather than aid through-going rupture. The interaction between dynamic stress shadowing from rupture on one segment and buildup of dynamic waves in the direction of rupture on subsequent segments governs whether or not rupture will jump the stepover, and how intense the resulting ground motion will be. These behaviors are sensitive to the length and basal depth of the intermediate segment. These results also suggest that it is not always easier for rupture to propagate through extensional stepovers as compared to compressional ones.

[10] Both of these results complicate the assessment of rupture and shaking hazard on geometrically-complex fault systems; since behaviors are so sensitive to geometrical details, using generalized or simplified models to assess the probability of rupture propagating through any given real stepover may not present a very realistic suite of possible ruptures, nor the most accurate expected peak ground motion. Using simplified geometries may result in either an overestimate or an underestimate of maximum shaking intensity. Leaving out an intermediate segment can lead to an artificially high likelihood of through-going rupture, but conversely, when fault systems which include an intermediate fault do rupture fully, ground motions may be stronger than in cases without an intermediate fault, especially if the small fault has a shallower basal depth than the main faults. The sensitivity to detail shown in our models – which are still very idealized – suggests that more detailed models specific to individual faults will be the best way to assess rupture and shaking hazard associated with those faults. Specifically, we recommend further detailed studies of the fault geometry and rupture propagation along the northern San Jacinto Fault and the San Gorgonio Pass of the San Andreas Fault to address the seismic hazard of the surrounding areas.

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