Rupture propagation beyond fault discontinuities: Significance of fault strike and location

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Abstract

Factors that control the rupture processes across the stepovers are important to an understanding of earthquake growth and termination. In this study, we investigate such factors by calculating the spontaneous rupture processes of two non-coplanar faults in a three-dimensional model. Dealing with two extreme models in which two strike-slip faults are either parallel or perpendicular, we show that rupture processes beyond fault discontinuities are drastically different between the two models. We find three factors influencing rupture processes beyond fault discontinuities: depth of the upper edge of the two faults, location of the edge of the first fault, and geometry of the two faults. These factors determine the time and location of rupture jumps to the second fault. Whether rupture on the first fault reaches the surface or not, especially, controls the difficulty and locations of rupture jumps. This is because the stress perturbation is affected by the free surface.

Introduction

Earthquake faults are often composed of several subfaults. Whether rupture can jump beyond the fault discontinuities or not is important to earthquake growth and termination, and this affects the earthquake's size. While distributions of initial stress, strength, and stress drop on faults are likely to affect rupture propagation beyond the fault discontinuities, there has also been interest in the role of fault geometry (e.g. King and Nábělek, 1985[1]).

The purpose of this study is to explore factors that influence rupture processes at fault discontinuities. We carry out 3-D numerical simulations of spontaneous rupture processes for two non-coplanar faults, including the interaction between the faults. Following Kase and Kuge (1998)[2], we deal with two extreme models in which two strike-slip faults are either parallel or perpendicular. Wishing to consider the effect of the earth's surface in detail, we carefully examine significance of the fault strike and location by performing a number of simulations. We show that rupture propagation beyond fault discontinuities are drastically different between the two extreme models. We also show that whether faults intersects with the earth's surface or not controls the degree of difficulty and location of the rupture jump beyond the fault discontinuities, relating to the strike and location of faults.

Simulation method

We put two vertical faults in a 3-D, semi-infinite, homogeneous, isotropic, and linear elastic medium (Fig. 1). The medium is subjected to uniform prestresses, σ_{XX} and σ_{YY}. The first fault (Fault 1) has an initial crack. Along with Fault 1, we locate a second fault (Fault 2) in the medium, which is either of two fault orientation types. For one type of fault orientation (model A), Fault 2 is parallel to Fault 1. For the other type (model B), Fault 2 is perpendicular to Fault 1.

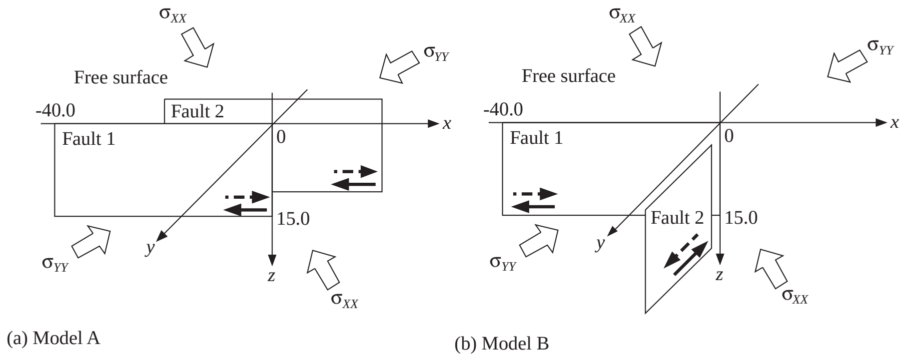

Figure 1: Three-dimensional models used in this study. Stars indicate the initial cracks. (a) Geometry of two faults in model A (case of compressional jog). Width of two faults is 15.0 km, and length is 40.0 km. (b) Geometry of two faults in model B. Two faults are perpendicular to each other. Width of two faults is 15.0 km, and length of Fault 1 and 2 are 40.0 km and 19.0 km, respectively.

At time $t = 0$, the shear stress on the initial crack of Fault 1 drops to dynamic frictional stress. The rupture then begins to propagate spontaneously on Fault 1. The rupture causes stress perturbation in the medium, which triggers rupture on Fault 2. Slip occurs on points where shear stress exceeds static frictional stress that is equal to the static coefficient of friction times normal stress. Then, after the slip starts, the shear stress obeys the slip-weakening friction law (Andrews, 1976[3]; Day, 1982[4]), and drops to dynamic frictional stress that is equal to the dynamic coefficient of friction times normal stress.

Distributions of strength and stress drop are uniform on each fault. We assume that the static and dynamic coefficients of friction and the ratio of strength to stress drop are the same value on the two faults.

Results

We carried out many numerical simulations, varying the depths of the upper edges of the two faults as well as the relative location of the two faults.

In the simulations in which we observed successful rupture propagation from Fault 1 to Fault 2, rupture was triggered on Fault 2 about 1 s after the rupture on Fault 1 arrived at the fault edge. The growth of the rupture on Fault 1 causes a stress perturbation around the rupture front. While the rupture propagates on Fault 1, the stress perturbation is too small to trigger rupture on Fault 2. After the rupture reaches the edge of Fault 1, the stress perturbation rapidly increases with time, and finally can trigger rupture on Fault 2. Thus, for rupture propagation to Fault 2, it is essential for the rupture on Fault 1 to arrive at the edge of the fault.

Our results in model A show that rupture jumps to Fault 2 only when the upper edges of the two faults are very close to or at the earth's surface. By rupture on Fault 1 intersecting with the earth's surface, rupture on Fault 2 was triggered at the earth's surface near the upper-right corner of Fault 1 (Fig. 2). This agrees with Harris and Day (1999)[5]. The triggered rupture was located ahead of the edge of Fault 1 in compressional cases (Fig. 2b), while it was back of the edge in extensional cases (Fig. 2c). On the other hand, when the upper edge of Fault 1 was beneath the earth's surface, rupture could be triggered at the upper edge of Fault 2 (Fig. 3a). On Fault 2 far from Fault 1, rupture was not triggered until the rupture on Fault 1 arrived at the upper-right edge of Fault 1 (Fig. 3b), whether or not Fault 1 reaches the earth's surface. Whether the rupture on Fault 1 reaches the earth's surface or not and the distance between the two faults determine the location where rupture jumps to Fault 2.

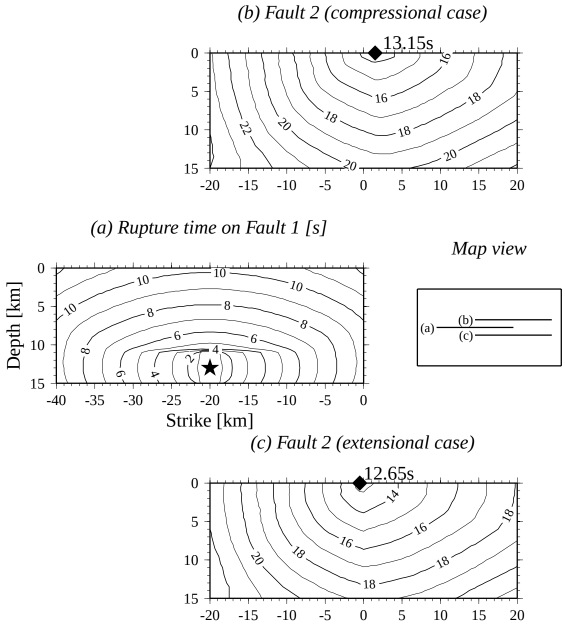

Figure 2: Rupture evolutions on (a) Fault 1, (b) Fault 2 composing compressional jog in model A, and (c) Fault 2 composing extensional jog in model A. Faults 1 and 2 have the same strength and stress drop. Both reach the earth's surface. Distance between Faults 1 and 2 is 1.0 km. Contours indicate rupture times in seconds. The star is the location of the initial crack. The diamonds are the location where ruptures are triggered on Fault 2.

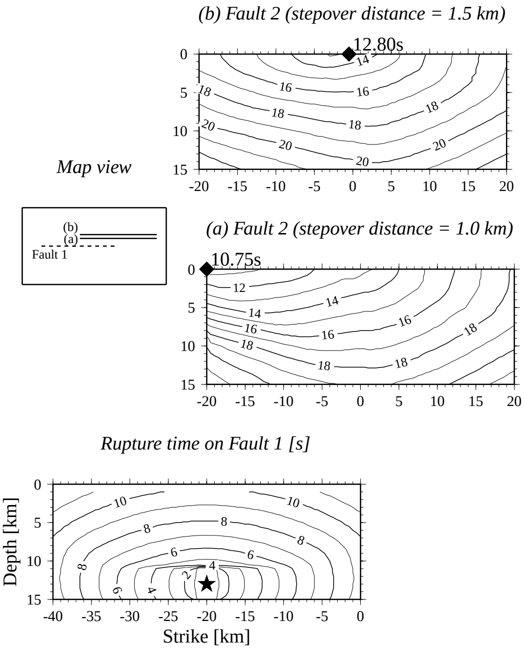

Figure 3: Rupture evolution on Faults 1 and 2 composing compressional jog in model A when Fault 1 does not reach the earth's surface. Depth of upper edge of Fault 1 is 1 km. Faults 1 and 2 have the same strength and stress drop as those for Fig. 2. Distance between Faults 1 and 2 is (a) 1.0 km and (b) 1.5 km, respectively. The details are the same as for Fig. 2.

In model B, the relative location of the two faults is very important to whether rupture can jump or not. In a region where the normal stress generated by rupture on Fault 1 is compressional, rupture never jumps to Fault 2, even if strength of Fault 2 is much less than that of Fault 1. In a region characterized by the extensional normal stress, rupture can jump to Fault 2 when Fault 2 is located close to the edge of Fault 1 (Fig. 4). The depth of the rupture jump drastically varies, depending on the location of Fault 2. It is especially noted that rupture can jump at a deep depth.

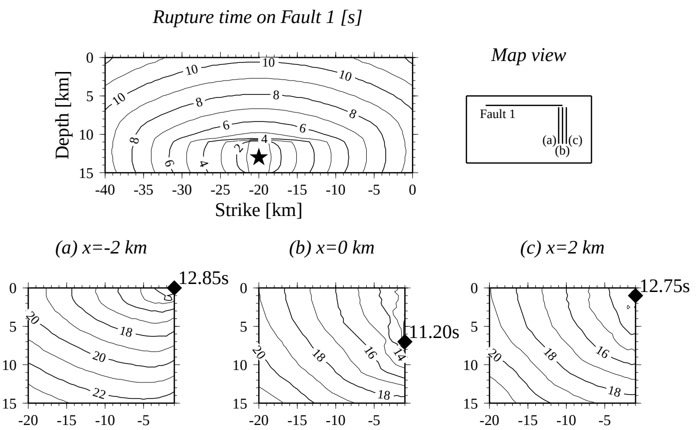

Figure 4: Rupture evolution on Faults 1 and 2 in model B when Fault 2 is located in the region with the extensional normal stress. Fault 2 is located in (a) $x = -2$ km, (b) $x = 0$ km, and (c) $x = 2$ km, respectively. Faults 1 and 2 reach the earth's surface. The details are the same as for Fig. 2.

Fig. 5 shows the relationship between the depth of the rupture jump and the horizontal location of Fault 2. Faults 1 and 2 reach the earth's surface. When Fault 2 is located at the edge of Fault 1 ($x = 0$ km; Fig. 4b), rupture jumps to Fault 2 at the deep depth of 7 km. The rupture on Fault 2 starts to propagate after the rupture on Fault 1 terminates completely (Fig. 4b). When Fault 2 is located near the edge of Fault 1 ($x = \pm 2$ km; Figs. 4a and c), rupture jumps at the shallow part and propagates. When Fault 2 is located more than 2 km back of the edge of Fault 1, rupture cannot propagate. The distance at which rupture can jump is longer ahead of the edge of Fault 1 ($x > 0$) than back ($x < 0$).

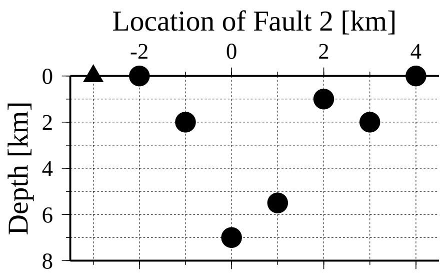

Figure 5: Relationship between the depth of the rupture jump and the horizontal location of Fault 2 in model B. Faults 1 and 2 reach the earth's surface. The edge of Fault 1 is located at $x = 0$. The horizontal axis is the location of Fault 2 given in the x coordinate. The vertical axis is the depth of rupture jump. Circles mean that ruptures propagate on Fault 2. The triangle means that rupture is triggered but terminates soon.

Our results reveal that relative location and strike of two faults are very important to not only whether rupture can jump or not but also rupture processes including locations and depths of rupture jumps. It is also remarkable that whether faults reach the earth's surface or not relate to rupture processes.

Discussion

Effect of the earth's surface

We showed that rupture jumps tend to occur at the earth's surface and the horizontal location of the rupture jump depends on whether the faults reach the earth's surface or not. We first discuss the role of the earth's surface on the rupture jumps, paying our attention on model A.

The dominant factor on rupture jumps is normal stress rather than shear stress. Normal stress on Fault 2 decreases efficiently near the earth's surface. Therefore, rupture can easily jump at a very shallow depth near the earth's surface. However, when the rupture on Fault 1 reaches the earth's surface, the shear stress concentration caused by the rupture is suppressed by dislocation at the free surface. As the result of the insufficient shear stress concentration, rupture on Fault 2 is not triggered until the rupture on Fault 1 arrives at the upper-right edge of Fault 1 and the stress increases near the earth's surface again (Fig. 2b and c).

When the rupture on Fault 1 terminates beneath the earth's surface, the shear stress concentration around the upper edge of Fault 1 is significant. If the distance between the two faults is short, the high stress concentration can cause rupture on Fault 2 (Fig. 3a). As the distance is longer, the stress concentration affects less shear stress on Fault 2. Rupture is not triggered on Fault 2 at a long distance until the rupture on Fault 1 arrives at the upper-right edge of Fault 1 (Fig. 3b).

Effect of fault strike and location

In model B, the relative location of the two faults is very important to whether rupture can jump or not. Our results have shown that rupture can jump to Fault 2 only in a region where the normal stress generated by the rupture on Fault 1 is extensional (Fig. 4). In contrast, in model A, rupture can jump in both compressional and extensional cases.

The observations suggest that normal stress generated by rupture on Fault 1 more strongly controls the rupture jumps in model B than A. This difference is attributed to the different components of normal stress. The normal stress component is τ_{yy} in model A and τ_{xx} in model B, respectively. Since a stress perturbation caused by slip on Fault 1, Δu_x, is more influential in τ_{xx} than in τ_{yy}, the difference between compressional and extensional cases is clearer in model B than A.

The depth variation of the rupture jump as shown in Fig. 5 can be also explained by considering normal stress and shear stress concentration close to the edge of Fault 1. Effective strength of Fault 2 becomes small due to small normal stress. When Fault 2 is located very close to the edge of Fault 1, a small stress perturbation generated at the deep edge of Fault 1 can trigger rupture on Fault 2. When Fault 2 is located at a long distance from the edge of Fault 1, the stress perturbation around the deeper edge is too small to trigger rupture on Fault 2. Rupture is triggered on Fault 2 by a large stress perturbation at a shallow edge of Fault 1. Back of the edge of Fault 1, concentration of shear stress is suppressed by rupture on Fault 1 when Fault 1 reaches the earth's surface. Rupture can jump to Fault 2 only at a short distance.

Conclusions

We carried out 3-D numerical simulations using two non-coplanar strike-slip faults. We found that rupture processes across fault discontinuities are influenced by three factors: (1) depth of the upper edge of the two faults, especially whether the faults reach the earth's surface or not, (2) location of the edge of the first fault, and (3) geometry (e.g. strike and step sense) of the two faults. These factors affect when and where rupture is triggered and how rupture propagates on the second fault.

Most of successful rupture jumps in our numerical simulations occur very close to the earth's surface. The exceptions are the limited cases when the two faults are perpendicular. Moreover, we have found that whether rupture on the first fault reaches the earth's surface or not controls not only the degree of difficulty but also locations of rupture jumps, relating to step senses of the two faults. The earth's surface thus has a strong influence to rupture processes across fault discontinuities.

Acknowledgments

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