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# FAULT STEPS AND THE DYNAMIC RUPTURE PROCESS: 2-D NUMERICAL SIMULATIONS OF A SPONTANEOUSLY PROPAGATING SHEAR FRACTURE

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Abstract. Fault steps may have controlled the sizes of the 1966 Parkfield, 1968 Borrego Mountain, 1979 Imperial Valley, 1979 Coyote Lake and the 1987 Superstition Hills earthquakes. This project investigates the effect of fault steps of various geometries on the dynamic rupture process. We have used a finite difference code to simulate spontaneous rupture propagation in two dimensions. We employ a slip-weakening fracture criterion as the condition for rupture propagation and examine how rupture on one plane initiates rupture on parallel fault planes. The geometry of the two parallel fault planes allows for stepover widths of 0.5 to 10.0 km and overlaps of -5 to 5 km. Our results demonstrate that the spontaneous rupture on the first fault segment continues to propagate onto the second fault segment for a range of geometries for both compressional and dilational fault steps. A major difference between the compressional and dilational cases is that a dilational step requires a longer time delay between the rupture front reaching the end of the first fault segment and initiating rupture on the second segment. Therefore our dynamic study implies that a compressional step will be jumped quickly, whereas a dilational step will cause a time delay leading to a lower apparent rupture velocity. We also find that the rupture is capable of jumping a wider dilational step than compressional step.

## Introduction

Fault segmentation is observed at many different length scales in the field, from centimeters to kilometers, but how does it affect the dynamic rupture process? It has been proposed that one type of fault segmentation, the fault step (Figure 1) may have controlled the sizes (magnitudes) of the 1966 Parkfield, 1968 Borrego Mountain, and 1979 Imperial Valley, earthquakes [Sibson, 1986], the 1979 Coyote Lake earthquake [Reasenberg and Ellsworth, 1982; Sibson, 1986], and the 1987 Superstition Hills earthquake [Rymer, 1989]. However, to date no one has given limits to the geometrical parameters that could affect the rupture process.

Can an earthquake 'jump' a 1 km step or a 5 km step? If we could determine which geometries stop a propagating earthquake rupture, then we might also determine the size of an expected earthquake. The length of fault rupture is directly proportional to seismic moment. A rupture which propagates through many equal-length fault segments will produce a much larger earthquake (e.g. the M8 1857 Ft. Tejon earthquake) than one which only propagates through one or two of the segments (e.g. the M5 1966 Parkfield earthquake). The problem is determining the minimum step distance which cannot be jumped by a dynamically propagating rupture. As an initial approach we examine the case of vertical strike-slip faults in a linearly elastic medium. We use a two-dimensional finite difference program to simulate the spontaneously propagating shear fracture.



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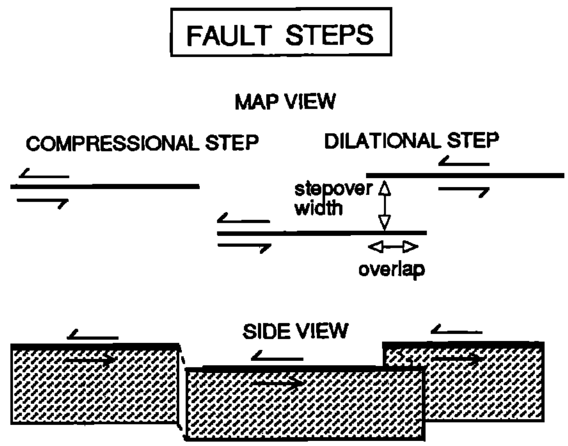


Fig. 1. Right and left steps in a left-lateral vertical strike-slip fault. When two of the fault segments are slipping at the same time, a right step is a compressional step and a left step is a dilational step. For right-lateral faults, right steps are dilational and left steps are compressional. The stepover width is the perpendicular distance between the two faults and the overlap is the along-strike distance of fault crossover. When the two fault ends do not pass each other the overlap is negative, as shown for the compressional step.

## Previous Studies

Sibson [1986] presented a number of case studies and proposed that fault steps might affect the rupture process; but to date no dynamic calculations (spontaneous rupture) have been made for discontinuous faults consisting of two or more non-coplanar segments. Rodgers [1980] studied the static problem of fault steps using dislocation theory but did not include the important factor of fault interaction. Segall and Pollard [1980] analyzed the 2-D (plane stress) quasi-static problem by looking at the effects of pre-existing *echelon* shear cracks on the regional stress field and including the elastic interactions between the cracks. Their static solution showed that for left steps in right-lateral shear, normal-traction on the overlapping crack tips increases, thereby inhibiting frictional sliding. For right steps in right lateral shear, the static solution suggests that sliding is enabled by a reduction in the normal-tractions. Based on these results, Segall and Pollard [1980] proposed that the left (compressional) steps should be a barrier to fault slip and could stop an earthquake.

Mavko [1982] also modeled fault interaction using 2-D quasi-static calculations. He used his results to successfully predict the creep records near Hollister, CA. Aydin and Schultz [1990] looked at the fault interaction problem in an attempt to understand the relationship between fault step and overlaps for *en echelon* strike-slip faults around the world. Using a quasi-static study, they concluded that fault interaction is responsible for the observed *en echelon* fault geometry.

One essential element not included in the quasi-static studies is the time dependence of fault rupture. Although the quasi-static studies give insight into processes which occur over a long time scale, they do not include the stress waves and time dependent stress concentrations generated during the earthquake rupture process. It is the stress field during the dynamic rupture that loads the next fault segment and satisfies a rupture criterion that determines if a M6 earthquake cascades into a M8 earthquake. To examine how the dynamic stress field affects rupture on an adjacent parallel segment we consider a spontaneously propagating shear fracture in an elastic medium.

## Method

To study the dynamic fault-step problem we use a 2-D finite difference program [Day and Skholler, written comm., 1990] which is a 2-D version of the 3-D method used by Day [1982]. The new program also accommodates non-coplanar fault segments. The 2-D case implies that we are solving the problem of plane strain. The two shear cracks have half-lengths of 14 km. We initiate the rupture in the middle of the first fault segment then allow it to spontaneously propagate using a slip-weakening fracture criterion [Ida, 1972; Day, 1982; Andrews, 1985] and a Coulomb friction law. Both static and dynamic friction are proportional to the normal stress. When the fault first begins to slip its strength drops linearly from a static yield strength to a dynamic yield strength. The slip distance over which this occurs is the slip-weakening critical distance, $d_0$. We use a $d_0$ of 10 cm [Day, 1982]. At the end of the first fault the static yield stress is very high and the rupture cannot break through. Three possible things can happen: 1) The rupture can die at the end of the first fault segment. This leads to the shortest rupture length and smallest earthquake. 2) The rupture can trigger the second fault segment, but then run out of energy and stop propagating. This leads to a slightly larger earthquake. 3) The rupture can trigger the second fault segment, then continue to propagate. This last case produces the largest earthquake since the rupture length is longest.

## Results

We present the results from a set of 2-D cases whose parameters are listed in Table 1. Each of these simulations is for two shear cracks, simulating two left-lateral vertical strike-slip faults of infinite vertical extent. Each test case simulates a 100 bar stress drop (a very large earthquake) using a static coefficient of friction of 0.75 (an 'average' value from Byerlee [1978]) and a dynamic coefficient of friction of 0.3. The initial shear stress is 200 bars, emulating a 'weak' fault setting [Brune et al., 1969]. It takes 2.9 seconds for the rupture to first reach the end of the first fault segment (a supershear rupture velocity as predicted by Das and Aki [1977] and Andrews [1985]). Rupture of the second segment then depends upon on its geometrical relationship to the initial fault segment. Figure 2 summarizes the location and time of the first point(s) to rupture on the second segment for the case of 5 km overlap. Note that the dilational steps generally trigger later than the compressional step with equal stepover width. Furthermore the locations of the initial point of rupture on the offset segment differ for the two geometries.

TABLE 1. Simulation variables

| | |
|---|---|
| Initial shear stress (bars) | 200. |
| Initial normal stress (bars) | 333. |
| Static coefficient of friction | 0.75 |
| Dynamic coefficient of friction | 0.30 |
| P-wave velocity (km/s) | 6.000 |
| S-wave velocity (km/s) | 3.464 |
| Density (g/cm$^3$) | 2.7 |
| Grid size (km) | 0.25 |

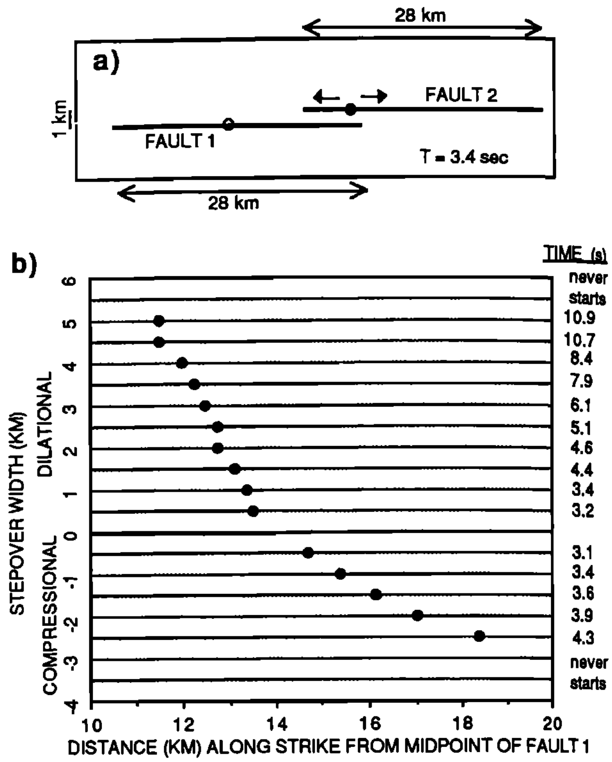


Fig. 2a). Map view of two faults at 3.4 seconds for the case of a dilational step (left step in left-lateral shear) and the parameters listed in Table 1. Both faults are 28 km long. Stepover width is 1 km, overlap is 5 km. Open circle indicates point where rupture first nucleated on fault 1 at 0 seconds. At 2.9 seconds the rupture first reached the end of fault 1. At 3.4 seconds the point marked by the solid circle on fault 2 starts to rupture. After 3.4 seconds, the rupture propagates bilaterally on fault 2. b) Summary (map view) of the results from 19 simulations of fault steps in left-lateral shear. For each simulation only two faults exist, as depicted in a). Fault 1 is drawn with a heavy dark line. All of the fault 2's are shown by the light parallel lines. Each solid circle indicates the point where a fault 2 is initially triggered. The times to the right of the figure are the trigger times for each fault 2.

To explain the location and timing of the triggering we analyze the stress perturbation due to rupture propagation on the first fault segment. It is important to realize that the single fault study only gives information on when a point on the second fault exceeds the static friction level and does not determine whether the stress concentration is sufficient to induce propagation on the second segment. Our models do include the rupture propagation on the second segment, therefore we present the single fault study (Figure 3) only as an aid to understanding the rupture initiation problem.

The rupture can start on the second fault segment when Coulomb friction has been exceeded (when the shear stress on the fault exceeds the normal stress times the coefficient of static friction). Because both the shear stress field and the normal stress field in the medium are perturbed by the propagating rupture on the first fault segment, rupture occurs on the second segment where and when the initial shear stress ($\tau_0$) plus the change in the shear stress ($\Delta\tau(t)$) exceeds the static coefficient of friction ($\mu$) times the initial normal stress ($\sigma_{n0}$) plus the change in the normal stress ($\Delta\sigma_n(t)$):

$$|\tau_0 + \Delta\tau(t)| > \mu\, |\sigma_{n0} + \Delta\sigma_n(t)| \qquad (1)$$

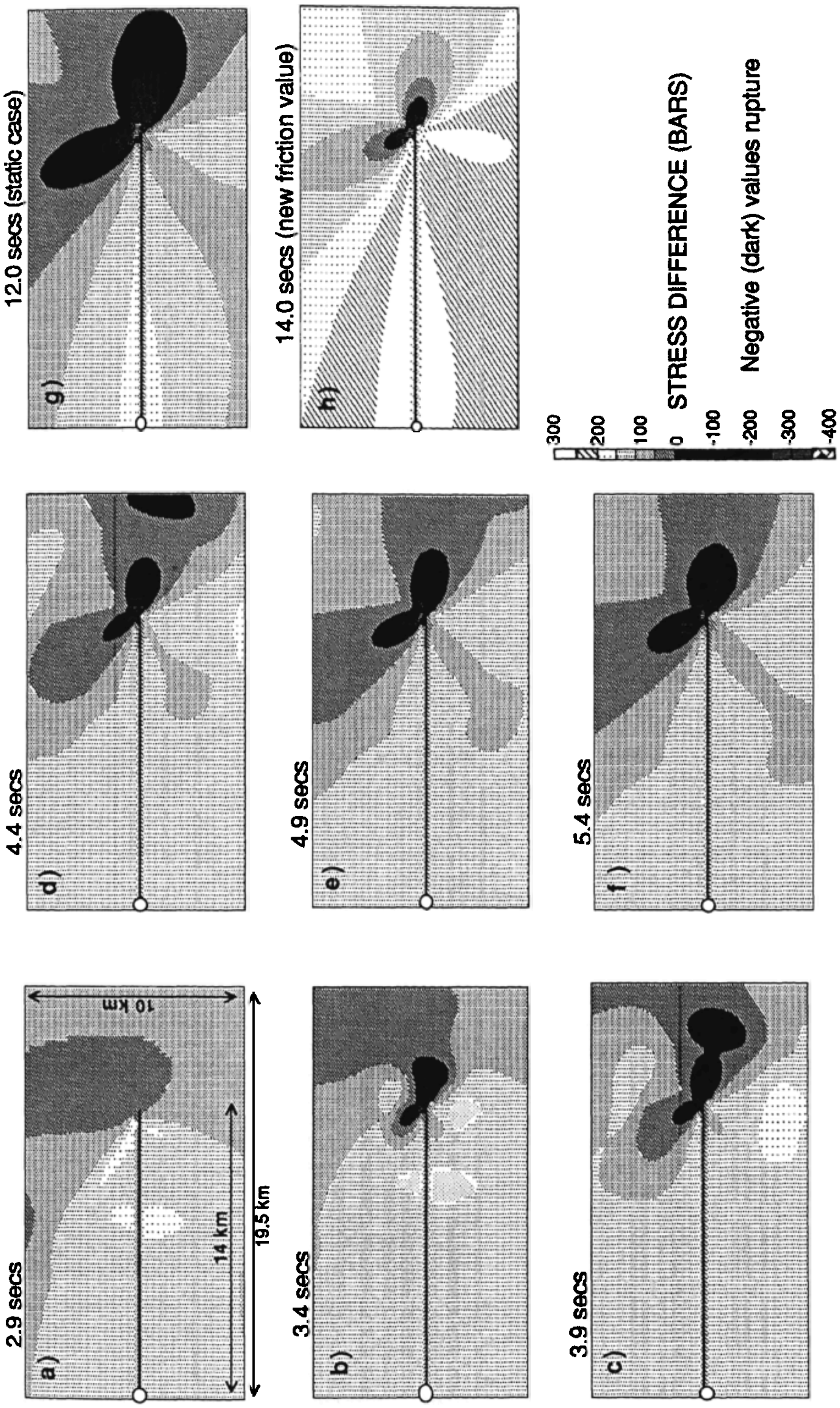


Fig. 3. a) Contoured map view of the stress difference (Δs) at 2.9 secs due to rupture propagation on fault 1 (the dark line). Fault 1 is a left-lateral fault.. Map scale is 1:1. Negative values of Δs indicate regions where a second parallel fault could start but do not determine if the rupture would continue to propagate on the second fault (see text). At 2.9 secs the rupture has just reached the end of fault 1. No negative regions exist so no parallel left-lateral strike-slip fault could trigger at this time. The parameters used in these simulations are listed in Table 1. b-f) Δs at 3.4, 3.9, 4.4, 4.9, 5.4 secs. g) Δs at 12.0 secs. This is the static solution (the waves have left the area) for a single fault segment which also defines the maximum possible stepover width for the second parallel fault. Any parallel fault beyond this distance will never trigger. h) The static solution using a static coefficient of friction equal to 1.1 (for a-g the value was 0.75). All other parameters are those listed in Table 1. The increase in the static friction coefficient creates a smaller potential rupture area, compared to Figures 2 and 3a-g, however the shape remains the same. Rupture first reached the end of fault 1 at 5.0 secs due to a subshear rupture velocity.

This implies that rupture can occur when and where the stress difference, Δs is less than zero:

$$\Delta s(t) = \mu \mid (\sigma_{n0} + \Delta\sigma_n(t) \mid - \mid \tau_0 + \Delta\tau(t) \mid < 0 \qquad (2)$$

Equations (1) and (2) assume a compressional stress field ($\sigma_{n0} + \Delta\sigma_n(t) < 0$) so that the faults remain closed.

Plots of Δs(t) due to rupture of the first fault segment are presented for a few time slices (Figure 3). The regions with negative contours indicate where a second parallel segment could begin to rupture. As time increases, the potential rupture region expands and this explains the time dependent rupture node pattern presented in Figure 2.

## Discussion

The purpose of the present study has been to explore the effect of a fault step on the dynamic rupture process. We assumed vertical strike-slip faults set in an otherwise linearly elastic material. It is possible that fluids play an important role in the static rupture process [e.g. Sibson, 1986] however, the results of this study neglect fluids. It is interesting to note that Sibson used fluid pressure to explain a time delay occasionally observed at dilational fault steps. We also predict a time delay (although at a much shorter time scale) for dilational steps even though we have neglected the effects of fluid pressure.

Another important factor in the numerical simulations is that we assume that the two parallel fault segments are vertical. At the present time we have limited information about what happens to neighboring strike-slip faults at depth [e.g. Kadinsky-Cade and Barka, 1989]. We do not know if they merge or if they remain separate entities throughout the seismogenic regime. Local seismicity has delineated separate fault strands for the San Andreas fault at Parkfield [Eaton et al., 1970] and the Coyote Creek fault in the southern San Jacinto fault zone [Hamilton, 1972].

One point of this study has been to determine if it is even possible for a rupture to 'jump' a fault step once the separation between two faults is greater than a certain critical distance. For example, our results for the specific case (Table 1) of a 100 bar stress drop (and supershear rupture velocity) show that a compressional step with a stepover width of 3 km will never be jumped, whereas a dilational step with a stepover width of 3 km could be jumped. Knuepfer [1989] notes that in his data collected from field observations of strike-slip faults, no rupture has ever jumped a compressional step (or double bend) wider than 5 km and no rupture has jumped a dilational step (or double bend) wider than 8 km. These observations, that ruptures jump compressional steps with narrower stepover widths, is predicted by our study. We also note that for dilational steps with negative overlap there is a very narrow range of stepover widths for a second 'triggerable' fault segment. We therefore expect that most dilational steps (in vertical strike-slip faults) have positive overlap even though they may be mapped as having negative overlap. An example of this is taken from the 1966 Parkfield earthquake where the stepover width between the fault segments is about 1 km. Hanna et al. [1972] map the dilational fault step at Parkfield with a negative overlap, but aftershocks of the 1966 earthquake [Eaton et al., 1970] show a positive overlap. Additional data are presented by Aydin and Schultz [1990] who compiled measurements of strike slip faults around the world. Beyond 0.5 km stepover width all of their dilational fault steps exhibit positive overlap. This observation is also predicted by our results.

Another important result of this study is the relative timing of the rupture nodes on the second fault. We have seen that although a wider dilational step can be jumped, the effect of the dilational step is to temporarily the delay the rupture. Compressional steps are jumped for a narrower stepover width, but when the rupture does continue to propagate, it is not delayed as much at the step. This implies that if the optimal geometries exist for both a compressional step and a dilational step then the rupture will take the faster path, which is usually the compressional step. Our results also imply that the average rupture velocity in a large earthquake which ruptures through a dilational step will be lower than the average velocity for an earthquake which ruptures through a compressional step.

To summarize, we have modelled the effects of fault steps on the dynamic rupture process. The purpose was to determine if a spontaneous rupture can 'jump' from one fault segment to another parallel fault segment with specified distance and overlap between the two fault segments. If we can understand what stops or allows a rupture to continue propagating along the length of a fault zone, then we might also determine the potential magnitude of the earthquake. We have shown examples of geometrical cases where the rupture does jump a step and continue propagating on the second fault segment. We have also shown cases where the step terminates the rupture on the first fault. This is the first time that numerical simulations have been presented for spontaneously propagating shear fractures encountering a fault step.

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