Nonuniform prestress from prior earthquakes and the effect on dynamics of branched fault systems

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Received 12 April 2006; revised 21 December 2006; accepted 5 January 2007; published 18 May 2007.

[1] To examine the effects of branched fault geometry on the dynamics of fault systems in the long term, we perform multicycle simulations on generic faulting models. An explicit finite element algorithm is used to simulate spontaneous dynamic rupture of earthquakes. The fault stress during the interseismic period is evaluated by an analytical viscoelastic model. We find that the fault prestress field becomes highly nonuniform near the branch point and on the two branch segments over multiple earthquake cycles, owing to the branched fault geometry and stress interaction between the two segments. The principal prestress on faults rotates over multiple earthquake cycles and departs from the regional stress field significantly near the branch point. After a number of earthquake cycles, the branched fault systems evolve to a steady state in which several patterns of the fault prestress and earthquake rupture repeat. The nonuniform prestress developed from previous earthquakes has large effects on the rupture and slip patterns. Several different rupture scenarios can occur on a given branched fault system. In addition, backward branching can occur in the nonuniform prestress field, either driven by slip on the “stem” of the fault system or through a triggering mechanism. These modeling results may have important implications for understanding fault-branching behavior observed in the 1992 Landers, the 1999 Hector Mine, and the 2002 Denali fault earthquakes and for seismic hazard analysis in the areas where branched fault systems exist.


1. Introduction

[2] Recent earthquakes such as the 1992 Landers (California, Mw 7.3), 1999 Hector Mine (California, Mw 7.1), and 2002 Denali fault (Alaska, Mw 7.9) have shown the importance of understanding the dynamics of branched fault systems. In the Landers earthquake, the rupture started on the Johnson Valley fault, branched onto the Kickapoo (Landers) fault (while continuing a few kilometers along the former) and then branched onto the Homestead Valley fault, the Emerson fault, and the Camp Rock fault [Sowers et al., 1994; Fliss et al., 2005]. In the subsequent branches, the rupture primarily propagated to the NW, but also progressed backward to the SSE. In the Hector Mine earthquake, the rupture nucleated near a bifurcation point, propagated bilaterally south and north on a buried fault, and also progressed onto a northwest branch [Scientists from the U.S. Geol. Surv. Prof. Pap. (USGS), Southern California Earthquake Center (SCEC), and California Division of Mines and Geology (CDMG), 2000; Oglesby et al., 2003]. The Denali fault earthquake branched off from the Denali fault and progressed exclusively along the Totschunda fault in the eastern part of the rupture [Eberhart-Phillips et al., 2003; Bhat et al., 2004; Oglesby et al., 2004].

[3] Some understanding of the mechanics underlying fault branching has been achieved recently. By studying the stress field near a dynamically propagating rupture, Poliakov et al. [2002] found that off-axis branching depends strongly on the prestress state and the rupture speed. Kame et al. [2003] extended this work and performed an extensive set of numerical simulations of dynamic fault-branching. They determined that the favorable side for branching rupture switches from the extensional to the compressional sides as the direction of maximum compressive prestress makes progressively shallower angles with respect to the main fault. They also found that the enhanced dynamic stressing when rupture velocity is very near the Rayleigh velocity facilitates simultaneous rupture on the main fault and the branch. As an example, Kame et al. [2003] showed that the rupture branching from the Johnson Valley fault to the Kickapoo fault in the Landers earthquake was consistent with the theoretical concepts developed in the two studies above. Bhat et al. [2004] adopted these theories to analyze the dynamic slip transfer from the Denali fault to the Totschunda fault during the Denali fault earthquake. They found that most of their simulations with different combinations of prestress state and rupture velocity at the branching point produced the observed branching.
“Backward branching,” where rupture propagates around an acute angle between the primary and secondary segments, is difficult to be understood in a uniform regional stress field because of the stress shadow effects. To explain field observations of backward branching, Fliss et al. [2005] proposed a jumping mechanism in which the main fault and the branch do not join and the stopping phase of rupture on an initial fault strand reactivates rupture on the “backward” branch. They used this idea to explain the backward branching from the Kickapoo fault to the Homestead Valley fault in the Landers earthquake.

In all the above studies, a simple, uniform regional stress field is assumed to be the stress state on the main fault and the branch prior to rupture. However, this assumption may be invalid on branched fault systems that have already experienced earthquakes. Recent multiphase models of fault systems with a bend or a stepover have shown that the fault initial stress before an earthquake can depart from a uniform regional stress field significantly near geometrical discontinuities [Duan and Oglesby, 2005, 2006] if the fault system has experienced many earthquakes. This nonuniform fault prestress can have large effects on such fault systems.

Several studies have shown that nonuniform initial stress is required to reproduce the observed rupture patterns in real earthquakes on branched fault systems. Aochi and Fukuyama [2002] slightly rotated the tectonic stress field along the Kickapoo fault to allow the rupture to propagate along the observed fault geometry in the Landers earthquake. In the study of dynamics of the Hector Mine earthquake, Oglesby et al. [2003] found that, to obtain rupture propagation over the entire fault, either additional shear stress or a reduction in normal stress amplitude must be assigned to the northwest and southern fault segments. They argued that the additional shear stress on these segments might be due to the fact that each segment has a different rupture history. In a study of inverse kinematic and forward dynamic models of the Denali fault earthquake, Oglesby et al. [2004] found that, while a uniform tectonic stress field can explain the abandonment of the Denali fault for the Totschunda fault, it cannot explain the complex slip pattern in the event. They used a highly heterogeneous fault stress for the dynamic model to produce a slip pattern that qualitatively matches a kinematic inverse model based on seismic and GPS data.

The stress field on each segment of a fault system must be a result of both the regional stress field and all earthquake cycles the fault system and nearby fault systems have experienced. As most large earthquakes occur on the fault segments that have experienced many earthquakes, the prestress field on a fault might depart from a uniform regional stress field significantly. Recently, several researchers have tried to incorporate effects of some historical earthquakes on the fault prestress into dynamic models. Harris and Day [1999] took the effect of the 1934 earthquake into account to explain why the 1966 Parkfield earthquake was able to jump a 1-km-wide stepover. In studying the 1999 Izmit (Mw 7.6, Turkey) earthquake, Harris et al. [2002] attempted to include the effect of past earthquakes on neighboring segments to explain the stopping of rupture and the mismatch of surface slip between their models and observations. Aochi and Madariaga [2003] used a slip deficit model to include the effect of previous events on the fault initial stress to study the dynamic rupture process and strong ground motion of the Izmit earthquake.

Although these attempts shed light on the importance of the rupture history of a fault system for dynamic rupture and strong ground motion, a practical approach by which the effect of previous earthquakes can be effectively included is needed for more accurate models of multiple earthquake cycles. Furthermore, stress buildup near geometrical complexities over multiple earthquake cycles must be limited by some physical processes during earthquake cycles [e.g., Nielsen and Knopoff, 1998; Duan and Oglesby, 2005]. More recently, we have developed a procedure in two dimensions to simulate multiple earthquake cycles on a fault system and applied it to examine long-term dynamics of fault systems with bends and stepovers [Duan and Oglesby, 2005, 2006]. In this procedure, we combine a viscoelastic model for the interseismic process and an elastodynamic model for the coseismic process to simulate multiple earthquake cycles.

In this work, we apply the procedure of Duan and Oglesby [2005, 2006] to branched fault systems. Our aim is to examine the nonuniform prestress patterns that develop from long rupture sequences and their effects on dynamics of branched fault systems. We will show that several distinct rupture scenarios can occur on the same branched fault system. Backward branching, which appears difficult to be understood in a uniform prestress state, may be a result of the nonuniform fault prestress.

2. Method and Model

We utilize the procedure developed by Duan and Oglesby [2005, 2006] to simulate multiple earthquake cycles on two-dimensional fault systems. In this procedure, an earthquake cycle consists of an interseismic period and a coseismic process. The stress buildup and relaxation on a fault system during the interseismic period are analytically solved by a Maxwell viscoelastic model. Following the work of Duan and Oglesby [2005], the shear and normal stresses on a fault segment at time $t$ during an interseismic period can be evaluated by

$$\sigma_s(t) = (\sigma_0^s - \eta \gamma_s) \exp\left(-\frac{\mu t}{\eta}\right) + \eta \gamma_s,$$

$$\sigma_N(t) = (\sigma_0^N - \sigma^s - \eta \gamma_n) \exp\left(-\frac{\mu t}{\eta}\right) + \eta \gamma_n + \sigma^s,$$

respectively. In these equations, $\mu$ is the shear modulus, $\eta$ is the viscosity, $\sigma^s$ is the ambient stress (for example, the lithostatic stress), $\sigma_0^s$ and $\sigma_0^N$ are the shear stress and normal stress on the fault segment at the beginning of an interseismic period ($t = 0$), and $\gamma_n$ and $\gamma_s$ are strain rates resolved onto normal and shear directions of the fault plane, respectively. Strain rates are assumed to result from the tectonic shear loading near a plate boundary. By tensor analysis, we have

$$\gamma_n = \gamma \sin(\theta), \quad \gamma_s = \gamma \cos(\theta),$$

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where $\theta$ is the angle between the strike of the fault segment and the maximum shear strain rate direction. For simplicity, we define this maximum shear strain rate direction as the tectonic-loading direction. In the above evaluation of fault stresses during an interseismic period, there are two components. One is stress buildup owing to the tectonic loading. The other is stress relaxation characterized by the viscosity in the model. Stress relaxation in the model is merely a proxy for a variety of real processes, such as off-fault deformations. Examples of these deformations are pull-apart features within a dilational regime or push-up features within a compressional regime. The stress relaxation component can prevent fault stresses from accumulating pathologically over the long-term near geometrical complexities [Nielsen and Knopoff, 1998; Duan and Oglesby, 2005, 2006]. In this viscoelastic model, we assume that the relaxation function is uniform in the entire model (for example, independent of the spatial coordinates). Notice that, in this model, the shear and normal stresses tend asymptotically toward the limit values $\eta_{\gamma\tau}$ and $\eta_{\gamma n} + \sigma_n$, respectively, in the absence of an earthquake event.

[11] An elastodynamic model is used to characterize the coseismic process of an earthquake cycle. A new explicit finite element method (FEM) code EQdyna [Duan and Oglesby, 2006] is used to numerically simulate spontaneous dynamic rupture on a fault system and wave propagation in the surrounding medium. Some general features of this code are summarized as follows. First, the code directly solves the equation of motion numerically. Second, a diagonal mass matrix is obtained through a lumping technique [Hinton et al., 1976] so that the solution can be advanced in the time domain explicitly (for example, without the necessity of solving a coupled set of equations). Third, one-point Gaussian quadrature is used to perform numerical integration for quadrilateral and triangular elements in two dimensions and hexahedral elements in three dimensions for computational efficiency. Fourth, a stiffness hourglass control technique [Kosloff and Frazier, 1978] is used to suppress hourglass modes induced by the one-point Gaussian quadrature. Fifth, a stiffness-proportional parameter of the general Rayleigh damping technique is used to control high-frequency numerical noise. Finally, the traction-at-split-node method [e.g., Andrews, 1999] and a slip-weakening friction law [Ida, 1972; Palmer and Rice, 1973; Andrews, 1976; Day, 1982] are used to implement fault boundaries. The slip-weakening friction law in this study can be expressed as

$$f(\Delta u) = f_s + (f_a - f_s)(1 - \Delta u/D_0)H(1 - \Delta u/D_0),$$

where $f_s$ and $f_a$ are the static and dynamic coefficients of friction, respectively. $\Delta u$ is slip on the fault, $H(\cdot)$ is the Heaviside function, and $D_0$ is the critical slip distance.

[12] A useful feature of the code EQdyna is that it can handle different element types. This feature provides EQdyna with great flexibility to model geometrical complexities. As an example, Figure 1 shows a FEM mesh for a branched fault system model. In this FEM mesh, most elements are quadrilateral. To avoid heavily deformed quadrilateral elements near the branching point, we use triangular elements along the branch. These triangular elements are obtained from quadrilateral elements by a degeneration technique [e.g., Hughes, 2000].

[13] The multiple earthquake cycle simulation starts from the first interseismic process in which the fault stresses (both shear and normal components) are evaluated by the viscoelastic model [equations (1) and (2)]. At the beginning of the first interseismic process, zero shear stress and an ambient normal stress are assigned on most of the branched fault system, except for a 5-km-long nucleation region (the center of the region is located at the center of the “stem” segment, see Figure 1a) on the main fault. A nonzero initial shear stress (15 MPa) is assigned to this nucleation region before the first interseismic process, which produces artificial initiation of dynamic rupture for the first event only. This nucleation region is needed in the current model because we do not simulate the slow growth of the nucleation phase, and spontaneous rupture propagation requires a finite nucleation patch size [e.g., Day, 1982]. The length of 5 km for the nucleation region is chosen by trial and error. It
Table 1. Material and Computational Parameters in Models

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branching Angle</td>
<td>±15°, ±30°</td>
</tr>
<tr>
<td>Loading Rate</td>
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</tr>
<tr>
<td>Equilibrium (Ambient) Stress</td>
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</tr>
<tr>
<td>Initial Normal Stress</td>
<td>$5 \times 10^5$ Pa</td>
</tr>
<tr>
<td>Initial Shear Stress</td>
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</tr>
<tr>
<td>Shear Modulus</td>
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</tr>
<tr>
<td>Poisson’s Ratio</td>
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</tr>
<tr>
<td>Density</td>
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</tr>
<tr>
<td>Viscosity</td>
<td>$2.0 \times 10^5$ Pa S</td>
</tr>
<tr>
<td>Static Frictional Coefficient</td>
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</tr>
<tr>
<td>Dynamic Frictional Coefficient</td>
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</tr>
<tr>
<td>Critical Slip Weakening Distance $D_0$</td>
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</tr>
<tr>
<td>Element Size on the Main Fault</td>
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</tr>
<tr>
<td>Length of the Rupture Initiation Region</td>
<td>5000 m</td>
</tr>
</tbody>
</table>

*Initial shear stress over a 5-km-long nucleation region on the main fault is nonzero to serve as the initiation location for the first earthquake in the sequence. It is not used thereafter. Additionally, there is a model in which nonzero shear stress is assigned on the main fault in order for the first event to initiate on the main fault, see section 3 for details.

is a small portion of the length of fault segments, and the use of this feature allows rupture to progress spontaneously on the fault systems. Notice that the critical crack size formulation [e.g., Andrews, 1976] does not apply here because of the nonuniform initial stress conditions. When the shear stress of each node over this nucleation region reaches the failure level, the interseismic process ends. Then we use the stress condition on the fault at the end of the first interseismic process as the initial stress for the first earthquake and simulate the event by the dynamic FEM algorithm. The simulation time for the dynamic process is chosen to be 50 s, which is long enough for seismic waves to decay to a level that has no effect on the residual stress. After the dynamic process, we reset the frictional coefficient to the static value to mimic the healing of the fault system in the current multiple earthquake cycle models. The fault stress output from the first event is then used as initial values for the second interseismic process. We run the second interseismic process until the shear stress over a 5-km-long nucleation region reaches the failure level. We remark that we allow the shear stress to increase above the failure level at the points that reach the failure level earlier within the nucleation region because of the nonuniform stress distribution on the fault systems. Note that the location of this nucleation region is a calculated result of the stress field on the fault system for the second and all subsequent events. From now on, the fault system evolves spontaneously. For example, the initial stress on the fault system before an earthquake is a result of both the tectonic-loading stress and the residual stress (including relaxation) from the previous earthquakes. The above processes are repeated as many times as desired to perform multicycle simulations.

Figure 1a shows an example of modeled fault geometry with right-lateral tectonic loading. We consider two-dimensional right-lateral branched fault systems that are embedded in a homogeneous whole space. The main fault has a length of 40 km. The branch intersects the main fault at its center and has various lengths depending on the branching angle. We model four branching angles, $\phi = \pm 15^\circ$ for narrow cases and $\phi = \pm 30^\circ$ for wide cases.

3. Results

In this section, we first report in detail the dynamics of the $-15^\circ$ branching angle fault system. We will examine the evolution of normal stress and shear stress, the event
patterns, and branching behavior over multiple earthquake cycles. Then, we report the results from other branching angle models. Finally, we explore how the principal fault prestress direction before an earthquake rotates in the long term, due to both the tectonic shear loading and previous earthquakes.

3.1. Dynamics of the −15° Branching Angle Fault System Over Multiple Earthquake Cycles

[19] In this subsection, we first report the spontaneous evolution of the fault system over multiple earthquake cycles. We particularly examine how backward branching can occur in our models. Then we use nonuniform prestress obtained from the above simulations and artificial nucleation at the left end of the main fault to examine whether the fault-branching behavior observed in the 2002 Denali fault earthquake is the only possible scenario or is one of several possible scenarios. We will show that the latter is the case in our models. Finally, we examine the effect of the tectonic-loading direction on fault-branching behavior.

3.1.1. Spontaneous Evolution of the Branched Fault System Over Multiple Earthquake Cycles

[19] In the configuration shown in Figure 1a, the tectonic loading produces an extensional increment in the normal stress on the branch, resulting in a lower yield (normal) stress on the branch than on the main fault. Thus the branch is more favorable for rupture than the main fault in the tectonic-loading stress field. In addition, for a rupture propagating toward the branching point from the “stem” (left half) segment of the main fault, the branch is on the extensional side, meaning that slip on the stem causes a decrease in normal stress on the branch.

[20] Figure 2 shows the spontaneous evolution of the branched fault system over 30 sequential earthquake cycles. In Figure 2a, initial shear and yield stresses before these 30 sequential earthquakes are given. Note that the yield stress here is directly proportional to the normal stress on the fault system. Figure 2b demonstrates the event pattern by showing the final slip on the fault system. Figure 2c illustrates the rupture process in these events by showing rupture time. The rupture time here is defined as the time at which the slip rate of a fault node first reaches 0.01 m/s. In these figures, the branch is projected onto the main fault and is denoted by dashed curves for these quantities.

[21] The initial fault stress for the first event is a uniform stress field resulting from the tectonic loading. In this event, rupture essentially abandons the main fault for the branch. This branching behavior is due to the branch’s more favorable orientation with respect to the tectonic and dynamic stress field and is consistent with previous studies using a uniform prestress field [Kame et al., 2003; Bhat et al., 2004].

[22] As shown in Figure 2a, the fault stress on the branched fault system is no longer a uniform stress field after the first event. For this branched fault system, the stresses increase on the left side and decrease on the right side of the branching point on the main fault, compared with the stresses far away from the branching point. The reduced stresses are also observed on the branch immediately near the branching point. In addition, stresses on the branch and the right half of the main fault segment (denoted as the right segment hereafter for simplicity) also depart from the uniform stress field. This appears to be caused by a strong stress interaction between the two branch segments. In this fault system, the normal stress on most of the right segment decreases because of the slip on the branch. Although tectonic loading tends to reduce the normal stress uniformly on the branch segment (see Figure 1a), rupture on the right segment tends to raise the normal stress over a wide range of the branch segment. These changes in fault stresses accumulate at the early stage of the evolution of the fault system (for example, the first 10 earthquake cycles). Overall, the effects of branched fault geometry and the stress interaction between the two branch segments superimpose on the uniform tectonic stress field, leading to a nonuniform prestress field on the fault system over multiple earthquake cycles.

[23] It can be seen from Figure 2 that a steady state develops on the fault system after a number of earthquake cycles (for example, about 10 cycles). In the steady state, several patterns of fault prestress distribution and earthquake rupture repeat. For example, large events that rupture most of the fault system are separated by one to three small events that rupture only the branch or a subset of the branch. This feature has also been observed in our previous studies on faults with a bend [Duan and Oglesby, 2005] or a stepover [Duan and Oglesby, 2006]. This result indicates that the increment of the fault stress during an earthquake is balanced by the stress relaxation during the interseismic process.

[24] Figure 2c illustrates the rupture process in these sequential earthquakes. As noted above, the initiation location is a calculated result of the fault stress field except for the first event. However, the 5-km-long nucleation region for rupture initiation discussed above can cause two or more locations to reach failure at the start of the rupture in some events. In most events, rupture initiates at the right end of the branch segment, where a relatively long fault patch has a low yield stress. In several large events, rupture initiates simultaneously at both the right end of the branch segment and the branching point and propagates from both points, such as events #5, #7, and #14. These events indicate that the branching point can be an initiation location for rupture, owing to low yield stress and/or high shear stress accumulated from previous events. In most small events, the branching point serves as a barrier for rupture.

[25] “Backward branching” is observed in several large events such as events #3, #9, #16, and #19. In these events, the rupture initiates at the right end of the branch and propagates toward the branching point. After the branching point fails, the rupture propagates forward first onto the stem segment of the main fault at a relatively high speed, then “backward” onto the right segment of the main fault, which makes an acute angle with the original segment (the branch segment in this case). Although the rupture on the branch segment sends the right segment into a stress shadow at the early stage of earthquakes, it appears that slip on the left side of the branching point overcomes the above stress shadow effect and drives the backward branching. To closely examine this backward-branching process, in Figure 3, we show the snapshots of slip rate on the fault system during rupture propagation of the event #16. The rupture starts from the right end of the branch and propagates toward the branching point (see the top panel for t = 5 and 7 s). At 9 s, the branching point on
Figure 2. The spontaneous evolution of the $-15^\circ$ branching angle fault system over 30 sequential earthquake cycles. (a) Initial shear (thick) and yield (thin) stresses before the 30 sequential earthquakes. (b) Final slip and (c) rupture time in the 30 earthquakes. The horizontal axis is the distance along the strike of the main fault with the origin at the branching point. The branch is projected onto the main fault. Solid curves are for the main fault, and dashed curves are for the branch. Shear stress and yield stress almost overlap on portions of the fault system in some events in the scale used here. Attention should be paid to the overall features of the initial shear and yield stress distribution.
the main fault has already failed. At 11 s, the rupture has propagated leftward about 8 km, while it has only propagated rightward (backward branching) about 1.5 km. A similar trend of rupture progression can be found at 13 s. At 15 s, the rupture has already reached the left end of the main fault, while it has only propagated rightward about 4.5 km. In the last three snapshots, the rupture appears to propagate rightward at a higher speed than before. Thus it can be seen that the slip on the left side of the branching point drives the rupture propagating rightward, making backward branching possible.

### 3.1.2. Possible Fault-Branching Behavior in Nonuniform Prestress Fields

[26] To achieve a better understanding of the fault branching behavior observed in the 2002 Denali fault earthquake, we run a series of simulations on this \(-15^\circ\) branching angle fault system using nonuniform fault prestress fields and artificially imposed nucleation locations. To avoid too low initial stress level for rupture to propagate, we take the fault stress field output from the above sequential earthquakes as the starting point and run the viscoelastic model to build the fault stress to a level at which there are three adjacent fault nodes in the fault system reaching failure level. Then, we artificially raise the shear stress to a level slightly higher (0.6 MPa) than the failure level over a 5-km-long patch (centered at \(x = -15\) km) to the left end of the main fault. In doing so, we force rupture to initiate on the stem segment of the main fault and to propagate toward the branching point, similar to the situation in the 2002 Denali fault earthquake.

[27] In this series of simulations, we find that three fault branching scenarios can occur. Figure 4 shows examples of these three scenarios. The event #6 in the first row denotes that the initial stress for this event is obtained after the event #5 in Figure 2 plus the above loading. The event numbers in the other two rows have similar meanings. The first fault branching scenario, the event #6, is similar to that observed in the 2002 Denali fault earthquake. In this scenario, the rupture essentially abandons the main fault for the branch segment. The left panel of Figure 5 shows snapshots of slip rate for this event. After \(t = 7\) s, the slip rate decreases rapidly on the main fault while it increases steadily on the branch segment. Thus the rupture abandons the main fault and takes the branch in this scenario.

[28] In the second scenario, the event #19, the rupture continues on the main fault. The rupture simultaneously progresses onto the branch segment, but quickly dies out with minor slip. The failure of the right end of the branch is due to a low yield stress there, but is not directly related to fault branching. This process can be seen in Figure 4c and in the middle panel of Figure 5. At \(t = 5\) s, the rupture tends to simultaneously propagate onto both the main fault and the branch. But at \(t = 6\) s, the rupture on the branch almost dies out. There is no slip on the branch at \(t = 7\) s. The right end of the branch fails at around \(t = 8\) s. However, the rupture continually propagates to the right end of the main fault.

[29] Simultaneous rupture on both segments is observed in the third scenario, event #29. The rupture on the branch is a little ahead of that on the main fault, as shown in Figure 4c and the right panel of Figure 5.

[30] There are obvious differences in rupture velocity when the rupture approaches the branching point from the left in these three events. The shear wave velocity is shown in Figure 4c for comparison. It can be seen that the rupture velocity is fastest, with a supershear speed (about 1.6 Vs), in the third scenario. The rupture velocity is slowest, about 0.6 Vs, in the first scenario and is in between (about 1.3 Vs) in the second scenario.

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**Figure 3.** Snapshots of slip rate on the \(-15^\circ\) branching angle fault system during the 16th event shown in Figure 2. Slip rate along the branch segment is projected onto the main fault. The origin of the horizontal axis is at the branching point. The snapshots are displayed at an equal time interval of 2 s.
The difference in fault-branching behavior and rupture velocity among the above three scenarios is dominated by the initial fault stress before these earthquakes. Although the qualitative features of the stress distribution on the fault system as shown in Figure 4a are similar, there are differences in how close the shear stress is to the yield stress on the different fault segments. A dimensionless parameter $S$, which characterizes the relative strength of a fault before an earthquake, has been proposed to control dynamic rupture propagation [Andrews, 1976; Das and Aki, 1977; Day, 1982]. A fault segment with a lower $S$ is more favorable for rupture than one with a higher $S$, and a lower $S$ results in a faster rupture velocity. $S$ is defined as

$$S = \frac{(\sigma_y^0 - \sigma_s^0)}{(\sigma_y^0 - \sigma_f^r)},$$

where $\sigma_y^0$, $\sigma_s^0$, and $\sigma_f^r$ are the initial yield stress, the initial shear stress, and the initial sliding stress on the fault before an earthquake, respectively. Figure 6 shows the distribution of $S$ on the fault system for these three events. There is a correspondence between $S$ values and the rupture velocities on the stem segment of the main fault. $S$ is largest in the event #6, smallest in the event #19, and in between in the event #29. More importantly, the difference in $S$ values between two branch segments beyond the branching point appears to play a critical role in determining the fault-branching behavior. In the event #6 (blue curves), the branch has a much smaller $S$ than the main fault; thus the rupture takes the branch and abandons the main fault. In the event #19 (red curves), the branch has a much higher $S$ than the main fault; thus the rupture essentially continues on the main fault. In the event #29 (black curves), the two segments have a similar $S$ value; thus the rupture simultaneously propagates onto the two segments.

The above results show that the fault-branching behavior observed in the 2002 Denali fault earthquake may be one of several scenarios, not the only one possibility, if we take into account the nonuniform fault prestress field developed from previous earthquake cycles. In this set of simulations, we have 29 events in total. We find that there are 1, 10, and 10 events exhibiting the first (#6), second (#19), and third (#29) fault-branching behavior, respectively. The other eight events are small events in which the rupture dies out before reaching the branching point. It appears that the branching behavior observed in the 2002 Denali fault earthquake is rare in this set of simulations. However, as will be shown in the subsequent section, this branching behavior can be observed in many simulated earthquakes if we use a different tectonic-loading direction.

3.1.3. Effects of the Tectonic-Loading Direction on the Event Pattern and the Fault-Branching Behavior

In the above simulations, the tectonic loading direction (the maximum shear strain rate direction due to tectonic loading at a plate boundary) is parallel to the strike of the main fault. In real fault systems, this situation is not necessarily the case. In the simulations of this subsection,
we assume that the tectonic-loading direction bisects the main and branch fault strikes. This results in a less exten-
sional increment in normal stress on the branch compared
with the above tectonic loading. Also, there is a compres-
sional increment in normal stress on the main fault in this
tectonic loading. Following the same procedure as above,
we run two sets of simulations. In the first set of simu-
lations, we allow the fault system to evolve spontaneously,
similar to the situation shown in Figure 2. In the second set
of simulations, we artificially nucleate rupture to the left end
of the main fault with the nonuniform fault stress from the
first set of simulated earthquakes used as the initial stress,
similar to the situation shown in Figure 4.

[34] In the first set of simulations, we obtain a more regular event pattern than that in Figure 2. Figure 7 shows
the last four of 30 sequential earthquakes. An alternating event pattern is observed in the spontaneous evolution of the fault system. A small event rupturing only the branch
segment is followed by a large event rupturing the entire fault system. This pattern starts from the second event (not shown) and repeats itself exactly. Overall, the level of the initial fault stress before events in the steady state on the entire fault system is higher, which results in larger final slip, compared with those in Figure 2. In large events, a slower rupture on the right half of the main fault, compared
with that on the left half of the main fault, is observed. This feature is similar to that shown in Figure 3; the slip on the left half of the main fault overcomes the stress shadow caused by the rupture on the branch and drives the rupture propagation onto the right segment. We remark that, in order for rupture to initiate on the left end of the main fault for the first event as in other models, we need a nonzero initial shear stress level on the main fault for the first cycle.

[35] In the second set of simulations with imposed nucleation on the fault stem, we also find three fault-
branching scenarios similar to those in Figure 4. Among

Figure 5. Snapshots of slip rate on the \(-15^\circ\) branching angle fault system during three events shown in
Figure 4. Slip rate along the branch segment is projected onto the main fault. The snapshots are displayed
at an equal time interval of 1 s.
the 29 total events, there are 11, 1, and 16 events exhibiting the first, second, and third branching scenario discussed in the above subsection, respectively. Thus the first branching scenario, which is observed in the 2002 Denali fault earthquake, is not rare in this tectonic-loading field. This may indicate that the direction of the maximum shear strain rate that loads the Denali fault system is oblique to the Denali fault near its junction with the Totschunda fault. Figure 8 shows the initial stress, final slip, and rupture time for the first (the top row) and the third (the bottom row) scenarios. Similar features as in Figure 4 are observed here.

3.2. Multicycle Dynamics of Other Branching Angle Fault Systems

3.2.1. The $\pm 30^\circ$ Branching Angle Fault System
[36] We run a set of simulations to examine spontaneous evolution of the $\pm 30^\circ$ branching angle fault system with the tectonic loading direction parallel to the strike of the main fault. Compared to the above $\pm 15^\circ$ branching angle fault system, the tectonic loading produces a larger extensional increment in normal stress on the branch, resulting in a lower initial stress level and a lower stress drop on the segment. With the same nucleation length of 5 km as above, most events on this fault system are small and rupture the branch segment or a subset of the branch only.

3.2.2. Results From the $\pm 15^\circ$ and $\pm 30^\circ$ Branching Angle Fault Systems
[37] In these two branched fault systems, the branch segment is on the compressional side of the main fault if...
rupture propagates toward the branch point from the left. Furthermore, the right-lateral tectonic loading produces a compressive increment in normal stress on the branch segment. Thus the branch segment is less favorable for rupture than the main fault.

With a tectonic-loading direction parallel to the main fault, we find that earthquakes can only occur on the main fault, if the fault systems evolve spontaneously. Figure 9 shows the results from the $+15^\circ$ branching angle fault systems. Here we only show the 1st and 30th events. The initial stress in the first event is a result of the tectonic loading, which produces a uniform stress field on the fault system, except within the artificial initiation patch. The initial shear and yield stresses on the main fault before the 30th event almost overlap in the scale used here. The final slip show that only the main fault fails in these events. However, a nonuniform fault stress develops on the branch segment, owing to these earthquakes on the main fault.

As shown in section 3.1.3, the tectonic-loading direction can have effects on the behavior of branched fault systems. To examine if the branch segment can fail in some earthquakes, we run a set of simulations on the $+30^\circ$ branching angle fault system, with tectonic loading bisecting the main and branch faults. Figure 10 shows the results

![Figure 8](image)

**Figure 8.** Two typical fault-branching scenarios observed on the $-15^\circ$ branching angle fault system with a tectonic-loading direction bisecting the main and branch faults. They are similar to the first and third scenarios in Figure 4, respectively. The dotted lines in Figure 4c represent the $S$ wave velocity for comparison with rupture velocity.

![Figure 9](image)

**Figure 9.** (a) The initial fault stress, (b) final slip, and (c) rupture time for 1st and 30th events of 30 sequential earthquake cycles on the $15^\circ$ branching angle fault system, with a tectonic-loading parallel to the main fault. In Figure 9a, the thick and thin curves denote the shear and yield stresses, respectively. The initial shear and yield stresses on the main fault almost overlap for the 30th event in the scale used here. Only the main fault fails in this model. The earthquakes on the main fault cause a nonuniform stress on the branch. The dotted lines in Figure 9c represent the $S$ wave velocity for comparison with rupture velocity.
from this set of simulations. Two out of thirty earthquakes are observed to rupture both the main and branch faults; the other events only rupture the main fault. The two earthquakes are events #13 (the third row) and #25 (the fifth row). We focus on the two events to examine how the entire fault system can fail in the nonuniform prestress. The rupture time (right panel in Figure 10) shows that the primary location of rupture initiation on the branch segment (after the main fault has largely ruptured) in the two events is several kilometers away from the branching point on the branch segment. The process can be more clearly seen on the snapshots of the slip rate shown in Figure 11. The rupture initiates on the branch about 6 km away from the branching point at around $t = 6$ s in event #13 and about 3 km away at around $t = 5.5$ s in event #25. Then, the rupture propagates on the branch segment bilaterally. Note that the rupture on the branch segment causes the slip rate on the neighboring portion of the main fault to decrease quickly.

The above analysis suggests that rupture does not necessarily go through the branching point to leave a branched path after an earthquake. Here the rupture is triggered at a favorable location and then propagates bilaterally on the branch segment in the two earthquakes shown in Figure 11. The favorable locations in these two events appear to be very close to failure before the earthquakes, as shown by the initial stress in Figure 10a. The relative fault strength $S$ (not shown) defined in equation (5) is very small at the favorable location on the branch segment. This process of triggering may be another mechanism for backward branching, in addition to the one discussed in section 3.1.1. In event #13, if we consider that the rupture initiates on the right segment of the main fault as shown in Figure 10c (the third row), the rupture path after the earthquake is a backward branching. The simultaneous initiation of rupture at several different locations in Figure 10c is an artifact, owing to the finite nucleation patch needed in the current models. In event #25, rupture initiates on the left side of the branching point on the main fault, indicating that the fault patch near the branching point can be an initiation location for rupture.

Figure 10. (a) The initial fault stress, (b) final slip, and (c) rupture time for six events of 30 sequential earthquake cycles on the $30^\circ$ branching angle fault system, with tectonic loading bisecting the main and branch faults. In Figure 10a, the thick and thin curves represent shear and yield stresses, respectively. The branch is ruptured only in two large events among 30 events. The arrows in Figure 10a for the two large earthquakes mark the favorable location for rupture initiation on the branch segment. Other earthquakes only rupture the main fault. The dotted lines in Figure 10c represent the $S$ wave velocity for comparison with rupture velocity.
This feature can also be clearly found in many events including events #20 and #30 in Figure 10 and others not shown here, particularly events after the 13th event with a lower yield stress level at the location.

3.3. Rotation of the Principal Fault Prestress on the Branched Fault Systems Over Multiple Earthquake Cycles

The above results have shown that the fault prestress prior to an earthquake becomes nonuniform in magnitude on a branched fault system over multiple earthquake cycles, though it starts from a uniform prestress field in the models. Principal stress analysis is widely used in characterizing the stress field on a fault system. In this subsection, we examine rotation of the principal stress orientations on the branched fault system over multiple earthquake cycles.

We use the Mohr circle construction to solve for principal stresses from the initial normal and shear stresses on the branched fault system. For strike-slip faults, the intermediate compressive principal stress \( \sigma_2 \) is vertical, and the maximum and minimum compressive principal stresses \( \sigma_1 \) and \( \sigma_3 \) are horizontal. We take tension as positive, and then we have

\[
\sigma_1 < \sigma_2 < \sigma_3. \tag{6}
\]

We assume that \( \sigma_2 \) does not change over multiple earthquake cycles. The ambient stress \( \sigma_a \) in equation (2) is the average of two horizontal principal stresses,

\[
\sigma_a = \frac{1}{2}(\sigma_1 + \sigma_3). \tag{7}
\]

If we know \( \sigma_a, \sigma_1, \sigma_3 \), we can solve for principal stresses \( \sigma_1 \) and \( \sigma_3 \) for a point on a fault. Figure 12 shows this procedure graphically by the Mohr circle construction.

![Figure 11](image1.png)

**Figure 11.** Snapshots of slip rate on the 30° branching angle fault system in the events #13 and #25 shown in Figure 10. The branch segment is projected onto the main fault.

![Figure 12](image2.png)

**Figure 12.** (a) The direction of the maximum and minimum compressive principal stresses and the orientation of a fault segment. (b) The Mohr circle construction for solving the principal stress field from the shear and normal stresses on a fault segment.
Figure 12a shows the orientations of the strike of a fault segment and two principal stresses. The angle $\Psi$ is measured from the maximum compressive principal stress to the fault strike counterclockwise. Figure 12b gives the Mohr circle construction to solve for principle stresses from normal and shear stresses. Note that we take sign of the stress into account in constructing the Mohr circle, for example, negative compressive stresses. Given $\sigma_a$, $\sigma_t$, and $\sigma_N$, one can immediately write

$$\Psi = \frac{1}{2} \arctan \left( \frac{\sigma_t}{\sigma_N - \sigma_a} \right).$$

$$\sigma_1 = \sigma_a - \sqrt{\sigma_a^2 + (\sigma_N - \sigma_a)^2},$$

and

$$\sigma_3 = \sigma_a + \sqrt{\sigma_a^2 + (\sigma_N - \sigma_a)^2}.$$

Figure 13 shows orientations of the maximum compressive principal stress prior to four of 30 sequential events shown in Figure 2 on the $-15^\circ$ branching angle fault system. The insets show detail near the branching point. Fault prestress rotates over multiple cycles.

In the following discussion, we focus on the orientation of the principal stress characterized by the angle $\Psi$ and examine the rotation of the maximum compressive principal prestress on branched fault systems over multiple earthquake cycles.

Figure 13 shows orientations of the maximum compressive principal prestress $\sigma_1$ on the $-15^\circ$ branching angle fault system for four earthquakes of 30 sequential events shown in Figure 2. A uniform prestress field on the fault system can be observed for the first event (the first row in Figure 13). The angle between $\sigma_1$ and the main fault strike is $\Psi = 45^\circ$. After the fault system experiences several earthquakes, the orientation of $\sigma_1$ rotates quite clearly near the branching point on both the main and branch faults, as shown in the second row for the fifth event. $\Psi$ becomes larger on the left side and smaller on the right side of the branching point on the fault system. $\Psi$ also becomes smaller on the entire branch segment. This rotation continues as more earthquakes occur on the fault system. Prior to the 10th event (the third row), $\sigma_1$ is nearly parallel to the fault strike on both the main and branch faults just beyond the branching point to the right. Most of the right segment of the main fault has a lower value of $\Psi$, compared with that prior to the 5th event. The orientation of $\sigma_1$ on the fault system prior to the 30th event is similar to that prior to the 10th event, indicating that a relatively stable fault stress (see section 3.1.1) develops on the fault system. Compared to the initial yield (a proxy for normal) stress in Figure 2, one can see that a larger $\Psi$ corresponds to a higher normal stress level and a smaller $\Psi$ corresponds to a lower normal stress level. Note that the orientation of $\sigma_1$ on most of the stem segment of the main fault does not rotate over multiple earthquake cycles. These results suggest that the branched fault geometry and fault interaction cause the above rotation of fault prestress field over multiple earthquake cycles.

Figure 14 shows orientations of $\sigma_1$ prior to the first event and the 30th event of 30 sequential events on different branching angle fault systems with the following two different tectonic-loading directions: parallel to the main fault, or bisecting the main and branch faults. The prestress
field is a uniform stress field prior to the first event in all cases. The 30th event illustrates the prestress field on the fault systems in the steady state. Compared to the case of loading parallel to the main fault (Figure 13), a similar in nature, but smaller rotation of $\sigma_1$, can be observed on the $-15^\circ$ branching angle fault system with the tectonic-loading direction that bisects the main and branch faults (Figure 14a). Although most events are small (i.e., only rupturing the branch segment; see section 3.2.1), the stress rotation can be clearly seen on the $-30^\circ$ branching angle fault system (Figure 14b). Because of the no failure of the branch segment in the sequences of the $+15^\circ$ (Figure 14c) and $+30^\circ$ (Figure 14d) branching angle fault systems with a tectonic loading parallel to the main fault, the rotation of the prestress field is minor on these fault systems. However, the prestress field rotates significantly on most of the main fault when the tectonic loading direction bisects the main and branch faults (Figure 14e). It is interesting to notice that there are few earthquakes (only 2 out of 30) rupturing the entire fault system in this case. This means that the rotation primarily results from the oblique tectonic shear loading.

4. Discussion

The earthquake cycle model in the current study is a simplified version of a more complete model in which several different phases, such as spontaneous nucleation, dynamic rupture, postseismic relaxation, and interseismic deformation, are constrained by many observations. We remark that a complete earthquake cycle model is desirable to examine the long-term behavior of realistically complex fault systems and that more sources of complexity need to be included. In this section, we first discuss some issues about the simplified model in the study. Then, we compare our results with previous theoretical studies on dynamic fault branching using a uniform prestress field. Finally, we examine implications of our modeling results in several natural earthquakes that involve fault branching, particularly backward branching.

4.1. Issues Concerning the Current Model

It is clear that the fault principal prestress field rotates near the branching point due to the branched fault geometry, and on the two branch segments owing to the fault interaction in earthquakes, if all segments can fail sometime in the evolution of the fault system. In the time domain, the orientation of $\sigma_1$ on the fault system rotates significantly over multiple earthquake cycles near a branching point and on the fault segment that has an extensional increment in normal stress due to the tectonic shear loading. In space domain, the orientation of $\sigma_1$ on a fault changes dramatically within a short distance near a branching point after the fault experiences many earthquake cycles. This nonuniform prestress field has large effects on dynamics of branched fault systems, as shown in section 3.1 and 3.2.
the spontaneous evolution of the fault systems. One example is simultaneous nucleation at two or more locations on a fault system shown in the rupture time plots (for example, Figures 2 and 10). Other types of friction laws more suitable for nucleation such as rate- and state-dependent friction law [Dieterich, 1979; Ruina, 1983] may be able to eliminate this artifact. In addition, the finite nucleation patch may result in a higher level of average shear stress due to a longer interseismic period, compared with spontaneous nucleation by rate- and state-dependent friction law [Dieterich and Kilgore, 1996]. The higher level of average shear stress may augment occurrences of supershear rupture in the models. However, the speed of incoming rupture is not the determining factor for rupture branching in the models. As shown in Figures 4 and 6, the difference in $S$ value between two branch segments beyond the branching point appears to play the most important role in rupture-branching scenarios. This difference in $S$ value is not very sensitive to the implementation of nucleation in the models. Nevertheless, we acknowledge that there might be more small events (that only rupture one segment or a subset of one segment) and richer rupture patterns on the branched fault systems if one uses a more natural nucleation mechanism such as rate- and state-dependent friction law.

[50] The source of heterogeneity in the current models solely arises from the branched fault geometry, in contrast to the real world which will have multiple sources of heterogeneity. This is actually one of the main points of this study, to isolate the effects of branched fault geometry from other sources of complexity. Thus slip distributions and event patterns in the current models are simpler than those observed in real earthquakes on real fault systems. Also, nucleation locations are mainly associated with the branched fault geometry. Additional complexity in the models would result in more heterogeneity in stress distributions, and thus richer patterns in nucleation locations, slip distributions, and event sizes. However, the results associated with the branched fault geometry, such as the branching point being a relatively favorable location for nucleation, will presumably hold even when other forms of complexity are included in the models.

[51] The viscoelastic model used in the current models is a proxy for many physical mechanisms that prevent fault stresses near geometrical complexities from being pathological, including effects of off-fault deformation on fault stress during the interseismic period. More recently, Duan and Day [2006] have implemented off-fault plastic yielding in EQdyna (two-dimensional version) and applied it to a bent fault model. They have found that off-fault plastic yielding during the coseismic process can reduce the magnitude of stress heterogeneity significantly near kinks. Dieterich and Smith [2006] have employed an earthquake rate formulation [Dieterich, 1994] to relax stress on geometrically complex faults. Nevertheless, the viscoelastic model has similar effects to these mechanisms in terms of limiting fault stress magnitude near the geometrical complexities. As shown in previous studies [Duan and Oglesby, 2005, 2006], viscosity in the model has important effects on fault systems’ long-term behavior, and different viscosities represent different levels of stress relaxation. One extreme case is that the stress heterogeneity near geometrical complexities from the previous earthquake is completely relaxed before the next earthquake. This would be the case of uniform initial stress conditions. We believe that this case is less likely in nature compared to the case in which there is a certain amount of residual stress from previous earthquakes. The value of viscosity used in this study is based on the previous studies [Duan and Oglesby, 2005, 2006] and represents a typical value of the range within which fault systems behave similarly (for example, similar patterns of event and initial stress distribution) in the long term [Duan and Oglesby, 2006].

4.2. Comparisons With Previous Theoretical Studies on Fault Branching

[52] Assuming a uniform prestress field, Poliakov et al. [2002] and Kame et al. [2003] have shown that the following three factors determine dynamic branching: the prestress state at a branching point, the rupture speed, and the branching angle. In our models, the first event in the sequences essentially has a uniform prestress field, and dynamic branching in these events is consistent with these previous studies. For example, the rupture abandons the main fault for the branch segment on the $-15^\circ$ branching angle fault system (Figure 2) while it takes both the main and branch faults on the $-30^\circ$ branching angle fault system (not shown).

[53] However, our models show that a branched fault system develops a nonuniform prestress field over multiple earthquake cycles. This nonuniform prestress field can depart from the regional uniform stress field significantly in terms of both magnitude and orientation, particularly near the branching point and on the two branch segments. This nonuniform prestress can have large effects on dynamic fault branching. Thus we argue that the rupture history, which operates through generating different nonuniform prestress conditions on a branched fault systems at different times, may be another important factor to determine dynamic branching.


[54] Stress fields around a dynamically moving mode II crack tip discourage backward branching. With a uniform prestress field, this effect seems to inhibit the possibility of direct backward branching [Poliakov et al., 2002, Fliss et al., 2005]. Fliss et al. [2005] proposed a mechanism of backward branching in which the stopping of rupture on one fault causes a jumping rupture onto a neighboring fault. This secondary rupture propagates bilaterally, leaving a backward-branching path after the earthquake. In this mechanism, the first fault must be disconnected from the second fault to generate the stopping phase.

[55] In our current models, we find that backward branching can occur through two other mechanisms in a nonuniform prestress field, which can develop from previous earthquake cycles due to the branched fault geometry and fault interaction. In our models, the branch connects with the main fault. The first mechanism is shown in the $-15^\circ$ branching angle fault models in section 3.1.1. In this mechanism, the slip on the stem drives the rupture to overcome stress shadow effect, generating a direct backward branching. This mechanism may provide a new view
of backward branching observed in the 1992 Landers earthquake, in addition to the mechanism proposed by Fliss et al. [2005]. Notice that the new mechanism does not require a disconnection between two fault segments.

36 The second mechanism of backward branching observed in our models is that the nonuniform fault prestress field allows the discontinuous triggering of rupture at a favorable location on one fault segment by a rupture on another fault segment. The triggered rupture propagates bilaterally on the fault segment, leaving a backward-branching path after the earthquake. This mechanism is shown on our models in section 3.2.2. In this mechanism, the backward branching is only a manifestation of a complex, discontinuous rupture process, not a direct backward branching. This triggering mechanism is different from the jumping mechanism proposed by Fliss et al. [2005] in that triggering does not require the initially rupturing fault to stop slipping and it does not take place right at the branching point.

37 The second mechanism may have implications for the 1999 Hector Mine earthquake. The regional stress field and the fault geometry on the northern part of the rupture in this earthquake [Hauksson et al., 2002; Oglesby et al., 2003] are similar to those of the 30° branching angle fault model in section 3.2.2. If the hypocenter were north of the segment junction as most studies suggest e.g., Hauksson et al., 2002; Oglesby et al., 2003], the earthquake displayed backward branching. The triggering mechanism might work in this earthquake. It is also possible that the hypocenter of the earthquake might have been directly on the segment junction or just to its south [Kaverina et al., 2002; Oglesby et al., 2003]. If this is the case in the earthquake, the rupture path would not correspond to backward branching. Our models have shown that this location is a favorable point for rupture initiation (Figure 10) due to a low yield stress there developed from previous earthquakes.

5. Conclusions
38 We perform multicycle dynamic simulations on two-dimensional generic branched fault models. We find that the fault prestress becomes highly nonuniform near the branching region and on the two branch segments after a number of earthquake cycles. This nonuniform prestress field can have large effects on dynamic fault branching. Several distinct branching scenarios can occur on a given branched fault system because of the different fault prestress patterns in the evolution of the fault system. We find that backward branching, which is difficult to obtain in uniform stress fields, can occur in the nonuniform prestress field through two different mechanisms.

39 Acknowledgments. This research was funded in part by NSF grant EAR-0409836. It was also partly supported by the Southern California Earthquake Center (SCEC). SCEC is funded by NSF Cooperative Agreement EAR-0106924 and U.S. Geol. Surv. Cooperative Agreement 02HQAG0008. This is SCEC contribution 984. We thank Brad Aagaard, Associate Editor Eric Dunham, and an anonymous reviewer for their insightful reviews. We also appreciate helpful conversations with Steven M. Day, Harry W. Green II, and Luis A. Dalguer.

References
Hughes, T. J. R. (2000), The finite element method: Linear static and dynamic finite element analysis, Dover, Mineola, N. Y.


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