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DYNAMIC RUPTURE MODEL OF THRUST AND STRIKE-SLIP FAULT INTERACTIONS IN THE LOS ANGELES BASIN

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TECHNICAL ABSTRACT

Earthquake magnitude is determined by rupture area. Thrust faults beneath the Los Angeles basin are offset, and thus segmented, by strike-slip faults. The objective of this work is to develop models of dynamic rupture sufficiently realistic to provide useful estimates of the likelihood of multiple segments of this fault system rupturing in a single earthquake. In a previous one-year effort, we developed and tested a 2D finite difference method for the dynamic simulation of rupture of parallel thrust faults offset by strike-slip segments. Under the current one-year effort we have completed the following: (1) Development and testing of a 3D finite difference code for modeling the rupture dynamics of segmented thrust faults. The method includes intersecting thrust and strike-slip ("tear fault") segments. (2) Sensitivity study of segmented thrust rupture in 2D. (3) Sensitivity study of segmented thrust rupture in 3D. (4) Completion of a 3D numerical simulation study of multi-segment ruptures on strike-slip fault systems (with R. Harris of the USGS). (5) Completion and publication of a study of seismological constraints on fault zone friction laws (with D. Wald of the USGS and G. Yu)

Results of 3D simulations (using 10 km long thrust fault segments and typical fault strength and stress drop values) indicate that, if the thrust segments are linked by a tear fault, rupture can jump segment offsets several km. In contrast, in the absence of a linking tear fault, offsets of only a few hundred meters become a barrier to rupture. The segment boundaries of Los Angeles area thrust fault segmentation models consist of offsets of up to about 5 km. Some of the offsets are occupied by lateral ramps and tear faults defined by surface fault traces or seismological observations. For blind thrusts, some of the fault offsets are inferred from offsets in the fold axes above the thrusts, and the presence of lateral ramps and tear faults is uncertain. Since the presence of a tear fault or lateral ramp linking offset thrust fault segments greatly abets multi-segment rupture, it is critical to accurately characterize the nature of the thrust fault segment offsets.

PREFACE

This final technical report is a compilation of three documents reporting progress in modeling the rupture dynamics of segmented fault systems.

Part I describes work performed in collaboration with Ruth Harris of the U.S.G.S. to investigate 3D effects in the rupture of segmented strike slip faults. Finite difference computations are used to perform 3D simulations of spontaneous rupture propagation on segmented strike-slip faults. These numerical simulations show how some earthquakes may cascade into multi-segment events, whereas others may be stopped by the geometrical complexity. Our simulations provide a physical basis to assess the likelihood of future cascade earthquakes, given seismological and geological information on fault zone geometry and slip history. Whether or not a rupture can jump across a narrow stepover will depend on a number of factors, including the strength and stress distribution and the geometry of the stepover, as demonstrated by our examples. Alternatively, our 3D physical models demonstrate that wide stepovers (>5 km) will very rarely be jumped during an earthquake. Part I has been submitted for publication in *Geophysical Research Letters* (R. A. Harris and S. M. Day).

Part II describes a dynamic model for rupture of a segmented thrust fault. Finite difference simulations in 2D and 3D are used to investigate the potential for multi-segment cascade ruptures to occur. The simulations extend the methods developed and applied in Part I, in that they include orthogonal, intersecting faults to model the interaction of the thrust fault segments with the tear fault. For reasonable assumptions for fault segment length, strength, and stress drop, rupture can jump offsets of up to 2 km if a tear fault is present, consistent with observations of well studied thrust earthquakes. Absent a tear fault, the maximum offset that can be breached is an order of magnitude smaller. Part II has been submitted for publication in *Geophysical Research Letters* (H. Magistrale and S. M. Day).

Part III describes a test of alternative hypotheses about fault zone rheology. We investigated three large earthquakes in this study: the 1992 Landers earthquake, the 1994 Northridge earthquake, and the 1995 Kobe earthquake. The slip time histories determined from near-source ground motions, teleseismic waves, and geodetic displacement by Wald and others were used in reconstruction of stress time histories on the fault planes. Results for the three events suggest that the dynamic stress drops on the fault plane occur monotonically after passage of the rupture front. The large stress drops are localized in small areas, surrounded by low, and often negative, stress drop regions. The stress time histories show no evidence of a self-healing mechanism, and short rise times can be explained by stress drop heterogeneity on the fault plane. Part III has been published in the *Bulletin of the Seismological Society of America* (S. M. Day, G. Yu, and D. Wald).

PUBLICATIONS

Harris, R. A., and S. M. Day (1997). Effects of a low-velocity zone on a dynamic rupture, *Bull. Seism. Soc. Am.*, 87, pp. 1267-1280.

Day, S.M., G. Yu, and D. Wald (1998). Dynamic stress changes during earthquake rupture, *Bull. Seism. Soc. Am*, *88*, 512-522.

Harris, R.A., and S.M. Day (1998). Dynamic 3D simulations of earthquakes on en echelon faults, submitted to *Geophysical Research Letters.*

Magistrale, H., and S.M. Day (1998). Three dimensional simulation of multi-segment thrust fault rupture, submitted to *Geophysical Research Letters.*

PART II

3D SIMULATIONS OF MULTI-SEGMENT THRUST FAULT RUPTURE

THREE DIMENSIONAL SIMULATIONS OF MULTI-SEGMENT THRUST FAULT RUPTURE

by

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ABSTRACT

Thrust faults, such as those that underlie the Los Angeles basin, are typically segmented by tear faults that offset the thrust fault segments. We perform 3D finite difference simulations of earthquake rupture to evaluate the effectiveness of these offsets in retarding rupture. The simulations include orthogonal, intersecting faults to model the interaction of the thrust fault segments with the tear fault. For reasonable assumptions for fault segment length, strength, and stress drop, rupture can jump offsets of up to 2 km if a tear fault is present, consistent with observations of well studied thrust earthquakes. Absent a tear fault, the maximum offset that can be breached is an order of magnitude smaller.

INTRODUCTION

Assessing the seismic hazard posed by a fault system requires estimating the magnitudes of future earthquakes on that system. Magnitude increases with the surface area which ruptures. Geometrical structures, such as fault-plane offsets and bends, can segment the fault system, and may limit the extent of individual earthquake ruptures. An important element of seismic hazard assessment is the evaluation of the effectiveness of geometrical structures in retarding rupture. Worldwide observations of strike-slip faults have shown that fault plane offsets of a few kilometers normal to strike constitute significant barriers to rupture. Such offsets frequently confine rupture to a single fault segment, although, less frequently, the dynamic stresses transferred between segments during rupture are sufficient to breach such fault plane discontinuities and rupture one or more additional segments. For example, the M 7.2 1992 Landers, California, earthquake ruptured multiple fault segments (Sieh et al., 1993). Computer simulations of rupture on discontinuous strike-slip faults exhibit similar behavior (Harris et al., 1991; Harris and Day, 1993; 1998). However, it may be misleading to apply the results obtained for strike-slip systems to assess the potential for multi-segment ruptures on thrust fault systems such as those which underlie the Los Angeles metropolitan area (Shaw and Suppe, 1996; Davis et al., 1989; Dolan et al., 1995; Yeats et al., 1994; Ehlig, 1975; Allen et al., 1971; 1975; Whitcomb et al., 1973; Hauksson, 1990). A key difference is that, because the dominant slip direction on thrust faults is perpendicular to the strike direction, parallel thrust fault segments can be offset normal to strike (Figure 1) by sharp bends (lateral ramps) or strike-slip faults (tear faults), with the offsetting structure still sharing a common slip direction with the thrust segments (that is, a conservative barrier as defined by King and Yielding, 1984). Seismological (Allen et al., 1971; 1975; Whitcomb et al., 1973; Hauksson, 1990) and geological (Shaw and Suppe, 1996; Davis et al., 1989; Dolan et al., 1995; Yeats et al., 1994; Ehlig, 1975) observations suggest that the thrust faults under and nearby the densely populated Los Angeles basin are segmented is this manner.

We investigate the possibility that, because they form connected structures with compatible slip directions, thrust fault systems segmented by tear faults or lateral ramps may be significantly more susceptible to through-going multi-segment ruptures than

segmented strike-slip systems or thrust systems without well-developed connecting structures. We use a finite difference (FD) method to simulate rupture of segmented thrust faults, in two and three dimensions. An important, and novel, element of the simulations is their incorporation of orthogonal, intersecting faults to model the interaction of the thrusts fault segments with an offsetting tear fault.

METHOD

While most earthquake simulations confine rupture to a single plane, the FD method has the flexibility to model more complex geometries. Previously, we simulated ruptures on multiple parallel, laterally offset, fault segments (Harris et al., 1991; Harris and Day, 1993; 1998) in order to model strike-slip earthquakes which rupture portions of two or more disjoint fault segments (such as the 1994 Landers, California, earthquake). However, in the segmented thrust systems, fault segments intersect and interact mechanically, introducing an element of complexity not present in previous earthquake simulations. We therefore extended the computational model to permit faults parallel to each of 2 orthogonal model coordinate planes (Figure 1). To our knowledge, this is the first time a FD code has had the ability to model intersecting faults. The method also permits the faults to intersect a free surface. However, thrust fault interactions with a free surface add additional elements of complexity to the behavior of earthquake ruptures (e.g., Oglesby et al., 1998; Brune, 1996). In order to isolate the effects of the fault interactions themselves, we restrict ourselves here to the case in which rupture is confined at depth (as was the case, for example, for the 1987 Whittier Narrows and 1994 Northridge, California, earthquakes), and neglect free surface interactions.

The FD code (based on Day, 1982a; 1982b) has second order accuracy in space and time. The faults are represented by surfaces of discontinuity in the velocity field, and the friction law is formulated in the form of jump conditions relating the amount and rate of slip to the shear and normal stresses on the fault surfaces. At points off the fault planes, the model behaves linearly elastically, but the problem becomes nonlinear through the nonlinearity of the friction law, which we model using a slip-weakening relationship: the coefficient of friction on the faults begins to degrade when the ratio of shear to normal stress exceeds a threshold static frictional level, and subsequently decays by an amount

proportion to the total accrued slip. The breakdown process is complete when slip reaches a value d_0, which we set at 20 cm, and subsequent slip proceeds at constant dynamic friction level. Slip ceases whenever the magnitude of the shear stress vector falls below the value given by the product of normal stress and the friction coefficient, and slip can reinitiate if this threshold is subsequently exceeded again.

The model has two parallel thrust fault segments, each 10 km in length along strike, offset by various distances (Figure 1). For some simulations, an orthogonal tear fault is added at the offset of the two thrust segments. The direction of tectonic loading (maximum principal stress) is assumed to be horizontal and parallel to the tear fault, so that there are applied shear and normal stresses on the thrust segments, but no direct tectonic load on the tear fault. The tear fault can be loaded only by slip on the thrust segments. In these simulations, we assume that such loads on the tear fault have been released in the most recent earthquake on the system (as would be the case following rupture of the entire fault zone), leaving the tear fault shear stress at the dynamic friction level throughout the current cycle of tectonic loading (i.e., until one of the thrusts ruptures). We examine the ability of a rupture, nucleated on one thrust segment, to jump the stepover and rupture the second thrust segment, focusing on the contrast in results with and without the presence of the tear fault. We find that 3D rupture geometry has a large effect on the behavior of the system when the tear fault is present. Therefore we present the quantitative results obtained from the 3D simulations, and discuss parameter sensitivities established through more extensive numerical experimentation in 2D.

The thrust fault segment lengths used in the simulations are at the lower end of the range of typical lengths proposed in various segmentation models of Los Angles basin thrust faults (Shaw and Suppe, 1996; Davis et al., 1989; Dolan et al., 1995; Yeats et al., 1994; Ehlig, 1975; Allen et al., 1971; 1975; Whitcomb et al., 1973; Hauksson, 1990). The stress drop, $\Delta\sigma$ (the difference between the initial shear stress before rupture and the dynamic frictional stress after slip weakening is complete) on the thrust segments is an important parameter influencing the behavior of rupture, as is the fault strength, represented here by the dimensionless strength parameter S (the amount by which the static frictional strength exceeds the pre-rupture shear stress, divided by the stress drop) for the thrust

segments. On the tear fault, the static frictional strength is assumed to be the same as on the thrust segments, but the stress drop is zero. We varied the initial stress conditions and the static frictional strength of the faults, performing simulations for three values of $\Delta\sigma$ (5, 7.5, and 10 MPa) and two values of S (1.5 and 3).

RESULTS

We first consider the 3D disjoint thrust model, i.e., offset thrust segments without a tear fault linking them. The first thrust fault segment rupture can trigger rupture of the second thrust segment only if the shear stress concentration at the second segment exceeds the static frictional strength. We considered only the case of S=1.5 (the thrust segments are relatively weak); the second thrust fault is triggered only for relatively small offsets (up to 200 m for $\Delta\sigma$ of 10 MPa), the maximum offset depending only weakly $\Delta\sigma$. For comparison, a 2D strike-slip rupture model of the same segment length, strength, and $\Delta\sigma$ of 10 MPa triggers a secondary rupture for offsets up to 250 m. The maximum offset which can be jumped scales as fault length, so the current result is consistent with the strike-slip simulations (Harris et al., 1991; Harris and Day, 1993; 1998) for much longer ruptures with similar frictional parameters, in which compressional stepovers of 500 m ruptured, but 1000 m did not. Note that, in the strike-slip case, rupture of one segment perturbs both the shear and the normal stress on the second fault, and both stress changes can contribute to triggering rupture on the second fault.

Next we consider the connected thrust model, i.e., offset thrust segments linked by a tear fault. In a typical three dimensional simulation (Figure 2), rupture initiates (time < 2.25 s) and travels along the first thrust fault segment to reach the tear fault (time ~2.5 s) at the thrust fault offset. The stress concentration at the rupture tip induces rupture on the tear fault. Since the stress drop is zero on the tear fault, rupture there absorbs energy rather than releasing energy, and the rupture will progress only a limited distance along the tear fault before its stress concentration fails to overcome the frictional strength. In the example of Figure 2, the tear fault rupture does reach the second thrust fault segment (time ~3.75 s), delivering sufficient shear stress to induce rupture of the second thrust fault segment. This represents a multiple thrust segment rupture case.

The influence of a tear fault linking the thrust fault segments is striking and unambiguous: it greatly increases the offset distance that the rupture can jump (several hundred m without a tear fault versus two km with a tear fault; Figure 3). In the connected thrust simulations, higher stress drop and lower S value permit larger offsets to be jumped. This is respectively due to the greater energy available to overcome the tear fault friction with increasing stress drop and the relative weakness of the faults with decreasing S.

DISCUSSION

Offsets of modern thrust earthquakes can be defined by mapping surface rupture and by seismological observations (aftershock and focal mechanism patterns, and rupture distribution inversions). A recent compilation of thrust earthquake surface ruptures (Rubin, 1996) concludes that rupture across stepovers is common; stepover distances are 1 to 10 km. The largest stepovers (5 and 10 km) are from the two earthquakes (M ~7.5 1896 Riku-u, Japan, and M ~7.6 1932 Chang Ma, China) for which the delay between earthquake and field studies was longest (Rubin, 1996), so the presence or absence of lateral ramps or tear faults is uncertain. The M 7.3 1980 El Asnam, Algeria, earthquake was a multisegment event that jumped a ~2 km tear fault offset defined by surface rupture and aftershock focal mechanisms (Philip and Meghraoui, 1983; King and Yielding, 1984). The M 6.8 1968 Meckering, Australia, earthquake jumped a ~3 km right step via a strike-slip fault that displayed surface rupture (Gordon and Lewis, 1980). Southern California thrust earthquakes include single and multiple segment ruptures. The M 7.6 1952 Kern County earthquake was a multisegment rupture; the surface rupture exhibited a ~1 km strike-slip offset between two thrust segments (Buwalda and St. Amand, 1955). Surface rupture of the M 6.4 1971 San Fernando earthquake showed an 1.5 km offset between thrust segments (Tsutsumi and Yeats, 1998; Sharp, 1975). Aftershocks (Allen et al., 1971; 1975; Whitcomb et al., 1973) and geological mapping (Yeats et al., 1994; Tsutsumi and Yeats, 1998) define a ~5 km lateral ramp offset in the fault plane that apparently confined the mainshock rupture (Allen et al., 1971; 1975; Whitcomb et al., 1973). The 1982 M 5.5 New Idria, 1983 M 6.5 Coalinga, and 1985 M 6.1 Kettleman Hills thrust earthquakes were single segment events on a blind thrust fault (Ekstrom et al., 1992; Stein and Ekstrom,

1992). Folds above the thrusts are offset by 2 and 4 km, suggesting similar offsets in the thrust faults; aftershock focal mechanisms suggest that a lateral ramp occupies the 4 km wide offset (Eaton, 1990). The M 5.9 1987 Whittier Narrows earthquake was a single segment blind thrust mainshock with aftershocks illuminating a strike-slip fault along the edge of the mainshock rupture zone; again, the strike-slip fault apparently confined the mainshock rupture (Hauksson and Jones, 1989). Rupture of the M 6.7 1994 Northridge earthquake may have been confined in the 7 to 15 km depth range by two lateral ramps (Hauksson et al., 1995) that offset the Santa Susanna fault zone by 2 and 5 km (Yeats et al., 1994) at the surface (the later ramp is the same feature that confined the 1971 San Fernando earthquake rupture).

The observations of the best documented thrust earthquakes indicate that, with a tear fault or lateral ramp present, offsets up to 2 km wide usually present little impediment to rupture, and offsets of 2 to 5 km are more significant barriers that may or may not rupture. These offsets are consistent with our 3D model simulations rupturing offsets of up to 2 km. However, in comparing the the model results to observations, several simplifying assumptions must be considered. Our model results are scaled to a fixed segment size, 10 km. This is important, in that the offset distance through which the tear fault model can rupture scales approximately as the thrust segment length (the scaling is exact if d_0 is also scaled to segment length): rupture of longer thrust fault segments could jump larger offsets.

The geometry of the interacting faults has been highly simplified: the intersections of the thrust and tear faults are sharp, without the complex system of branching faults and other complications that are likely to be present in nature. Such complications would tend to blunt the rupture front and reduce the likelihood of a full connecting rupture developing. We assess this simplification with 2D simulations in which the tear fault extends beyond the two thrust fault segments. This fault geometry reduces the stress concentration at the intersections of the thrust segments and the tear fault, reducing the offset distance that can be jumped by about 25%. We have also assumed that the thrusting direction is parallel to the tear fault, whereas any rotation of the rake angle that induced compression on the tear would tend to inhibit its rupture. This cuts both ways, of course, as a rotation of the rake

that induced an extensional component of motion on the tear fault would seem to be equally likely, and this would tend to enhance rupture.

We have also made some simplifications of the dynamics. For example, we have neglected the high variability of stress drop that is invariably observed for earthquake ruptures. However, the range of stress drop values investigated is representative of the range of spatially averaged stress drops observed for thrust earthquakes. Spatial variability might work to inhibit an earthquake from cascading into a multi-segment event in some cases (e.g., if the part of the initial thrust fault near the segment boundary happened to be an area of very low stress release), but would work to abet the cascade in other cases (e.g., high stress drop near the segment boundary). The most uncertain parameter in the model is the static frictional strength, represented here in non-dimensional form by the parameter S. The static strength values used in the rupture simulations ranged from less than 10 MPa up to 40 MPa (measured relative to the dynamic friction level). Numerous earthquake slip models (deduced from ground motion recordings) have been found to be consistent with static strength levels in the same range (Ide and Takeo, 1997; Beroza and Mikumo, 1996; Bouchon, 1997; Olsen et al., 1997; Day et al., 1998) On the other hand, these estimates may be no more than lower bounds, given the limited resolution of fault slip which is achievable from ground motion recordings. Some conceptual models of earthquake rupture imply somewhat higher static strength (e.g., Heaton, 1990), of the order 50-100 MPa. Compared with such models, the highest strength values employed in our study might be too low by as much as a factor of 2. If the higher estimates are appropriate, the distance threshold for suppressing stepover rupture (for a given stress drop) would be reduced by a similar factor. This would not change our conclusion that the presence of an intersecting tear fault increases the threshold by roughly an order of magnitude, compared with the behavior of disjoint faults interacting purely through the interchange of elastic waves.

Our 3D simulations (using 10 km long thrust fault segments and typical fault strength and stress drop values) indicate that, if the thrust segments are linked by a tear fault, rupture can jump segment offsets comparable to observations: offsets < 2 km wide usually do not limit rupture, and offsets 2 to 5 km wide sometimes limit rupture and sometimes do not. The segment boundaries of Los Angeles area thrust fault segmentation

models consist of offsets of up to about 5 km (Shaw and Suppe, 1996; Davis et al., 1989; Dolan et al., 1995; Yeats et al., 1994; Ehlig, 1975; Allen et al., 1971; 1975; Whitcomb et al., 1973; Hauksson, 1990). Some of the offsets are occupied by lateral ramps and tear faults defined by surface fault traces or seismological observations (Yeats et al., 1994; Ehlig, 1975; Allen et al., 1971; 1975; Whitcomb et al., 1973; Hauksson, 1990). For blind thrusts, some of the fault offsets are inferred from offsets in the fold axes above the thrusts, and the presence of lateral ramps and tear faults is uncertain (Shaw and Suppe, 1996; Davis et al., 1989; Dolan et al., 1995; Ekstrom et al., 1992; Stein and Ekstrom, 1992). The presence of a tear fault or lateral ramp linking offset thrust fault segments greatly abets multi-segment rupture, so it is critical to accurately characterize the nature of the thrust fault segment offsets.

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FIGURE CAPTIONS

Figure 1. Model fault geometry. The thrust fault segments are offset by an amount that varies between simulations. Offset is measured normal to the thrust faults. Simulations are performed both with and without a tear fault present in the offset; in the former case most of the simulations have the tear fault only between the thrust fault segments (shaded), and in a few simulations the tear fault extends 6 km beyond the thrust segments (dashed lines). Arrows indicate the slip direction.

Figure 2. Perspective view of snapshots of slip velocity (red and blue high, brown low) for the multi-segment rupture simulation with a tear fault present, $\Delta\sigma$ =10 MPa, S=1.5, and offset=2 km. Model geometry as in Figure 1. Axes are model grid numbers, grid spacing is 50 m.

Figure 3. Summary of 3D simulation results. Open (closed) symbols represent cases where rupture did (did not) jump the offsets, with (squares and triangles) and without (circles) a tear fault present.

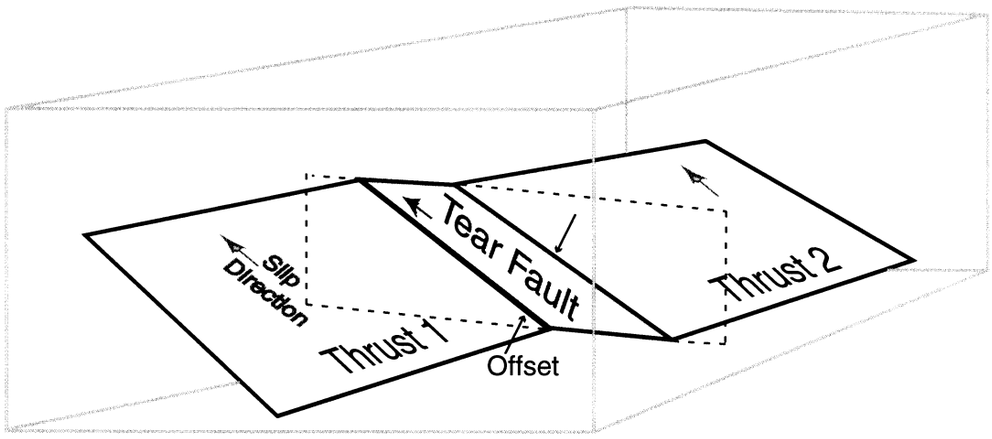

FIGURE 1

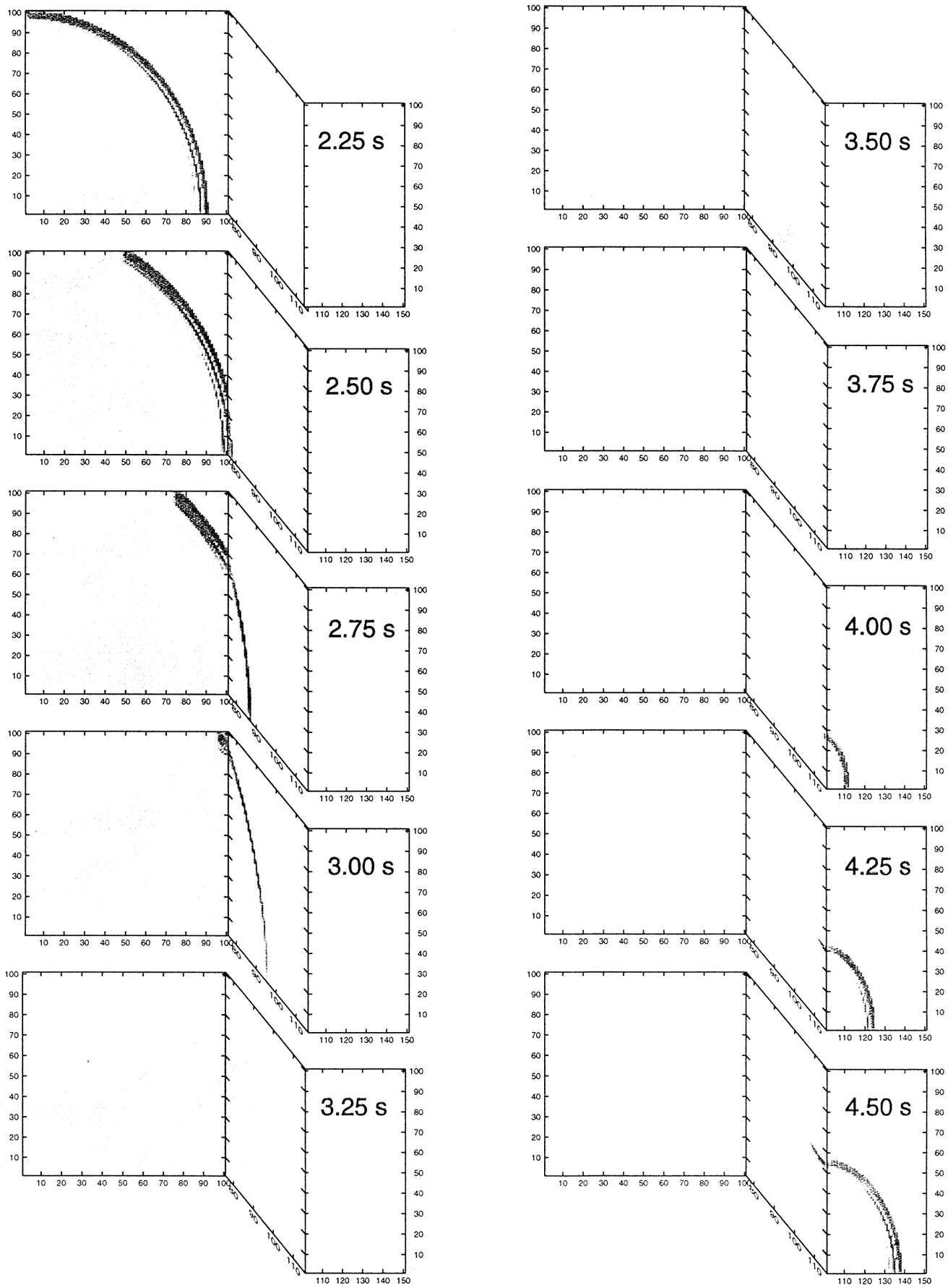

FIGURE 2

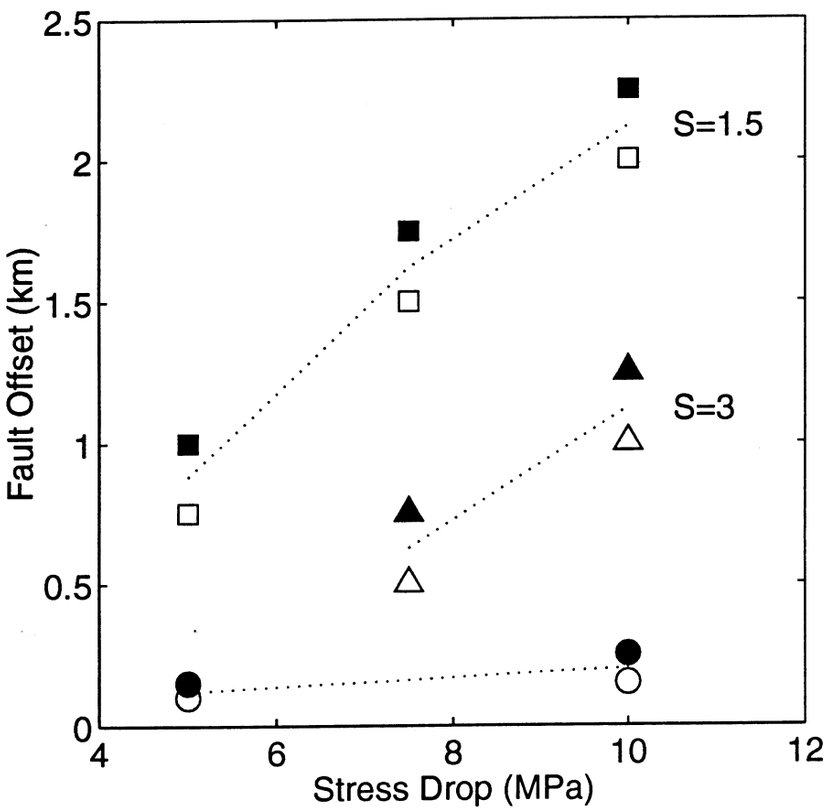

FIGURE 3