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The static stress change triggering model: Constraints from two southern California aftershock sequences

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Abstract. Static stress change has been proposed as a mechanism of earthquake triggering. We quantitatively evaluate this model for the apparent triggering of aftershocks by the 1992 M_W 7.3 Landers and 1994 M_W 6.7 Northridge earthquakes. Specifically, we test whether the fraction of aftershocks consistent with static stress change triggering is greater than the fraction of random events which would appear consistent by chance. Although static stress changes appear useful in explaining the triggering of some aftershocks, the model's capability to explain aftershock occurrence varies significantly between sequences. The model works well for Landers aftershocks. Approximately 85% of events between 5 and 75 km distance from the mainshock fault plane are consistent with static stress change triggering, compared to ~50% of random events. The minimum distance is probably controlled by limitations of the modeling, while the maximum distance may be because static stress changes of <0.01 MPa trigger too few events to be detected. The static stress change triggering model, however, can not explain the first month of the Northridge aftershock sequence significantly better than it explains a set of random events. The difference between the Landers and Northridge sequences may result from differences in fault strength, with static stress changes being a more significant fraction of the failure stress of weak Landers-area faults. Tectonic regime, regional stress levels, and fault strength may need to be incorporated into the static stress change triggering model before it can be used reliably for seismic hazard assessment.

1. Introduction

Static stress change triggering of earthquakes has been proposed as a model for evaluating short-term earthquake hazards. It is one of a number of models relating to the apparent triggering of earthquakes, "triggering" meaning that one earthquake causes another earthquake which would not have otherwise occurred at that time. The idea is that static stress change due to an earthquake can move another fault toward failure stress, advancing the time of the next earthquake on that fault.

Previous work has used static stress theory to identify faults which may have been moved closer to or farther from failure. For example, the effects of the 1989 Loma Prieta and 1992 Landers earthquakes on the San Andreas fault and other major faults in California have been studied [e.g., *Reasenberg and Simpson*, 1992; *Harris and Simpson*, 1992; *Jaumé and Sykes*, 1992; *Stein et al.*, 1992; *King et al.*, 1994; *Stein et al.*, 1994]. Static stress triggering has also been used to explain sequences of earthquakes in a region: for instance, the Eastern California Shear Zone [e.g., *Stein et al.*, 1992; *King et al.*, 1994]; the Los Angeles area [e.g., *Stein et al.*, 1994]; southern California [e.g., *Deng and Sykes*, 1997]; and the San Francisco bay area [e.g., *Jaumé and Sykes*, 1996].

There have been only a few quantitative studies of how consistent the locations and orientations of apparently triggered events are with modeled static stress changes. *Harris et al.* [1994] and *Simpson et al.* [1994] computed the percentage of aftershocks of the 1994 Northridge earthquake consistent with static stress change triggering. *Beroza and Zoback* [1993] and *Kilb et al.* [1997] studied whether static stress changes could explain the diverse mechanisms of the 1989 Loma Prieta aftershock sequence. *Harris et al.* [1995] investigated the static stress change triggering of $M \geq 5$ events in southern California by each other, but the data were limited to only 16 pairs.

In this paper, we test the static stress change triggering model using the aftershock sequences of the 1992 Landers and 1994 Northridge earthquakes. Each sequence includes tens of thousands of recorded events [e.g., *Hauksson et al.*, 1993, 1995], providing sufficient data quantity for a robust quantitative analysis.

Our primary goal is to determine how well modeled static stress changes explain the apparent triggering of

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aftershocks by a mainshock. Specifically, we test if the fraction of aftershocks consistent with triggering by mainshock-induced static stress changes is larger than the fraction of random events (with appropriate probability distributions) which would appear consistent by chance. If it is statistically significantly greater, static stress change is a viable model for explaining aftershock triggering; otherwise, it is not.

A secondary goal is to determine whether the usefulness of the static stress change triggering model is dependent on the size of the stress change, distance from the fault plane, event magnitude, or elapsed time since the mainshock. This may establish some guidelines as to when and where static stress change triggering is an appropriate model for use in seismic hazard assessment.

2. Data

We analyze data from the 1992 Landers and 1994 Northridge earthquake sequences (Figure 1.) These two southern California sequences were recorded by the Southern California Seismic Network (SCSN) and portable stations installed after the mainshocks.

The Landers earthquake of June 28, 1992, a M_W 7.3 strike-slip event, ruptured a cumulative length of 85 km along five faults. The event occurred in the Eastern California Shear Zone, a 80 km wide and 400 km long region of right-lateral strike-slip faults, east of the San Andreas fault, thought to be taking up ~8 mm/yr of the 48 mm/yr Pacific-North America relative plate motion. The Landers sequence is discussed in detail by *Hauksson et al.* [1993].

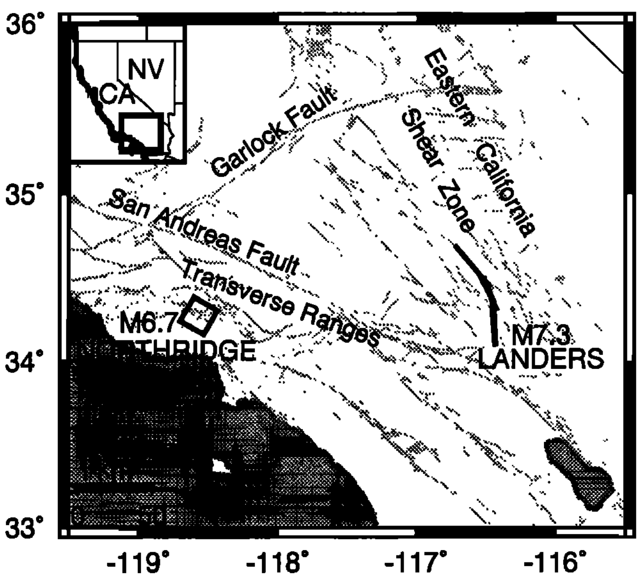

Figure 1. Map of southern California showing the Landers and Northridge mainshocks. Surface projections, solid, from rupture models of *Wald and Heaton* [1994] and *Wald et al.* [1996]. Traces of mapped faults shown shaded.

The January 17, 1994, M_W 6.7 Northridge earthquake occurred on a 20 km length of a previously unrecognized blind thrust beneath the western San Fernando Valley. The earthquake occurred in a region of north-south contractional deformation related to the uplift of the Transverse Ranges at a constraining bend in the San Andreas fault. The Northridge sequence is described by *Hauksson et al.* [1995].

We determine locations and focal mechanisms for $M \geq 2.0$ recorded events in a box around each mainshock, including events not strictly considered aftershocks. Arrival time data from selected aftershocks recorded by the SCSN are used with the VELEST code [*Kissling et al.*, 1994] to jointly determine hypocenters and a refined velocity model. Hypocenters for the remaining events are then determined using HYPOINVERSE [*Klein*, 1985], and mechanisms found using the codes of *Reasenberg and Oppenheimer* [1985]. Only events with focal mechanism parameter uncertainties less than 30° are used.

3. Method

We model the Landers and Northridge mainshocks as dislocations in an elastic half-space and compute the resulting static stress changes. The Coulomb stress changes on aftershock nodal planes are determined, and the Coulomb index (the percent of events consistent with static stress change triggering) is found. The Coulomb index for the first month of each observed sequence is compared to the Coulomb indices of 500 random synthetic sequences (chosen from appropriate probability distributions) to test the null hypothesis that the Coulomb index of the observed sequence is no greater than the Coulomb indices of the synthetic sequences. This test is performed for various subsets of the data.

3.1. Coulomb Failure

The Coulomb failure criterion is commonly used to quantify the effect of static stress change on a plane [e.g., *Reasenberg and Simpson*, 1992; *Harris and Simpson*, 1992; *Jaumé and Sykes*, 1992; *Stein et al.*, 1994; *King et al.*, 1994]. We compute only the incremental stress added by the mainshock because we are testing whether the mainshock-induced static stress changes could have triggered the aftershocks. The importance of the background stress state will be addressed in the comparison of results from the two aftershock sequences.

The change in Coulomb stress, ΔCS, on a plane is

$$\Delta CS = \Delta\tau + \mu'\Delta\sigma \qquad (1)$$

where $\Delta\tau$ is the change in shear stress in the direction of slip on the plane, $\Delta\sigma$ is the change in normal stress (tension positive), and μ' is the effective coefficient of friction.

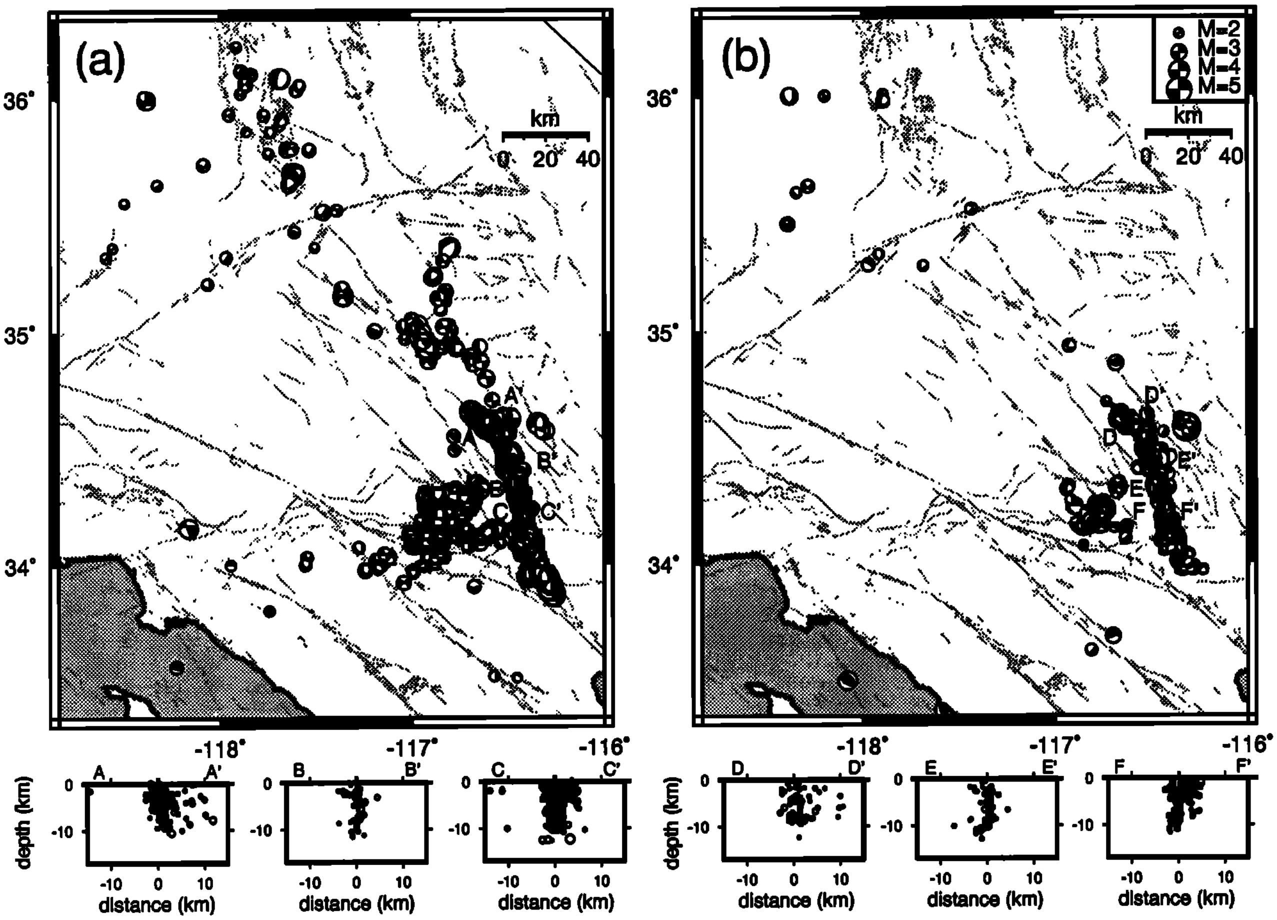

Figure 2. Map view and cross sections of the first month of Landers aftershocks used in this study. (a) Aftershocks with at least one plane consistent with static stress change triggering. (b) Aftershocks with both planes inconsistent. Here μ'=0.4. Mapped faults shown shaded. The mainshock fault plane (adapted from *Wald and Heaton* [1994]) is indicated with solid lines.

We find the Coulomb stress change using the nodal planes and slip directions of individual aftershocks (following *Harris et al.* [1994] and *Simpson et al.* [1994]) because it is important to test whether aftershock slip occurs in a direction consistent with the static stress change model. We feel that using representative planes (such as optimally oriented planes) is not as accurate, considering the diversity of aftershock mechanisms that can occur in close proximity (e.g., Figures 2 and 3). Determining the stress changes on representative planes causes a loss of information by reducing the static stress change tensor to a scalar and not incorporating the aftershock focal mechanisms.

The effective coefficient of friction, μ', accounts for the effect of fluid pressure on the failure plane. When $\mu' = \mu$ (the coefficient of friction for dry rock), the pore pressure has no effect on the normal stress. At the other extreme, when $\mu' = 0$, the rock is so saturated that the pore pressure cancels the effect of the normal stress on the plane. Laboratory experiments on rocks typically find values for μ of around 0.6 to 0.85 [e.g., *Byerlee*, 1978], and values of μ' between 0 and 0.75 are considered plausible [e.g., *King et al.*, 1994]. Low values of μ' (0 to 0.4) are typical in the stress change literature [e.g., *Reasenberg and Simpson*, 1992; *King et al.*, 1994; *Kagan*, 1994]. In this paper, we try a range of values for μ' between 0 and 0.8.

3.2. Technique

We model the mainshocks as planar dislocations in an elastic half-space. The Landers earthquake is modeled as three vertical faults (Camp Rock/Emerson, Homestead Valley, and Landers/Johnson Valley from north to south) with 186 subfaults and a maximum slip near 7 m [*Wald and Heaton*, 1994]. A single fault plane with 196 subfaults and a maximum slip of about 3 m is employed for the Northridge earthquake [*Wald et al.*, 1996]. The M_W 6.1 Joshua Tree preshock and M_W 6.2 Big Bear aftershock of the Landers sequence are modeled as single dislocations of 12 to 15 km diameter (from the inferred rupture lengths of *Hauksson et al.* [1993]) and average

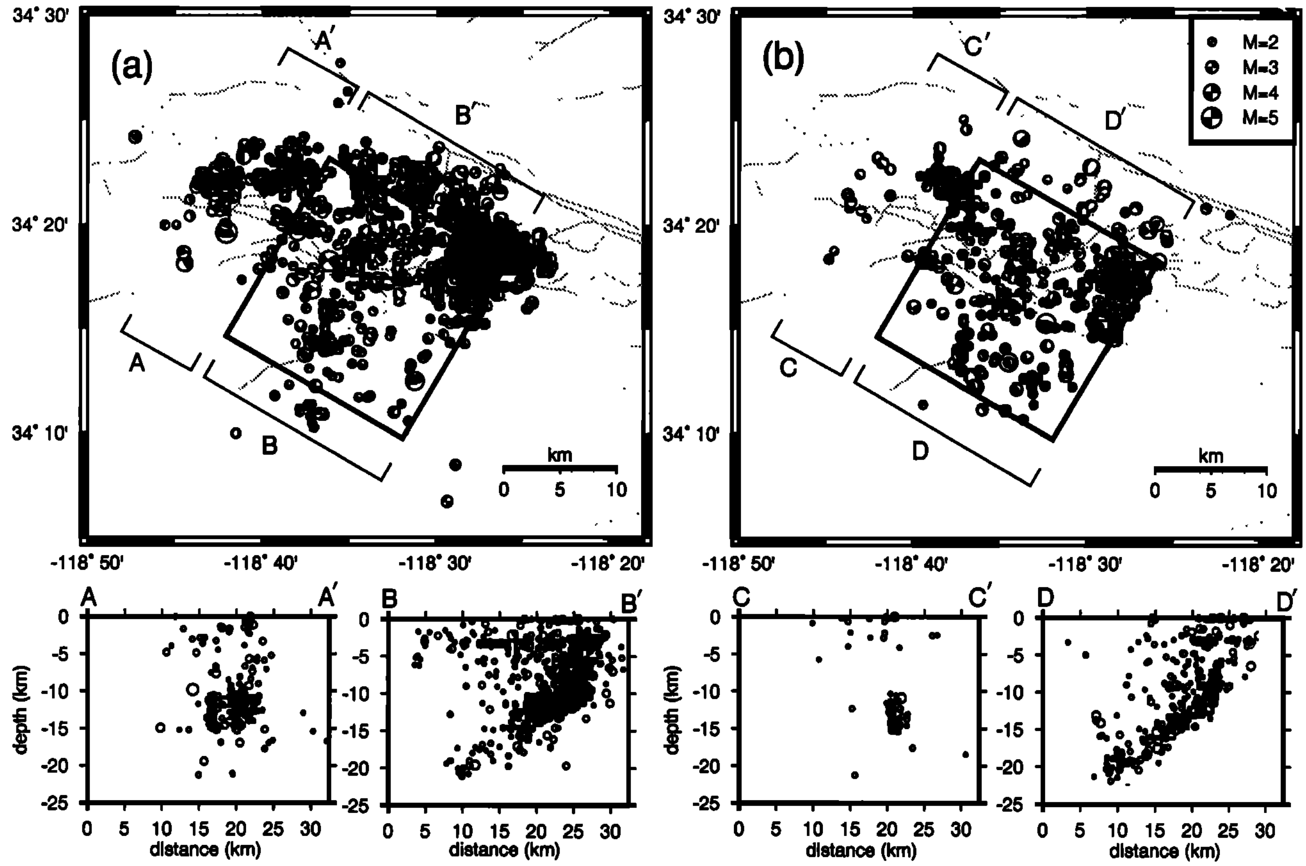

Figure 3. Map view and cross sections of the first month of Northridge aftershocks used in this study. (a) Aftershocks with at least one plane consistent with static stress change triggering. (b) Aftershocks with both planes inconsistent. Here $\mu'=0.4$. Mapped faults are shown shaded. The projection of the mainshock fault plane (adapted from *Wald et al.* [1996]) is shown as a solid rectangle.

slip of 0.35 m. The smaller aftershocks are not modeled because it impractical to do so and because their effects on the stress field are small compared to those of larger events.

The changes in the stress tensor at the hypocenters of the aftershocks are calculated using the subroutines of *Okada* [1992], assuming the half-space is a Poisson solid with a shear modulus of 3 GPa. We resolve the change in the stress tensor onto the two nodal planes of each aftershock and calculate the Coulomb stress change on each plane.

We then compute the Coulomb index, the percent of aftershocks in an aftershock sequence consistent with static stress change triggering. An aftershock is considered to be consistent with static stress change triggering if it occurred on a plane with ΔCS> 0. Aftershocks with positive ΔCS on both nodal planes are clearly consistent with static stress change triggering, while those with negative ΔCS on both planes are clearly inconsistent. We initially assume that 50% of the events with only one ΔCS> 0 nodal plane occurred on the plane with the static stress increase, and vary this parameter during error estimation. (Since the shear stress changes on the two nodal planes are always the same, fewer than 20% of all events fall into this ambiguous category.)

A confidence interval for the Coulomb index of an aftershock sequence is obtained via a bootstrapping technique. We resample the observed sequence 500 times, with replacement, with the focal mechanism parameters randomly chosen from their confidence intervals. The fraction of events with only one ΔCS> 0 plane considered consistent with triggering is chosen from a binomial distribution with a mean of 0.5. The 2σ confidence interval is obtained from the distribution of the Coulomb indices of the resampled sequences.

3.3. Random Synthetic Sequences

We test the static stress change triggering model by comparing the Coulomb indices of the observed sequences with the Coulomb indices of random synthetic sequences (e.g., Figure 4). The synthetic sequences serve as a control group, separating the effects of basic aftershock sequence geometry on Coulomb index from the effects of triggering. The synthetic sequences are designed to geometrically resemble aftershock sequences in that the events are clustered around the mainshock fault plane and in seismogenic depth ranges.

Each parameter of a synthetic event is chosen randomly from a plausible distribution of values. To facilitate creating the synthetic sequences, we use a some-

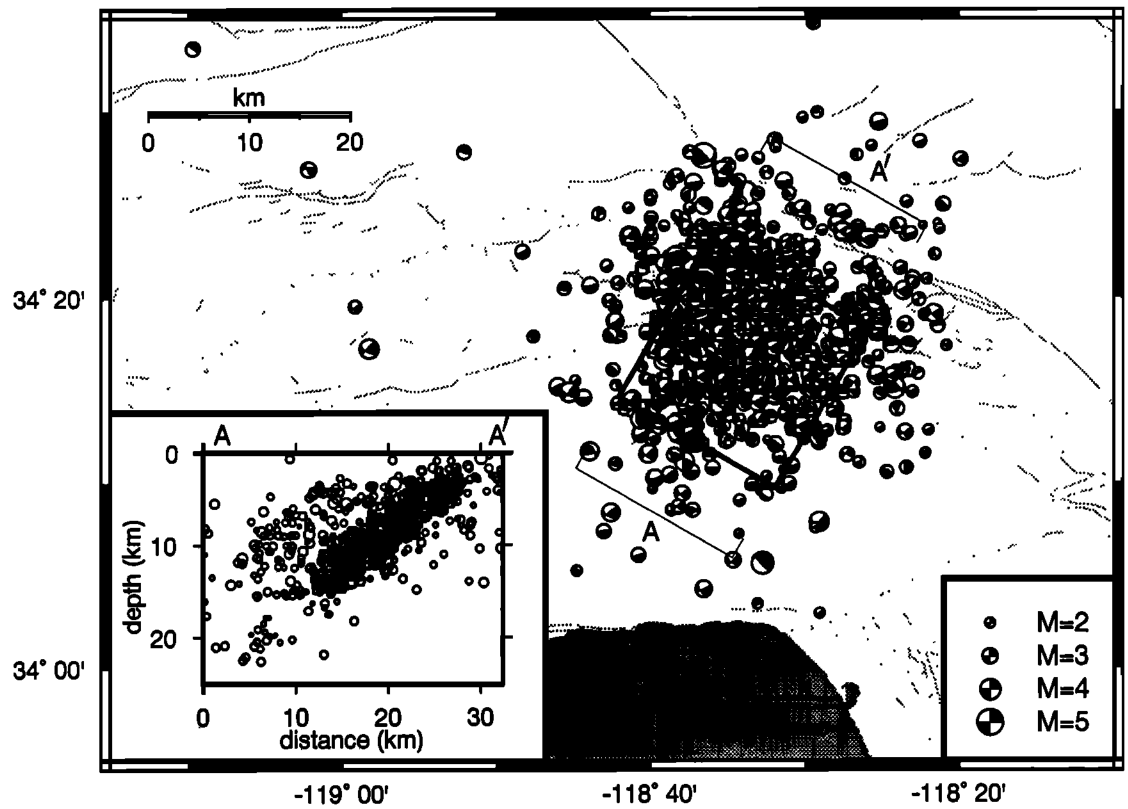

Figure 4. A random synthetic sequence of events for Northridge, shown in map view and fault-normal cross section. The projection of the mainshock slip plane (adapted from *Wald et al.* [1996]) is shown as a rectangle in map view.

what unusual, mainshock-fault-plane-dependent coordinate system. The three coordinates are depth, strike direction distance, and normal distance to the fault plane (Figure 5). Each coordinate is chosen randomly and independently for the events in a synthetic sequence, with the probability distributions as shown in Figures 6a-6f. Because aftershocks also occur in spatial clusters, ~25% of the synthetic events are placed in clusters. The first event in a cluster is located randomly using the given probability distributions, and the locations of the subsequent events are determined by perturbing the parameters. The focal mechanisms are also chosen randomly, the P axis trend and P and T axis plunges selected independently with the probability distributions shown in Figures 6g-6l. Magnitudes are randomly assigned assuming a Gutenberg-Richter distribution.

The probability distribution functions are created using the relevant parameters of the observed aftershock sequences as guides. These parameters are as follows: how fast the synthetic seismicity drops off as one goes away from the fault, the seismogenic depth ranges, the kinds of focal mechanisms, and the b values. We do not generate the synthetic sequences by resampling the observed hypocenters or attempt to recreate the details of the observed sequences. We wish to include synthetic events in areas which are unrepresented in the observed sequences (perhaps due to inhibiting static stress changes) and avoid bias towards areas of aftershock

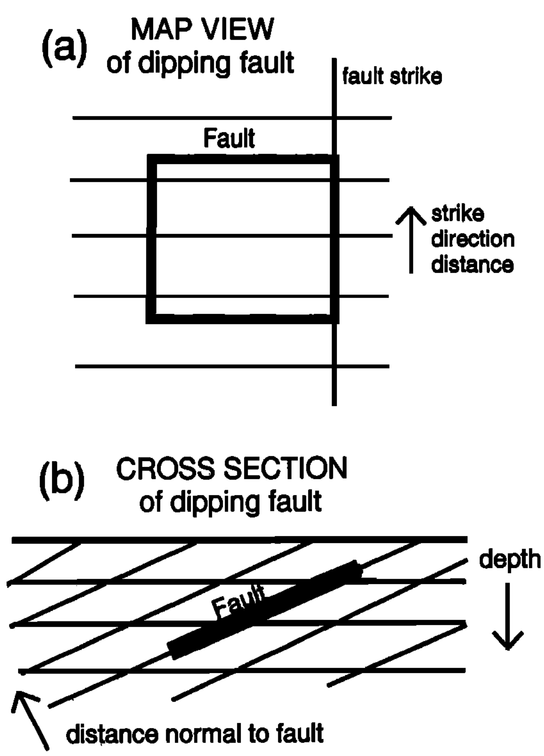

Figure 5. Cartoon (a) map view and (b) fault-normal cross section of a dipping rectangular fault which illustrates the coordinate system used in defining aftershock locations: depth, strike direction distance, and normal distance from the fault plane.

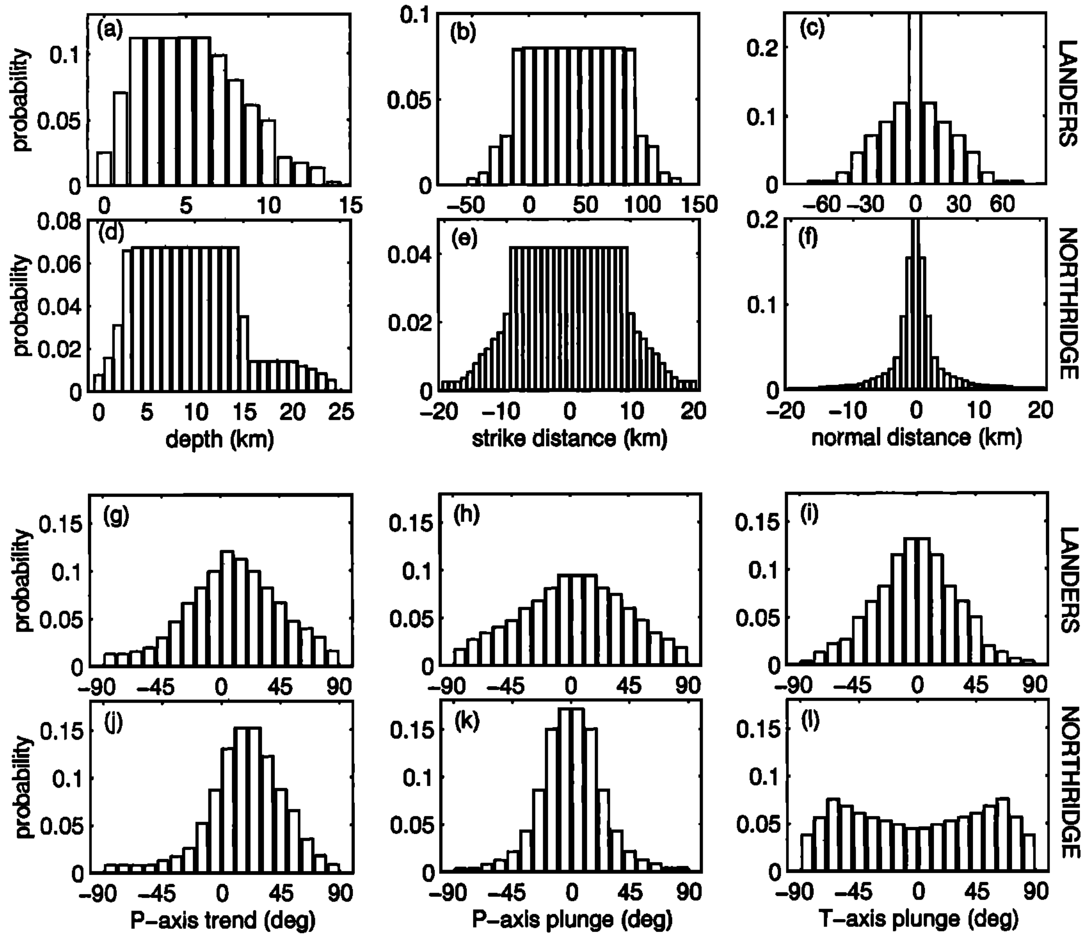

Figure 6. Probability distribution of synthetic event coordinates: (a)-(c) Landers sequence spatial coordinates, (d)-(f) Northridge sequence spatial coordinates, (g)-(i) Landers sequence focal mechanism parameters, (j)-(l) Northridge sequence focal mechanisms parameters. The spatial coordinates are as shown in Figure 5. The strike distance is measured east from the center of the Northridge fault and north from the southern tip of the Landers fault, with the approximation that the three fault segments are end-to-end, and normal distance is measured from the nearest segment or its extention. The *P* axis trend is measured clockwise from north, and the plunge is down from horizontal. The *T* axis plunge is positive for a clockwise rotation about the *P* axis.

clusters (possibly areas of encouraging stress changes.)

The Coulomb indices of 500 synthetic sequences are calculated in the same way as the Coulomb indices of the observed sequences. All of the synthetic events with two ΔCS> 0 nodal planes and a random fraction of events with only one ΔCS> 0 nodal plane are considered consistent with triggering.

3.4. Statistical Test

We perform a simple statistical test of the null hypothesis that the Coulomb index of the observed sequence is no greater than the Coulomb indices of the synthetic sequences. Since this is a one-tailed test, the null hypothesis can be rejected at the 95% confidence level if the Coulomb index of the observed sequence is greater than the Coulomb indices of 95% of the synthetic sequences.

We include the error estimate for the Coulomb index of the observed sequence by taking the average confidence level determined from the bootstrap resamplings. This can be expressed as a weighted average of the confidence levels corresponding to each possible observed Coulomb index

$$CL = \sum_{CI=0}^{100} O(CI)S(CI) \qquad (2)$$

where CL is the average confidence level of rejecting the null hypothesis. O(CI) is the fraction of observed sequence resamplings with a Coulomb index of CI (the weight), and S(CI) is the cumulative fraction of synthetic sequences with a Coulomb index less than CI (the corresponding confidence level.) If CL$\geq$ 95%, the null hypothesis can be rejected, and we can conclude that the static stress change triggering model explains the

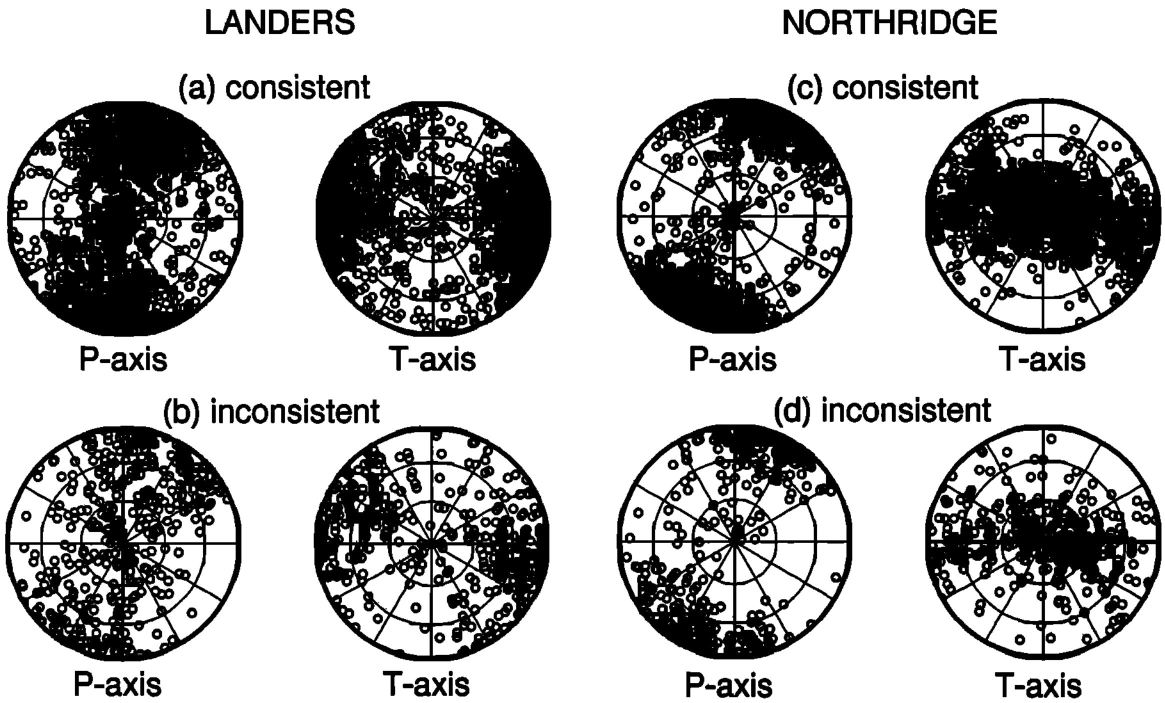

Figure 7. Stereographic plots of the compressional (P) and tensional (T) axes of the first month of aftershocks. Here μ'=0.4. (a) Landers aftershocks with at least one plane consistent with static stress change triggering. (b) Landers aftershocks with both planes inconsistent. (c) Northridge aftershocks with at least one plane consistent. (d) Northridge aftershocks with both planes inconsistent.

aftershocks better than it does a random set of events.

Repeated trials with the Landers dataset indicate that CL is stable to within ±2%. Therefore, we consider CL$\geq$ 97% firm basis to reject the null hypothesis, and 93% $\leq$CL< 97% to be ambiguous.

4. Results

Both the Landers and Northridge sequences include events consistent and inconsistent with static stress change triggering. These have generally indistinguishable distributions of hypocenters and mechanisms. The spatial mixture of aftershocks consistent and inconsistent with static stress change triggering can be seen in the map views and fault-normal cross sections in Figures 2 and 3. Many events inconsistent with static stress triggering appear to concentrate around the mainshock fault planes, which may be explained by limitations of the data and models, as discussed later. Events consistent and inconsistent with triggering also have similar focal mechanisms, as illustrated by the stereographic projections of the tensional and compressional axes (Figure 7). The mechanisms are consistent with the inferred first-order southern California stress field of NNE trending compression [e.g., *Zoback and Zoback*, 1980].

Approximately 65% of the Landers and 60% of the Northridge aftershocks occurring within a month of the mainshock are consistent with static stress change triggering. The null hypothesis, that the Coulomb index of the observed sequence is no greater than the Coulomb indices of the synthetic sequences, can be rejected at the 95% confidence level for the Landers sequence, indicating that static stress change triggering is a useful model in explaining that sequence. However, the null hypothesis cannot be rejected at the 95% confidence level for the Northridge sequence, or any of its subsets we tested. The null hypothesis could be rejected for the Northridge sequence (for μ'=0.4) with only 75% confidence. Since there are 1200 events in our Northridge data set, we interpret this as a failure of the model, not as a case of insufficient data to test the hypothesis.

The quantitative results for all the data subsets tested are shown in Figure 8 and are summarized in Table 1. We find that the results are independent of aftershock magnitude and time after the mainshock. Varying μ' also does not make a significant difference to our results, since the null hypothesis can be rejected for the Landers sequence and cannot be rejected for the Northridge sequence for most tested values of μ' (Figures 8a and 8b). The only possible exceptions are for the Landers data with μ' = 0.8 or $t \leq 2$ days, for which the confidence level is in the ambiguous region.

For the Landers sequence, the null hypothesis cannot be rejected at the 95% confidence level for aftershocks less than 5 km or greater than 75 km from the

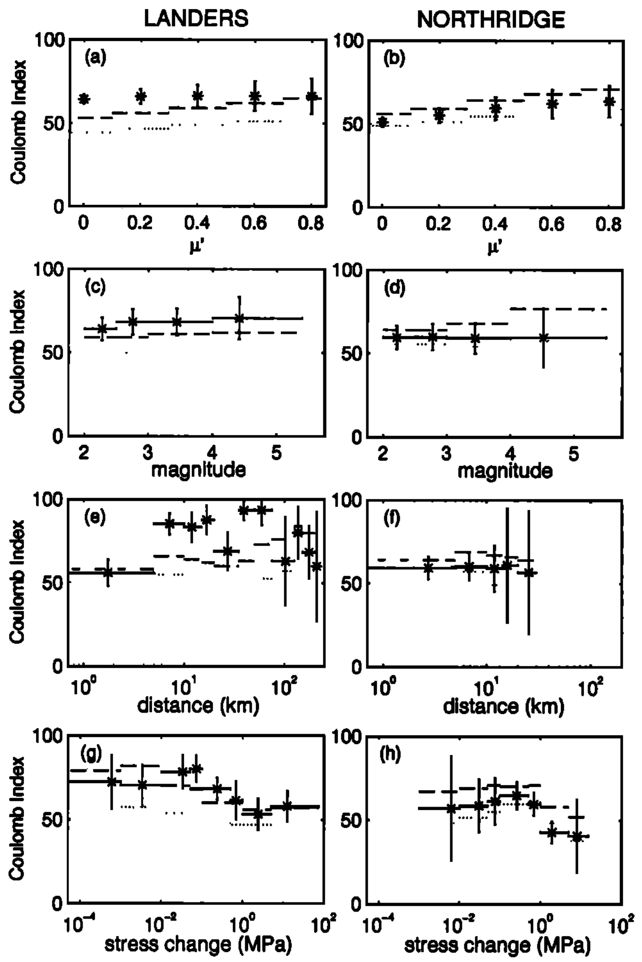

Figure 8. Coulomb index (CI), the percent of events consistent with static stress change triggering, versus various parameters. The asterisks indicate the Coulomb index for a bin versus the mean parameter value of events in that bin. The vertical error bars are the 2σ error estimates, and the horizontal error bars indicate the bins. The horizontal dotted and dashed lines represent the mean Coulomb index of 100 random synthetic sequences and the division between the upper 5% and the lower 95%, respectively. If the Coulomb index of the observed sequence is above this dashed line, one can conclude with 95% confidence that the static stress change triggering model explains the aftershocks better than it can a random set of events. (Aftershocks from the first month are used. Here μ'=0.4 except in Figures 8a and 8b.) (a) CI versus μ', Landers. (b) CI versus μ', Northridge. (c) CI versus aftershock magnitude, Landers. (d) CI versus magnitude, Northridge. (e) CI versus distance to the nearest point on a modeled rupture plane, Landers. (f) CI versus distance, Northridge. (g) CI versus stress change, $|\Delta CS|$, the average of the absolute values of the Coulomb stress changes on the two nodal planes, Landers. (h) CI versus $|\Delta CS|$, Northridge.

mainshock fault plane (Figure 8e), or for aftershocks with $|\Delta CS| < 0.01$ MPa or $|\Delta CS| > 0.5$ to 1 MPa (Figure 8g). This means that the static stress change triggering model is not useful close to the fault where stress changes are high or far from the fault where stress changes are low. Between these extremes, ~85% of the aftershocks and 50% of the synthetics events are consistent with static stress change triggering.

The Coulomb index is found for 4.5 years of seismicity both preceeding and following the Landers mainshock (Figure 9). The premainshock events serve as a control group reflecting regional seismicity patterns independent of mainshock-induced static stress changes, although they may not be an ideal control because they may reflect processes leading up to the mainshock. The Coulomb index of pre-event seismicity is consistently 50±8, while that of the aftershocks is 65±8. There is no detectable decrease in Coulomb index in the 4.5 years following the mainshock, indicating that mainshock-induced static stress changes can be useful in explaining regional seismicity for at least that long.

5. Discussion

We find that the aftershocks consistent and inconsistent with triggering by static stress changes are spatially mixed, with a majority of aftershock mechanisms in agreement with the first-order regional stress field. Because mainshock-induced static stress changes are very small, they are more likely to trigger earthquakes on planes already close to failure. These planes are presumably primarily loaded by tectonic stresses, and so it is not surprising that they fail oriented with the regional stress field.

The static stress change triggering model is useful in explaining the first month of the Landers aftershock sequence but not the first month of the Northridge sequence. This difference is not because the stress changes from the Landers mainshock are a stronger signal, since for the same range of stress changes, 0.01 to 0.5 MPa, the model works well for the Landers sequence and not for Northridge.

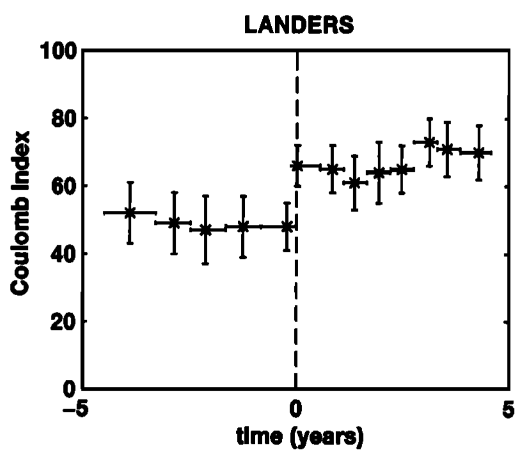

Figure 9. Coulomb index versus time in years for 4.5 years of seismicity preceeding and following the Landers mainshock. The vertical error bars are the 2σ error estimates and the horizontal error bars indicate the bins. The vertical dotted line indicates the time of the mainshock.

Table 1. Coulomb Index of First Month of Aftershock Sequences

	Landers				Northridge			
Data Set or Parameter Value	Number of Events	Observed CI ($\pm 2\sigma$)	Synthetic CI ($\pm 2\sigma$)	Confidence Level	Number of Events	Observed CI ($\pm 2\sigma$)	Synthetic CI ($\pm 2\sigma$)	Confidence Level
μ^T=0	1471	64 ±3	45 ±10	99%	1200	51 ±3	49 ±8	61%
μ'=0.2	1471	66 ±4	47 ±10	99%	1200	55 ±4	52 ±8	73%
μ'=0.4	1471	66 ±7	49 ±11	99%	1200	59 ±7	55 ±10	75%
μ'=0.6	1471	66 ±9	52 ±12	97%	1200	62 ±8	57 ±12	72%
μ'=0.8	1471	66 ±10	53 ±13	93%	1200	64 ±9	59 ±13	70%
$M \leq 2.5$	734	64 ±7	49 ±12	98%	741	59 ±7	55 ±11	73%
$2.5 < M \leq 3$	416	68 ±8	49 ±12	99%	265	60 ±8	56 ±9	73%
$3 < M \leq 4$	264	68 ±8	50 ±12	99%	163	59 ±9	54 ±15	70%
$M > 4$	57	71 ±13	48 ±16	98%	31	60 ±18	58 ±23	52%
$D \leq 5$ km	897	56 ±8	50 ±8	84%	883	59 ±7	57 ±8	64%
$5 < D \leq 10$	225	85 ±6	55 ±12	99%	253	60 ±8	57 ±14	60%
$10 < D \leq 15$	70	83 ±9	52 ±14	99%	48	59 ±14	49 ±21	77%
$15 < D \leq 20$	54	88 ±8	46 ±19	99%	8	61 ±34	38 ±27	84%
$20 < D \leq 35$	65	69 ±11	42 ±19	98%	7	57 ±37	39 ±27	77%
$35 < D \leq 50$	60	93 ±6	44 ±24	99%	1	- -	- -	-
$50 < D \leq 75$	20	94 ±9	53 ±26	99%	0	- -	- -	-
$75 < D \leq 125$	14	63 ±26	57 ±22	63%	0	- -	- -	-
$125 < D \leq 150$	23	80 ±15	58 ±29	90%	0	- -	- -	-
$150 < D \leq 200$	33	69 ±15	57 ±27	78%	0	- -	- -	-
$D > 200$	10	60 ±32	55 ±63	55%	0	- -	- -	-
$\|\Delta CS\| \leq 0.001$ MPa	29	72 ±16	59 ±24	81%	1	- -	- -	-
$0.001 < \|\Delta CS\| \leq 0.01$	65	70 ±12	57 ±24	86%	6	57 ±31	49 ±25	64%
$0.01 < \|\Delta CS\| \leq 0.05$	150	78 ±10	54 ±18	98%	58	59 ±16	51 ±21	68%
$0.05 < \|\Delta CS\| \leq 0.1$	160	80 ±8	52 ±18	99%	104	61 ±14	55 ±18	67%
$0.1 < \|\Delta CS\| \leq 0.5$	506	68 ±7	48 ±15	99%	649	65 ±8	60 ±12	73%
$0.5 < \|\Delta CS\| \leq 1$	119	61 ±11	47 ±15	93%	207	60 ±7	61 ±10	38%
$1 < \|\Delta CS\| \leq 5$	311	53 ±9	47 ±10	81%	156	43 ±7	49 ±9	13%
$\|\Delta CS\| > 5$	131	58 ±9	44 ±13	94%	19	41 ±22	38 ±16	56%
$t \leq 2$ days	137	64 ±10	49 ±14	95%	345	60 ±8	55 ±13	71%
$2 < t \leq 7$	359	68 ±8	49 ±12	99%	396	59 ±7	55 ±13	70%
$7 < t \leq 14$	437	64 ±7	49 ±12	98%	279	60 ±8	55 ±14	72%
$t > 14$	538	67 ±7	49 ±12	99%	180	60 ±9	55 ±14	69%

However, the static stress changes due to the Landers mainshock may be a stronger signal relative to the local background stress and failure stress of faults. *Hauksson* [1994] inferred that the Eastern California Shear Zone is a weak zone, supporting low shear stresses, based on stress inversions indicating that the northern part of the Landers rupture relieved nearly all of the applied shear stress. The stress field inferred from Northridge aftershocks [e.g., *Zhao et al.,* 1997; *Kerkela and Stock,* 1996], on the other hand, implies that the Northridge earthquake was not a complete stress drop event, and hence that fault is relatively strong. Faults in thrust regimes are generally expected to support higher stresses because the overburden pressure is the minimum principal stress, whereas in strike-slip regimes one of the horizontal principal stresses is less than the overburden.

If the Landers area is relatively weak, and static stress triggering is observed there but not at Northridge, this implies that static stress changes may be too small to trigger a detectable number of events except in relatively weak areas. Presumably, this is because the small stress changes are a more significant fraction of the failure stress of a weak fault.

The difference between the results from the two sequences may also be due in part to limitations of the modeling. Approximating the Earth as a homogeneous elastic half-space may be appropriate for the Landers sequence because the Eastern California Shear Zone is relatively homogeneous on a 85 km length scale but inappropriate for the Northridge sequence, which is partially in the Transverse Ranges and partially in the San Fernando Valley. The Northridge mainshock was also smaller and did not rupture the surface, so there may be more error in the modeling of mainshock slip.

Regardless of its source, the difference between the results for the Landers and Northridge sequences implies that, although the static stress change triggering model can be useful in explaining aftershock triggering, it is not consistently applicable for different events. This is also indicated by the variability of the results from other studies.

A study of larger events found that the model performs much better than it does in this study. *Harris et al.* [1995] studied 16 pairs of $M \geq 5$ southern California earthquakes occurring less than 1.5 years apart, 5 km distant, and with $|\Delta CS|$ on the plane of the second event due to the first at least 0.01 MPa. They find that 15 event pairs, or 94%, have $\Delta CS > 0$ on the failure plane of the second event.

In other studies, 70% to 75% of the first few months of Northridge aftershocks have been found to be consistent with static stress change triggering [*Simpson et al.*, 1994; *Harris et al.*, 1994], a greater percentage than we find for the first month of aftershocks. The difference may be due in part to the use of different criteria, the other studies consider consistent with triggering all events with at least one ΔCS>0 nodal plane, and in part to the use of different events.

Beroza and Zoback [1993] and *Kilb et al.* [1997] study the Loma Prieta sequence and conclude that mainshock-induced static stress changes do not adequately explain the individual aftershock mechanisms. However, the poor performance of the model may be because many Loma Prieta aftershocks occur very close to the mainshock rupture. It appears that the Loma Prieta aftershocks consistent with mainshock-induced shear increase are generally farther away from the major slip patches, while those inconsistent are closer to these patches [see *Beroza and Zoback*, 1993, Figure 3], consistent with the observation that the static stress triggering model does not work very close to the mainshock.

The presence of a minimum distance for which static stress change appears to be a viable triggering mechanism for Landers and other sequences need not reflect any physical process, it may merely reflect limitations of the data and models used. The slip models lack small-scale detail and are discretized, affecting the computed value of ΔCS for events near the fault plane. Location errors may also be more important for events close to the fault plane than for those farther away. Other studies also find or assume that the static stress change triggering model shouldn't be used closer to the fault than a few km [e.g., *Harris et al.*, 1995; *King et al.*, 1994].

The minimum Coulomb stress change for which the model appears to be valid for the Landers sequence, 0.01 MPa, is similar to values found in other studies: 0.01 MPa for Loma Prieta [*Reasenberg and Simpson*, 1992], 0.01 to 0.03 MPa for Landers [*King et al.*, 1994], and 0.02 MPa for Double Springs Flat, Nevada [*Jaumé*, 1996]. The corresponding maximum distance from the fault plane, 75 km, or approximately one fault length, however, is smaller than those determined from seismicity rates: 80 to 100 km, or about two fault lengths, for Loma Prieta [*Reasenberg and Simpson*, 1992], and about three fault lengths for Landers [*King et al.*, 1994].

There is no theoretical reason why a minimum stress change capable of triggering should exist, and it seems reasonable that an arbitrarily small static stress increase should be able to trigger an earthquake on a plane arbitrarily close to failure. A possible explanation for the existence of an apparent minimum triggering stress is that smaller static stresses trigger so few events that they are undetectable with the data sets used.

The effects of the static stress changes on regional seismicity appear to continue for at least 4.5 years after the Landers mainshock. This is longer than the 1.5 year interval found by *Harris et al.* [1995] for $M \geq 5$ events but considerably shorter than the decades which can pass between larger events postulated to be linked by static stress changes [e.g., *Stein et al.*, 1992; *King et al.*, 1994; *Stein et al.*, 1994; *Jaumé and Sykes*, 1996; *Deng and Sykes*, 1997].

Although coseismic static stress changes are essentially instantaneous, the aftershocks triggered by them do not necessarily occur immediately after the mainshock. A static stress increase could advance the time of an earthquake, which may then occur in the following months or years. Additionally, postseismic relaxation at depth may continue to load the brittle upper crust in the same patterns as the coseismic static stress changes [e.g., *King et al.*, 1994]. The rate- and state-dependent seismicity model of *Dieterich* [1994] also explains how a static stress change can produce an Omori's law temporal distribution of aftershocks.

The poor performance of the static stress change triggering model for the Northridge sequence and the presence of many aftershocks in the Landers sequence not consistent with static stress change triggering imply that there are other triggering mechanisms involved. Other triggering models, primarily proposed for far-field triggering, include dynamic strains [e.g., *Anderson et al.*, 1994; *Hill et al.*, 1993], transient changes in pore pressure due to dynamic strains [e.g., *Hill et al.*, 1993], long-term changes in pore pressure due to pore-fluid movements after fluid seals are broken [e.g., *Hill et al.*, 1993], and increases in pore pressure by dynamic strains via rectified diffusion [*Sturtevant et al.*, 1996].

6. Conclusions

The static stress change triggering model has been quantitatively evaluated for the 1992 Landers and 1994 Northridge aftershock sequences. Specifically, we test whether the fraction of aftershocks consistent with static stress change triggering is significantly greater than the fraction of random events which would appear consistent by chance.

We find that the model is useful in explaining the Landers aftershocks, particularly those which are not too close to ($d < 5$ km or $|\Delta CS| > 0.5$ to 1 MPa) or too far from ($d > 75$ km or $|\Delta CS| < 0.01$ MPa) the mainshock fault plane. However the model is not useful in explaining the first month of the Northridge sequence. The difference between the two sequences may be due to differences in tectonic regime and stress state, with weaker faults in the Landers region being more susceptible to triggering by small stress increases.

Our results suggest that the static stress change triggering model has some validity and can be useful in explaining apparently triggered seismicity within one fault length of a large mainshock. However, because its applicability varies between different sequences, its general application to seismic hazard evaluation requires more refinement and the inclusion of parameters such as tectonic regime, regional stress state, and fault strength.

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