JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. 0, XXXX, doi:10.1029/2001JB000678, 2002

A strong correlation between induced peak dynamic Coulomb stress change from the 1992 *M*7.3 Landers, California, earthquake and the hypocenter of the 1999 *M*7.1 Hector Mine, California, earthquake

Debi Kilb

Institute of Geophysics and Planetary Physics, University of California, San Diego, La Jolla, California, USA

Received 19 June 2001; revised 13 May 2002; accepted 30 May 2002; published XX Month 2002.

[1] The 1992 *M*7.3 Landers earthquake may have played a role in triggering the 1999 *M*7.1 Hector Mine earthquake as suggested by their close spatial (∼20 km) proximity. Current investigations of triggering by static stress changes produce differing conclusions when small variations in parameter values are employed. Here I test the hypothesis that large-amplitude dynamic stress changes, induced by the Landers rupture, acted to promote the Hector Mine earthquake. I use a flat layer reflectivity method to model the Landers earthquake displacement seismograms. By requiring agreement between the model seismograms and data, I can constrain the Landers main shock parameters and velocity model. A similar reflectivity method is used to compute the evolution of stress changes. I find a strong positive correlation between the Hector Mine hypocenter and regions of large (>4 MPa) dynamic Coulomb stress changes (peak $\Delta\sigma_f(t)$) induced by the Landers main shock. A positive correlation is also found with large dynamic normal and shear stress changes. Uncertainties in peak $\Delta\sigma_f(t)$ (1.3 MPa) are only 28% of the median value (4.6 MPa) determined from an extensive set (160) of model parameters. Therefore the correlation with dynamic stresses is robust to a range of Hector Mine main shock parameters, as well as to variations in the friction and Skempton's coefficients used in the calculations. These results imply dynamic stress changes may be an important part of earthquake trigging, such that large-amplitude stress changes alter the properties of an existing fault in a way that promotes fault failure. *INDEX TERMS:* 7209 Seismology: Earthquake dynamics and mechanics; 7215 Seismology: Earthquake parameters; 7230 Seismology: Seismicity and seismotectonics; 7260 Seismology: Theory and modeling; *KEYWORDS:* Hector Mine earthquake 1999, Landers earthquake 1992, Coulomb stress, dynamic stress change, earthquake triggering, reflectivity

Citation: Kilb, D., A strong correlation between induced peak dynamic Coulomb stress change from the 1992 *M*7.3 Landers, California, earthquake and the hypocenter of the 1999 *M*7.1 Hector Mine, California, earthquake, *J. Geophys. Res.*, *107*(0), XXXX, doi:10.1029/2001JB000678, 2002.

1. Introduction

[2] The 1992 *M*7.3 Landers and 1999 *M*7.1 Hector Mine California earthquakes are separated by 20 km, roughly one-third of their fault lengths, suggesting that these earthquakes constitute a main shock/aftershock pair. Yet the commonly employed static stress triggering models, as well as viscous relaxation models, are unable to determine unequivocally if stress changes induced by the Landers earthquake acted to enhance the likelihood of the Hector Mine earthquake [e.g., *Pollitz*, 2000; *Freed and Lin*, 2001; *Harris and Simpson*, 2002]. Although some studies produce results that substantiate these triggering hypotheses, these conclusions are controversial because small changes in the input parameter values result in the opposite conclusion. This ambiguity suggests it is worth investigating whether additional triggering mechanisms are at play. To this aim, I investigate whether large dynamic stress changes, lasting only minutes, induced by the passage of seismic waves from the Landers earthquake could contribute to triggering the Hector Mine earthquake seven years later.

[3] Studies of the Landers earthquake sequence revealed a number of unexpected discoveries. For example, aftershocks were identified in distant locations such as Cedar City, Utah; Boise, Idaho; and Yellowstone, Montana [*Hill et al.*, 1993]. These observations redefined the spatial extent of an aftershock zone from the previously assumed one-to-two main shock fault lengths to upward of 10 main shock fault lengths. These distant aftershocks are not likely to have been triggered by static Coulomb stress changes ($\Delta\sigma_f$) induced by the main shock because static stresses at these distances are so small (<0.01 MPa, a value less than tidal stress changes) [*Hill et al.*, 1993]. These distant aftershocks are more reasonably triggered by dynamic stress changes generated by the passage of seismic waves, which are often an order of magnitude or more greater than static stress changes. It seems likely that if dynamic stress changes

0148-0227/02/2001JB000678$09.00

trigger aftershocks multiple fault lengths away, they could also do so within just a few fault lengths. Such near-field dynamic triggering is the focus of this study.

[4] In accordance with other studies, I hypothesize that large dynamic stress changes induced by a main shock can act in a way to promote aftershocks [e.g., *Belardinelli et al.*, 1999; *Henry et al.*, 2000; *Voisin et al.*, 2000; *Gomberg et al.*, 2001; *Power et al.*, 2001; *Voisin*, 2001]. In particular, I assume large stress changes induced by the Landers main shock altered the basic fault properties (weaken asperities, change the pore pressure, or unclamp the fault) of the yet to rupture Hector Mine fault. To test this hypothesis I examine the correlation between the hypocenter of the Hector Mine main shock and peak $\Delta\sigma_f(t)$ induced by the Landers main shock; I also examine the correlation with the static equivalent $\Delta\sigma_f$ (see section 2 for definitions of $\Delta\sigma_f$ and peak $\Delta\sigma_f(t)$).

[5] A number of different measures can be used to assess dynamic stress changes induced by a main shock event. These include the peak-to-peak amplitude of the stress changes, the duration of oscillatory stress change above a given threshold value, or a measure of the frequency content of the radiated seismic waves, such as the number of oscillations at a given frequency occurring above a given threshold amplitude [e.g., *Voisin*, 2001]. Because my aim is to determine if dynamic stress changes could have played a role in triggering the Hector Mine earthquake and not necessarily to pin down the precise dynamic mechanics of the triggering, I pick a simple measure of dynamic stress change, namely, the peak positive Coulomb stress change (peak $\Delta\sigma_f(t)$).

[6] One important difference between this study and other studies of dynamic triggering is that the lag time between the main shock (Landers) and aftershock (Hector Mine) is 7 years instead of just a few seconds or minutes [e.g, *Harris and Day*, 1993; *Belardinelli et al.*, 1999; *Harris and Day*, 1999; *Henry et al.*, 2000; *Power et al.*, 2001]. One explanation of the relatively long time delays between a main shock and its aftershock is that the vigorous shaking and/or squeezing that occurs during the passage of large-amplitude seismic waves significantly alters the frictional properties of the surrounding faults. For example, stress change oscillations may alter fluid pressures, connect adjacent voids, or create a fault that did not previously exist. Such changes may depend on normal stress variations or the frequency and/or duration of the dynamic stress change oscillations [*Voisin*, 2001].

[7] From the data available today, it is not likely that we can definitively prove or disprove that large stress changes from the 1992 Landers earthquake played a role in triggering the 1999 Hector Mine earthquake, because the 7-year lag time allows for an abundance of possible triggering mechanisms. The most conclusive result attainable is to find that a multitude of tests show no correlation between these two events. This study shows that such results are unattainable.

2. Method and Data

[8] On a fault of a given orientation, the time-dependent Coulomb failure function is defined as

$$\Delta\sigma_f(t) = \Delta\tau(t) - \mu(\Delta\sigma_n(t) - \Delta P(t)), \tag{1}$$

where τ is shear stress (positive in the rake direction), σ_n is the stress normal to the fault (positive in compression), P the pore pressure (positive in compression), and μ is the coefficient of friction [*Harris*, 1998]. I assume an isotropic homogeneous material and approximate the pore pressure change by

$$\Delta P(t) = B\frac{1}{3}(\Delta\sigma_{11}(t) + \Delta\sigma_{22}(t) + \Delta\sigma_{33}(t)), \tag{2}$$

where B is Skempton's coefficient [*Harris*, 1998]. Initially, I assume $B = 0.75$ and $\mu = 0.6$, and in section 4.2 I investigate how robust the results are to variations in these parameter values ($0.5 \leq B \leq 1.0$ and $0.0 \leq \mu \leq 1.0$). I assume both B and μ are constant in time.

[9] The temporal evolution of $\Delta\sigma_f(t)$, $\Delta\tau(t)$, $\Delta\sigma_n(t)$, and $\Delta P(t)$ do not necessarily mimic one another (Figure 1), and therefore results from the peak $\Delta\sigma_f(t)$ calculations are not necessarily applicable to that of the individual components. So I additionally test for a correlation between the Hector Mine hypocenter and the peak values of the individual components. Positive stress changes are assumed to promote fault failure, whereas negative changes are assumed to discourage fault failure. By definition peak $\Delta\sigma_f(t)$ are never negative, so they can only promote failure. Static stress changes, on the other hand, can be either positive or negative and therefore can either promote or delay earthquake rupture.

[10] As exhibited in the seismic waveforms shown in Figure 1, the amplitude of the stress oscillations are relatively symmetric about the null value, so often a large positive stress change is immediately followed by an equally large negative stress change (i.e., maps of the most negative value of Coulomb stress often have the same shape and symmetry as the corresponding peak positive stress maps). However, these consecutive and similar amplitude stress changes that are of different signs do not "cancel" each other, just as material detached during dynamic shearing from motion in one sliding direction can not be reattach by reversing the sliding direction [see also *Marone*, 2000; *Gomberg et al.*, 2001]. I therefore assume that large-amplitude negative stresses within an oscillatory stress field cannot delay fault rupture.

[11] I use a discrete wave number reflectivity program to model the displacement waveforms and compute stress changes produced by the Landers main shock [*Cotton and Coutant*, 1997]. A 3-D boundary element algorithm is used to confirm the static stress change results [*Gomberg and Ellis*, 1994]. To model the Landers main shock rupture, I use a collection of 23 point sources, such that each point source has an associated fault orientation (strike and dip), direction of slip (rake), fault width, fault length, time of rupture, and an associated solar time function. Parameters used to model the Landers' main shock are listed in Table 1.

3. Parameter Constraints

[12] To constrain parameters of the Landers main shock, I require my synthetic displacement seismograms to reproduce the relative amplitudes, arrivals and durations of the displacement (doubly integrated from acceleration) TERRAscope data. I also require my fault locations/orientations,

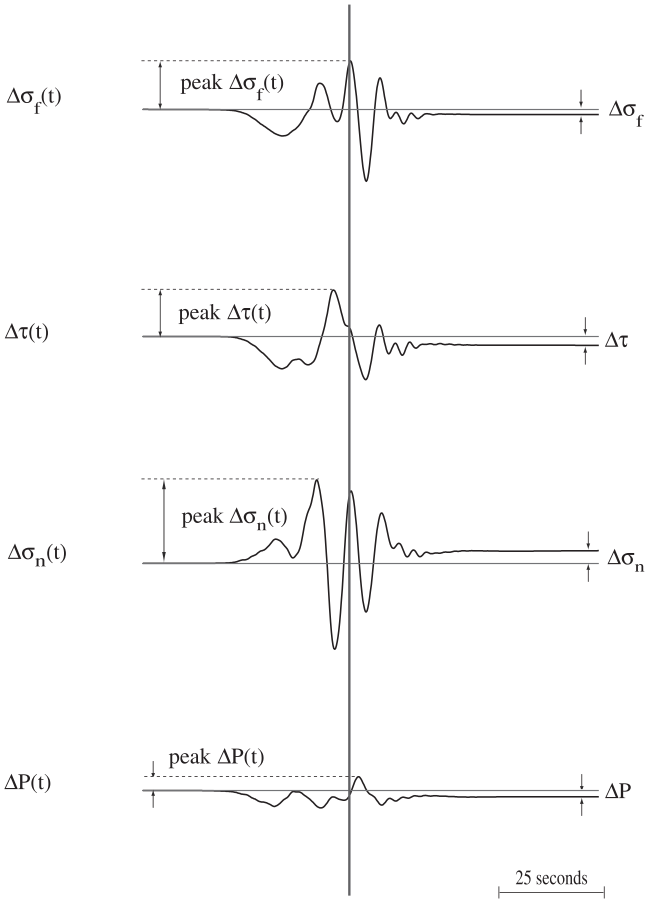

Figure 1. Example stress grams of Coulomb stress ($\Delta\sigma_f(t)$), shear stress $\Delta\tau(t)$), normal stress ($\Delta\sigma_n(t)$), and pressure ($\Delta P(t)$). The latter three stress change components linearly combine to compose $\Delta\sigma_f\,(t)$ (see equation (1)). I assume the maximum positive stress change value (dashed lines) is a good estimate of the dynamic stress change. The solid vertical line illustrates that peak $\Delta\sigma_f(t)$ does not necessarily occur simultaneously with the peaks of the other components. The corresponding static stress changes ($\Delta\sigma_f$, $\Delta\sigma_n$, $\Delta\tau$, and ΔP) are equivalent to the asymptotic values (i.e., for large t, $\Delta\sigma_f(t) = \Delta\sigma_f$), and so the static values are always less than or equal to the peak dynamic equivalent.

slip model parameters and seismic moment release to be within the published constraints [e.g., *Campillo and Archuleta*, 1993; *Cohee and Beroza*, 1994; *Dreger*, 1994; *Wald and Heaton*, 1994; *Cotton and Campillo*, 1995]. A key parameter is a rupture directivity filter, which is required to reproduce the relatively large-amplitude waveforms north of the main shock [*Aki and Richards*, 1980; *Gomberg*, 1996].

[13] Forward modeling the displacement data, using trial and error, was a more difficult task than expected. For example, the velocity model can drastically influence the final waveforms [*Belardinelli et al.*, 1999]. To model accurately the waveform durations of the Landers earthquake, a low-velocity layer (from 0 to 1.5 km depth) was required [*Wald and Heaton*, 1994]. In this way, waveform modeling also constrained the velocity model. Relatively large differences in the synthetic waveforms are also introduced from small changes (e.g., fault length variations of 3 km or 5° variations in fault strike) in the main shock fault segments (compare the fault models of *Cohee and Beroza* [1994], *Dreger* [1994], and *Wald and Heaton* [1994]). Similarly, the *Wald and Heaton* [1994] slip model and a simplified version of this model [*King et al.*, 1994] yield somewhat different displacement waveforms, neither of which are in good agreement with the displacement data. The synthetic waveforms computed by *Wald and Heaton* [1994] match the data, indicating that similar parameters used in different modeling algorithms can introduce differences in the final synthetic waveforms. As a precaution, I use the same reflectivity method to compute the displacement waveforms (that constrain my parameters) as I use to compute the stressgrams, which are ultimately used to obtain my results (for a more detailed discussion of how the parameters were constrained, see *Kilb et al.* [2002]).

4. Results

4.1. Correlation of Peak $\Delta\sigma_f(t)$ With the Hector Mine Hypocenter

[14] Initially, I assume the Hector Mine earthquake ruptured a 70° dipping planar fault striking 343°, with right-lateral slip motion, and that the epicenter was at (−116.3°, 34.6°) and the hypocentral depth was 4.5 km [*Harris and Simpson*, 2002; *Hauksson et al.* [2002]]. Sensitivity of the results to reasonable variations in these parameters is addressed in section 4.2.

[15] Contoured peak $\Delta\sigma_f(t)$ induced by the Landers main shock has four main lobes of large (>4 MPa) stress change (Figure 2a). The largest lobe is northwest of the Landers main shock rupture and correlates in spatial extent with a seismicity rate increase immediately following the Landers event [*Kilb et al.*, 2000; *Wyss and Wiemer*, 2000]. The lobe to the southeast tends toward the *M*6.1 Joshua Tree main shock fault plane that ruptured ~3 months prior to the Landers main shock, and the southwest lobe almost encompasses the *M*6.5 Big Bear earthquake fault plane that ruptured ~3.5 hours after the Landers main shock [*Harris and Simpson*, 1992; *Jaume and Sykes*, 1992; *Stein et al.*, 1992; *King et al.*, 1994]. The lobe to the northeast, which is small in spatial extent but large in amplitude, is the focus of this study. Stress change contours of this lobe mark a bull's-eye that surrounds the hypocenter of the Hector Mine earthquake. For these initial parameter values, a similar correlation is absent from the $\Delta\sigma_f$ model (Figure 2e), which instead shows a stress shadow ($\Delta\sigma_f < 0$ MPa) indicating an expected decrease in seismicity at this location [*Harris*, 1998]. Sensitivity tests in section 4.2 show that the corre-

Table 1. Lander's Main Shock Parameters[a]

Parameter	Value
Average slip	0.75–1.78 m
Earthquake magnitude	7.3
Fault dimensions	
(length, width, area)	(80 km, 17 km, 1360 km^2)
Average rupture velocity	2.5–3.0 km/s
Fault (strike, dip, rake)	(331–354, 90, right latitude)
Moment	1.1×10^{20} N m
Number of material layers	5
Incorporation of directivity	yes

[a]See *Kilb et al.* [2002] for a full discussion of how these parameters were derived.

lation with the peak $\Delta\sigma_f(t)$ model is robust to parameter variations, but the $\Delta\sigma_f$ model is not.

[16] A strong positive correlation also exists between the hypocenter of the Hector Mine earthquake and both peak $\Delta\tau(t)$ and peak $\Delta\sigma_n(t)$ (Figures 2b and 2c), but the correlation with peak $\Delta P(t)$ is indeterminate (Figure 2d). The opposite is true for the individual static components, such that the Hector Mine hypocenter locates in a stress shadow of the $\Delta\tau$ and $\Delta\sigma_n$ components (Figures 2f and 2g), whereas ΔP has a value of 0.1 MPa at this location (Figure 2h).

[17] *Parsons and Dreger* [2000] find a positive correlation between the $\Delta\sigma_f$ induced by the Landers earthquake and the Hector Mine hypocenter. Their positive correlation differs from the anti-correlation I find using similar parameter values of epicenter (34.596°, 116.288°), depth 6 km, and friction 0.8. The inconsistency of our results is primarily due to differences in our velocity models and Landers main shock slip models and fault orientations. Because of nonuniqueness in determining these parameters, both study models are viable. Thus the role induced $\Delta\sigma_f$ from the Landers earthquake played in increasing the probability of the Hector Mine earthquake remains unresolved [*Harris and Simpson*, 2002].

4.2. Sensitivity Tests

[18] *Harris and Simpson* [2002] find that variations in model parameters can drastically influence the $\Delta\sigma_f$ induced by the Landers main shock in the region of the Hector Mine hypocenter. Here, I perform similar sensitivity tests for the peak $\Delta\sigma_f(t)$ model. The base parameters for these tests encompass some parameter values proposed in the literature (5 focal mechanisms, 4 epicenter locations, and 8 depths, see Table 2) and also permutations of these values (160 parameter sets). I also test a range of friction ($0.0 \leq \mu \leq 1.0$) and Skempton ($0.5 \leq B \leq 1.0$) coefficients. My goal is to determine if reasonable parameter variations introduce

Table 2. Hector Mine Shock Parameters[a]

Epicenter	Hypocentral Depth, km	(Strike, Dp, Rake)
(34.5968, 116.2705)[b]	0.75	(354, 81, 149)[b]
(34.59, 116.27)[c,d]	2.5	(345, 77, 180)[c,f]
(34.60, 116.27)[e]	4.5[b]	(325, 77, 180)[c]
(34.5955, 116.2879)[f]	5.0[d]	(331, 77, 10)[d,e]
	6.0[c,e,f]	(343, 70, 175)[e]
	7.5[b]	
	10.0	
	15.0	

[a] I investigate 160 different combinations of these parameters.
[b] *Hauksson et al.* [2002].
[c] A. Kaverina et al. (Source process of the October 19, 1999, Hector Mine Earthquake (M_w7.2) form the inversion of broadband and Regional data, submitted to *Journal of Geophysical Research*, 2002).
[d] *Scientists from the U.S. Geological Survey* [2000].
[e] Machanism originally released on the Hector Mine website shortly after the earthquake.
[f] *Parsons and Dreger* [2000].

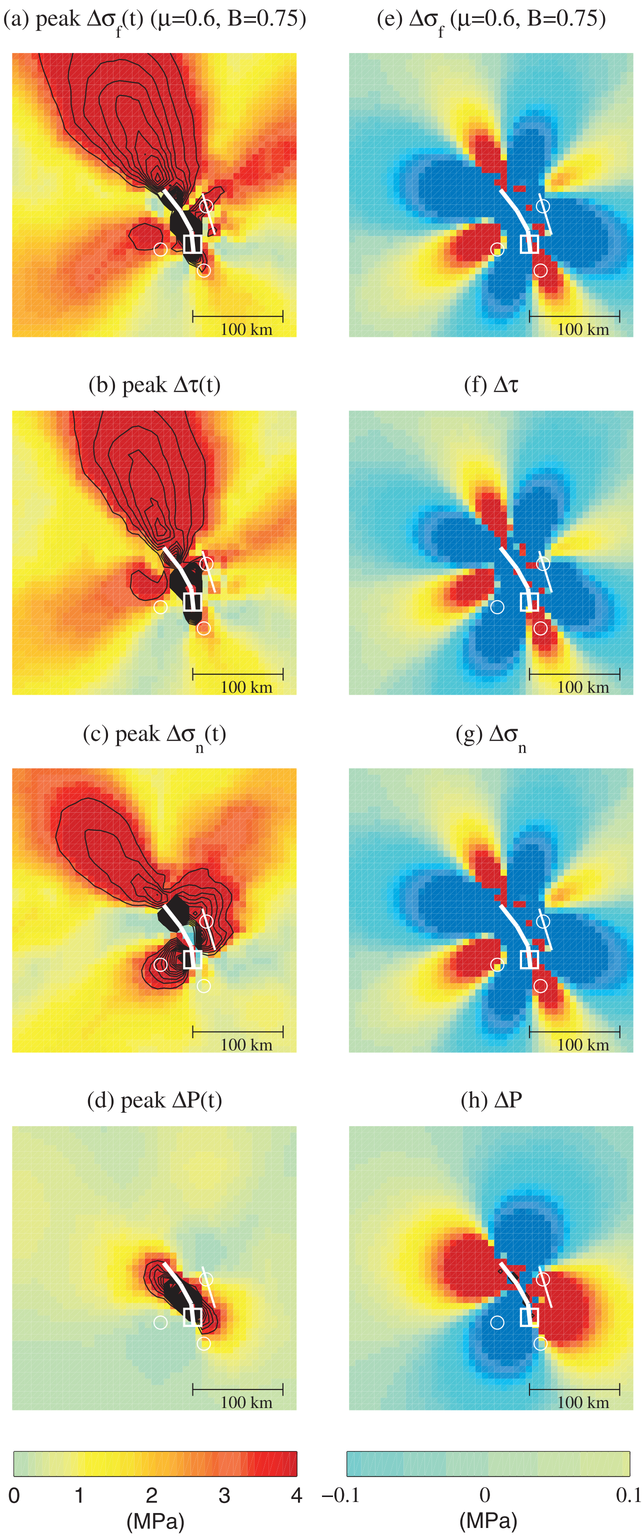

Figure 2. (opposite) Maps at 4.5 km depth of stress changes (left, dynamic stress changes; right, static stress changes) induced by the *M*7.3 Landers main shock (thick line segments, the square shows the epicenter), as derived on fault orientations consistent with the Hector Mine earthquake (strike 343°, dip 70°, and direction of slip 180°) (thin line). Also shown are the epicenters of the 1999 *M*7.1 Hector Mine, the 1992 M_w6.2 Big Bear, and the 1992 M_w6.1 Joshua Tree earthquakes (circles from north to south, respectively). Contours indicate stress levels equal to or above 4.0 MPa, with intervals of 1.5 MPa, for (a) peak $\Delta\sigma_f(t)$, (b) peak $\Delta\tau(t)$, (c) peak $\Delta\sigma_n(t)$, (d) peak $\Delta P(t)$, (e) $\Delta\sigma_f$, (f) $\Delta\tau$, (g) $\Delta\sigma_n$, and (h) ΔP.

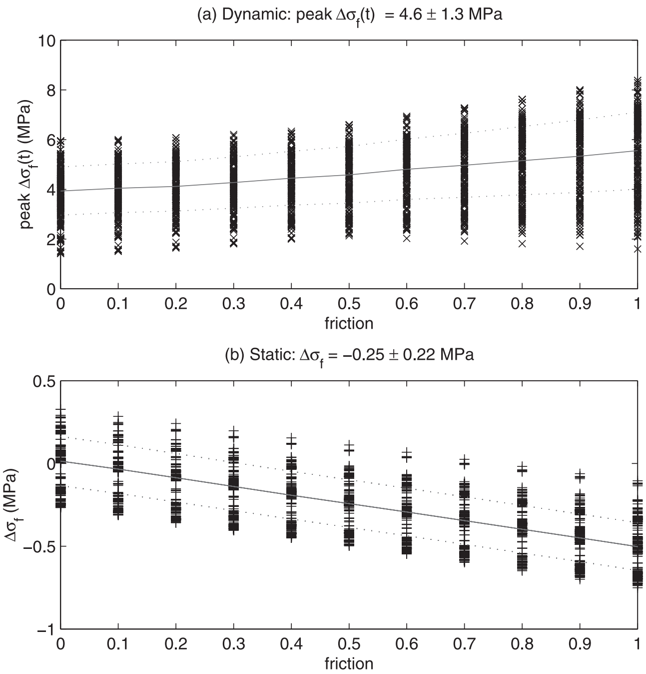

Figure 3. Sensitivity of induced stress changes ($\Delta\sigma_f$ and peak $\Delta\sigma_f(t)$) from the Landers main shock to variations in the friction coefficient. Skempton's coefficient is assumed constant (B = 0.75, see equation (1)) and 160 different models of the Hector Mine main shock are tested (see Table 2). Variations in (a) peak $\Delta\sigma_f(t)$ and (b) $\Delta\sigma_f$. The solid and dashed lines indicate the respective median and standard deviation for each friction value. The overall median and standard deviation title each plot. Note that the parameter set investigated here is extensive and therefore these results represent upper bounds [e.g., *Harris and Simpson*, 2002] determine the range of possible $\Delta\sigma_f$ values to be −0.23 to 0.047 compared to the −0.79 to 0.33 MPa determined in this study).

uncertainties that are significantly above the value that I strive to measure.

[19] I first test the influence of the friction coefficient. For each parameter set, I searched for the friction coefficient that produced the largest peak $\Delta\sigma_f(t)$ at the proposed Hector Mine hypocenter. The friction coefficient most conducive to slip (e.g., highest value of peak $\Delta\sigma_f(t)$) favors the highest value tested, which in this case was μ = 1.0 (Figure 3a). The opposite is true for $\Delta\sigma_f$, showing instead that the highest $\Delta\sigma_f$ values are attained with the lowest friction value tested (μ = 0.0) (Figure 3b). A similar study that tests the influence of Skempton's coefficient does not show any significant favoritism toward low or high values.

[20] Tests of the 160 parameter sets for B = 0.75 and $0.0 \le \mu \le 1.0$ produce $\Delta\sigma_f$ = −0.26 ± 0.21 MPa and peak $\Delta\sigma_f(t)$ = 4.6 ± 1.3 MPa; similar results are attained when instead the friction is held constant and Skempton's coefficient is varied (μ = 0.6; $0.5 \le B \le 1.0$): $\Delta\sigma_f$ = −0.29 ± 0.14 MPa and peak $\Delta\sigma_f(t)$ = 4.9 ± 1.2 MPa. Because the parameter set I investigate is so extensive, I expect these uncertainty estimates are upper bounds. The percent deviation from the median for the $\Delta\sigma_f$ tests is ~48–81%, which is much higher than the ~24–28% found for the peak $\Delta\sigma_f(t)$ tests. Therefore the peak $\Delta\sigma_f(t)$ results are more robust to parameter variations.

[21] These uncertainty estimates are not necessarily applicable for other main shock/aftershock sequences with different geometries. In fact, because of the extreme spatial fluctuation of the stress changes in the region of the Hector Mine hypocenter (see Figure 2a), these uncertainties are likely to be larger than typical for the 20 km separation distance between these two events.

[22] For μ = 0.6 and B = 0.75 peak $\Delta\sigma_f(t)$ is maximum at relatively shallow depths (e.g., 4.5 km), whereas $\Delta\sigma_f$ is maximum at deeper depths (15 km was the maximum tested) (Figures 4a and 4b). I find that, for the depths studied, the peak $\Delta\sigma_f(t)$ stress grams typically have two large peaks that are approximately equal, and thus large stress change values are attained multiple times (e.g., Figure 4c). Assuming the dynamic stress changes induced by the Landers earthquake are the primary triggering agent of the Hector Mine earthquake, I estimate a stress "threshold"

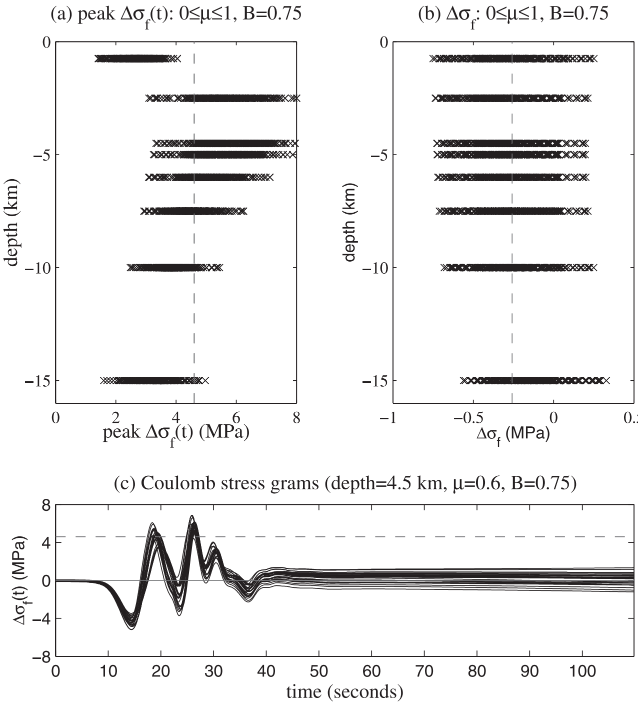

Figure 4. Sensitivity of induced stress changes ($\Delta\sigma_f$ and peak $\Delta\sigma_f(t)$) from the Landers main shock to variations in the Hector Mine main shock model parameters as a function of depth. (a) Peak $\Delta\sigma_f(t)$ induced by the Landers main shock for fixed values of friction ($0.0 \le \mu \le 1.0$) and Skempton (B = 0.75) coefficients (see equation (1)). The stress changes are derived on fault planes consistent with the Hector Mine fault, for which I consider 160 different parameter sets (i.e., various different fault orientations, directions of slip, and epicenters as listed in Table 2 and permutations thereof). The dashed vertical line indicates the median value (4.6 MPa), which is consistent with an estimated triggering threshold (4.0 MPa) for this region [*Kilb et al.*, 2000]. (b) as in Figure 4a but for $\Delta\sigma_f$. (c) Coulomb stress grams, $\Delta\sigma_f(t)$, computed at 4.5 km depth. Note that the assumed triggering threshold, 4.6 MPa (dashed line), is exceeded at least once and often twice.

required for triggering from the median peak $\Delta\sigma_f(t)$, specifically 4.6 MPa. This estimate is consistent with the suggested ~4 MPa threshold value determined by correlating seismicity rate change (computed using nine months of aftershock data from the Landers earthquake) with contours of induced peak $\Delta\sigma_f(t)$ from the Landers main shock [*Kilb et al.*, 2000].

[23] I assume that the median peak dynamic stress change value is a relatively nonbiased estimate of the triggering threshold. This infers that the threshold was either just met or exceeded. If the threshold was just met the median would be a lower-bound estimate; if it was exceeded then it would be an upper-bound estimate. Because triggering amplitudes may vary by an order of magnitude, and a single triggering level may not be applicable for all faults, I make no attempt to more accurately identify a threshold amplitude [*Gomberg et al.*, 2001].

5. Discussion

[24] Viability of a triggering hypothesis is best supported by a multitude of studies of different main shock-aftershock sequences that yield similar conclusions. The hypothesis that main shock induced positive $\Delta\sigma_f$ triggers aftershocks is supported by, for example, numerous events in California [*Stein and Lisowski*, 1983; *Reasenberg and Simpson*, 1992; *King et al.*, 1994], the 1999 *M*7.4 earthquake in Izmit, Turkey [*Parsons et al.*, 2000], and the 1995 *M*6.9 earthquake in Kobe, Japan [*Toda et al.*, 1998]. However, a study of the 1994 *M*6.7 Northridge, California earthquake finds lack of a correlation [*Hardebeck et al.*, 1998], and other studies conclude that $\Delta\sigma_f$ may not be the primary triggering agent [*Harris and Simpson*, 1992; *Du and Aydin*, 1993; *Bennett et al.*, 1995; *Dodge et al.*, 1995]. Additionally, the symmetry properties of $\Delta\sigma_f$ and aftershock distributions are not always in agreement [*Cotton and Coutant*, 1997; *Astiz et al.*, 2000; *Gomberg et al.*, 2001].

[25] To date, studies that examine the correlation of dynamic stress changes and seismicity rate changes are few [*Marone*, 2000], and they can be separated into two main categories. The first category investigates triggering concurrent with the passage of the seismic waves [e.g., *Hill et al.*, 1993]. For example, following the 6 December 1999 M_w 7.0 Karluk Lake earthquake near the Kodiak Islands, four small events are identified in the coda of the seismic wave recorded at a station 100 km from the main shock earthquake [*Power et al.*, 2001]. These small events occurred in a region that was previously not producing earthquakes; therefore it is unlikely these four earthquakes occurred just by chance at the time of the seismic waves' passage. Similarly, a study of the 25 March 1998 M_w 8.1 Antarctic plate earthquake shows apparent triggering at a location ~100 km away [*Henry et al.*, 2000], and this triggering also occurred at the time of the seismic waves' passage. At closer range, less than 20 km, the large-magnitude aftershocks in the Irpinia, Italy, sequence occurred approximately 10 to 20 s after the peak $\Delta\sigma_f(t)$ [*Belardinelli et al.*, 1999]. This lag time can be explained with rate-and-state dependent frictional laws [*Belardinelli et al.*, 1999; *Voisin et al.*, 2000]. Alternatively, the second category allows a lag time of weeks to years between the triggering and triggered events. A few of these studies find the asymmetry in mapped seismicity rate change following the main shock event is mimicked in the peak $\Delta\sigma_f(t)$ pattern but not in the $\Delta\sigma_f$ pattern [*Kilb et al.*, 2000; *Gomberg et al.*, 2001].

[26] Clearly, more studies are necessary before we can validate or dismiss the dynamic triggering hypothesis. The results of this study show that the positive correlation between stress changes forms the Landers earthquake and the location of the Hector Mine epicenter makes it impossible for us to rule out the possibility of a cause/effect between the two. However, this does not necessarily imply a causal relationship exists.

[27] The conclusions that the lowest coefficients of friction produce the highest $\Delta\sigma_f$ values and the highest coefficients of friction produce the highest peak $\Delta\sigma_f(t)$ values may eventually help discriminate which triggering model dictates which, if any, of the faulting processes. Recall from equation (1) that large friction coefficients imply that normal stress changes are an important component of the triggering process, and small friction coefficients place more importance on shear stress changes. If the true fault friction is that which produces the largest stress change in equation (1), then, maybe static normal stress changes that act to promote rupture are not as important in ultimately triggering earthquakes as large oscillatory dynamic normal stress changes; similarly, maybe large oscillatory shear stress changes are not as effective at promoting rupture as static shear stress changes.

6. Conclusions

[28] I find a strong positive correlation between the Hector Mine earthquake hypocenter and induced large dynamic Coulomb stress changes (peak $\Delta\sigma_f(t)$) from the Landers main shock, as the contoured peak $\Delta\sigma_f(t)$ mark a bull's-eye at the Hector Mine earthquake hypocenter. In general, peak $\Delta\sigma_f(t)$ increases with increasing friction and is maximum at a depth of 4.5 km. Conversely, $\Delta\sigma_f$ decreases with increasing friction and it is maximum at deeper depths (15 km was the maximum tested).

[29] Model parameters of the Landers main shock were constrained using waveform modeling of the displacement data; therefore variations in these parameters were not considered. Main shock parameters of the Hector Mine earthquake are not as well constrained, and 160 different parameter sets were investigated. Sensitivity tests using these parameters in addition to variations in the Skempton and the friction coefficient's ($0.5 \leq B \leq 1.0$; $0.0 \leq \mu \leq 1.0$) yield uncertainty estimates of 1.3 and 0.22 MPa in the amplitudes of peak $\Delta\sigma_f(t)$ and $\Delta\sigma_f$, respectively. These uncertainty estimates are likely upper limits because the parameter set I investigate is so extensive. The estimated uncertainties deviate from the median by at most 28% for the peak $\Delta\sigma_f(t)$ model and 82% for the $\Delta\sigma_f$ model. Therefore the correlation of the Hector Mine hypocenter with dynamic stress changes (measured using peak $\Delta\sigma_f(t)$) is robust with respect to parameter variations, whereas the correlation with the static Coulomb stress changes ($\Delta\sigma_f$) are not [*Harris and Simpson*, 2002].

[30] In accordance with other studies, I propose that large stress changes induced by the passage of seismic waves may physically change a faults' properties [e.g., *Cotton and Coutant*, 1997; *Belardinelli et al.*, 1999; *Voisin et al.*, 2000;

Gomberg et al., 2001; *Power et al.*, 2001; *Voisin*, 2001]. It is most likely these physical changes promote rather than inhibit fault failure, thus contributing to the production of aftershocks. In this way, large stress changes applied for only a short time (seconds) may play a role in the near-field earthquake triggering process. The possibility that a time delay between triggering and triggered earthquakes could be years is suggested by the strong correlation between the bulls-eye pattern of large Coulomb stress changes induced by the Landers earthquake and the Hector Mine hypocenter.

[31] **Acknowledgments.** I thank Fabrice Cotton and Olivier Coutant for supplying me with their computer code that was an essential part of this work. Thoughtful reviews by Karen Felzer, Jeanne Hardebeck, Ruth Harris, David Oglesby, Allan Rubin, and an anonymous reviewer greatly improved this paper.

References

Aki, K. and P. G. Richards, *Quantitative Seismology*, W. H. Freeman, New York, 1980.
Astiz, L., P. M. Shearer, and D. C. Agnew, Precise relocations and stress change calculations for the Upland earthquake sequence in southern California, *J. Geophys. Res.*, *105*, 2937–2953, 2000.
Belardinelli, M. E., M. Cocco, O. Coutant, and F. Cotton, Redistribution of dynamic stress during coseismic ruptures: Evidence for fault interaction and earthquake triggering, *J. Geophys. Res.*, *104*, 14,925–14,945, 1999.
Bennett, R. A., R. E. Reilinger, W. L. Rodi, and Y. Li, Coseismic fault slip associated with the 1992 M_w 6.1 Joshua Tree, California, earthquake: Implications for the Joshua Tree-Landers earthquake sequence, *J. Geophys. Res.*, *100*, 6443–6461, 1995.
Campillo, M., and R. J. Archuleta, A rupture model for the 28 June 1992 Landers, California, earthquake, *Geophys. Res. Lett.*, *20*, 647–650, 1993.
Cohee, B. P., and G. C. Beroza, Slip distribution of the 1992 Landers earthquake and its implications for earthquake source mechanics, *Bull. Seismol. Soc. Am.*, *84*, 692–712, 1994.
Cotton, F., and M. Campillo, Stability of the rake during the 1992, Landers earthquake: An indication for a small stress release?, *Geophys. Res. Lett.*, *22*, 1921–1924, 1995.
Cotton, F., and O. Coutant, Dynamic stress variations due to shear faults in a plane-layered medium, *Geophys. J. Int.*, *128*, 676–688, 1997.
Dodge, D. A., G. C. Beroza, and W. L. Ellsworth, Foreshock sequence of the 1992 Landers, California, earthquake and its implications for earthquake nucleation, *J. Geophys. Res.*, *100*, 9865–9880, 1995.
Dreger, D. S., Investigation of the rupture process of the 28 June 1992 Landers earthquake Utilizing TERRAscope, *Bull. Seismol. Soc. Am.*, *84*, 713–724, 1994.
Du, Y., and A. Aydin, Stress transfer during three sequential moderate earthquakes along the central Calaveras fault, California, *J. Geophys. Res.*, *98*, 9947–9962, 1993.
Freed, A. M., and J. Lin, Delayed triggering of the 1999 Hector Mine earthquake by viscoelastic stress transfer, *Nature*, *411*, 180–183, 2001.
Gomberg, J., Stress/strain changes and triggered seismicity following the M_w 7.3 Landers, California, earthquake, *J. Geophys. Res.*, *101*, 751–764, 1996.
Gomberg, J. S., and M. A. Ellis, Topography and tectonics of the central New Madrid Seismic zone: Results of numerical experiments using a three-dimensional boundary-element program., *J. Geophys. Res.*, *99*, 20,299–20,310, 1994.
Gomberg, J., P. A. Reasenberg, P. Bodin, and R. A. Harris, Earthquake triggering by seismic waves following the Landers and Hector Mine earthquakes, *Nature*, *411*, 462–466, 2001.
Hardebeck, J. L., J. J. Nazareth, and E. Hauksson, The static stress change triggering model: Constraints from two southern California aftershocks sequences, *J. Geophys. Res.*, *103*, 24,427–24,437, 1998.
Harris, R. A., Introduction to special section: Stress triggers, stress shadows, implications for seismic hazard, *J. Geophys. Res.*, *103*, 24,347–24,358, 1998.
Harris, R. A., and S. M. Day, Dynamics of fault interaction: Parallel strike-slip faults, *J. Geophys. Res.*, *98*, 4461–4472, 1993.
Harris, R. A., and S. M. Day, Dynamic 3d simulations of earthquakes on en echelon faults, *Geophys. Res. Lett.*, *26*, 2089–2092, 1999.
Harris, R. A., and R. W. Simpson, Changes in static stress on southern California faults after the 1992 Landers earthquake, *Nature*, *360*, 251–254, 1992.
Harris, R. A., and R. W. Simpson, The 1999 M_w7.1 Hector Mine, California earthquake—A test of the stress shadow hypothesis?, *Bull. Seismol. Soc. Am.*, *92*, 1497–1512, 2002.
Hauksson, E., L. M. Jones, and K. Hutton, The 1999 M_w7.1 Hector Mine, California earthquake sequence: Complex conjugate strike-slip faulting, *Bull. Seismol. Soc. Am.*, *92*, 1154–1170, 2002.
Henry, C., S. Das, and J. H. Woodhouse, The great March 25, 1998, Antarctic plate earthquake: Moment tensor and rupture history, *J. Geophys. Res.*, *105*, 16,097–16,118, 2000.
Hill, D. P., et al., Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake, *Science*, *260*, 1617–1623, 1993.
Jaume, S. C., and L. R. Sykes, Changes in the state of stress on the southern San Andreas Fault resulting from the California earthquake sequence of April to June 1992, *Science*, *258*, 1325–1328, 1992.
Kilb, D., J. Gomberg, and P. Bodin, Earthquake triggering by dynamic stresses, *Nature*, *408*, 570–574, 2000.
Kilb, D., J. Gomberg, and P. Bodin, Aftershock triggering by complete Coulomb stress changes, *J. Geophys. Res.*, *107*(B4), 2060, doi:10.1029/2001JB000202, 2002.
King, G. C. P., R. S. Stein, and J. Lin, Static stress changes and the triggering of earthquakes, *Bull. Seismol. Soc. Am.*, *84*, 935–953, 1994.
Marone, C., Shaking faults loose, *Nature*, *408*, 533–535, 2000.
Parsons, T., and D. S. Dreger, Static-stress impact of the 1992 Landers earthquake sequence on nucleation and slip at the site of the 1999 M = 7.1 Hector Mine earthquake, southern California, *Geophys. Res. Lett.*, *27*, 1949–1952, 2000.
Parsons, T., S. Toda, R. S. Stein, A. Barka, and J. H. Dieterich, Heightened odds of large Earthquakes near Istanbul: An interaction-based probability calculation, *Science*, *288*, 661–665, 2000.
Pollitz, F., Stress triggering of the 1999 Hector Mine earthquake by transient deformation following the 1992 Landers earthquake, *Eos Trans. AGU*, *81*(48), Fall Meet. Suppl., F860, 2000.
Power, J. A., S. C. Moran, S. R. McNutt, S. D. Stihler, and J. J. Sanchez, Seismic response of the Katmai Volcanoes to the 6 December 1999 magnitude 7.0 Karluk Lake earthquake, Alaska, *Bull. Seismol. Soc. Am.*, *91*, 57–63, 2001.
Reasenberg, P. A., and R. W. Simpson, Response of regional seismicity to the static stress change produced by the Loma Prieta earthquake, *Science*, *255*, 1687–1690, 1992.
Scientists from the U. S. Geological Survey, Southern California Earthquake Center, and California Division of Mines and Geology, Preliminary report on the 16 October 1999 *M*7.1 Hector Mine, California, earthquake, *Seismol. Res. Lett.*, *17*, 11–23, 2000.
Stein, R. S., and M. Lisowski, The 1979 Homestead Valley earthquake sequence, California: Control of aftershocks and postseismic deformation, *J. Geophys. Res.*, *88*, 6477–6490, 1983.
Stein, R. S., G. C. King, and J. Lin, Change in failure stress on the southern San Andreas Fault system caused by 1992 the magnitude = 7.4 Landers earthquake, *Science*, *258*, 1328–1332, 1992.
Toda, S., R. S. Stein, P. A. Reasenberg, J. H. Dieterich, and A. Yoshida, Stress transferred by the 1995 M_w = 6.9 Kobe, Japan, shock: Effect on aftershocks and future earthquake probabilities, *J. Geophys. Res.*, *103*, 24,543–24,565, 1998.
Voisin, C., Dynamic triggering of earthquakes: The linear slip-dependent friction case, *Geophys. Res. Lett.*, *28*, 3357–3360, 2001.
Voisin, C., M. Campillo, I. R. Ionescu, F. Cotton, and O. Scotti, Dynamic versus static stress triggering and friction parameters: Inferences from the November 23, 1980, Irpinia earthquake, *J. Geophys. Res.*, *105*, 21,647–21,659, 2000.
Wald, D. J., and T. H. Heaton, Spatial and temporal distribution of slip for the 1992 Landers, California, earthquake, *Bull. Seismol. Soc. Am.*, *84*, 668–691, 1994.
Wyss, M., and S. Wiemer, Change in the probability for earthquakes in southern California due to the Landers magnitude 7.3 earthquake, *Science*, *290*, 1334–1338, 2000.

D. Kilb, Institute of Geophysics and Planetary Physics, MS 0225, University of California, San Diego, La Jolla, CA 92093, USA. (dkilb@epicenter.ucsd.edu)