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Stress Triggering of the 1999 Hector Mine Earthquake by Transient Deformation Following the 1992 Landers Earthquake

by Fred F. Pollitz and I. Selwyn Sacks

Abstract The *M* 7.3 June 28, 1992 Landers and *M* 7.1 October 16, 1999 Hector Mine earthquakes, California, both right lateral strike-slip events on NNW-trending subvertical faults, occurred in close proximity in space and time in a region where recurrence times for surface-rupturing earthquakes are thousands of years. This suggests a causal role for the Landers earthquake in triggering the Hector Mine earthquake. Previous modeling of the static stress change associated with the Landers earthquake shows that the area of peak Hector Mine slip lies where the Coulomb failure stress promoting right-lateral strike-slip failure was high, but the nucleation point of the Hector Mine rupture was neutrally to weakly promoted, depending on the assumed coefficient of friction. Possible explanations that could account for the 7-year delay between the two ruptures include background tectonic stressing, dissipation of fluid pressure gradients, rate- and state-dependent friction effects, and post-Landers viscoelastic relaxation of the lower crust and upper mantle. By employing a viscoelastic model calibrated by geodetic data collected during the time period between the Landers and Hector Mine events, we calculate that postseismic relaxation produced a transient increase in Coulomb failure stress of about 0.7 bars on the impending Hector Mine rupture surface. The increase is greatest over the broad surface that includes the 1999 nucleation point and the site of peak slip further north. Since stress changes of magnitude greater than or equal to 0.1 bar are associated with documented causal fault interactions elsewhere, viscoelastic relaxation likely contributed to the triggering of the Hector Mine earthquake. This interpretation relies on the assumption that the faults occupying the central Mojave Desert (i.e., both the Landers and Hector Mine rupturing faults) were critically stressed just prior to the Landers earthquake.

Introduction

Paired earthquakes—the occurrence of one large earthquake close in space and time to a preceding one—are known on timescales of seconds (e.g., 1998 Antarctic Plate earthquake [Henry *et al.*, 2000]), hours (e.g., Landers–Big Bear sequence [Wald and Heaton, 1994; King *et al.*, 1994]), months (August 1999 Izmit–November 1999 Düzce, Turkey, earthquakes [Hubert-Ferrari *et al.*, 2000; Parsons *et al.*, 2000]), years (1944 Tonankai–1946 Nankaido earthquakes [Ando, 1975]), and possibly decades (migration of western North America seismicity [Pollitz *et al.*, 1998]). The *M* 7.1 16 October 1999 Hector Mine, California, earthquake was a right-lateral strike-slip event in the central Mojave Desert (Fig. 1). It occurred 7 years after the *M* 7.3 28 June 1992 Landers earthquake along a parallel fault section about 30 km northeast of the Landers source region. Both earthquakes occurred within a part of the active Eastern California Shear Zone, where earthquake recurrence times are estimated to be about 4000 years (Sauber *et al.*, 1994; Rubin and Sieh, 1997).

The problem of explaining the time delay between paired earthquakes or mainshock–aftershock sequences has stimulated several proposed mechanisms (see review by Harris, 1998), including pore fluid flow (Jaume and Sykes, 1992), rate- and state-dependent friction (Dieterich, 1994; Gomberg *et al.*, 1998), and postseismic viscoelastic flow in the lower crust (Deng *et al.*, 1999). The first two mechanisms act to weaken the secondary fault with time; the third changes the stress resolved on it, in some cases compounding the static stress change. Typical mainshock–aftershock sequences in the upper continental crust occur on timescales of days to years. The rate- and state-dependent friction model has successfully explained the decay rate of aftershock sequences (Dieterich, 1994; Gross and Kisslinger, 1997; Gross and Bürgmann, 1998); it relies on the combi-

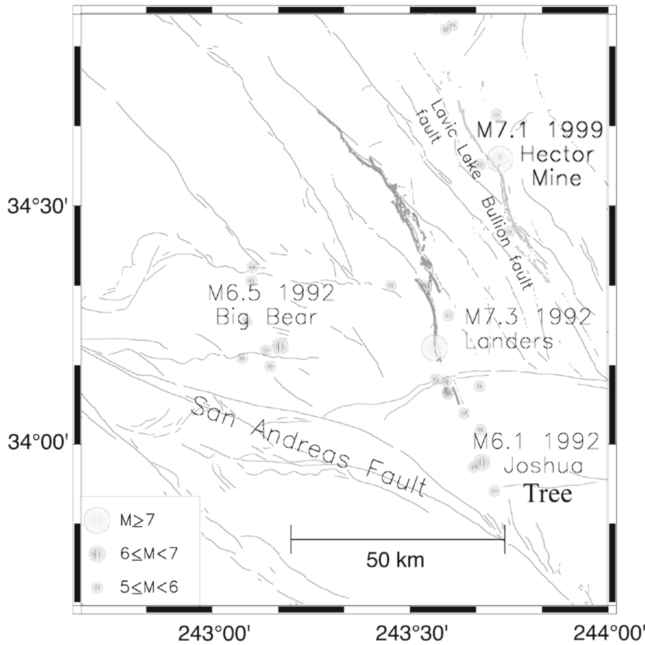

Figure 1. Active faults in the western-central Mojave Desert and epicenters of $M \geq 5$ earthquakes from April 1992 to August 2000. The surface ruptures of the 1992 Landers and 1999 Hector Mine earthquakes (Sieh *et al.*, 1993; Treiman et al., 2002) are shown as dark and light thick gray lines, respectively.

nation of static stress change from the mainshock and background loading rate to trigger a population of secondary faults. The rate of occurrence of Landers aftershocks in the epicentral region had effectively returned to pre-Landers seismicity rates about 3 years after the Landers earthquake [Gross and Kisslinger, 1997]. The spatial pattern of aftershock activity is generally well explained in terms of a change in static Coulomb failure stress (King *et al.*, 1994; Stein, 1999). The Landers–Hector Mine earthquake pair is atypical because of the relatively long delay, because the background loading rate is small, and because the nucleation point of the Hector Mine rupture lies in a neutral to weakly encouraged zone of static stress change from the Landers earthquake, depending on the coefficient of friction (Plate 2c of Parsons and Dreger, 2000).

Here we investigate whether postseismic relaxation of the lower crust and mantle following the Landers earthquake could have contributed significant postseismic stress to the future Hector Mine rupture area. This is motivated by the observation of elevated horizontal strain rates in the central Mojave Desert for several years following the Landers earthquake (Savage and Svarc, 1997), complemented by large transient vertical motions (Peltzer et al., 1998). These anomalously high rates appear best explained by deep viscoelastic relaxation (Deng *et al.*, 1998; Pollitz *et al.*, 2000). While the model of Deng *et al.* (1998) consists of a weak lower crust and strong upper mantle beneath the Mojave Desert, the model of Pollitz *et al.* (2000) consists of a stronger lower crust underlain by a weak mantle. We prefer this model because it was derived on the basis of much more data than was available to Deng *et al.* (1998). A sharp increase in strength with depth at the crust–mantle transition has long been assumed for continental regions on the basis of the relative strength of lower crustal materials (i.e., granulite) and olivine, but the strength contrast also depends on the local temperature gradient and water content of olivine, factors which may be especially important in tectonically active regions. In fact, a relatively ductile upper mantle has been inferred in all studies of tectonically active regions where data resolution allows sufficient sensitivity to mantle flow. This includes postseismic relaxation investigations made around subduction zones (e.g., Thatcher *et al.*, 1980; Miyashita, 1987; Rydelek and Sacks, 1990); around the NE Rift Zone, Iceland (Hofton and Foulger, 1996; Pollitz and Sacks, 1996); in the Mojave Desert (Pollitz *et al.*, 2000); and in post-lake-drainage (e.g., Bills *et al.*, 1994) and lake-filling (Kaufmann and Amelung, 2000) studies in the Basin and Range province, and postglacial rebound studies of Iceland (Sigmundsson and Einarsson, 1992) and the Pacific Northwest (James *et al.*, 2000).

The choice of viscoelastic stratification affects the magnitude and distribution of regional postseismic stress (e.g., Yang and Toksöz, 1981; Cohen, 1982). In the present study we use the weak-upper mantle viscoelastic model of Pollitz *et al.* (2000) to estimate post-Landers stress changes. We find that the Coulomb failure stress in the Hector Mine rupture area increased by several tenths of a bar during the period 1992 to 1999, was positive over nearly the entire Hector Mine rupture area, and (where positive) exceeded the Landers static stress change over about 50% of the Hector Mine rupture area.

Postseismic Stress Model

The viscoelastic stratification used in this study is assumed laterally homogeneous and consists of an elastic upper crust underlain by ductile lower crust and upper mantle (Fig. 2). It was derived from a grid search for a set of viscosities in a one-layer lower crust and two-layer upper mantle which, in conjunction with the known elastic stratification, best explains postseismic geodetic measurements made after the Landers earthquake (Pollitz *et al.*, 2000). A robust feature of the geodetic modeling is that the mantle is highly ductile, and bulk relaxation of the mantle has shaped the post-Landers crustal deformation field more strongly than lower crustal relaxation. The fit of this model to the surface horizontal velocity field over the period 1992 to 1995 (post-Landers and pre–Hector Mine) is shown in Figure 3. We assume that the viscoelastic model is well calibrated by these data and is suitable for calculating time-dependent stress evolution at all upper crustal depths and all times following the Landers earthquake. As in Pollitz *et al.* (2000), we calculate time-dependent postseismic strain in a gravitational

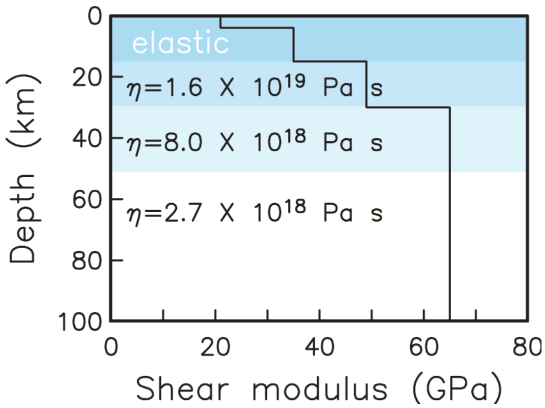

Figure 2. Viscoelastic stratification of the central Mojave Desert based on the seismic velocity modeling of Wang and Teng (1994) and geodetic modeling of Pollitz *et al.* (2000). Poisson's ratio is assigned the value 0.25. The upper crustal layer is elastic. Viscosity values are indicated in the one-layer lower crust and two-layer mantle. For simplicity, a homogeneous mantle is assumed from depth 50 km to the base of the model at depth 1000 km.

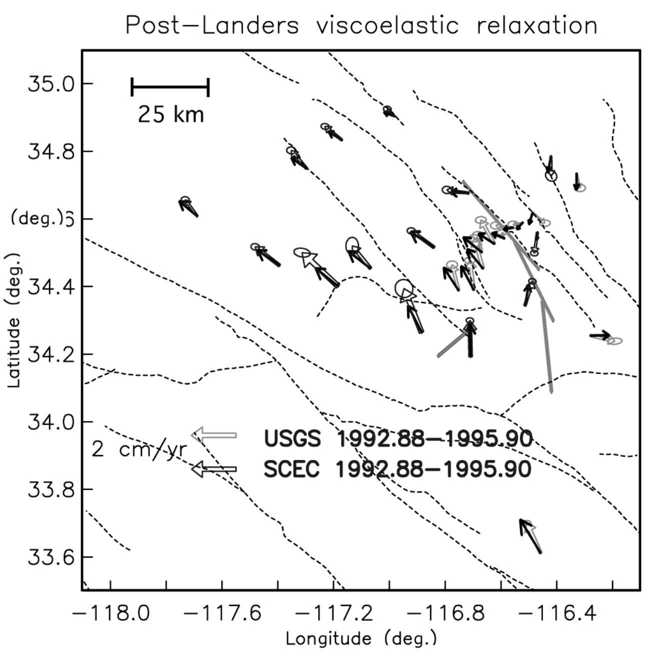

Figure 3. Observed horizontal velocity with respect to a fixed site from November, 1992 to December, 1995 and corresponding 1σ error ellipses obtained from Global Positioning System measurements by the U.S. Geological Survey (USGS; light gray arrows) and Southern California Earthquake Center (SCEC; dark gray arrows). Superimposed as black arrows are horizontal velocity vectors resulting from lower crust and mantle relaxation following the Landers and Big Bear earthquakes, calculated using appropriate Landers and Big Bear coseismic rupture models (see text) and the viscoelastic stratification of Fig. 2 (after Pollitz *et al.*, 2000).

elastic–viscoelastic coupled medium using the method of Pollitz (1997). Static strain changes in a depth-dependent elastic model are calculated using the method of Pollitz (1996). From these strains the stresses are calculated using the depth distribution of isotropic elastic constants of Figure 2.

To calculate both static and postseismic stress changes we use the distributed slip model of Wald and Heaton (1994) for the Landers earthquake and the Jones and Helmberger (1993) model for the *M* 6.5 28 June 1992 Big Bear earthquake, which occurred just 3 hours after and 30 km SW of the Landers earthquake. The static stress pattern around the Landers rupture is sensitive to the choice of Landers coseismic model (Parsons and Dreger, 2000; Harris and Simpson, 2001), but the postseismic stress change is found to depend little on this choice. For this reason, as well as for consistency with the Parsons and Dreger (2000) study, we use the Wald and Heaton (1994) model for the coseismic rupture.

The assigned elastic layer thickness of 16 km is consistent with the cutoff depth of seismicity between about 15 and 20 km depth (Richards-Dinger and Shearer, 2000), thought to coincide with the brittle-to-ductile transition. For a given slip model, there is moderate sensitivity of postseismic velocity to the thickness of the elastic layer (e.g., Fig. 7 of Yang and Toksöz, 1981, or Fig. 9 of Cohen, 1982). However, there is a trade-off between this thickness and the slip model such that slightly larger slip combined with a thicker elastic layer produces similar postseismic behavior at a given distance from the fault. Alternatively, slightly reduced lower crustal viscosity combined with a thicker elastic layer produces similar postseismic behavior. To first order, compounded revisions to the viscoelastic model are inconsequential, provided that the model used is consistent with the postseismic strain observations (Fig. 3).

Stress Evolution

We evaluate the change in Coulomb failure stress defined by

$$\Delta\sigma_f = \Delta\tau + \mu' \, \Delta\sigma_n \quad (1)$$

where $\Delta\tau$ is the change in shear stress (positive for right-lateral shear), $\Delta\sigma_n$ is the change in normal stress (positive tensile), and μ' is the effective coefficient of friction which includes the effects of pore pressure changes. Both $\Delta\tau$ and $\Delta\sigma_n$ are evaluated on a secondary fault surface with specified orientation. The best-fitting point source for the Hector Mine earthquake is right-lateral strike-slip faulting on a N29°W-striking plane dipping 77° NE (U.S. Geological Survey, Southern California Earthquake Center, and California Division of Mines and Geology, 2000, hereafter USGS *et al.*, 2000). The earthquake, however, ruptured two principal faults (Fig. 1): the southern portion of the Bullion fault, which strikes NW, and the Lavic Lake fault further north, which strikes NNW near its junction with the Bullion fault but curves to a more westerly trend further north. We represent the potentially failing Hector Mine rupture surface as a single N29°W-striking, 48-km-long vertical fault for two reasons: (1) this is the average strike of the Lavic Lake segment where rupture nucleated and where most of the slip was concentrated (USGS *et al.*, 2000); (2) postseismic stress changes in this locality are found to be insensitive to small-to-moderate changes in the strike and dip of the secondary fault plane. The chosen fault plane spans the area of significant surface rupture (USGS *et al.*, 2000).

We consider two values of the effective coefficient of friction, $\mu' = 0.3$ and $\mu' = 0.7$. The first value is typical of that inferred for faults with tens of km of cumulative slip (Stein, 1999), while the second value is that expected from rock mechanics experiments (Lachenbruch and McGarr, 1990), and appears typical for immature faults (Stein, 1999). The best correlation of Landers aftershocks with the static Coulomb failure stress change has been obtained with $\mu' = 0.85$ (Seeber and Armbruster, 2000). This suggests that a relatively large value of μ' is appropriate for the Hector Mine rupture area. Figure 4 shows the regional pattern of $\Delta\sigma_f$ with $\mu' = 0.7$ just after the Landers–Big Bear earthquakes and just before the Hector Mine earthquake at depth 7 km, approximately the depth of the Hector Mine nucleation point. Just after the Landers earthquake (Fig. 4a); the southern 60% of the future Hector Mine rupture was located in a stress shadow (negative $\Delta\sigma_f$), and the northern 40% lay in a stress-encouraged zone, $\Delta\sigma_f$ reaching up to 2.9 bars. The nucleation point was neither encouraged nor discouraged. This picture is altered by the addition of 7.3 years of post-Landers crust and mantle relaxation (Fig. 4b), with the magnitude and spatial extent of the stress-encouraged zone increasing by more than 0.5 bars over the northern 50% of the Hector Mine rupture zone. The stress field continues to evolve with the addition of Hector Mine coseismic (Fig. 4c) and postseismic (Fig. 4d) stress changes. The latest snapshot in Figure 4d projects the compounded post-Landers and post-Hector Mine stress changes forward to a time 7.3 years after the Hector Mine earthquake. It is clear that several active faults in the Mojave Desert, as well as portions of the San Andreas fault, are predicted to be subject to greater loading over the coming years as the region continues to relax. The contributions of the post-Landers and post-Hector relaxation to the Coulomb stress changes over the various time periods are presented in Figure 5. Figure 5a illustrates more clearly that the northern portion of the future Hector Mine rupture zone, including the Hector Mine epicenter, was stressed by an additional several tenths of a bar during the 7-year period after the Landers earthquake.

The evolution of $\Delta\sigma_f$ along the Hector Mine rupture surface is shown in the depth sections of Figure 6. During the intervening 7.3 years, the nucleation point passed from being encouraged at $\Delta\sigma_f = 0.0$ bars to being encouraged at $\Delta\sigma_f \sim 0.7$ bars, a value which is known to produce strong correlations with triggered seismicity in static Coulomb failure stress studies (Stein, 1999). The stress encouragement was amplified on the entire portion of the Hector Mine rupture for which the static stress change was positive, the postseismic stress change exceeded the static stress change over approximately the middle 50% of the Hector Mine rupture, and the maximum $\Delta\sigma_f$ on the Hector Mine rupture plane increased from 2.9 to 3.7 bars.

These calculations are very sensitive to the choice of μ'. Figure 7 shows the depth profiles of $\Delta\sigma_f$ obtained with $\mu' = 0.3$. The zone of stress encouragement from the Landers static stress change is reduced in both magnitude and spatial extent with the smaller coefficient of friction. This is because the static shear stress change $\Delta\tau$ is negative over almost the entirety of the Hector Mine rupture zone, but the static normal stress change is positive (i.e., tensile) over the northern half, and the Coulomb stress change is strongly dependent on the coefficient of friction, also found by Parsons and Dreger (2000). In this case the Hector Mine nucleation point evolves from an initial -0.7 bars stress shadow (Fig. 7a) to -0.1 bars at the time of the Hector Mine earthquake (Fig. 7b). The viscoelastic relaxation contribution is only weakly sensitive to μ' (compare Fig. 6c and 7c), because most of the postseismic $\Delta\sigma_f$ results from the shear stress change $\Delta\tau$. In this case, the postseismic stress change exceeds the coseismic stress change over about 75% of the Hector Mine rupture. Regardless of the value of the coefficient of friction, the calculations of the stress evolution model point strongly towards viscoelastic relaxation of the lower crust and mantle following the Landers earthquake as contributing to the triggering of the Hector Mine earthquake.

Discussion

The Hector Mine earthquake may be considered as the fourth event in a cascade of recent large Mojave Desert earthquakes, preceded by the 1992 Joshua Tree, 1992 Landers, and 1992 Big Bear earthquakes. Each event, beginning with the Joshua Tree earthquake, stressed the rupture zone of the succeeding event by ~1 bar (King *et al.*, 1994). The inclusion of the Hector Mine earthquake in this succession is based on the fact that, according to our model with $\mu' = 0.7$, the viscoelastic stress change rate over much of the Hector Mine rupture zone averaged 0.14 and 0.10 bars/yr for the first 3 and 7.3 years, respectively, following the Landers earthquake. This is consistent with an observed horizontal tensor shear strain rate of $\sim 0.20 \times 10^{-6}$/yr for the first 3 years following the Landers earthquake (Savage and Svarc, 1997). Although the measurements constraining the post-Landers strain rates were made primarily west of the Landers rupture, one might expect symmetry of post-Landers strain with respect to the Landers rupture, so that these measurements are an effective constraint on post-Landers strain rates in the Hector Mine epicentral area east of the Landers rupture. This symmetry is also produced by the 1-D viscoelastic model.

From the measured post-Landers strain rate, the inferred horizontal shear stress rate during the time period between

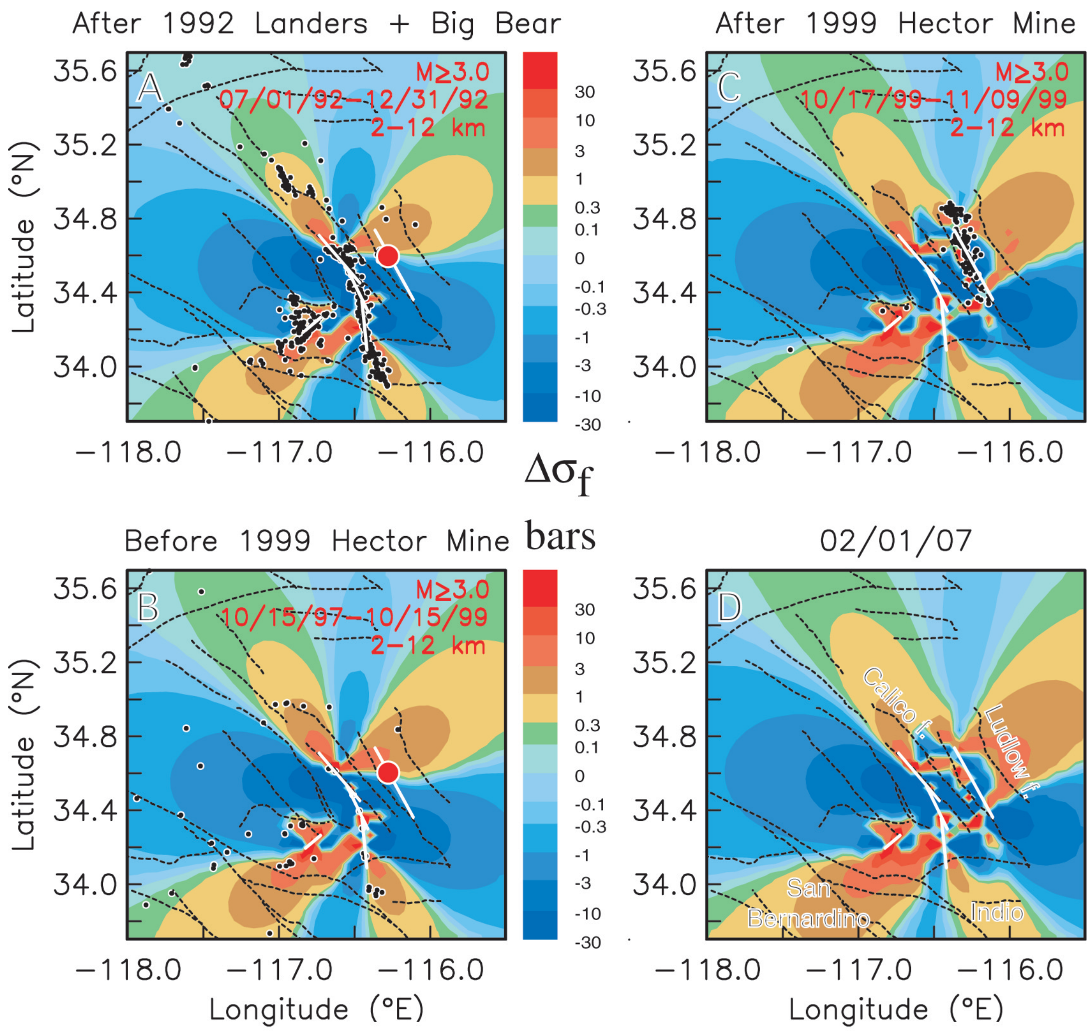

Figure 4. Snapshots of change in Coulomb failure stress $\Delta\sigma_f$ at depth 7 km (a) just after the 1992 Landers earthquake, (b) just before the 1999 Hector Mine earthquake, (c) just after the Hector Mine earthquake, and (d) projected forward to February 2007. A coefficient of friction of 0.7 is assumed. The difference between (a) and (b) arises from the postseismic stress change from viscoelastic relaxation of the lower crust and mantle accumulated during the 7.3 years between the two earthquakes. Representative fault surfaces for the Landers, Big Bear, and Hector Mine earthquakes are indicated by white lines, and the Hector Mine nucleation point by red circles. Epicenters of earthquakes with magnitude ≥3.0 and depth 2–12 km are superimposed, covering the indicated time periods.

the Landers and Hector Mine earthquakes is about three times greater than the interseismic stress accumulation rate based on pre-Landers geodetic measurements of strain accumulation in the Mojave Desert (Sauber *et al.*, 1994; Shen *et al.*, 1996; Savage and Svarc, 1997, p. 7575) and is comparable with the stress accumulation rate on the San Andreas fault based on geodetic measurements (e.g., Savage *et al.*, 1986). Nevertheless, the accumulated 0.7 bars is much less than the ~20 bars stress drop expected for a strike-slip earthquake of this magnitude (Kanamori and Anderson, 1975). Analysis of fault state based on friction mechanics indicates that a small positive stress step will lead to short-term triggering of earthquakes only if the secondary fault being considered is already near failure (Fig. 3 of Gomberg *et al.*, 1998). This conclusion agrees with a cellular automata model study of the response to a small stress perturbation by a fault system characterized by a highly heterogeneous absolute stress distribution (Rydelek and Sacks, 1999). This suggests that the Hector Mine rupture zone was already critically stressed just prior to the Landers earthquake.

Our result of 0.7 bars post-Landers stress change is similar to the ~1 bar postseismic stress change obtained by Zeng (2001) and Freed and Lin (2001; their Model 1) using similar values for the coefficient of friction. Each of these studies predicts stress evolution on the Hector Mine rupture surface close to that of our model (Fig. 6), but the stress

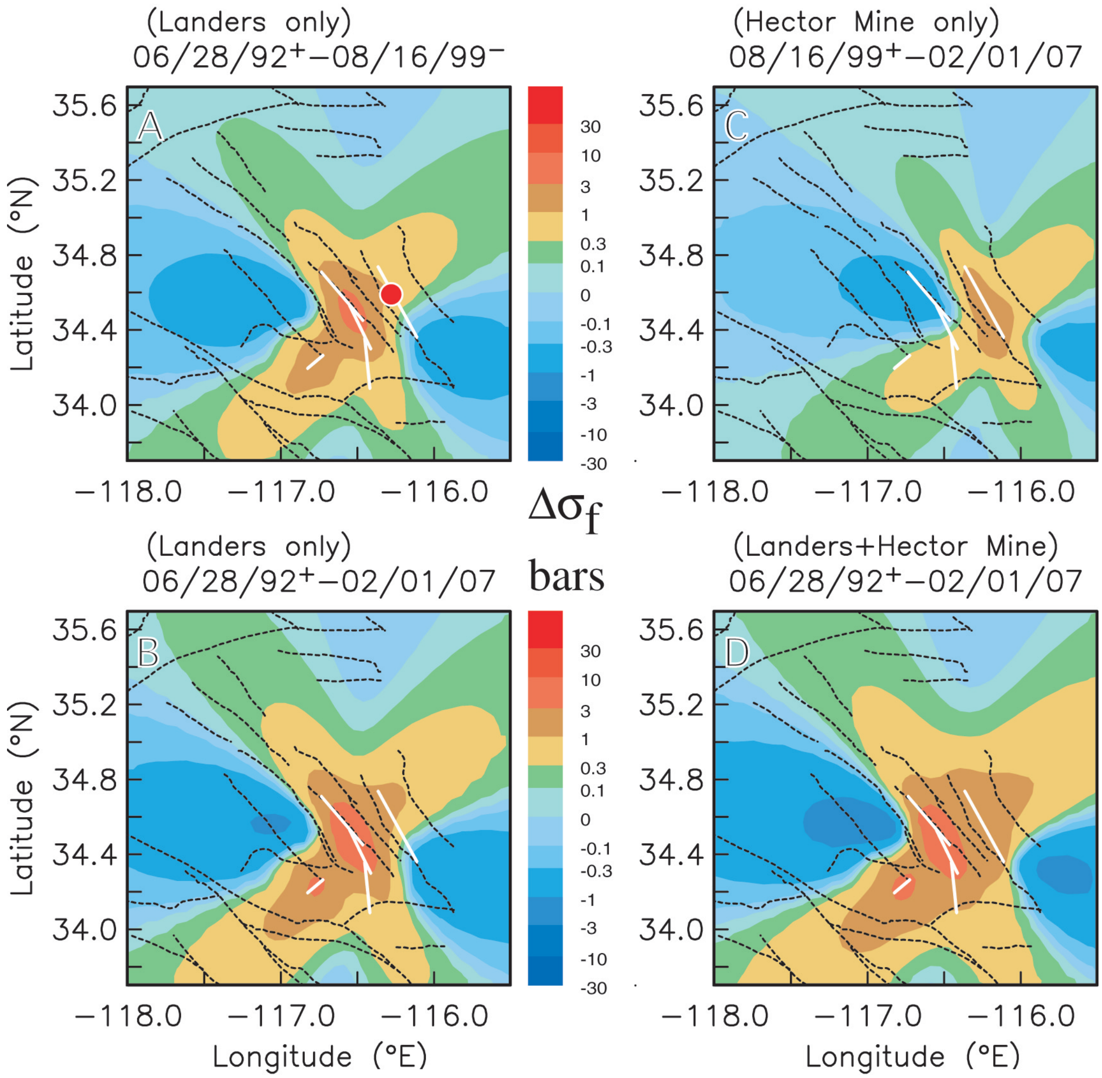

Figure 5. Contribution of viscoelastic relaxation of the lower crust and mantle from the Landers or Hector Mine earthquake during various epochs: post-Landers $\Delta\sigma_f$ from (a) just after the Landers earthquake to just before the Hector Mine earthquake or (b) to February 2007, (c) post-Hector Mine $\Delta\sigma_f$ from just after the Hector Mine earthquake to February 2007, and (d) combined post-Landers and post-Hector Mine relaxation accumulated up to February 2007.

evolution over the entire region generally differs from ours (Fig. 4), because these studies assume a viscoelastic model consisting of a weak lower crust and strong upper mantle. As explained in the Introduction, we believe that a weak-mantle model is more applicable to the region. Model 2 of Freed and Lin (2001) is a weak-mantle model, and it results in a post-Landers Coulomb stress increase of 1.5 bars at the Hector Mine epicenter for $\mu' = 0.2$ and 2.0 bars for $\mu' = 0.8$. The former value is about two times higher than our stress change for $\mu' = 0.3$ (Fig. 7c) and about three times higher than our stress change for $\mu' = 0.7$ (Fig. 6c). These differences arise mainly from the greater postseismic normal stresses generated in Freed and Lin's model. Since the viscoelastic stratifications in their Model 2 and the present study are very similar, we attribute these differences to the somewhat different Landers source models used in the two studies.

Projected forward to February 2007, the individual post-Landers and post-Hector Mine relaxation (Fig. 5c,d) combine to focus additional stress on Mojave Desert faults east (i.e., Ludlow fault) and north (i.e., Calico fault) of the Landers–Hector Mine ruptures, raising the likelihood of failure of these active faults. Moreover, the San Bernardino and Indio segments of the San Andreas fault are predicted to have Coulomb stress increases of about 5 and 0.5 bars, respectively (Fig. 4c); the postseismic contributions to these stress increases are about 2 and 0.4 bars, respectively (Fig. 5d). The values around the Indio segment would be greater if the effects of the 1992 Joshua Tree earthquake were included (King *et al.*, 1994).

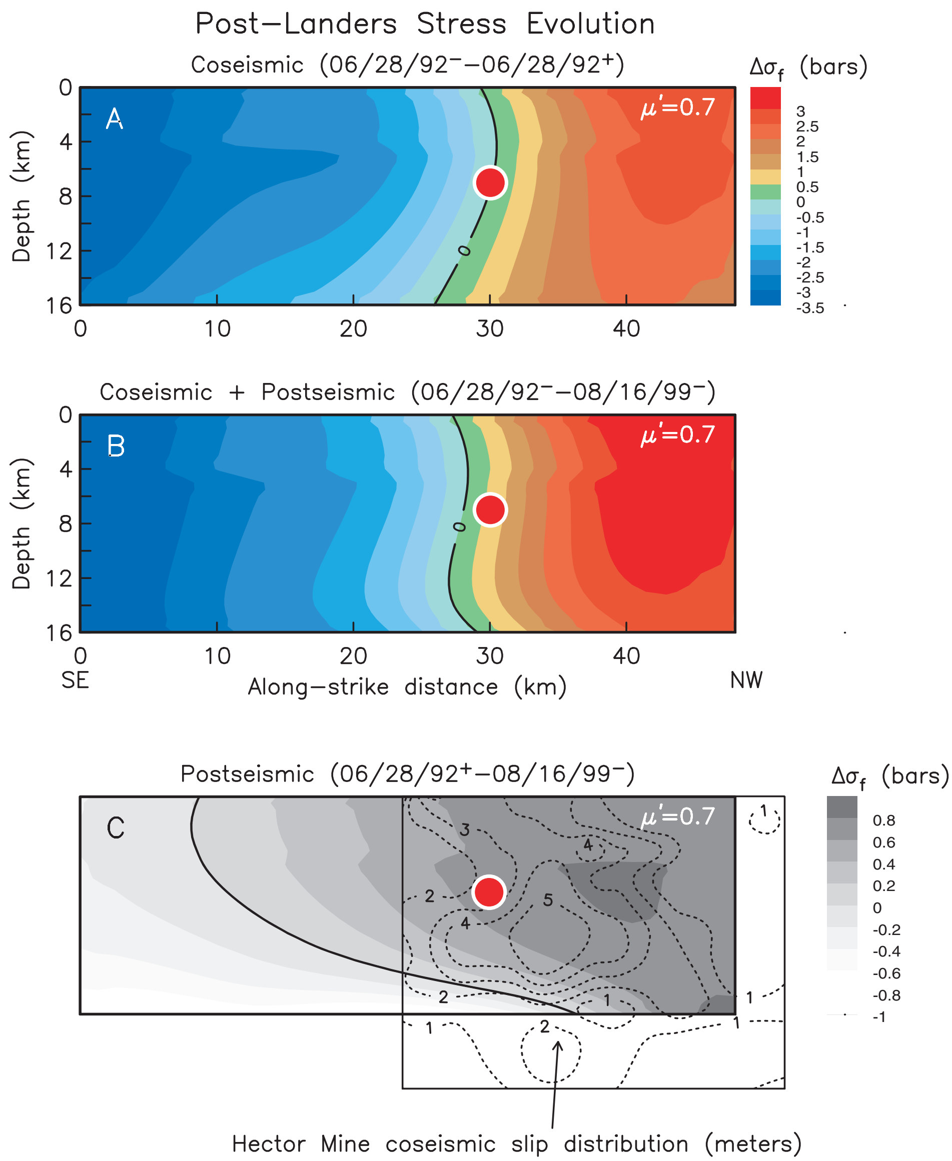

Figure 6. Depth profile of change in Coulomb failure stress $\Delta\sigma_f$ derived from (a) the Landers static stress change, (b) the static stress change plus the total postseismic stress change at the time of the Hector Mine earthquake, and (c) the postseismic stress change alone. The stress changes are calculated on potentially failing vertical faults striking N29°W and passing through the Hector Mine nucleation point (indicated by red circle), with effective coefficient of friction $\mu' = 0.7$. Superimposed in (c) is the projection of the right-lateral slip distribution of the Hector Mine earthquake (Dreger and Kaverina, 2000).

The accumulated viscoelastic stress change is well correlated with the Hector Mine coseismic slip distribution (Figs. 6 and 7). This may be coincidental, or it may reflect a stress concentration capability which is unique to a slow transient (versus sudden static) stress change. The mechanism of viscoelastic relaxation of the sublithosphere for triggering earthquakes was suggested by Yang and Toksöz (1981) to explain the migration pattern of earthquakes along the North Anatolian fault. The effectiveness of this process was demonstrated by a statistical correlation between land (intraplate) and trench (interplate) earthquakes in northern Honshu, Japan (Rydelek and Sacks, 1988, 1990). Transient postseismic $\Delta\sigma_f$ of 1 to 3 bars accumulated over decades have been correlated with the occurrence of the 1995 Kobe earthquake (Pollitz and Sacks, 1997), the 1944 Tonankai earthquake (Pollitz and Sacks, 1995), and the inhibition of the anticipated Tokai earthquake in Suruga Bay, Japan (Pollitz and Sacks, 1995). Transient postseismic stress is also believed to play a role in the generation of repeated earthquakes in the New Madrid Seismic Zone (Kenner and Segall, 2000). At a much shorter timescale, transient stress changes have been correlated with the occurrence of Northridge

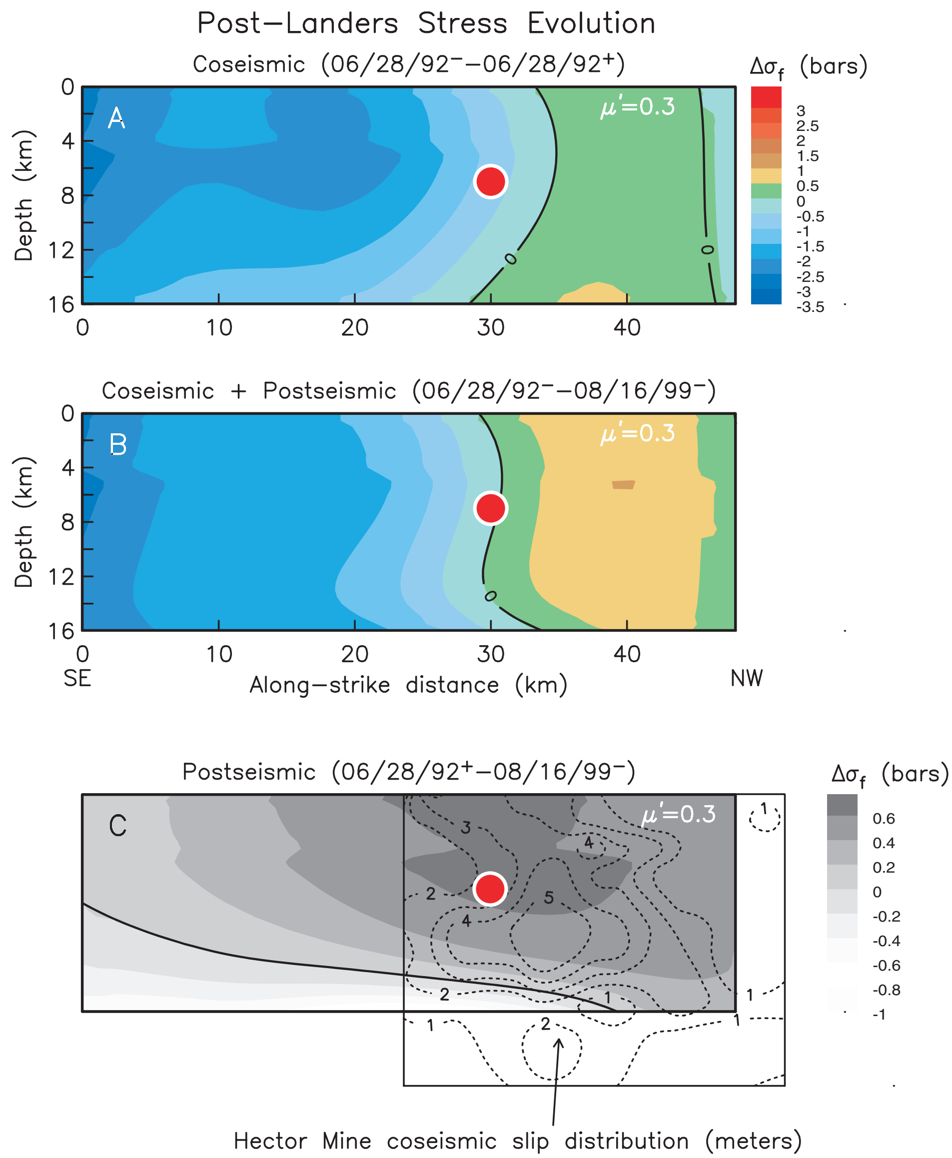

Figure 7. Depth profile of change in Coulomb failure stress $\Delta\sigma_f$ as in Fig. 6, with $\mu' = 0.3$.

aftershocks (Deng et al., 1999). If the transient stresses generated by viscoelastic relaxation of the lower crust and mantle are capable of bringing major faults closer to (or away from) failure, as suggested by these studies, then its potential impact should be closely examined in regions surrounding major historic earthquake ruptures.

Acknowledgments

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U.S. Geological Survey
345 Middlefield Road, MS 977
Menlo Park, California 94025
(F.F.P.)

Carnegie Institution of Washington
Department of Terrestrial Magnetism
5241 Broad Branch Road, N.W.
Washington, D.C. 20015
(I.S.S.)

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