# 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

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**Abstract.** The proximity in time (~7 years) and space (~20 km) between the 1992 **M**=7.3 Landers earthquake and the 1999 **M**=7.1 Hector Mine event suggests a possible link between the quakes. We thus calculated the static stress changes following the 1992 Joshua Tree/Landers/Big Bear earthquake sequence on the 1999 **M**=7.1 Hector Mine rupture plane in southern California. Resolving the stress tensor into rake-parallel and fault-normal components and comparing with changes in the post-Landers seismicity rate allows us to estimate a coefficient of friction on the Hector Mine plane. Seismicity following the 1992 sequence increased at Hector Mine where the fault was unclamped. This increase occurred despite a calculated reduction in right-lateral shear stress. The dependence of seismicity change primarily on normal stress change implies a high coefficient of static friction ($\mu \geq 0.8$). We calculated the Coulomb stress change using $\mu$=0.8 and found that the Hector Mine hypocenter was mildly encouraged (0.5 bars) by the 1992 earthquake sequence. In addition, the region of peak slip during the Hector Mine quake occurred where Coulomb stress is calculated to have increased by 0.5-1.5 bars. In general, slip was more limited where Coulomb stress was reduced, though there was some slip where the strongest stress decrease was calculated. Interestingly, many smaller earthquakes nucleated at or near the 1999 Hector Mine hypocenter after 1992, but only in 1999 did an event spread to become a **M**=7.1 earthquake.

## Introduction

The October 16, 1999 **M**=7.1 Hector Mine earthquake occurred about 20 km northeast of the 1992 **M**=7.3 Landers earthquake in southern California (Plate 1). The proximity of the two ruptures raises the question whether the Hector Mine quake was advanced by static stress changes [e.g., *Harris*, 1998, and references contained therein] caused by the 1992 Joshua Tree/Landers/Big Bear earthquake sequence. We investigate the relationship between these earthquakes by using previously defined slip models for the Landers sequence [e.g., *Wald and Heaton*, 1994; *Hudnut et al.*, 1994] and a new slip model for the Hector Mine rupture [*Dreger and Kaverina*, 2000] in an elastic dislocation model. We calculate the static stress change on the eventual Hector Mine rupture plane caused by the 1992 earthquake sequence and investigate effects on microseismicity, as well as on nucleation and slip distribution of the Hector Mine shock.

### Tectonic Setting

The Landers and Hector mine earthquakes occurred in a remote, sparsely-populated part of the Mojave desert (Plate 1). The dominantly right-lateral Hector Mine earthquake ruptured about 41 km at the surface and involved parts of two previously mapped fault zones - the Bullion fault, and an unnamed, more northerly trending fault that is now informally referred to as the Lavic Lake fault [*U.S. Geological Survey, Southern California Earthquake Center, and California Division of Mines and Geology*, 2000]. It is one of a series of northwest-trending, right-lateral strike slip faults that traverse this portion of the Mojave Desert. Together, these faults are part of the eastern California shear zone, which accommodates about 12 mm/yr of Pacific-North American relative plate motion [e.g., *Sauber et al*., 1994].

## 1992 Joshua Tree/Landers/Big Bear Earthquake Sequence Effects on the Hector Mine Rupture

### Fault Models and Stress Calculations

We used the program, DLC, written by R. Simpson (based on the subroutines of *Okada* [1992]) to calculate changes in the stress tensor at points along a specified receiver fault surface caused by slip on a source fault in an elastic half space. We used dislocation models of the 1992 **M**=6.1 Joshua Tree, **M**=7.3 Landers, and **M**=6.5 Big Bear earthquakes [*Wald and Heaton*, 1994; *King et al.*, 1994] for source faults. Calculation of static stress change using a different Landers slip model [*Hudnut et al.*, 1994] yielded only very small differences in calculated stress change. The receiver fault is set of rupture planes developed from finite-source modeling [*Dreger and Kaverina*, 2000]. The Hector Mine model we use has three planes, to account for curvature in the rupture, that strike from N35˚W to N15˚W, dip 77˚ down to the northeast and have 180˚ rakes (Plate 1). The three planes are shown projected onto one in Plate 2 for ease of viewing. The Hector Mine hypocenter is

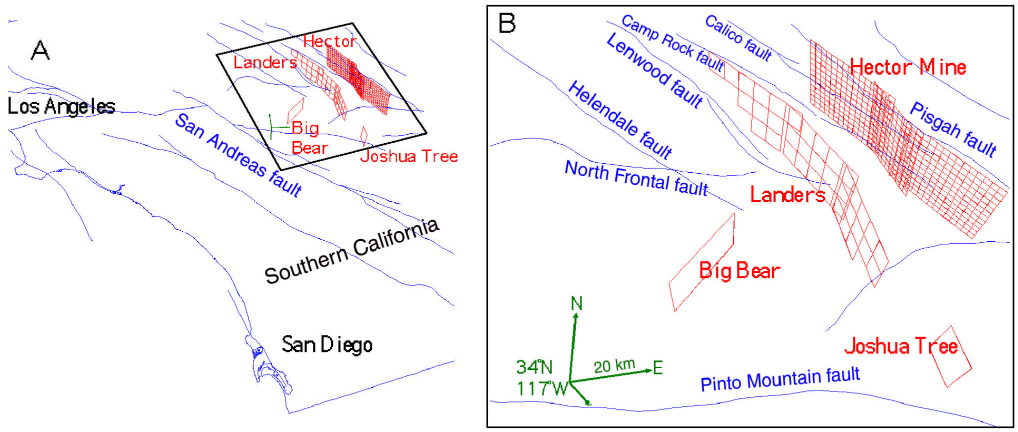


Plate 1. (a) Locations of the 1992 **M**=6.1 Joshua Tree, **M**=7.3 Landers, **M**=6.5 Big Bear, and the 1999 **M**=7.1 Hector Mine ruptures with respect to the California state lines and (b) to the mapped faults in the Mojave Desert part of the eastern California shear zone. The boxed area in (a) corresponds to (b).

located near 34.5955˚N and 116.2879˚W at ~6 km depth.

We calculate shear stress change on the rupture planes parallel to the rake, and change in the component of stress normal to the rupture planes. These stress components can be combined into a Coulomb failure criterion ( $\Delta CF$ ) by

$$\Delta CF \equiv \left|\Delta \bar{\tau}_f\right| + \mu(\Delta\sigma_n + \Delta p) \qquad (1)$$

where $\Delta\bar{\tau}_f$ is the change in shear stress on the receiver fault, μ is the coefficient of friction, $\Delta\sigma_n$ is the change in normal stress acting on the receiver fault, and $\Delta p$ is pore pressure change. Since a change in the Coulomb failure stress is calculated, μ on the receiver faults is treated as a constant, and is assumed not to change as a result of slip on the rupture plane. Commonly, Skempton's coefficient $B_k$ (which varies from 0 to 1) is used to incorporate pore fluid effects, in which the effective coefficient of friction $\mu' = \mu(1 - B_k)$ is adjusted and used in the Coulomb failure criterion as

$$\Delta CF \equiv \left|\Delta\bar{\tau}_f\right| + \mu'(\Delta\sigma_n)$$
(2)

after *Rice*, [1992].

Our dislocation modeling shows that right-lateral shear stress on most of the Hector Mine rupture plane was relaxed by the 1992 earthquake sequence in southern California by an average of ~1.5 bars (Plate 2a). We calculate a small zone (~10 km wide) of mild right-lateral loading (<0.5 bars) beginning 5 km beneath the Hector Mine hypocenter. This calculation suggests that the Landers sequence did not advance the Hector Mine rupture in shear. In contrast, normal stress calculations show a 0.5-to-1-bar unclamping stress change in the Hector Mine hypocentral region, and unclamping on most of the rupture plane northwest of the hypocenter (Plate 2b). If a Coulomb failure criterion applies to the Hector Mine rupture, then our calculations indicate that the normal stress change caused by the 1992 earthquake sequence acts to encourage failure while the shear stress change acts to inhibit it. The normal stress is scaled by the coefficient of friction μ in Equations 1 and 2, thus we require an estimate of μ to assess whether the Hector Mine hypocentral region was brought closer or farther away from failure by the 1992 earthquake sequence.

## Friction on the Hector Mine Rupture Plane

One way to estimate the coefficient of friction on a fault is to examine the response in the microseismicity rate following a stress perturbation [e.g., *Reasenberg and Simpson*, 1992; *Parsons et al.*, 1999]. If seismicity is most correlated with shear stress and is insensitive to normal stress changes, then friction may be low. Conversely, if seismicity is more associated with normal stress changes, then friction is likely high. We can use seismicity rate change observations to estimate a coefficient of friction if three assumptions are made: 1) earthquakes that have been located within ±1 km of the eventual Hector Mine rupture happened on the fault, 2) the microseismicity assumed to occur on the Hector Mine rupture plane has the same approximate rake (180˚, right-lateral) as the main shock, and 3) the pore fluid pressure in the fault zone is not greater than lithostatic.

In Plate 2 we show relocated earthquake hypocenters by *Dinger and Shearer* [2000] associated with the Hector Mine rupture plane (within ±1 km) that happened five years prior to the 1992 sequence (colored blue) and five

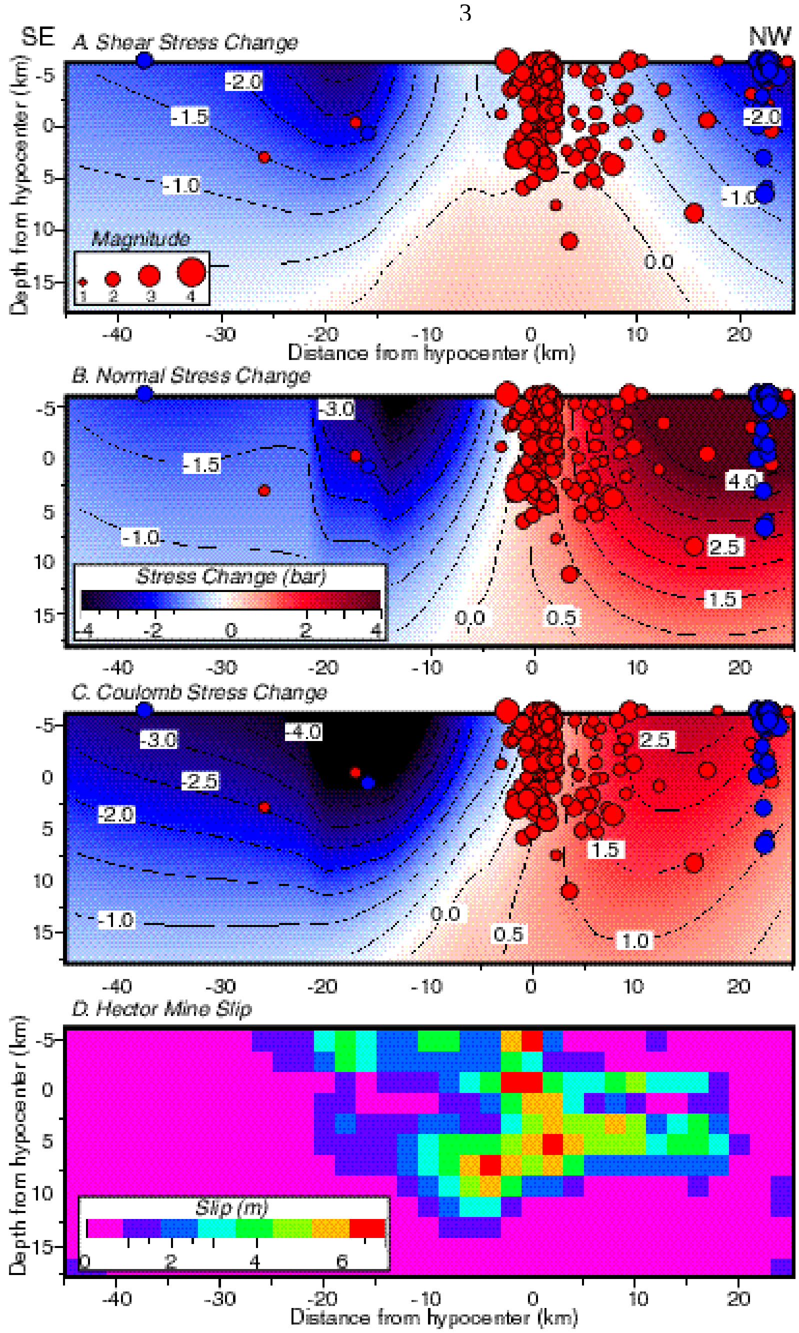


Plate 2. (a) The shear stress change from the 1992 earthquake sequence on the Hector Mine rupture plane shown with 5 years of seismicity before the 1992 Joshua Tree quake (blue dots) and 5 years after the 1992 Big Bear event (red dots). Depth and distance coordinates are with respect to the Hector Mine hypocenter, which occurred at ~6 km depth. Shear stress is resolved in the rake direction of the Hector Mine rupture (180˚). Most post-Landers earthquakes occurred where shear stress was decreased. (b) The normal stress resolved on the Hector Mine plane shows unclamping northwest of the Hector Mine hypocenter. The post-Landers seismicity on the Hector Mine rupture plane is more associated with normal stress change than shear stress change, implying high friction. (c) Coulomb stress change is calculated with a high coefficient of friction (μ=0.8). The Hector Mine hypocenter was encouraged (~0.5 bars) by the Landers earthquake sequence, and the region of greatest slip (d) appears to have been limited to where Coulomb stress was increased by 0.5-1.5 bars.

years after (colored red). There was a significant rate increase after 1992. A small cluster (~10 km wide) of earthquakes occurred after 1992 that coincides with the eventual 1999 Hector Mine hypocenter. This cluster is located mostly above 10 km depth where we calculate a 0-to-0.5-bar reduction in right-lateral shear stress (Plate 2a). However, the cluster is also associated with a zone of calculated unclamping stress (0 to 3 bars) (Plate 2b). If a Coulomb criterion is used as in Equation 2, then seismicity northwest of the Hector Mine hypocenter is best explained if the coefficient of friction is high (≥0.8). Southeast of the Hector Mine hypocenter, there was virtually no seismicity either before or after the Landers earthquake sequence. We show seismicity superimposed on Coulomb stress with a coefficient of friction of 0.8 in Plate 2c.

A high coefficient of friction might be expected for the Hector Mine rupture. Previous evaluations of the Lavic Lake fault indicated no Holocene slip [*Hart et al.*, 1988]. Faults with infrequent, limited slip tend to have less gouge built up [e.g., *Scholz*, 1987], and can be described by applying a failure criterion with approximately hydrostatic pore pressure and the higher coefficients of friction more consistent with laboratory measurements (0.5-0.8) [e.g., *Parsons et al.*, 1999]. This behavior may result from a lack of a gouge seal that allows coseismic pressurized fluids to escape the fault zones [e.g., *Scholz*, 1990].

**Static Stress Change at the Hector Mine Hypocenter and Areas of Large Slip**

The calculated Coulomb stress at the Hector Mine hypocenter was increased by ~0.5 bars if a high coefficient of friction ($\mu$=0.8) is used (Plate 2c). Therefore nucleation at the Hector Mine site is consistent with triggering by the 1992 earthquake sequence. In addition, our calculations indicate that nearly all earthquakes that occurred within ±1 km from the rupture plane are consistent with having been triggered by unclamping following the 1992 Landers sequence (Plate 2c).

The static stress change we calculate from the 1992 earthquake sequence on the Hector Mine rupture is very small compared with the dynamic stresses generated during the earthquake, and thus might not be expected to affect slip appreciably. However, we find that there is a spatial association between parts of the rupture plane where we calculate Coulomb stress increase and where most of the slip occurred (compare Plates 2c and 2d). There was, however, some shallow slip in the region where we calculate the strongest Coulomb stress decrease.

If the association between calculated Coulomb stress change and peak seismic slip distribution is causal, then it implies that a very small change in Coulomb stress (~0.5-1.5 bars) can influence the slip distribution of a large earthquake. A similar result was found by *Perfettini et al.* [1999], who showed that relatively small foreshocks of the 1989 Loma Prieta earthquake unclamped the zone of peak slip. Also, *King et al.* [1994] and *Caskey and Wesnousky* [1997] suggested that static stress changes influenced slip during the 1992 Landers-Big Bear and 1954 Fairview Peak-Dixie Valley sequences. In addition, laboratory experiments show that small proportional changes in normal stress can have large influence on frictional resistance [e.g., *Linker and Dieterich*, 1992].

**Apparently Triggered, but Delayed Slip at the Hector Mine Hypocenter**

It appears that stress imparted by the 1992 Joshua Tree/Landers/Big Bear earthquake sequence promoted nucleation of the 1999 Hector Mine earthquake, and may have influenced its slip distribution. Almost all post-1992 seismicity in the vicinity of the Hector Mine rupture occurred where Coulomb stress was increased. However, there is a puzzling aspect to the relationship between these earthquakes and the nucleation of the larger earthquake. Multiple small (**M**<4.5) earthquakes occurred at or near the eventual nucleation site (Plate 2), yet slip did not spread during any of those events. Instead, more than seven years passed before large slip originated in the same zone, spreading out to become the Hector Mine shock.

The delayed response to static stress change at the Hector Mine site could be explained under a special circumstance if a stress threshold required for large slip had not been reached until 1999. Alternatively, aspects of rate- and state-dependent friction theory predict an exponential time-decay of triggered earthquakes following a stress perturbation that depends on an array of nucleation sites, each with a different set of failure criteria [*Dieterich*, 1994]. If this model applies to the Hector Mine site, then the implication is that very specific conditions were required for nucleation and spread of the **M**=7.1 Hector Mine quake that were not met by repeated other earthquakes that nucleated at or very near the site of the eventual 1999 event.

## Conclusions

Changes in microseismicity after the 1992 Landers earthquake sequence on the eventual Hector Mine rupture plane are most associated with calculated unclamping stresses. This association implies high friction. We can thus match the microseismicity with Coulomb stress change if the coefficient of friction is 0.8 or higher. Using the $\mu$=0.8 coefficient of friction, we calculate that the 1992 earthquake sequence increased the Coulomb stress by ~0.5 bars at the Hector Mine hypocenter. In addition, the areas of peak slip northwest of the hypocenter were mostly limited to where Coulomb stresses were increased by 0.5-1.5 bars, possibly implying an influence on slip distribution and extent by static stress change. The Hector Mine hypocenter is located where a cluster of post-1992 seismicity has been occurring, yet none of those previous events initiated significant slip.

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