Accelerated stress buildup on the southern San Andreas fault and surrounding regions caused by Mojave Desert earthquakes

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ABSTRACT

A sequence of four $M_w > 6$ earthquakes, including the 1992 $M_w = 7.3$ Landers and $M_w = 7.1$ Hector Mine earthquakes, occurred in the Mojave Desert in the 1990s in close proximity to the southern San Andreas fault, inducing stress changes on several of its segments. We calculate that coseismic slip combined with postseismic relaxation of viscous lower crust and/or upper mantle has led to a Coulomb stress increase of 2.3–3.5 bar on the San Bernardino Mountain segment of the southern San Andreas fault between 1992 and 2001, with a projected increase of 3.6–4.9 bar by the year 2020. In comparison, the calculated coseismic stress increase is 1.8 bar for this segment. This accelerated buildup of stresses is predicted to bring the San Bernardino Mountain segment, which last ruptured more than 190 yr ago, closer to a potentially major rupture. Meanwhile we project a net stress decrease of as much as −3.5 bar between 1992 and 2020 for the western Coachella Valley segment if the fault is governed by low effective friction, or an increase of 1.5 bar if the fault is governed by high effective friction. Coulomb stresses are calculated to decrease on the Mojave segment by as much as −1 bar between 1992 and 2020. Accelerated stress buildup is also predicted to occur on parts of the San Jacinto, Elsinore, and Calico faults. The pattern of the observed post-Landers aftershock clustering and the calculated Coulomb stress buildup on the Calico fault is similar to that noted in the Hector Mine region prior to the 1999 $M_w = 7.1$ earthquake. These results imply that the stress changes caused by an earthquake may still play a role in triggering future quakes in neighboring crust many years later through viscoelastic processes.

Keywords: earthquake stress triggering, viscoelastic deformation, Landers earthquake, San Andreas fault, southern California.

INTRODUCTION

A sequence of four $M_w > 6.1$ earthquakes has shaken the Mojave Desert in southern California over the past decade, including the 1992 $M_w = 7.3$ Landers and 1999 $M_w = 7.1$ Hector Mine earthquakes (Fig. 1). These events are well within the distance of stress interaction with the southern San Andreas fault, potentially changing its earthquake probability. The parts of the southern San Andreas fault most likely influenced by the Mojave earthquakes are the Mojave, San Bernardino Mountain, and Coachella Valley segments (Fig. 1), all of which are capable of producing major ($M_w > 7.5$) earthquakes (Working Group on Californian Earthquake Probabilities, 1988). The Mojave segment last ruptured in 1857, the San Bernardino Mountain segment in 1812 (Jacoby et al., 1988; Sieh et al., 1989), and the Coachella Valley segment in 1680 (Sieh, 1986). Historic repeat times for major earthquakes, although highly variable, have been estimated from ~130 yr on the Mojave segment (Jacoby et al., 1988; Sieh et al., 1989) to >235 yr on the Coachella Valley segment (Sieh, 1986; Stein et al., 1992). If some of these segments are very late in their earthquake cycle, small stress changes induced during the next several years may be sufficient to trigger a major earthquake.

Previous studies (Stein et al., 1992; Harris and Simpson, 1992) have calculated that the 1992 $M_w = 6.1$ Joshua Tree, $M_w = 7.3$ Landers, and $M_w = 6.3$ Big Bear earthquakes (here collectively referred to as the Landers sequence) have increased coseismic stresses on the San Bernardino Mountain and Coachella Valley segments and decreased stress on the Mojave segment. In the decade since the Landers sequence, the stress field in the Mojave Desert region has been modified by transient viscoelastic flow in the lower crust and/or upper mantle (Deng et al., 1998; Pollitz et al., 2000; Freed and Lin, 2001; Pollitz and Sacks, 2002) and by the 1999 Hector Mine earthquake (U.S. Geological Survey et al., 2000; Pollitz et al., 2001). In this study we use available postseismic GPS (Global Positioning System) data after the 1992 earthquakes to infer crustal and mantle viscosity structure beneath the Mojave Desert. We then use these viscoelastic models to investigate the detailed pattern of stress evolution on the

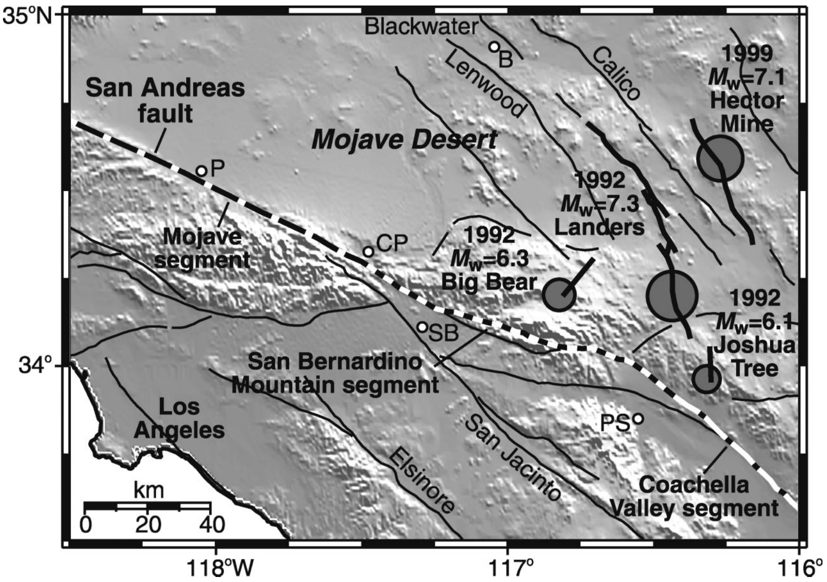

Figure 1. Geometry of southern San Andreas fault system and four significant earthquakes that occurred in Mojave Desert between 1992 and 1999 (circles proportional to earthquake magnitude). San Andreas fault in this region includes Mojave, San Bernardino Mountain, and Coachella Valley segments. Other regions influenced by Mojave earthquakes include San Jacinto, Elsinore, Calico, and Lenwood fault zones. Cities: B—Barstow, SB—San Bernardino, PS—Palm Springs, P—Palmdale, CP—Cajon Pass.

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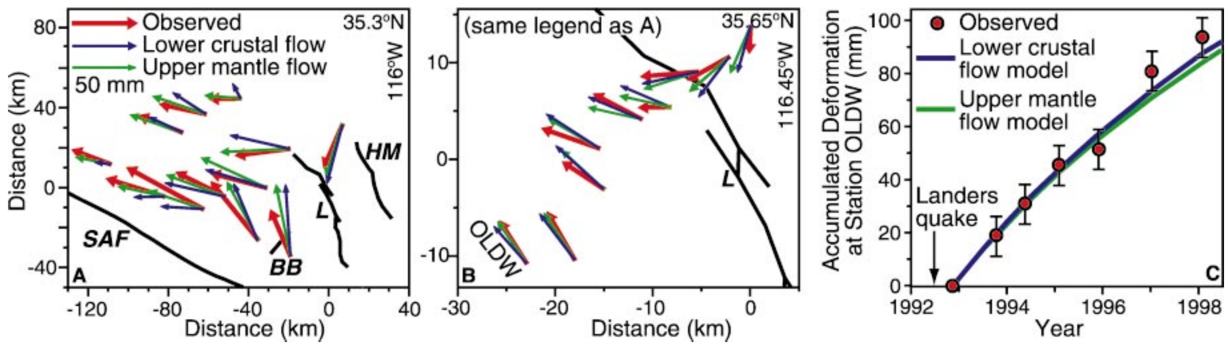

Figure 2. A: Observed Global Positioning System (GPS) far-field postseismic (October 1992 to December 1995) horizontal surface deformation (Southern California Earthquake Center, 2001) and deformation calculated by models considering lower crustal and upper mantle flow. B: Observed GPS near-field postseismic (October 1992 to December 1995) horizontal deformation along U.S. Geological Survey Emerson transect (Savage and Svarc, 1997) and calculated deformation. C: Observed accumulated deformation at GPS station OLDW (see B for station location) from October 1992 to January 1998 (circles) (Savage and Svarc, 1997; Prescott, 2001) and accumulated deformation predicted by models of lower crustal and upper mantle flow. Labels on solid lines (fault segments) in A and B: L—Landers, BB—Big Bear, HM—Hector Mine, and SAF—San Andreas fault.

southern San Andreas and surrounding fault systems since 1992 and to predict future changes in the decades to come.

ANALYSIS APPROACH

We have developed a three-dimensional viscoelastic finite element model of a wide region encircling the Mojave Desert that considers coseismic slip associated with the 1992 and 1999 earthquakes and the corresponding postseismic viscoelastic flow. We used the I-deas finite-element program (see http://www.eds.com) that was also used in a previous study of the relationship between the 1992 Landers and 1999 Hector Mine earthquakes (Freed and Lin, 2001). Compared to the previous study, however, the current model is better defined by more recent postseismic GPS data (Prescott, 2001), considers additional effects of the Hector Mine earthquake (Agnew et al., 2002), and uses more realistic elastic models based on seismic reflection studies (Qu et al., 1994).

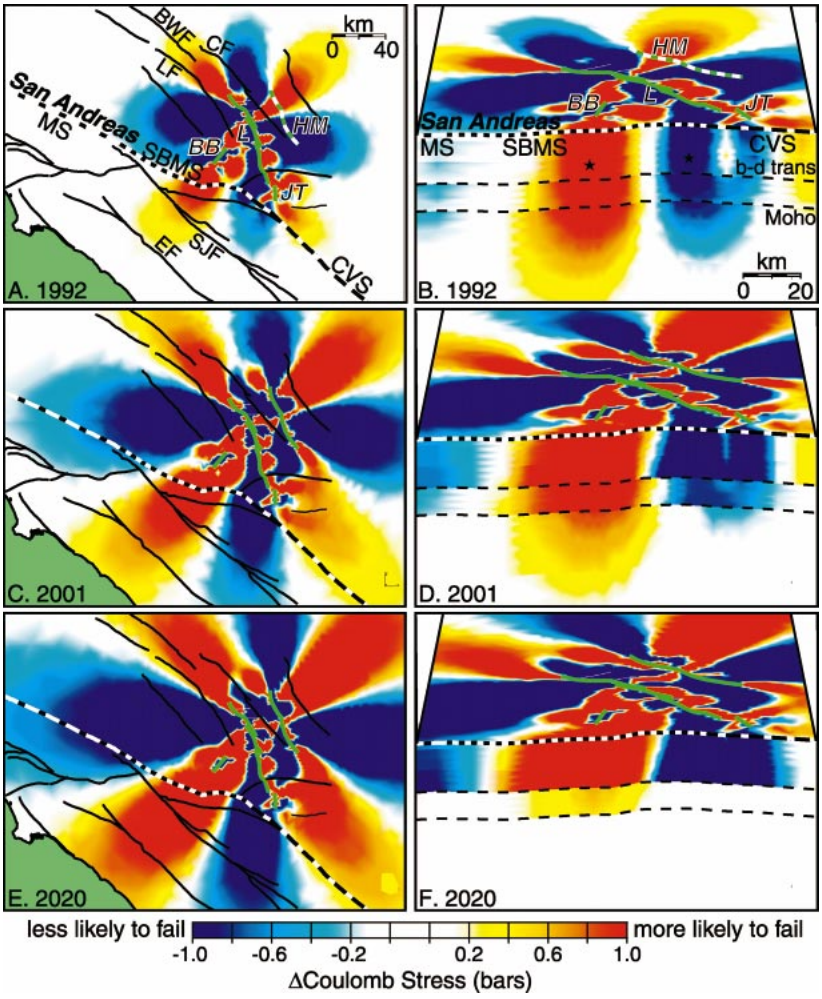

Figure 3. A: Calculated coseismic Coulomb stress changes caused by fault slip associated with 1992 Joshua Tree (JT), Landers (L), and Big Bear (BB) earthquakes (green lines). Other faults: MS—Mojave segment, SBMS—San Bernardino Mountain segment, and CVS—Coachella Valley segment of San Andreas fault; SJF—San Jacinto fault, EF—Elsinore fault, CF—Calico fault, LF—Lenwood fault, and BWF—Blackwater fault. Location of future 1999 Hector Mine earthquake (green dashed line) is also shown. B: Same as A but stresses are shown for top surface and cut plane (front) along San Andreas fault. Brittle-ductile transition (b-d trans) and Moho depths are shown in cut plane. Stars in B show locations within San Bernardino Mountain and Coachella Valley segments, respectively, where stresses are sampled for Figure 4. C, E: Same as A but with addition of stresses associated with 1999 Hector Mine earthquake and postseismic relaxation for years 2001 and 2020, respectively. D, F: Same as C, E, respectively, but stresses are shown for top surface and cut plane (front) along San Andreas fault. Receiver faults for Coulomb stress calculations shown are assumed to strike N60°W with apparent friction coefficient $\mu' = 0.2$.

MODEL VERIFICATION

The coseismic slip distribution for the 1992 Landers earthquake is based on a joint inversion of strong-ground-motion records, teleseismic waveforms, and geodetic data, and assumes pure right-lateral strike-slip rupture (Wald and Heaton, 1994). For the smaller 1992 Joshua Tree and Big Bear earthquakes, we used coseismic slip models similar to those in Stein et al. (1992). We mapped this coseismic slip onto vertical planes with geometry dictated by the observed surface ruptures (Hauksson et al., 1993). We found good correspondence between the observed Landers coseismic deformation vectors as determined by GPS measurements (Wald and Heaton, 1994) and the calculations by our finite-element model. We found that observed post-Landers horizontal deformations are best matched by postseismic viscoelastic flow occurring either within the lower crust (18–28 km depth) with a viscosity $\eta = 3 \times 10^{18}$ Pa·s or within the upper mantle with $\eta = 5 \times 10^{18}$ Pa·s (28–50 km depth) and $\eta = 3 \times 10^{18}$ Pa·s (50–120 km depth). Our postseismic deformation models can reproduce reasonably well the observed horizontal deformations during October 1992 to December 1995 both in far-field (Fig. 2A, Southern California Earthquake Center, 2001) and in near-field (Fig. 2B; Savage and Svarc, 1997). The decay rate of the magnitude of accumulated deformation at GPS station OLDW from October 1992 to January 1998 (Savage and Svarc, 1997; Prescott, 2001) is matched reasonably well by either the lower crustal or the upper mantle flow model (Fig. 2C).

The slip distribution associated with the 1999 Hector Mine earthquake is based on the inversion of traveltime and waveform records of regional and local seismic stations (Dreger and Kaverina, 2000). This slip distribution was also assumed to be purely right-lateral strike slip and was mapped onto a vertical plane with geometry based on observed surface ruptures. We found good correlation between the observed GPS coseismic horizontal deformation (Agnew et al., 2002) and that calculated for the Hector Mine earthquake by our model. We assume that the viscosity structure of the entire model region is similar to that inferred from the Landers postseismic modeling.

STRESS CALCULATIONS

To gauge how an earthquake influences the loading of adjacent faults, it is common to calculate changes in Coulomb failure stress $\Delta\sigma_f$ by $\Delta\sigma_f = \Delta\tau_s + \mu'\Delta\sigma_n$, where $\Delta\tau_s$ is the change in shear stress, $\Delta\sigma_n$ is the change in normal stress, and μ' is the apparent friction coefficient that incorporates pore-fluid pressure (Stein and Lisowski, 1983; Oppenheimer et al., 1988; King et al., 1994; Stein, 1999). Here we focus on the component of Coulomb stress along vertical, right-lateral strike-slip planes aligned parallel to the San Andreas fault in the study region, where the strike varies from N50°W (Coachella Valley segment) to N85°W (San Gorgonio pass area—portion of the San Bernardino Mountain segment striking nearly east-west).

Effects on San Andreas Fault

Figure 3, A and B, shows how fault slip associated with the 1992 Landers sequence is calculated to have influenced the southern San Andreas fault and surrounding region if a low effective friction ($\mu' = 0.2$) and a strike of N60°W are assumed. We calculated that the 1992 Landers sequence caused a coseismic Coulomb stress increase of 1.8 bar along the central part of the San Bernardino Mountain segment. This value is about half that calculated in a previous elastic half-space boundary-element analysis (Stein et al., 1992). The differences arise primarily because the model of Stein et al. (1992) overestimated slip on the Landers rupture, because the much better defined slip model of Wald and Heaton (1994), which was used in our analysis, was not available in 1992. We calculate a coseismic Coulomb stress increase of 3 bar in the San Gorgonio pass area (assuming a strike of N85°W), a decrease of 1.5 bar along the western edge of the Coachella Valley segment (N50°W), and a decrease of 0.5 bar on the Mojave segment (N65°W).

We calculate that the southern San Andreas fault has undergone significant postseismic stress changes since 1992 due to viscous relaxation of the lower crust and/or upper mantle and the occurrence of the 1999 Hector Mine earthquake. Figure 3, C and D, shows the calculated total changes in Coulomb stress from just before the 1992 Landers sequence to 2001 for a model considering viscous flow in the upper mantle (preferred model based on post–Hector Mine InSAR observations; Pollitz et al., 2001), low effective friction ($\mu' = 0.2$), and a strike of N60°W. In the brittle upper crust, the region of stress increase (red area) at the San Bernardino Mountain segment is calculated to have spread from a 40-km-wide zone immediately after the 1992 earthquakes (Fig. 3, A and B) to a 70-km-wide zone by 2001 (Fig. 3, C and D), and is projected to grow to be an 85-km-wide zone by the year 2020 (Fig. 3, E and F). For constant viscosity, our model suggests that by 2020 most of the relaxation process will be complete. However, a comparison between the observed post-Landers and post–Hector Mine surface deformations led Pollitz et al. (2001) to suggest that the viscosity may increase with time as stresses diminish. If this is the case, our model may have overpredicted the rate of stress changes for later years. Thus, our stress results should be considered upper bounds.

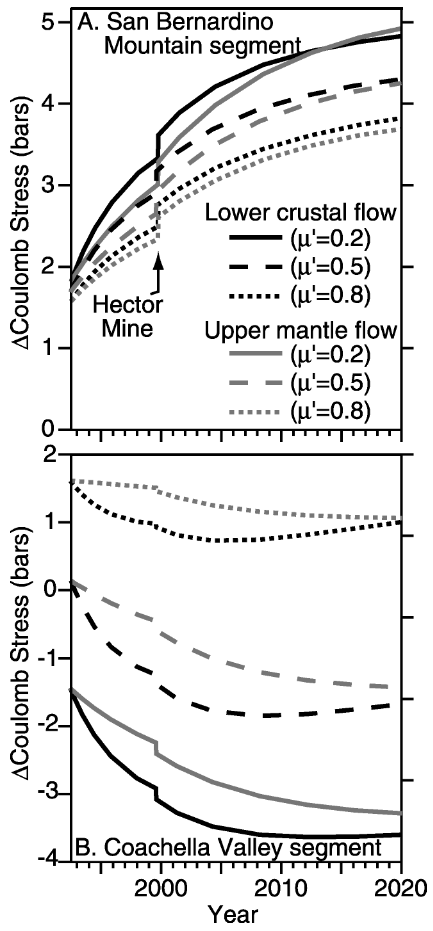

Figure 4. Calculated changes in Coulomb stress within (A) San Bernardino Mountain segment and (B) Coachella Valley segment of San Andreas fault caused by 1992 and 1999 earthquakes and postseismic viscous relaxation as function of time for both lower crustal and upper mantle flow cases and for weak ($\mu' = 0.2$), intermediate ($\mu' = 0.2$), and strong ($\mu' = 0.8$) fault models. See stars in Figure 3B for stress-sampling locations. Calculations assumed strike directions of N60°W for San Bernardino Mountain segment and N50°W for Coachella Valley segment.

Figure 4 shows the calculated evolution of Coulomb stress changes within the central San Bernardino Mountain and western Coachella Valley segments of the San Andreas fault as a function of time for lower crust and upper mantle flow models and for assumed low ($\mu' = 0.2$), intermediate ($\mu' = 0.5$), and high ($\mu' = 0.8$) friction cases. In addition to showing that the evolution of stress in the brittle upper crust is not overly sensitive to whether postseismic flow occurs in the lower crust or upper mantle, Figure 4 also illuminates several other important characteristics of stress transfer: (1) Because the 1999 Hector Mine earthquake was located farther away from the San Andreas fault and was of smaller magnitude, it is calculated to have a much smaller influence on the San Andreas fault than the 1992 Landers sequence. (2) Significant stress increases (>3.5 bar) are calculated for the brittle upper crust of the San Bernardino Mountain segment by the year 2020 regardless of whether the San Andreas fault is assumed weak ($\mu' = 0.2$) or strong ($\mu' = 0.8$). (3) The calculated stress changes on the Coachella Valley segment are very sensitive to the assumed apparent friction coefficient, being negative for the low friction case and positive for the high friction case. In addition to the results shown in Figure 4, the San Gorgonio pass area of the San Bernardino Mountain segment is calculated to have an increase of Coulomb stress between 4.5 bar for a low-friction case and 6.0 bar for high friction by 2020. The Mojave segment is predicted to decrease by 1.5 bar by 2020.

Effects on Other Faults in Southern California

In addition to the San Andreas fault, our model shows that several other fault zones have been influenced by the Mojave earthquakes since 1992 and will be subject to continuous stress buildup in coming years due to viscous relaxation. Because of their proximity to Los Angeles and San Diego, the Elsinore and San Jacinto fault zones are notable. The San Jacinto and Elsinore fault zones are capable of producing $M_w = 6.5–7$ earthquakes (Anderson et al., 1989; Rockwell et al., 1990; Sanders and Magistrale, 1997). We calculated that the zone of Coulomb stress increase that is extending to the southwest from the Mojave Desert will lead to stress increases of as much as 3 bar by 2020 on a part of the San Jacinto fault zone that last ruptured ($M_w = 6.7$) in 1899 (Hanks et al., 1975), while Coulomb stress increases will reach ~1 bar on a northern part of the Elsinore fault zone (Fig. 3E).

The Calico, Lenwood, and Blackwater faults are all in close proximity to the northern part of the Landers rupture zone (Fig. 1), potentially being greatly influenced by the Mojave earthquakes. The north edge of the Calico fault and the southern tip of the Blackwater fault are calculated to undergo Coulomb stress increases of as much as 3 bar by 2020 (Fig. 3E). This region attracts particular attention because a large cluster of aftershocks was triggered here following the 1992 Landers earthquake (Hauksson et al., 1993). The pattern of observed post-Landers aftershock clustering and calculated Coulomb stress buildup on the Calico fault is similar to that noticed in the Hector Mine region prior to the 1999 earthquake. The northern part of the Lenwood fault straddles a transitional region in which Coulomb stress goes from positive changes to negative changes (Fig. 3). The southern part of the Lenwood fault is squarely in a zone of Coulomb stress decrease and is thus inferred to have been drawn away from failure (Fig. 3).

CONCLUSIONS

Results of this investigation suggest that crustal stress changes caused by an earthquake will continue to be modified by viscous flow many years after the earthquake, potentially induced by continued loading of neighboring faults. Particular attention should be paid to the seismic hazard of the San Bernardino Mountain segment of the southern San Andreas fault and the Calico fault, both of which will continue to be pushed closer to failure by viscous flow following the Mojave earthquakes for years to come. The San Bernardino Mountain segment is of concern because it is capable of producing large events and may be late in its earthquake cycle. The Calico fault is of special interest because in addition to undergoing stress increases, it harbored abundant aftershocks after the 1992 Landers earthquake; a pattern similar to that occurred in the Hector Mine region prior to the 1999 earthquake.

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