

Stress triggering of earthquakes: evidence for the 1994 $M = 6.7$ Northridge, California, shock

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Abstract

A model of stress transfer implies that earthquakes in 1933 and 1952 increased the Coulomb stress at the site of the 1971 San Fernando earthquake. The 1971 earthquake in turn raised stress and produced aftershocks at the site of the 1987 Whittier Narrows and 1994 Northridge ruptures. The Northridge main shock raised stress in areas where its aftershocks and surface faulting occurred. Together, $M \geq 6$ earthquakes near Los Angeles since 1933 have stressed parts of the Oak Ridge, Sierra Madre, Santa Monica Mountains, Elysian Park, and Newport-Inglewood faults by > 1 bar. While too small to cause earthquakes, these stress changes can trigger events if the crust is already near failure, or advance future earthquake occurrence if it is not.

Key words earthquake prediction – Coulomb stress – Southern California

1. Introduction

The 17 January 1994 Northridge earthquake was the most costly shock in the history of the United States, underscoring the vulnerability of urban areas to earthquakes. The event struck on a blind or buried thrust fault (Davis *et al.*, 1989; Stein and Yeats, 1989) inclined to the south. The 1971 $M = 6.7$ San Fernando earthquake struck on adjacent thrust faults inclined to the north (Heaton, 1982). Both earthquakes are a response to crustal compression across the greater Los Angeles area. Aftershocks of the San Fernando (Whitcomb *et al.*, 1973) and Northridge (Hauksson *et al.*, 1994) earthquakes spatially overlap (fig. 1), and in addition, the 23-year span between the events is small relative to their probable thousand-year repeat times (Crook *et al.*, 1987; Yeats, in press), suggesting that the two shocks are related. Here

we argue that the San Fernando shock increased stress at the future Northridge rupture zone by up to 2 bars, potentially advancing its occurrence by two decades. This hypothesis is supported by the observation that aftershocks of the 1971 and 1994 earthquakes concentrate where the stresses are calculated to have risen, and aftershocks are sparse where the stresses are calculated to have dropped.

2. Method

We calculate the Coulomb stress change caused by one earthquake on the rupture surface of a subsequent shock or on a known fault. We use an elastic halfspace and let Young's modulus $E = 8.0 \times 10^5$ bars and Poisson's ratio $\nu = 0.25$, so the shear modulus $G = 3.2 \times 10^5$ bars. The tendency of rocks to fail in a brittle manner is thought to be a function of both shear and confining stresses, commonly formulated as the Coulomb criterion.

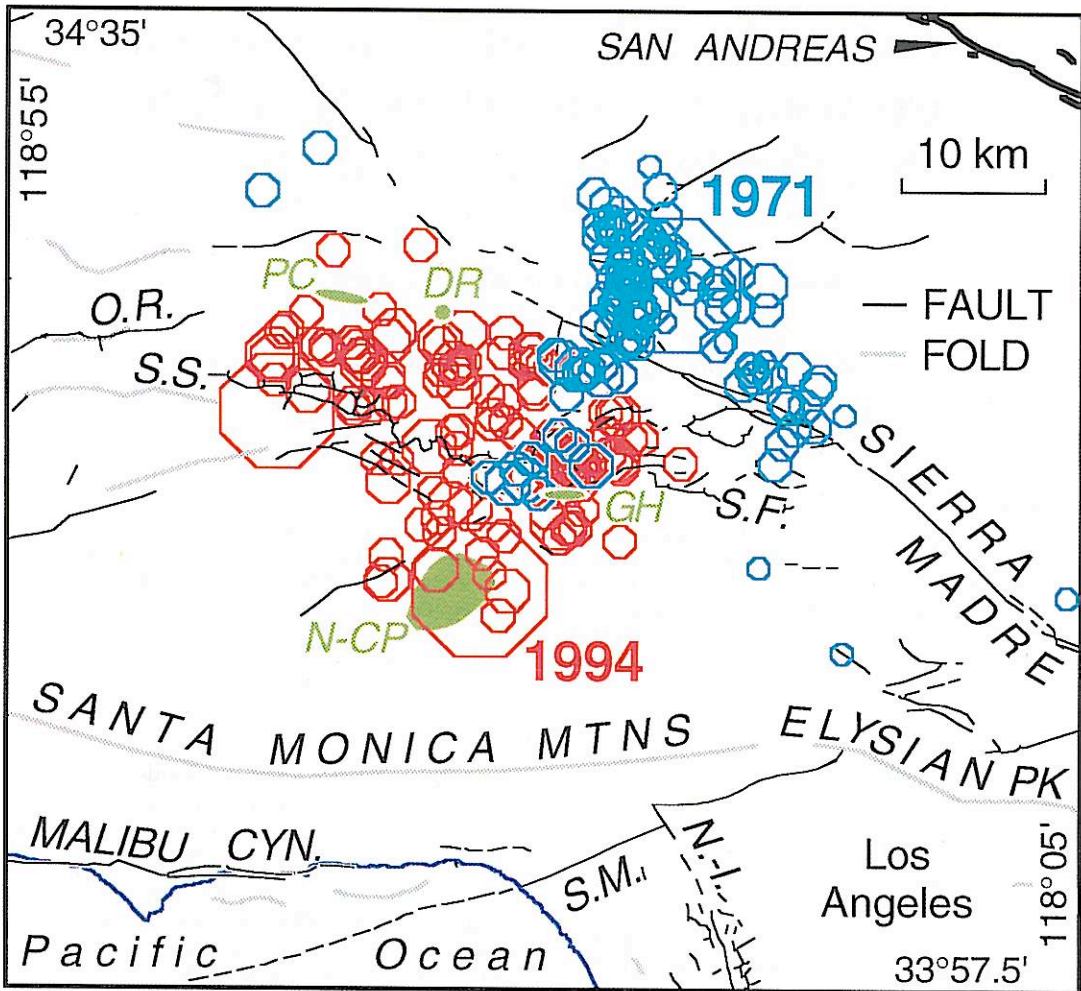


Fig. 1. Overlapping aftershocks of the 1971 San Fernando (blue: first year, $M \geq 2$) and 1994 Northridge (red: first 24 days, $M \geq 3$) earthquakes. S.F. Vly. is the San Fernando Valley. Sites of mapped secondary surface faulting or cracked ground (Ponti *et al.*, 1994): N-CR = Northridge-Canoga Park; GH = Granada Hills; PC = Potrero Canyon; DR = Davidson Ranch. Faults: O.R. = Oak Ridge; S.S. = Santa Susana; S.F. = San Fernando; S.M. = Santa Monica; N-I. = Newport-Inglewood.

The Coulomb stress change depends on the geometry and slip of the earthquake, the geometry and sense of slip of the fault or surface of interest, and the effective coefficient of friction (Stein and Lisowski, 1983; Harris and Simpson, 1992; Jaumé and Sykes, 1992; Reasenberg and Simpson, 1992; Stein *et al.*, 1992). Very

close to the slipped fault, the Coulomb stress change depends on the unknown details of the fault slip. Thus, stress changes calculated within a few kilometers of the earthquake sources are not meaningful. In contrast, stress changes far from the fault do not depend on the detailed slip function, and are thus most di-

agnostic. We use this method to estimate how successive Southern California earthquakes transferred stress.

We further developed a Coulomb criterion for small earthquakes or aftershocks. Since small shocks can occur on small isolated faults that exist with a wide variety of orientations throughout the crust, the faults most likely to slip are those optimally oriented for failure as a result of the regional stress and the stress change caused by a preceding earthquake (Stein *et al.*, 1992). Aftershocks of several strike-slip earthquakes (the 1979 Homestead Valley, and the 1992 Joshua Tree, Landers, and Big Bear shocks) occur in regions where the stress change on optimally oriented vertical faults was increased by > 0.3 bars, and their aftershocks were sparse where the stress dropped by the same amount (King *et al.*, 1994). For this study we have extended the method to consider the stress changes accompanying thrust earthquakes. We first calculate the optimally oriented vertical strike-slip and dipping thrust faults. We then resolve the earthquake-induced Coulomb stress on these planes, and find the stress change that most promotes failure.

The Coulomb stress change on optimally oriented faults is sensitive to the orientation of the regional tectonic stress field. Inversion of small-earthquake focal mechanisms and 1971-1988 aftershock sequences in the greater Los Angeles region by Gephart and Forsyth (1984), Jones (1988), Hauksson and Jones (1991) yields consistent values for the principal compressional axis of $N0^{\circ}$ - $12^{\circ}E$ from the San Andreas fault south to Los Angeles, and $N10^{\circ}$ - $32^{\circ}E$ from south Los Angeles to Newport. Borehole breakouts of 10 oil wells in the Los Angeles and northeastern Ventura basin axis (Mount and Suppe, 1992) furnish a $N21^{\circ}E$ compression. Here we use $N16^{\circ}E$, an average of these measurements.

3. Results

We calculate that the 1933 $M = 6.4$ Long Beach (Hauksson and Gross, 1991) and 1952 $M = 7.3$ Kern County (Stein and Thatcher,

1981) shocks raised the Coulomb stress at the site of the future San Fernando and Northridge shocks by at least 0.1 bar. The 0.1 to 0.2 bar stress changes shown in fig. 2a are for an elastic halfspace and thus do not include the effects of postseismic asthenospheric relaxation during the two-six decades following the 1933 and 1952 earthquakes. The stress in the seismogenic crust must rise as the asthenosphere relaxes after the earthquakes. Complete relaxation of the asthenosphere, simulated by replacing the halfspace with a faulted 12.5-km thick plate overlying an inviscid fluid, would yield a 0.8 bar stress rise at San Fernando, and a 0.9 bar rise at Northridge.

Our calculations reveal that the 1971 San Fernando earthquake raised the Coulomb stress an additional 0.5-2.0 bars at the site of the future Northridge earthquake, and 0.5 bars at the site of the future 1987 $M = 6.0$ Whittier Narrows shock (fig. 2b). In both cases the stress change is greatest on strike-slip faults, even though the 1987 and 1994 earthquakes are largely thrust events. We use $\mu = 0.4$ and a regional compression oriented $N16^{\circ}E$. Calculated stress increases at the future Whittier Narrows and Northridge sites are twice as high for $\mu = 0.75$ than for $\mu = 0.0$. A $N6^{\circ}E$ direction favors failure at the Northridge earthquake site more than at Whittier Narrows; a $N26^{\circ}E$ direction favors rupture at Whittier Narrows more than at Northridge. A band of 1971 aftershocks extended to the future 1994 rupture zone (fig. 1), aftershocks in this band becoming more concentrated during the next 5 years (fig. 2b). Aftershocks also spread to the future Whittier Narrows rupture zone. Seismicity filled most of the lobes where stress is calculated to have risen by > 0.3 bars and was nearly absent where the stress is calculated to have dropped by > 0.5 bars (fig. 2b). Seismicity during the 5-year or 10-year period before the San Fernando earthquake was nearly absent in the lobes that extended to the future Northridge and Whittier Narrows ruptures, reinforcing the deduction that the San Fernando earthquake stress changes triggered the small shocks. San Fernando aftershocks locate near the shallow part of the future Northridge rupture, where stress changes favor strike-slip or oblique failure.

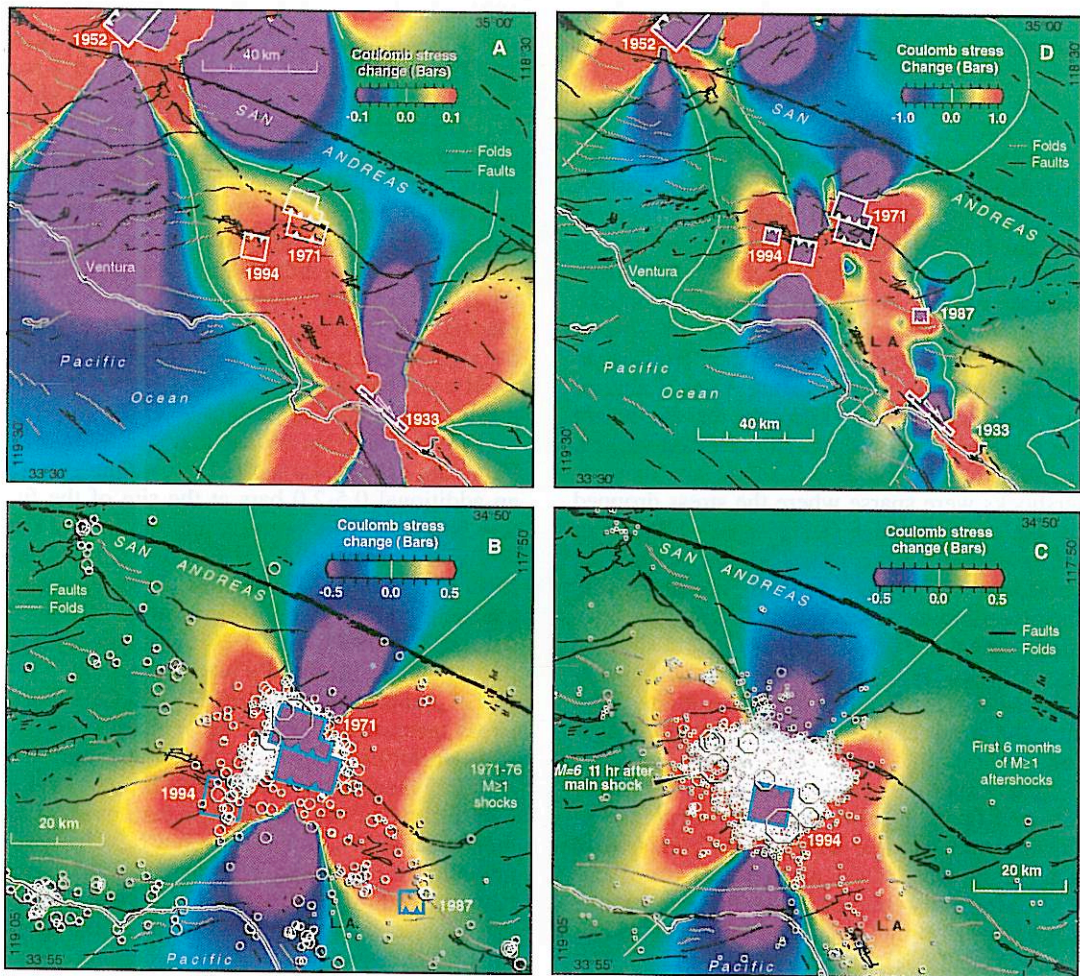


Fig. 2a-d. Map views of calculated Coulomb stress changes on optimally oriented strike-slip or thrust faults in an elastic halfspace, for a regional stress direction of $N16^{\circ}E$ and a friction coefficient m of 0.4. Earthquakes causing the stress changes are denoted by purple-filled rectangles with teeth on the upper edge; future sources are unfilled rectangles. Note that color gradients representing stress change saturate below the calculated peak stress change caused by the 1933 $M = 6.4$ Long Beach and 1952 $M = 7.3$ Kern County earthquakes, sampled at 10 km depth, showing sites of the future San Fernando and Northridge earthquakes. b) Stress changes caused by the 1971 $M = 6.7$ San Fernando earthquake. The most positive stress change at a depth of 3 to 10 km is shown, along with 5 years of post-earthquake $M \geq 2$ shocks (number of stations ≥ 4 , rms ≤ 1 s). c) Stress changes caused by the 1994 $M = 6.7$ Northridge earthquake. The most positive stress change at a depth of 3 to 10 km is shown, along with $M \geq 1$ shocks during 17 January-12 July 1994 (rms ≤ 0.3 s). d) Effect of all $M \geq 6$ shocks within 125 km of Los Angeles since 1933, with stress change calculated at a depth of 10 km.

Table I. $M \geq 6$ earthquakes within 125 km of Los Angeles since 1933.

Earthquake	Date	M , moment magnitude	Reference
Long Beach	10 Mar. 1933	6.4	(Hauksson and Gross, 1991)
Kern County	21 Jul. 1952	7.3	(Stein and Thatcher, 1981)
San Fernando	9 Feb. 1971	6.7	(Heaton, 1982)
Whittier Narrows	1 Oct. 1987	6.0	(Lin and Stein, 1989)
Joshua Tree	23 Apr. 1992	6.1	(Hauksson <i>et al.</i> , 1993)
Landers	28 Jun. 1992	7.4	(Wald and Heaton, 1994)
Big Bear	28 Jun. 1992	6.6	(Jones and Hough, 1995)
Northridge	17 Jan. 1994	6.7	(Hudnut <i>et al.</i> , 1994) (Hauksson <i>et al.</i> , 1994)
Northridge aftershock	17 Jan. 1994	6.0	(Dreger <i>et al.</i> , 1994)

Most aftershocks of the 1994 Northridge earthquake occurred in regions where the stress is calculated to increase by > 0.3 bars as a result of the fault slip; few aftershocks occurred where the stress is calculated to have dropped (fig. 2c). The rate of $1 \leq M \leq 2$ shocks appears to have climbed in metropolitan Los Angeles, 30 km southeast of the mainshock, where the stress is calculated to have risen. Some 11 h after the main shock, the Northridge aftershock zone expanded abruptly 6 km westward with a $M = 6$ aftershock (Dreger *et al.*, 1994) to an area where the calculated Coulomb stress rise caused by the initial rupture was 0.75 bars (fig. 2c). Surface faulting, cracking, and concentrated surface deformation were found at several sites after the Northridge earthquake (fig. 1), and these contributed significantly to the earthquake damage Ponti *et al.*, 1994. The calculated Coulomb stress increases at these sites are large (1-3 bars), suggesting that the ground disturbance was the product of the off-fault stress or strain changes in the compliant surface sediments. Thus the location of the recorded $1 \leq M \leq 6$ aftershocks and surface faulting in the Northridge sequence is consistent with a model of stress triggering by the initial earthquake rupture.

The cumulative effect of all $M \geq 6$ earthquakes near Los Angeles since 1933 (table I) is calculated to decrease Coulomb stress throughout a zone extending from the San Fernando

Valley south to the coast (fig. 2d). Stress also diminishes by ~ 1 bar along the San Andreas fault between Tejon Pass and Palmdale, although the secular or steady stress accumulation on the San Andreas fault during 1952-1994 of about 0.1 bar/yr likely erases the calculated stress drop there. A broad region in which stress is calculated to have risen by > 1 bar encompasses the central Los Angeles basin and areas west of Northridge. We calculate that the eastern Oak Ridge fault, the eastern Santa Monica Mountains and western Elysian Park blind thrust faults, the central Sierra Madre fault, and the central Newport-Inglewood fault, have all been subjected to stress increases of > 1 bar (fig. 2d).

4. Conclusions

The stress rises we report can trigger events if a region or fault was within a few bars of failure before the triggering earthquake struck. Although a 1-bar Coulomb stress change is 50 to 100 times the tidal stress changes (Hill *et al.*, 1993), it is only 1 to 10% of the typical shear stress drop $\Delta\tau$ of an earthquake, and so the stress increases we calculate are alone insufficient to cause earthquakes of any size (Abercrombie, 1994). Likely stress accumulation rates in the greater Los Angeles area are ≤ 0.1 bar/yr, based on the measured strain rate

(Lisowski *et al.*, 1991), so a 1-bar stress change corresponds to more than a decade of secular stress buildup.

Thus if faults fail when the Coulomb stress on a segment exceeds the failure threshold, then the 1933 and 1952 events advanced the occurrence of the San Fernando earthquake by about a decade, and the 1971 earthquake advanced the 1994 shock by as much as a few decades. If, however, the Coulomb stress changes trigger small earthquakes or creep that cascade into widespread failure (Abercrombie and Mori, 1994; Cowie *et al.*, 1993), then earthquake triggering may not require that a broad region has reached its failure threshold. It is also possible that the dynamic stresses play a role in earthquake triggering. Hill *et al.* (1993) and Anderson *et al.* (1994) argue that distant aftershocks of the Landers earthquake, for example, were triggered by dynamic strains associated with the Landers rupture. Spudich *et al.* (1995) point out that the dynamic stresses excited by Landers are 3-6 times larger than the static stress changes at Big Bear, but they persist for only < 20 s, and do not have lobes of stress decrease.

We interpret the close correspondence of the mainshocks and their aftershocks to the modeled stress changes to imply that the sequence of large earthquakes since 1933 is, at least in part, a consequence of the static stress changes. This correspondence would not be possible unless some portions of the seismogenic crust in Southern California were currently close to failure. Because we do not know precisely how close the major faults are to failure, our results cannot be used to predict the timing of large earthquakes. Instead we suggest that these calculations describe where the earthquake potential in the greater Los Angeles region has risen, and where it has dropped.

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