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Evolution of the stress field in southern California and triggering of moderate-size earthquakes: A 200-year perspective

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Abstract. Changes in stress in southern California are modeled from 1812 to 2025 using as input (1) stress drops associated with six large ($7.0 \leq M < 7.5$) to great ($M \geq 7.5$) earthquakes through 1995 and (2) stress buildup associated with major faults with slip rates ≥ 3 mm/yr as constrained by geodetic, paleoseismic, and seismic measurements. Evolution of stress and the triggering of moderate to large earthquakes are treated in a tensorial rather than a scalar manner. We present snapshots of the cumulative Coulomb failure function (ΔCFF) as a function of time for faults of various strike, dip, and rake throughout southern California. We take ΔCFF to be zero everywhere just prior to the great shock of 1812. We find that about 95% of those well-located $M \geq 6$ earthquakes whose mechanisms involve either strike-slip or reverse faulting are consistent with the Coulomb stress evolutionary model; that is, they occurred in areas of positive ΔCFF. The interaction between slow-moving faults and stresses generated by faster-moving faults significantly advanced the occurrence of the 1933 Long Beach and 1992 Landers events in their earthquake cycles. Coulomb stresses near major thrust faults of the western and central Transverse Ranges have been accumulating for a long time. Future great earthquakes along the San Andreas fault, especially if the San Bernardino and Coachella Valley segments rupture together, can trigger moderate to large earthquakes in the Transverse Ranges, as appears to have happened in the Santa Barbara earthquake that occurred 13 days after the great San Andreas shock of 1812. Maps of current ΔCFF provide additional guides to long-term earthquake prediction.

Introduction

The state of stress and its variation with time are two of the most fundamental physical parameters controlling the earthquake process. An earthquake occurs when the stress exceeds the strength of the corresponding fault. Earthquakes in a sequence generally are not independent [*Scholz*, 1990]. Each is affected by both tectonic loading and stress changes caused by prior events, especially by either great earthquakes or other shocks that occur nearby.

Large earthquakes can affect the rates of occurrence of nearby microearthquakes. Changes in stress caused by the 1989 Loma Prieta earthquake, for example, are correlated with the rates of occurrence of small earthquakes on central California faults [*Reasenberg and Simpson*, 1992; *Simpson and Reasenberg*, 1994]. Similarly, moderate to large earthquakes in central and northern California are believed to occur only after the stresses have recovered from the stress release associated with previous great earthquakes. *Simpson and Reasenberg* [1994] computed the accumulated changes in stress for segments of the Hayward and Calaveras faults in central California since the 1906 San Francisco (M_w=7.8) [*Wald et al.*, 1993] earthquake. Their result for segments of the Calaveras fault indicates that $M \geq 5$ earthquakes started to reoccur after stresses had recovered from the shadow zone created by the occurrence of the 1906 event. In their study on evolution of the stress field in the San Francisco Bay region for the period between 1850 and 1993, *Jaumé and Sykes* [1996] also found that moderate-size earthquakes occurred in regions that were located either outside of or had recovered via strain accumulation from the stress shadows created by past large and great earthquakes.

The configuration of the plate boundary in southern California (Figure 1), the region of interest to this paper, is much more complicated than that in the bay area. Stress changes in southern California have often been investigated on an earthquake-by-earthquake basis. Large earthquakes, such as the 1812 Wrightwood, 1857 great Fort Tejon (M_w = 7.9), 1992 Landers (M_w = 7.3), and 1994 Northridge (M_w = 6.7) earthquakes, have all been shown to advance the time of occurrence, i.e., to trigger subsequent, moderate-size events [*Harris and Simpson*, 1992; *Jaumé and Sykes*, 1992; *Stein et al.*, 1992; *King et al.*, 1994; *Stein et al.*, 1994; *Simpson and Reasenberg*, 1994; *Harris et al.*, 1995; *Deng and Sykes*, 1996]. Southern California, however, is one of a few regions in the world where extensive earthquake-related monitoring studies have been underway for many years. Much progress has been made in the past decade in collecting a variety of data bearing upon the earthquake process and the state of stress in southern California. These data include geodetic measurements, focal mechanism solutions of earthquakes, long-term rates of fault slip, fault geometries, paleoseismic determinations of displacement in prehistoric events, and better modeling of historic shocks. While the direct measurement of stress changes is very difficult, it is now possible to pull together stress-related data to infer the time-dependent cumulative stress

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