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Long-range and long-term fault interactions in Southern California

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ABSTRACT

Paleoseismological data suggest the occurrence of four bursts of seismic moment release in the Los Angeles region during the past 12,000 yr. The historic period appears to be part of an ongoing lull that has persisted for about the past 1000 yr. These periods of rapid seismic displacement in the Los Angeles region have occurred during the lulls between similar bursts of activity observed on the eastern California shear zone in the Mojave Desert, which is now seismically active. A kinematic model in which the faults of the greater San Andreas system suppress activity on faults in the eastern California shear zone, and vice versa, can explain the apparent switching of activity between the two fault networks. Combined with the observation that short-term geodetic and longer-term geologic rates co-vary on major southern California fault systems, this suggests that either (1) a temporal cluster of seismic displacements on upper-crustal faults increases ductile deformation on their downward extensions, or (2) rapid ductile slip in the lower crust beneath faults loads the upper crust, driving a seismic cluster. We suggest that alternating periods of rapid seismic displacement may be the expected mode of seismicity when two fault systems accommodate the same plate-boundary motion, and slip on one system suppresses slip on the other.

Keywords: fault interactions, paleoseismology, eastern California shear zone, strain transients, Southern California.

INTRODUCTION

It has long been recognized that seismic moment release is heterogeneous over short time scales. Whereas the most recognizable examples of this are aftershock sequences, an emerging body of evidence indicates that seismic moment release from large earthquakes can occur in brief bursts over paleoseismological time scales. For example, over the past 12,000 yr short intervals of rapid seismic displacements on faults of the eastern California shear zone in the Mojave Desert region of California have been separated from one another by several thousand years of relative seismic quiescence (Fig. 1) (Rockwell et al., 2000).

Earthquake-generated changes in Coulomb failure function stress (ΔCFF) have been used successfully to explain earthquake triggering over short time scales along both single faults and regional fault networks (e.g., King et al., 1994; Simpson and Reasenberg, 1994; Stein et al., 1997; Nalbant et al., 1998). It is not clear, however, that such modeling can successfully explain long-term fault interactions because typical ΔCFF changes are overwhelmed by secular loading over geologically brief (i.e., decades-centuries) time scales (e. g., Harris and Simpson, 1996; Jones and Hauksson, 1997; Stein, 1999; Dolan and Bowman, 2004).

In this paper, we use paleoseismologic data to document long-term clustering on the complex fault network beneath metropolitan Los Angeles, California. Remarkably, these Los Angeles–region clusters appear to be temporally anticorrelated with similar clusters observed on eastern California shear zone faults in the Mojave Desert (Fig. 1). We examine the origin of these long-term and long-distance fault interactions, propose a simple kinematic model that explains the temporal anticorrelation, and discuss these results in light of their implications for earthquake occurrence and seismic hazard assessment.

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PALEOSEISMOLOGIC OBSERVATIONS

North-south shortening of the Los Angeles region is accommodated by a combination of east-west reverse and left-lateral strike-slip faults, and northwest-trending right-lateral strike-slip faults (Wright, 1991; Dolan et al., 1995). Over the past several decades, numerous paleoseismological data have been collected from these faults (see the GSA Data Repository[1] and references therein). Although this paleoseismologic catalog is by no means complete, and several faults exhibit significant data gaps, the available data offer intriguing insights into the system-level behavior of these faults on a millennial time scale. The available data reveal apparently episodic strain release, with brief bursts of seismic moment release during large earthquakes separated by relative lulls in seismic activity. One remarkable feature of the record is the apparent absence of large earthquakes during the past ~1000 yr. Although several moderate-sized events have occurred on Los Angeles–region faults during this time interval (e.g., the historic 1933 M_w 6.4 Long Beach, 1971 M_w 6.7 San Fernando, and 1994 M_w 6.7 Northridge earthquakes), the cumulative seismic moment for these events is small compared to that released during the clusters.

In contrast to the current seismic lull, the period between ~1000 and 5000 yr ago was apparently characterized by a high level of seismic activity. This active period included two subclusters, which occurred ~1000–2000 yr ago (during which the Raymond–Hollywood–Santa Monica fault system, the Whittier fault, and possibly the Puente Hills thrust and Newport-Inglewood faults, all ruptured) and ~3000–5000 yr ago (during which the Whittier fault, and possibly the Newport-Inglewood and Puente Hills thrust faults, ruptured).

[1]GSA Data Repository item 2007205, supporting data, references, and notes for paleoearthquakes in the Los Angeles region, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

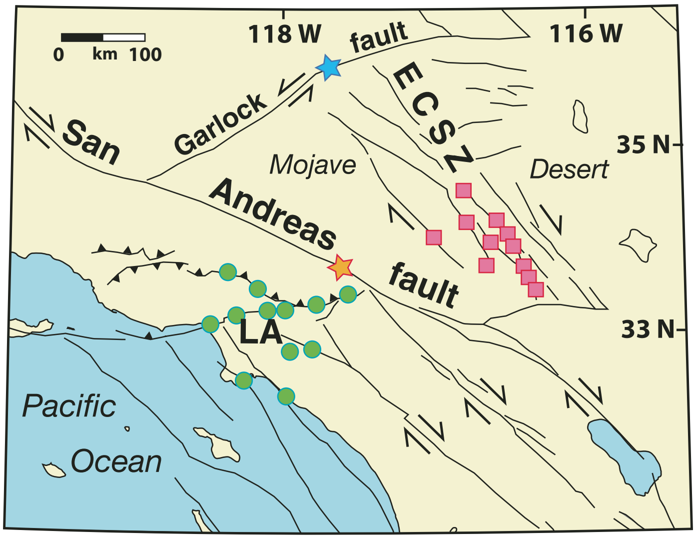

Figure 1. Map of major active faults of Southern California showing locations of paleoseismological trench sites used to construct Figure 2. Green circles denote Los Angeles–region sites (see GSA Data Repository [text footnote 1]). Pink squares show locations of trenches in Mojave section of eastern California shear zone (ECSZ) (Rockwell et al., 2000). Orange star denotes Wrightwood trench site of Weldon et al. (2004) on Mojave section of San Andreas fault. Blue star denotes Garlock fault trench site of Dawson et al. (2003). LA is downtown Los Angeles.

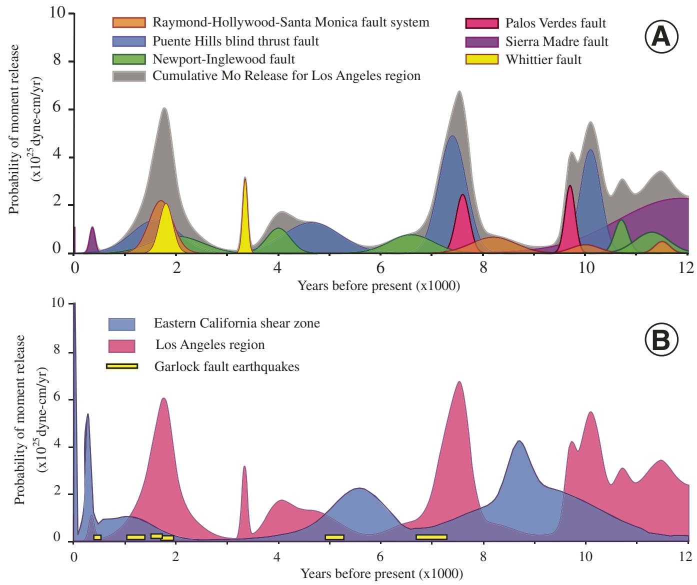

Figure 2. A: Compilation of data from Los Angeles–region fault network showing ages and estimated seismic moment (M_o) release in individual paleoearthquakes (see GSA Data Repository and references therein [text footnote 1]). Vertical axis shows probability of M_o release per year; horizontal axis shows paleoseismologically defined age ranges for individual earthquakes. Area under each curve represents inferred seismic moment for each paleoearthquake (see the GSA Data Repository for discussion). B: Comparison of cumulative seismic moment release through time for fault networks in Los Angeles region (pink) and Mojave Desert part of eastern California shear zone (blue) (latter from Rockwell et al., 2000). Seismic moment-release curves for eastern California shear zone and Los Angeles–region fault systems are based on methodology of Rockwell et al. (2000). This method utilizes Gaussian probability distribution functions (pdfs) for each earthquake, which are summed to generate cumulative moment-release curves. Use of Gaussian distributions has a "centralizing" effect that emphasizes central part of allowable age range for each earthquake. Alternative, "boxcar" probability distribution functions, which do not exhibit this centralizing tendency, are presented for same paleoseismologic data in the GSA Data Repository. Both methods yield same basic result, with apparent temporal clustering of seismic moment release in both regions, and peaks and lulls in moment release for the two regions that appear to be anticorrelated. Yellow horizontal bars denote paleoseismologically defined ages of Garlock fault surface ruptures (Dawson et al., 2003). Continuous paleoseismologic record at Wrightwood site along San Andreas fault extends back 1500 yr (Weldon et al., 2004). Due to scale of figure, individual earthquakes at this site are not shown.

This most recent period of rapid strain release was preceded by an apparent lull from ~5000–6500 yr ago. Earlier seismic bursts occurred between 6500 and 8000 yr ago (Palos Verdes fault, Puente Hills thrust, and possibly the Newport-Inglewood fault) and 9500–11,000 yr ago (Puente Hills thrust, Newport-Inglewood fault, Palos Verdes fault, and possibly the Raymond, Hollywood, and Sierra Madre faults).

The eastern California shear zone constitutes a 50- to 100-km-wide zone of north-northwest–trending, predominantly right-lateral strike-slip faults (Fig. 1). Faults in this zone have generated several of California's largest historical earthquakes, including the 1872 M ~7.6 Owens Valley, 1992 M_w 7.3 Landers, and 1999 M_w 7.1 Hector Mine events. The latter two events motivated numerous paleoseismological studies of the Mojave part of the eastern California shear zone. A compilation of these data (Rockwell et al., 2000) revealed clustered behavior similar to that presented here for the Los Angeles region (Fig. 2). For example, in addition to the faults involved in the 1992 M_w 7.3 Landers and 1999 M_w 7.1 Hector Mine earthquakes, the Helendale, Camp Rock, Lenwood, and Old Woman Springs faults have all ruptured to the surface in the past ~1000 yr (Rockwell et al., 2000).

Rockwell et al. (2000) showed that this current eastern California shear zone cluster was preceded by a seismic lull from ~1500–4500 yr ago, with no detectable earthquakes. Prior to this lull, a cluster occurred between 4500 and 6500 yr ago, during which the Lenwood, northern and southern Johnson Valley, and Kickapoo faults ruptured to the surface. A lull between ~6500 and 8000 yr ago was preceded by an early Holocene cluster that peaked at ~8500–9000 yr ago. This early Holocene cluster involved the Lenwood, Old Woman Springs, Helendale, Emerson, northern and southern Johnson Valley, Kickapoo, and Camp Rock faults, and possibly the Homestead Valley fault.

KINEMATIC MODEL

A comparison of the available paleoseismological data sets suggests that when seismic strain release rates are high in the Los Angeles region, they are low in the Mojave section of the eastern California shear zone. Conversely, when the eastern California shear zone faults are most active, Los Angeles–region faults are relatively quiet. If these temporal relationships are not random, they suggest that activity on eastern California shear zone faults suppresses activity on Los Angeles–region faults, and vice versa. It is possible, of course, that the observed clustering is either Poissonian or an artifact of an incomplete catalog, and the apparent clustering must continue to be tested with future paleoseismologic research. In the following discussion, however, we take the apparent anticorrelation between Los Angeles–region and Mojave-region clusters observed in the current paleoseismologic data sets at face value, and we explore the possible causes and mechanical consequences of this behavior.

The mechanism that produces the observed anticorrelation is difficult to understand in the context of standard stress modeling. Given the large distance between the two fault networks, and the fact that numerous large San Andreas fault earthquakes occur during any single Los Angeles–region or eastern California shear zone cluster (e.g., Weldon et al., 2004), one must conclude that standard Coulomb failure function (ΔCFF) models of individual San Andreas fault earthquakes are inadequate to describe the observed long-term clustering. We propose that a simple kinematic model of the plate boundary can explain the observed pattern of seismic activity.

To see why the seismicity might alternate between the eastern California shear zone and Los Angeles regions, consider the schematic diagram of the major structures that accommodate plate-boundary motion in Southern California (Fig. 3). These are the right-lateral San Andreas fault (SAF), including the N70°W Big Bend section, the left-lateral Garlock fault, the right-lateral faults of the eastern California shear zone, and the reverse and conjugate strike-slip faults of the Los Angeles region. Our hypothesis is that these elements can be divided into two mechanically complementary systems. The subsystem in Figure 3A is made up of the entire San Andreas fault system, including the Big Bend, and the Garlock and Los Angeles–region faults, and the various strands of the San Andreas fault system in southernmost California (e.g., San Jacinto fault, Imperial fault). The subsystem shown in Figure 3B includes the eastern California shear zone and the southern San Andreas fault. We now show that activity on the system incorporating the Big Bend section of the San Andreas fault tends to suppress activity on the eastern California shear zone, and vice versa.

When system A is active (as in Fig. 3A), motion on the greater San Andreas fault system results in north-south compression in the vicinity of the Big Bend. This north-south compression is accommodated collectively by motion along the Big Bend part of the San Andreas fault, the faults of the Los Angeles region, and the Garlock fault. The net effect of motion on the Big Bend section of the San Andreas fault and Garlock fault is to drive the Mojave block eastward, putting the entire Mojave region, including the faults of the eastern California shear zone, in east-west compression. This compression suppresses activity on the eastern California shear zone by increasing the normal stresses acting on the eastern California shear zone faults. Conversely, when system B is active (as in Fig. 3B), motion on the eastern California shear zone and southern San Andreas fault accommodates a larger percentage of total relative plate motion, thereby reducing stress accumulation on the San Andreas fault. System B effectively short-circuits system A, suppressing its activity. We emphasize that we are not suggesting that activity on the eastern California shear zone "shuts off" the San Andreas fault Big Bend, but rather that this part of the San Andreas fault will slip more slowly during periods when the eastern California shear zone is active and accommodating more of the total plate-boundary motion.

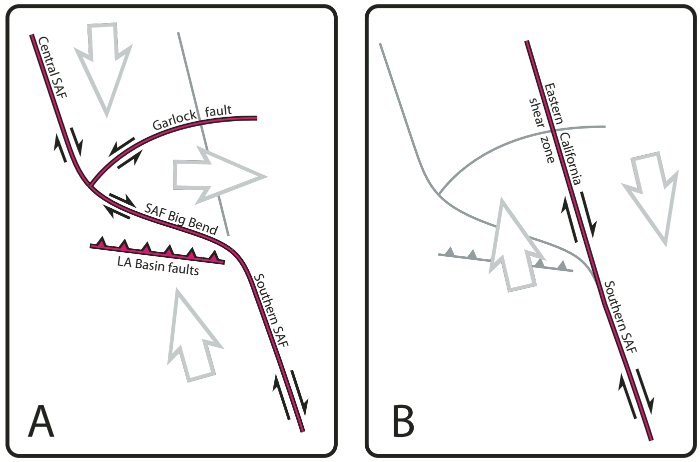

Figure 3. Kinematic cartoons showing relationships between activity on major fault systems in Southern California. A: Conjugate slip on Big Bend section of San Andreas fault (SAF) and Garlock fault, together with motion on Los Angeles–region faults, serves to accommodate north-south compression in Southern California. Resultant motion of Mojave block will suppress motion on eastern California shear zone faults. B: When eastern California shear zone is active, it will reduce motion along Mojave section of San Andreas fault, which will in turn suppress motion on Los Angeles–region faults.

DISCUSSION

The central implication of this kinematic hypothesis is that periods of faster slip on the Big Bend section of the San Andreas fault, the Garlock fault, and the Los Angeles–region fault network should correlate with periods of slower slip on the eastern California shear zone, and vice versa. Paleoseismological data from the Big Bend section of the San Andreas at Wrightwood (Weldon et al., 2004) illustrate the impact of these interactions on the geologic observations. The slip rate of the San Andreas fault at this location has been relatively slow (~2.4 cm/yr) for the past 1100 yr. This period of slow slip rate corresponds with the current lull in activity on the Los Angeles fault network. During the same period, the eastern California shear zone has experienced an ongoing cluster of large earthquakes (Rockwell et al., 2000). In contrast, from 1100 to ~1500 yr ago, the slip rate on the San Andreas fault at the Wrightwood site was much faster (~9 cm/yr) than the recent rate (Weldon et al., 2004). This period of rapid slip, which may extend back to the oldest continuous data at the Wrightwood site, coincides with at least the latter part of the most recent Los Angeles–region cluster. As the kinematic model predicts, paleoseismologic data (Fig. 2B) indicate that the eastern California shear zone was in a seismic lull during this same period of heightened activity on the San Andreas fault and Los Angeles–region faults. Available paleoseismological data from the Garlock fault are less clear-cut, but they do not rule out this hypothesis. Dawson et al. (2003) reported a cluster of four earthquakes on the central Garlock fault during the past ~2000 yr. At least the first two, and probably the first three, of these earthquakes occurred during the most recent Los Angeles–region cluster; only the most recent of the four definitely occurred during the current Los Angeles–region lull (Fig. 2B).

Interestingly, available data suggest that the current slow slip rate on the various faults described here as "system A" correlates with relatively slow rates of interseismic fault loading as revealed by geodesy. For example, the long-term San Andreas fault slip rate at Wrightwood averaged over the past 1500 yr is at least 3.1 cm/yr (Weldon et al., 2004). This is much faster than the geodetically determined, 2.0 ± 0.4 cm/yr rate of interseismic elastic strain accumulation on this section of the San Andreas fault (Argus et al., 2005 [based mainly on trilateration data from 1971 to 1992]). The current slow geodetically determined rate of fault loading is, however, in generally good agreement with the 2.4 cm/yr slip rate of the San Andreas fault measured over the past 1100 yr by Weldon et al. (2004). Similarly, modeling of geodetic data from the vicinity of the Garlock fault suggests that strain accumulation on the western part of the fault is occurring at a rate that is significantly slower than the long-term slip rate of the fault. Specifically, calendric calibration of radiocarbon dates from a fluvial terrace offset by 66 ± 3 m yields a latest Pleistocene–Holocene minimum slip rate of ≥6.3 ± 2.0 mm/yr (McGill et al., 2003), whereas a geodetically constrained block model indicates storage of elastic strain along the western Garlock fault at only 3.7 ± 0.7 mm/yr (McClusky et al., 2001 [based on geodetic data from 1993 to 2000]). Other geodetic studies (e.g., Peltzer et al., 2001) suggest even slower rates of elastic strain accumulation on the central Garlock fault (≤2 mm/yr). In contrast, geodetic data from the seismically active eastern California shear zone in the Mojave Desert suggest that these faults are accumulating strain at a faster rate (12 ± 2 mm/yr) (Bennett et al., 1997; Dixon et al., 2000; McClusky et al., 2001) than the long-term rate (~5–7 mm/yr) suggested by available geologic and geomorphologic observations (Rockwell et al., 2000; Frankel et al., 2002; Rymer, 2002; Oskin and Iriondo, 2004; Oskin et al., 2004).

These observations suggest that the crust in regions where the geodetic rates are higher than the long-term slip rate is also more seismically active than the long-term average, as is currently the case in the eastern California shear zone. Conversely, regions where the geodetically measured slip rates are slower than the long-term rate are on average experiencing fewer than average large earthquakes, as is the case for the San Andreas fault Big Bend–Garlock–Los Angeles–region fault system. Mechanically, this implies that either (1) a temporal cluster of seismic displacements on upper-crustal faults increases ductile deformation on their downward extensions, or (2) rapid ductile slip in the lower crust (and upper mantle?) beneath faults loads the upper crust, driving a seismic cluster.

If seismicity is controlled by deep ductile deformation, then the observed clustering might be driven by fluctuations in the loading rate at depth associated with cycles of strain hardening and annealing. Strain hardening occurs during relatively low-temperature creep when the dislocations accommodating the strain intersect and become pinned (Ashby and Jones, 1980). In contrast, annealing is a process whereby dislocations and their tangles are removed by thermal diffusion. High-temperature creep can be viewed as a competition between strain hardening and annealing.

During periods of rapid creep on the downdip ductile extension of a fault, activity in the seismogenic crust above increases, resulting in a cluster of large events. However, rapid slip at depth leads to strain hardening and a consequent reduction in slip rate, thus ending the seismic cluster above. Activity will then switch to the now-annealed downdip extension of the alternate fault system. As this alternate system deforms and hardens, the original system becomes less active and anneals. Thus, the two faults cycle alternately (out of phase) between hardening and annealing—when one is slipping rapidly and hardening, the other is slipping slowly and annealing.

If future paleoseismological observations support the long-term and long-distance fault interactions presented here, this would have fundamental implications for seismic hazard assessment. Specifically, the observed temporal anticorrelation of seismic bursts in Southern California suggests that earthquake occurrence is not a spatially and temporally random process, thus calling into question seismic hazard assessments (e.g., Frankel et al., 2002) that are based on the assumption of Poissonian behavior (i.e., that earthquake occurrence is a random process, with no "memory" of the timing of previous events). Rather, our results suggest that regional fault networks experience alternating "more active" and "less active" periods that are controlled by long-distance and long-term fault interactions.

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