Wrightwood and the earthquake cycle: What a long recurrence record tells us about how faults work

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ABSTRACT

The concept of the earthquake cycle is so well established that one often hears statements in the popular media like, "the Big One is overdue" and "the longer it waits, the bigger it will be." Surprisingly, data to critically test the variability in recurrence intervals, rupture displacements, and relationships between the two are almost nonexistent. To generate a long series of earthquake intervals and offsets, we have conducted paleoseismic investigations across the San Andreas fault near the town of Wrightwood, California, excavating 45 trenches over 18 years, and can now provide some answers to basic questions about recurrence behavior of large earthquakes.

To date, we have characterized at least 30 prehistoric earthquakes in a 6000-yr-long record, complete for the past 1500 yr and for the interval 3000–1500 B.C. For the past 1500 yr, the mean recurrence interval is 105 yr (31–165 yr for individual intervals) and the mean slip is 3.2 m (0.7–7 m per event). The series is slightly more ordered than random and has a notable cluster of events, during which strain was released at 3 times the long-term average rate. Slip associated with an earthquake is not well predicted by the interval preceding it, and only the largest two earthquakes appear to affect the time interval to the next earthquake. Generally, short intervals tend to coincide with large displacements and long intervals with small displacements. The most significant correlation we find is that earthquakes are more frequent following periods of net strain accumulation spanning multiple seismic cycles.

The extent of paleoearthquake ruptures may be inferred by correlating event ages between different sites along the San Andreas fault. Wrightwood and other nearby sites experience rupture that could be attributed to overlap of relatively independent segments that each behave in a more regular manner. However, the data are equally consistent with a model in which the irregular behavior seen at Wrightwood typifies the entire southern San Andreas fault; more long event series will be required to definitively outline prehistoric rupture extents.

INTRODUCTION

It is widely believed that recurrence of great earthquakes on large faults like the San Andreas is regular to some degree. While this hypothesis has notable critics (e.g., Davis et al., 1989; Kagan and Jackson, 1999), its credence is rooted in acceptance of the elastic rebound theory, the constant drive of plate tectonics, and their implications for the earthquake cycle. As first published (Reid, 1910) and as applied today (e.g., Working Group on California Earthquake Probabilities, 2003), the theory implies that tectonic strain accumulates gradually between earthquakes and is suddenly released during earthquakes. Implicitly or explicitly (see Matthews et al. [2002] for an excellent summary of the application of the elastic rebound theory to earthquake forecasting), earthquake rupture on a fault is assumed to occur at a strain threshold and the earthquake decreases the strain to some base level, essentially "resetting the clock" for the next cycle.

If the earthquake strain cycle contains either upper or lower strain thresholds, one would expect to see relationships between earthquake time intervals and displacements, often called time- and slip-predictable earthquake behavior (Shimazaki and Nakata, 1980). A time-predictable model has an upper strain threshold, so the time to the next earthquake can be "predicted" by the displacement of the last earthquake; the more strain released in an earthquake, the longer it will take to build up the required strain for the next one. Slip-predictable models have a lower threshold, so the length of the interseismic period "predicts" the amount of slip in the next earthquake. If both upper and lower thresholds in strain exist, the system is "characteristic" and the fault cycles between two fixed strain levels (e.g., Ellsworth, 1995); variations in interval length are due only to variations in strain accumulation or the "load path" (Matthews et al., 2002).

Resetting of the clock during each earthquake not only is conceptually important but also forms the practical basis for all earthquake forecasting because earthquake recurrence

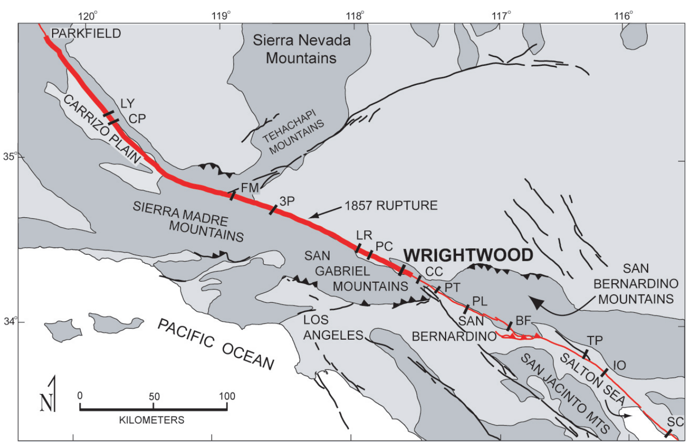

Figure 1. The San Andreas fault (red) passes less than 100 km northeast of Los Angeles and bounds the urban region near San Bernardino. The last rupture (1857, bold red line) included 300 km of the 530 km of fault southeast of Parkfield. Black bars across the fault are sites with paleoseismic or slip rate data (abbreviations and references in Fig. 12).

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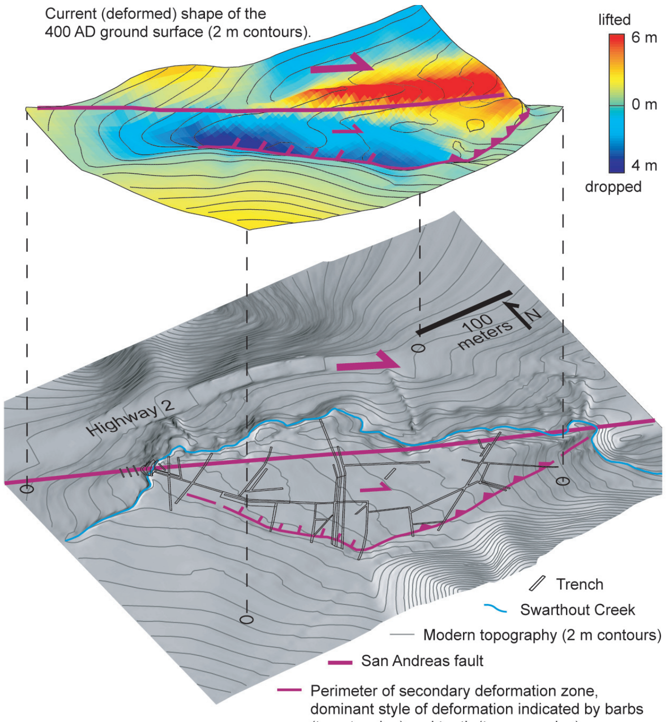

Figure 2. The Wrightwood paleoseismic site is a flake or half-flower structure that was incised and drained by Swarthout Creek in the late nineteenth century. The colored map portrays the ground surface at the time of a key marker bed at the base of our "Upper Section." Contours show the reconstructed shape of this surface and colors indicate how much the surface has been deformed since 400 A.D. A combination of north-side-up slip across the northern trace, transtension across the southwest portion of the southern trace, and transpression across the southeast portion of the southern trace creates a closed depression that was continuously and rapidly filled with peat and debris flows from Government Canyon (a steep canyon southwest of the mapped area).

is statistically modeled as a renewal process (Cornell and Winterstein, 1988). In a renewal process, intervals between earthquakes must be unrelated so their variability can be expressed by (and conditional probabilities calculated from) independent random variables. Thus, if the next earthquake depends upon the strain history prior to that earthquake cycle, both our understanding of Earth and our forecasts of earthquake hazard must be modified.

A critical limitation to testing this important hypothesis is the length of earthquake records from individual faults (Ogata, 1999; Biasi et al., 2002). Attempts to circumvent this limit by combining many short records (e.g., Nishenko and Buland, 1987; McCalpin and Slemmons, 1998) have been unsuccessful (Goes, 1996; Matthews et al., 2002). An equally significant limitation, not as often explored in the literature, is the paucity of data on the variability of earthquake displacements on individual faults. With the exception of seismological data from a few potentially unusual settings (Ellsworth, 1995; Nadeau and Johnson, 1998), the lack of displacement data precludes direct comparison of recurrence interval and slip for individual earthquake cycles. The southern San Andreas (Fig. 1) has been a region of pioneering paleoseismic research (Sieh, 1978; Sieh et al., 1989) but until now has not had long records of displacements and enough sites with long records to seriously consider the extent of paleoearthquakes.

THE WRIGHTWOOD SITE

The Wrightwood paleoseismic site is a structural depression created by the San Andreas fault that is intermittently inundated by debris flows deposited into the linear valley that follows the fault (Fig. 2; see Weldon et al. [2002] for a detailed description of the site, structure, and stratigraphy). The northern edge of the depression has been fixed for at least 6000 yr, but the southern margin has migrated outward, enlarging the depression through time. While we have been able to unravel the timing of nine earthquakes on the narrow northern trace (Fumal et al., 1993; 2002b), the outward migration of the structure to the south separates evidence for earthquakes in space, allowing us to characterize dozens of paleoearthquakes. While some of the structures south of the straight and narrow northern trace have documented right-lateral slip, in many cases we can only recognize the normal or reverse components of deformation, and the linkages and kinematics of structures must be inferred. It is possible that some of the deformation in the previously water-saturated bog is shaking related rather than primarily fault driven. However, for the time intervals for which we have deposits preserved across the entire site, the southern traces have always slipped simultaneously with the

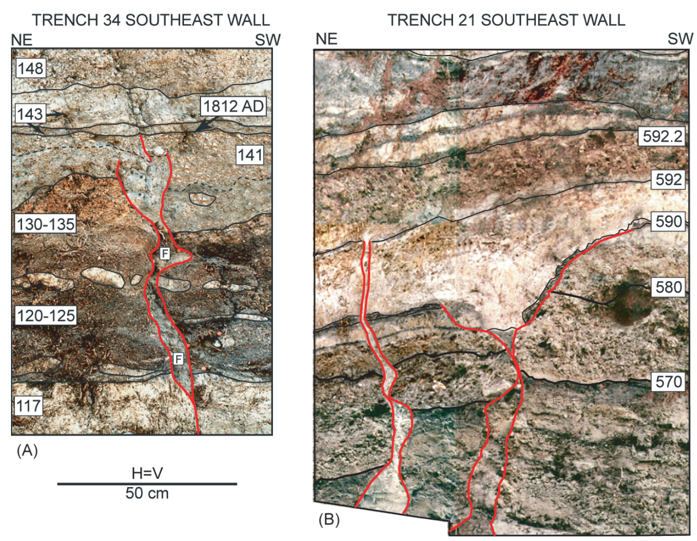

Figure 3. Photos of earthquake evidence from (A) Upper and (B) Deep Section at Wrightwood. Red lines indicate faults and fissures, black lines mark stratigraphic contacts. (A) Centered at meter 25.7, a fissure formed during the historic 1812 A.D. rupture. At this location, debris flow 141 was in place before the event, subsequently capped by unit 143. (B) Exposure of two closely timed paleoearthquakes. The older event created the U-shaped fissure in the center of the photo during growth of peat 590, which continued to grow after the earthquake on the southwest side of the fissure. The younger event is represented by a liquefaction feature, a pipe (left) that broke through layers 592 and older.

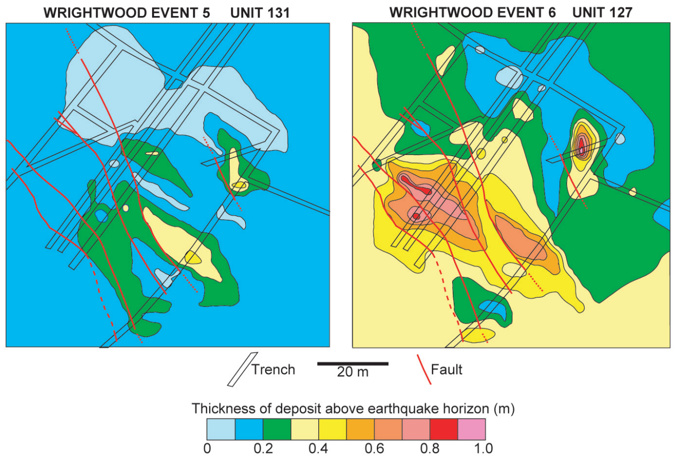

Figure 4. Isopach maps of debris flow layers map out the vertical component of deformation associated with individual paleoearthquakes (from Fumal et al., 2002b). Coseismic folding and faulting results in thickness variations in the sedimentary units that bury the deformed ground surface. Lateral displacements may also be reconstructed from the subsequent offset of these thickness variations and calculations relating the vertical displacement to lateral slip across the known three-dimensional geometry of the faults (see Weldon et al. [2002] for details).

narrow northern trace. This suggests that any gravity-driven deformation occurred during earthquakes (see Weldon et al. [2002] for a detailed discussion of this issue).

The stratigraphic section is at least 30 m thick and consists of alternating debris flow deposits and organic peat-like layers laid out in such a way that the entire record is within trenching depth somewhere on the site (Fig. 2). We have dated ~50 of the several hundred peat layers, focusing on the past ~1500 yr (the "Upper Section") and 3000–1500 B.C. (the "Deep Section"), intervals which we have explored sufficiently to infer a record of earthquakes. Debris flow layers comprise ~70% of the stratigraphy but the organic bog deposits probably represent nearly 100% of the time, which is determined by C-14 dating. Historic debris flows in the region usually occurred during quick snow thaw events and do not temporally correlate with earthquakes (Sharp and Nobles, 1953; Morton and Campbell, 1974). Clast sizes are primarily medium-grained gravel to fine sand and silt; subangular cobbles and boulders up to a meter across occur in the southwest part of the site (Fig. 2). All clastic units are matrix supported, moderately to poorly sorted, and many are reversely graded. In many cases, the layers are continuous across the site (physically traced in trenches for 100s of meters), have centimeter-scale variation in thickness in undeformed regions, and generally thin slightly toward the northern and southeastern boundaries of the site. In over 2 km of excavations of debris flows in cross section, we observe only one depositional feature that might be a transverse ridge and no features that resemble lateral or terminal margins, strongly suggesting that these debris flows extended well beyond the site.

As earthquake ruptures passed through the site, the layers below the wet surface were offset and folded and the surface ruptured, fissured, and warped (Fig. 3). Following the earthquake, sedges and other wetland plants resumed growing, and eventually a debris flow buried the deformed bog surface, often filling still-open fissures (sometimes we even see a thin coating of peat that grew on a fissure wall before the debris flow filled it). It is possible that another earthquake could occur before the evidence from the previous is buried, perhaps causing us to miss an event. However, the rapid sedimentation (on average ~0.7 m of sediments separate each earthquake in the Upper Section), continuous peat growth, and the fact that earthquakes often offset faults and folds formed during previous earthquakes makes it unlikely that we have missed many earthquakes. The only known exception is ~1300–1400 A.D. when there was no clastic sedimentation and the swamp briefly dried up and developed a soil. During this time an event is recognized at San Andreas fault sites to the northwest and southeast, so we infer that an event probably occurred at Wrightwood without a decipherable record (Table 1).

We also have confidence in our event recognition because we see evidence for each earthquake in multiple trenches, and each event has its own signature or style of deformation. This can be seen in Figure 4 (from Fumal et al., 2002b) where event 5 had minor deformation, whereas the previous event (6) had substantial faulting and folding. In some cases deformation overlaps, but in other areas we see evidence for only one of the events. The timing evidence for individual earthquakes is summarized in Figure 5 (for the Upper Section, we have placed the numerical values for the ages and offsets that we will use in our analysis in Table 1).

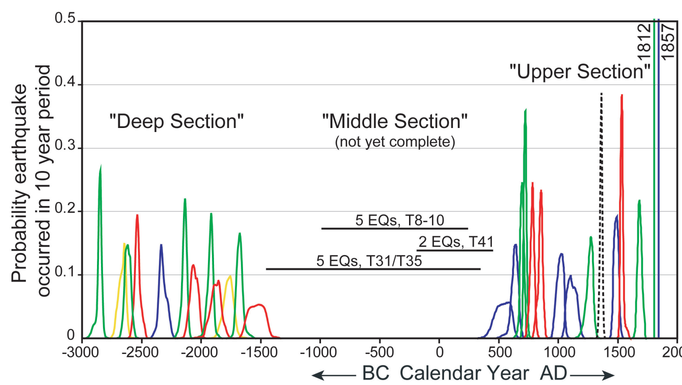

Figure 5. Our current understanding of the ages of ground rupturing earthquakes at Wrightwood. Peaks represent probability distribution functions (pdfs) for the ages of the earthquakes (historic 1812 and 1857 would extend to 1.0 on the vertical scale). Colors represent the relative abundance and quality of the data; green is average, red is exceptional, blue is below average, and yellow is poor or may not be events. The black dashed pdf is an event seen northwest and southeast of our site that falls in a depositional hiatus at Wrightwood. The "Upper Section" is complete and each earthquake's offset is estimated; the "Deep Section" is believed to be complete but does not yet have displacement estimates. The "Middle Section" is certainly incomplete because we have not yet exposed enough of this portion of the sedimentary and structural record. For the complete sequences, Poisson behavior can be dismissed at ~70% confidence level (Biasi et al., 2002).

TESTS OF EARTHQUAKE BEHAVIOR

To investigate the relationship between recurrence interval and displacement we have plotted the data from Table 1 to evaluate slip or time predictability (Figs. 6 and 7). The series is certainly not slip predictable. Any possibility of time predictability resides in the long intervals following the two largest displacements; except for them, one could argue for a negative correlation similar to that seen for the slip predictable test.

The possibility that the two exceptional displacements had a different effect than the moderate or small displacements may be significant because it has been argued that an exceptionally large 1906 rupture depressed activity on the northern San Andreas fault system for most of the twentieth century (Working Group on California Earthquake Probabilities, 2003). It has also been proposed (e.g., Sieh et al., 1989) that rupture of the entire 530 km of the southern San Andreas fault occurs occasionally. If exceptionally large events occur they may depress regional earthquake activity more than typical ruptures of the fault.

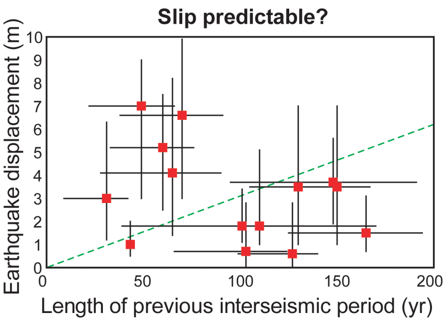

Figure 6. If the size of an earthquake depends upon the amount of time since the previous earthquake, all points should fall on the green dashed line. If there is any relationship, it appears that long intervals are followed by small displacements and short intervals are followed by a wide range of displacements (data from Table 1).

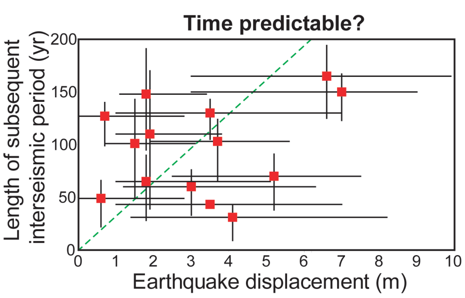

Figure 7. If the amount of time following an earthquake depends upon the size of the earthquake, all points should fall on the green dashed line. With the exception of the two largest earthquakes, it appears that there is a negative correlation, if any. The fact that the two largest earthquakes are followed by the two longest recurrence intervals may suggest that exceptionally large slip events depress fault activity (data from Table 1).

Implicit to our test of time and slip predictability is that strain accumulation is constant through time. The ~3 cm/yr average slip rate determined from the earthquake offsets matches the longer term geologic rate, the current geodetically determined strain accumulation rate, and the San Andreas' kinematically required fraction of the plate rate (e.g., Humphreys and Weldon, 1994; Powell and Weldon, 1992; Working Group on California Earthquake Probabilities, 1995). These similarities suggest that variations in strain accumulation rate on time scales relevant to the earthquake cycle are small and may be completely within the uncertainties of the different measurement systems. While some authors have suggested that strain accumulation rates can vary significantly through time (e.g., Romanowicz, 1993, Peltzer et al., 2001; Friedrich et al., 2003), at Wrightwood the strain accumulation rate would have to vary by more than an order of magnitude between individual seismic cycles and reach values triple the plate boundary rate to make the fault time or slip predictable (Fig. 8).

While we doubt that the strain accumulation rate varies so dramatically through time, the strain release rate certainly does. Variation in rate of strain release is best seen by looking at a cumulative plot of strain release through time (Fig. 9). Between ca. 600 and 900 A.D., strain was released at a rate of almost 9 cm/yr, ~3 times the average, and between 800 and 1900 A.D., the rate is just over 2 cm/yr. The high rate is due to both shorter than average recurrence intervals and larger than average displacements. Since the strain release rate between 600 and 900 A.D. is twice the entire plate boundary rate, it is hard to escape the conclusion that strain accumulated over many earthquake cycles was responsible for the flurry of large

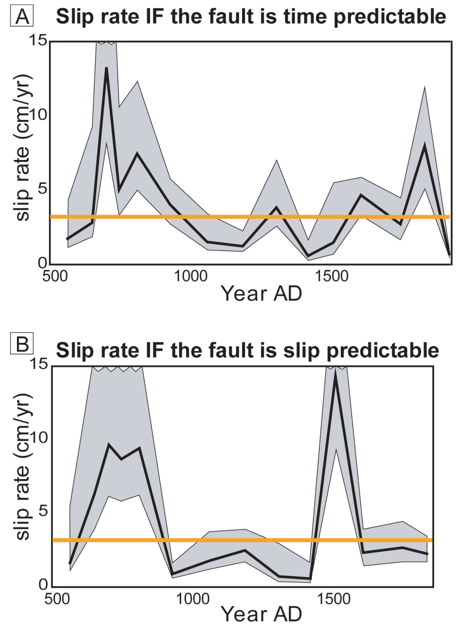

Figure 8. If the fault were time or slip predictable, the loading rate would have to vary by over an order of magnitude within 100s of years. Bold line is the calculated loading rate that would be required to accommodate (A) time and (B) slip predictable behavior (gray shading is ~1 sigma uncertainty; extreme peaks of uncertainty ranges are truncated). Orange line is observed average slip rate.

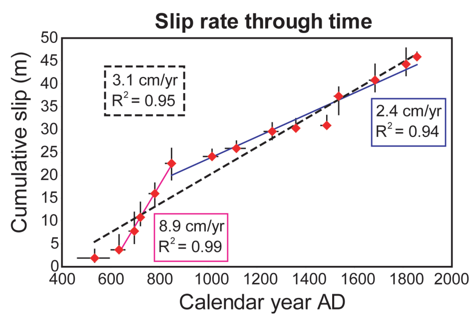

Figure 9. A plot of cumulative slip suggests variability that cannot be captured by considering individual seismic cycles. Between 600 and 900 A.D., the fault accumulated slip at three times the mean rate (black dashed line) or approximately twice the entire plate rate. Error bars show uncertainty in age and offset of individual events, not cumulative age or slip.

slip events and that a surplus of ~1 cm/yr has been accumulating since.

The magnitude and possible periodicity of the long-term cycling of strain can be seen by constructing a time line of the accumulation and release of strain

(Fig. 10). It appears that the range of relative strain is approximately the strain released in 4–5 average earthquakes, and a complete cycle could be ~1000 yr or 10 times the average recurrence interval. There appears to be no relationship between strain level and the size of earthquakes (a regression of relative strain level to displacement yielded an R^2 of 0.01). However, there does appear to be some relationship between the strain level and the interval between earthquakes (Fig. 11), although the relationship is dominated by the single longest interval, which occurred at the lowest observed strain level.

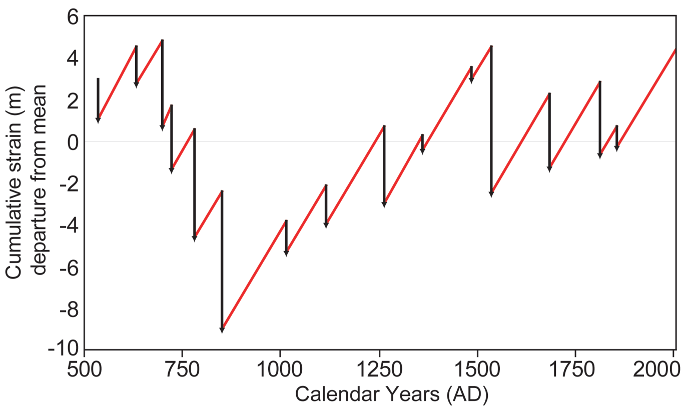

Figure 10. If the strain accumulation rate is the long-term slip rate, a record of the accumulation and release of strain through time can be constructed from earthquake ages and offsets (Table 1). Vertical drops (black arrows) are the release of strain during earthquakes (m of slip) and sloped portions (red lines) are strain accumulation between earthquakes at 3.1 cm/yr. Because the absolute strain level is unknown, we have set the mean value at zero. Periods of high relative strain appear to be followed by a large earthquake or a series of relatively large and frequent earthquakes. We are currently approaching the highest level of accumulated strain seen in the past 1500 yr.

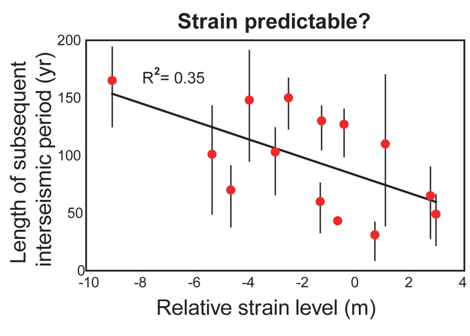

Figure 11. Recurrence intervals appear to be weakly predicted by the relative strain level at the beginning of the interval. If true, there could be as much as a factor of 3 variation in the average recurrence interval depending upon the cumulative strain level. Uncertainties are only shown in recurrence intervals because the relative strain level depends upon the cumulative slip and strain accumulation rate, which cannot be determined independently.

BEYOND WRIGHTWOOD

The most significant limitation to our analysis is that at a site like Wrightwood, we know only the displacements at that site, which may not be representative of the entire rupture. Ruptures decrease and may become more variable in displacement toward their ends (Hemphill-Haley and Weldon, 1999; Hecker and Abrahamson, 2004). Small displacements at Wrightwood may be small earthquakes or the tail ends of large ruptures (as in 1857) and large displacements may be 1857-sized ruptures that are centered nearby. To determine

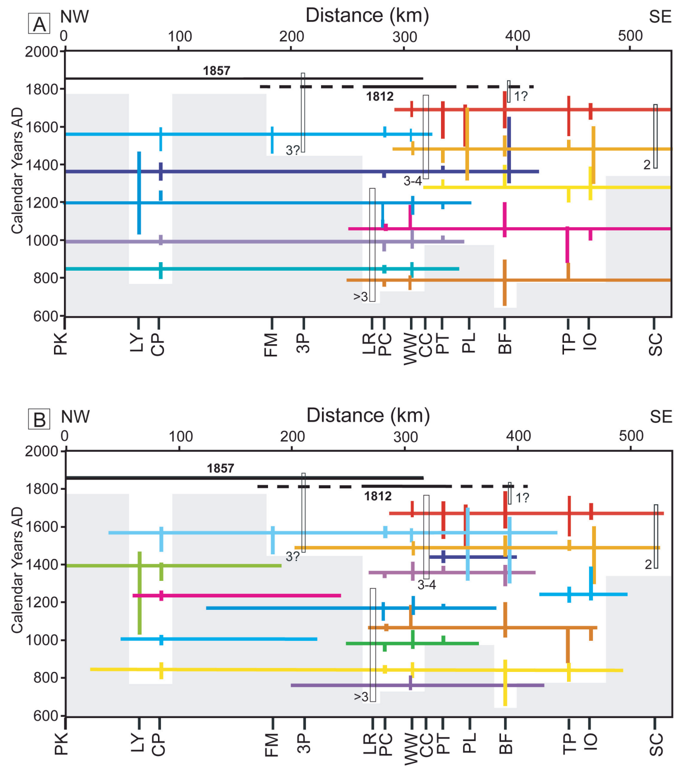

Figure 12. Two possible rupture sequences on the southern San Andreas fault. Vertical colored bars are ranges in age for earthquakes at the sites listed at the lower margin and horizontal bars are rupture lengths. Open boxes represent multiple event age ranges; the individual event ages are unknown. Grey shading indicates regions and times with no data. (A) In this model, the data are interpreted in terms of north and south ruptures with substantial overlap and the 1812 event is anomalous. (B) A random distribution of event timing and rupture lengths also appears to fit the data, suggesting the variability seen in the central part could be characteristic of the fault. Site abbreviations: PK—Parkfield; LY—Las Yeguas, Young et al. (2002); CP—Carrizo Plain, integration of Liu et al. (2004), Sims (1994), Grant and Sieh (1994); FM—Frasier Mountain, Lindvall et al. (2002); 3P—Three Points, reinterpretation of Rust (1982); LR—Littlerock, reinterpretation of Schwartz and Weldon (1986); PC—Pallett Creek, Salyards et al. (1992), Biasi et al. (2002), Sieh et al. (1989); WW—Wrightwood, Biasi et al. (2002), Fumal et al. (2002b), Weldon et al. (2002); CC—Cajon Creek, Weldon and Sieh (1985); PT—Pitman Canyon, Seitz et al. (2000), G. Seitz et al. (2003, personal commun.); PL—Plunge Creek, McGill et al. (2002); BF—Burro Flats, Yule and Sieh (2001), D. Yule and K. Sieh (2003, personal commun.); TP—Thousand Palms Oasis, Fumal et al. (2002a); IO—Indio, reinterpretation of Sieh (1986), Sieh and Williams (1990), Fumal et al. (2002a); SC—Salt Creek, Williams (1989), P.L. Williams (2003, personal commun.)

TABLE 1. EVENT AGES AND DISPLACEMENTS

Event	Mean age (1σ range)	Mean Interval	Offset (m; 1σ range)†
W1857	1857 (Historic)	44	1.0 (0.5–2.0)
W1812	1812 (Historic)	130	3.5 (1.0–7.0)‡
W3	1685 (1662–1700)	150	3.5 (1.0–7.0)‡
W4	1536 (1518–1542)	49	7.0 (3.0–9.0)
W5	1487 (1463–1502)	127	0.7 (0.0–2.8)§
PC-T§	1360 (1343–1370)	97	0.7 (0.0–2.8)§
W6	1263 (1230–1286)	148	3.7 (1.9–5.6)
W7	1116 (1071–1152)	101	1.8 (1.1–3.4)
W8	1016 (981–1039)	165	1.5 (0.7–3.1)
W9	850 (825–864)	70	6.6 (3.0–9.9)
W10	781 (758–794)	60	5.2 (2.5–7.5)
W11	722 (706–729)	31	3.0 (1.2–6.3)
W12	697 (676–708)	65	4.1 (1.4–8.2)
W13	634 (602–658)	110	1.8 (1.0–5.1)
W14	534 (464–594)	—	1.9 (1.0–3.8)

Note: Updated from Biasi et al. (2002), Fumal et al. (2002b), and Weldon et al. (2002). Approximately 2/3 of the intervals and 1/2 of the offset values are within 50% of their means (105 years and 3.2 m, respectively).

†It is impossible to quantify the uncertainty because determining offsets requires qualitative estimates of what is a "likely" match or geologic relationship. We estimate that this would be equivalent to a 50%–75% uncertainty range if it could be quantified.

‡While there are unique offsets of up to ~1 m each for 1812 and 1685, the best displacement data (7 ± 1 m) span both offsets, so we split the combined offset into two equal parts, and allow that all of the combined offset but 1 m can be caused by each earthquake.

§The Wrightwood site has a depositional hiatus at the time of event T at Pallett Creek to the northwest (Sieh et al., 1989) and event 4 at Pitman Canyon to the southeast (Seitz et al., 2000), so we infer that the event occurred at Wrightwood as well. We split the displacement observed between W5 and a hypothetical event that we assign the age of event T at Pallett Creek; we include a range that allows all or none of the displacement to be associated with each event.

how a complete rupture history modifies our understanding of fault behavior, we are actively building a complete space-time rupture history for the entire southern San Andreas fault. Figure 12 shows two end member rupture scenarios; in the first (A), prehistoric ruptures are constructed to be limited to either the northern two-thirds (as in 1857) or southernmost one-half (as in ca. 1685) portions of the fault. This scenario, first proposed by Weldon and Sieh (1985) and strongly supported by Fumal et al. (2002a), yields a quite periodic behavior of "northern" and "southern" events, with more random-looking overlap in between. However, the 1812 earthquake violates the pattern, and beyond the past 3–4 earthquakes, the extents of individual events are poorly defined. More irregular scenarios (e.g., Fig. 12B) are equally consistent with the data, so many more sites with much deeper records will be required before we can consider complete rupture sequences.

It is important to keep in mind that the offsets at a single site, like Wrightwood, represent the release of strain at that point and that strain release must balance accumulation over time, whether it occurs at the tails or middle of ruptures. Overlapping tails of essentially separate large ruptures may explain two small events in a short interval of time at a point, but this cannot explain the 600–900 A.D. flurry of four events with (on average) large displacements or the past 1000 yr of less-frequent, smaller-than-average events. Similar clusters of earthquakes are seen in most long earthquake records. For example, along the Cascadia subduction zone, the intervals between the last 12 earthquakes vary from a few hundred years to over 1000 (summarized in Witter et al., 2003). An even more remarkable cluster of events is seen in a 50,000-yr-long record of earthquakes from the Dead Sea Graben (Marco et al., 1996); based on stratigraphic arguments, intervals may vary by three orders of magnitude. There is no evidence for any relationship between interval lengths and displacement in these two records, although in both reports the authors caution that the proxies used to infer offset (subsidence at Cascadia and seismite thickness in the Dead Sea) may not be very sensitive to earthquake magnitude.

A synthetic series that contains a long-term pattern like Figure 10 was generated by Palmer et al. (1995) in a finite element model containing a strike-slip fault (like the San Andreas) and subparallel dip-slip faults. Infrequent slip on subparallel dip-slip faults modulated the timing of more frequent earthquakes on the large strike-slip fault because displacement on the dip-slip fault dramatically changed the normal stress on the strike-slip fault. While this may explain the long-term pattern, it doesn't explain the detailed relationship between interval and displacement because slip occurs at a defined ratio of shear to normal stress in the model, which appears unlikely at our site. Perhaps we need to consider more complex models that describe a large earthquake as a slip pulse (e.g., Heaton, 1990), whose timing is due to a stochastic-like growth from randomly occurring triggers, and whose displacement is controlled not just by the amount of accumulated strain but also intrinsic properties of the fault that vary over multiple seismic cycles.

CONCLUSIONS

Strain released in an earthquake is not simply that accumulated since the last earthquake. It appears likely that slip occurs at a wide range of strain levels and does not always release the same amount of strain or return the strain level to a fixed value after an earthquake. While it will remain difficult to say how typical our site is until there are long records of complete ruptures on the San Andreas and other faults, there can be little doubt that the simple renewal model of an elastic rebound driven seismic cycle will need to be expanded to accommodate variations that span multiple seismic cycles. If the Wrightwood record is representative of large earthquake behavior, conditional probability estimates will need to incorporate information beyond the randomly distributed variables currently used.

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