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RESEARCH ARTICLE

A 100-Year Average Recurrence Interval for the San Andreas Fault at Wrightwood, California

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Evidence for five large earthquakes during the past five centuries along the San Andreas fault zone 70 kilometers northeast of Los Angeles, California, indicates that the average recurrence interval and the temporal variability are significantly smaller than previously thought. Rapid sedimentation during the past 5000 years in a 150-meter-wide structural depression has produced a greater than 21-meter-thick sequence of debris flow and stream deposits interbedded with more than 50 datable peat layers. Fault scarps, colluvial wedges, fissure infills, upward termination of ruptures, and tilted and folded deposits above listric faults provide evidence for large earthquakes that occurred in A.D. 1857, 1812, and about 1700, 1610, and 1470.

The next large earthquake on the southern San Andreas fault could affect 10 million people or more in the developed areas of southern California (Fig. 1). Forecasting the time and location of such an event requires an estimate of how often large earthquakes have occurred in the past and the sections of the fault that ruptured during these events. The recurrence times of large earthquakes are most accurately determined from historical records and geologic site investigations of paleoearthquakes. However, sites with well-dated records of more than a few events are rare. For the southern San Andreas fault, Pallett Creek (Fig. 1) has been the best documented site; it records 12 events since about the early second century A.D. (*1–3*). From a single site, though, it is impossible to evaluate the length of rupture for individual events or completeness of the earthquake record. These uncertainties are best answered by studying additional paleoseismic sites. Although some data are available from Cajon Creek (*4*) and Indio (*5*), neither of these sites has recorded as many events as the Pallett Creek site nor are the events as precisely dated. In this article we present the most recent 500 years of a paleoseismic record comparable to and potentially longer than that at Pallett Creek from near the town of Wrightwood (Fig. 1). This site contains evidence for 12 large earthquakes during the past 1300 years (*6–9*); we discuss the evidence for the latest five events at Wrightwood, which are the most precisely dated.

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Stratigraphy and structure. Our paleoseismic site is located where the active traces of the San Andreas fault zone (SAFZ) cross Swarthout Creek and a small tributary, Government Canyon, 3 km northwest of Wrightwood (Fig. 2). Two

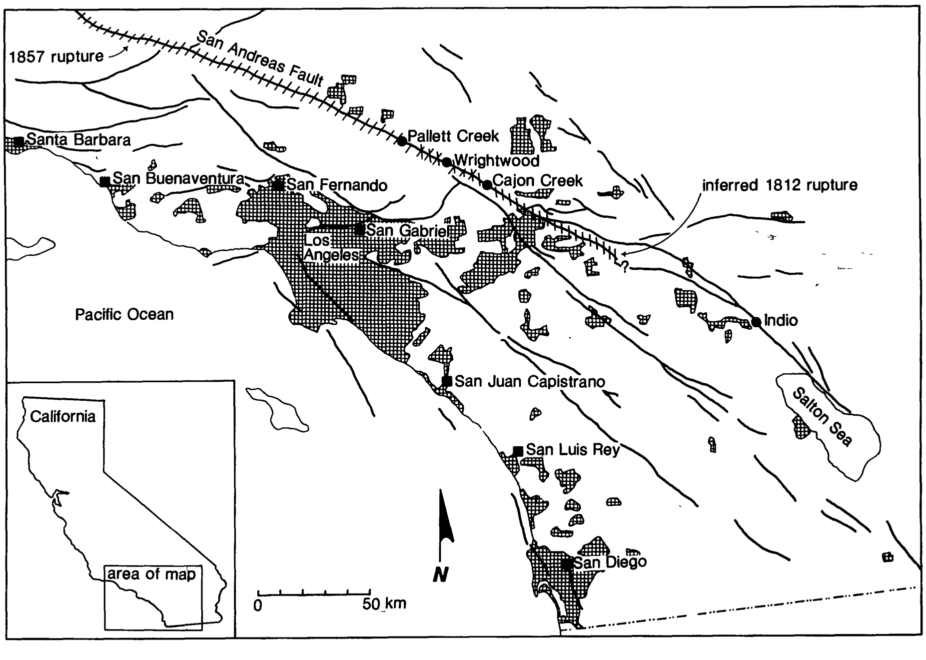
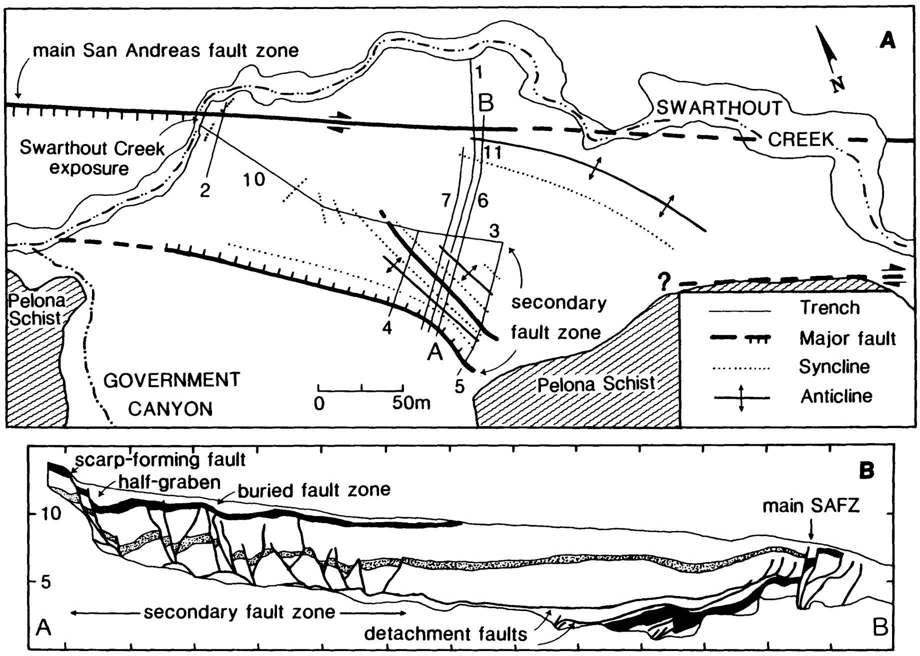


Fig. 1. Map of southern California showing major faults (heavy lines) and urban areas (patterned). Locations of paleoseismic sites along the San Andreas fault northeast of Los Angeles are shown as solid circles. Southern part of the 1857 rupture and inferred 1812 rupture are indicated by hatchured lines. Locations of missions active in 1812 are shown as solid squares. The 1812 earthquake was reported at San Diego but not at Santa Barbara; strong shaking was reported at San Buenaventura and San Fernando; damage was most severe at San Gabriel and San Juan Capistrano (*17*).

Fig. 2. (**A**) Map of Wrightwood paleoseismic site showing location of trenches (numbered), major fault zones, and associated folds. For clarity, the lower level trenches (*8, 9*) excavated between trenches 6 and 7 to examine deeper structures and several short trenches near the gully exposure (*14–16*) are not shown. (**B**) Schematic cross section across the site [line marked AB in (A)] using data from trenches 1, 6, 9, and 11. Faults are shown by heavy lines; three prominent debris flow units (black, stippled) are shown to illustrate style of deformation across each fault zone.

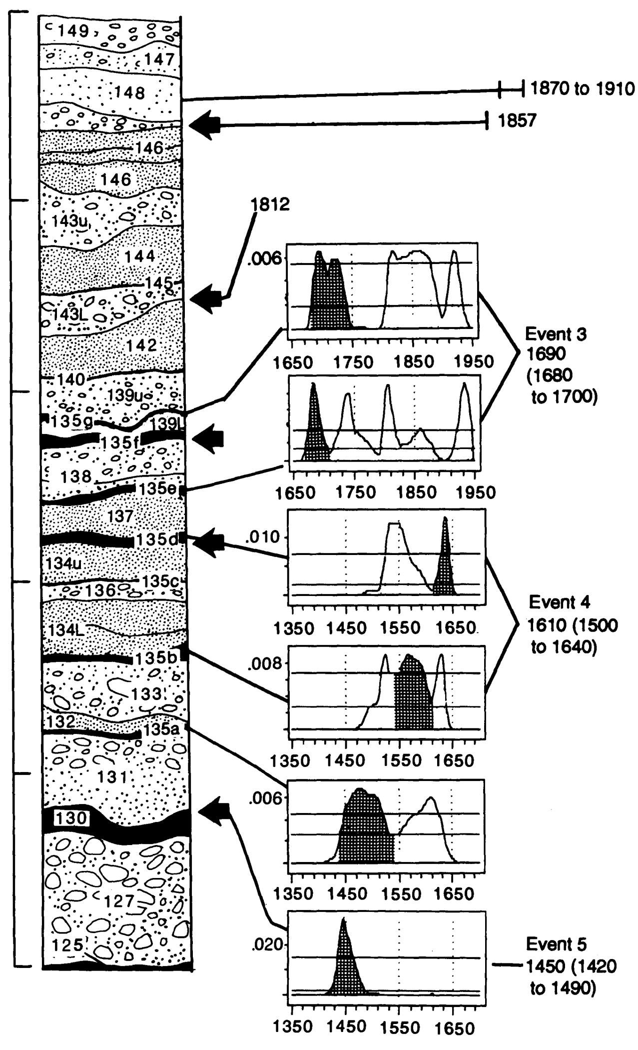


major fault zones bound the valley: (i) the main SAFZ to the northeast and (ii) a secondary fault zone to the southwest that has a northeast-facing scarp that aligns with fault exposures 1 km to the southeast. We infer that the area between these faults is a 150-m-wide pull-apart basin at a right step in the SAFZ. The oldest deposits we have exposed are fluvial sediments about 6800 years old. These deposits underlie a section of thick debris flows immediately northeast of the main fault (near B in Fig. 2A). Starting about 3 m above this contact, the debris flow deposits are interbedded with peat layers, indicating that a marsh has occupied the basin almost continuously for the past 5000 years until the site was drained by incision of Swarthout Creek within the last century. Periodically, debris flows issued from Government Canyon and flowed into the marsh and deposited massive beds up to 1 m thick of very poorly sorted gravel derived from the Pelona Schist. These debris flows have deflected Swarthout Creek and kept it confined to near its present position on the northeast side of the valley; granitic sediments carried by Swarthout Creek are interbedded with peat layers and debris flow deposits only along the northern margins of the site.

To examine these deposits we excavated a series of 16 backhoe trenches; part of the section is also exposed in the walls of the Swarthout Creek gully at the northwest corner of the site where sedimentation was most rapid (1 m per 100 years) during the past 500 years (Fig. 2A). We have concentrated our work in two areas where the youngest sediments are involved in faulting: (i) the main fault zone exposed in the gully and trenches 2, 10, 12, and 14 to 16; and (ii) the secondary fault zone (trenches 1 and 3 to 13). Exposures of the main fault show a complex zone of deformation about 5 to 7 m wide. The section exposed in Swarthout Creek contains an unconformity dated at about 500 years old; we have not been able to resolve individual events on the main trace below this unconformity. For this reason we focus our discussion on the latest five events, which are common to both zones.

The excavations across the southwest

Fig. 3. Stratigraphic column of the upper 5 m of deposits at Wrightwood. Peat layers are shown as black units numbered as multiples of 5. Units 132, 134, 137, 142, 144, and 146 are stream deposits of Swarthout Creek. All other units are debris flow deposits from Government Canyon. The thicknesses of the units above 135a are taken from the end of trench 10 near the gully; thicknesses for units below 135a are taken from the secondary zone. Probability density functions for the calibrated radiocarbon dates of the peat layers are shown (*14*) with the horizontal axis in calendar years A.D. and the vertical axis in relative probability per year. Shaded peaks indicate our preferred age range for each peat. The unshaded peaks are other possible age ranges for peats 130 and 135a–d but these ages are less likely as they require either high or low rates of sedimentation or violate stratigraphic superposition. Arrows indicate horizons during which earthquakes occurred. A.D. 1857 and A.D. 1812 are historic earthquakes. Our best estimates of the dates of events 3 to 5 and 2-σ intervals were determined from radiocarbon ages.



margin of the site (Fig. 2A) reveal a 50-m-wide zone of deformation with numerous high-angle, northeast-dipping faults that show right-oblique normal slip. Major structures in this zone include the scarp-forming fault and associated half-graben, a major buried fault zone, and associated folds. These faults join a detachment fault at a depth of about 5 m. The detachment ends near the main SAFZ in a complex of southwest-dipping, high-angle faults showing both reverse and normal slip (Fig. 2B). This system of secondary faults seems to have accommodated transport of material toward the center of the basin and may be, in part, gravity-driven. Although we do not understand the detailed history of the secondary zone structures, we demonstrate below that during the past five earthquakes they have moved synchronously with the main trace.

Event recognition and dating. We used several lines of evidence to identify event horizons. Upward termination of fault ruptures was used where there is clear evidence that a fault ruptured to the ground surface, such as scarps or fissures or where several faults cut a particular bed. This was particularly useful in the main fault zone. In the secondary zone, however, many of the faults cut across different beds from exposure to exposure; hence, the upward termination of these faults in any particular trench is not a reliable indicator of the timing of events. Debris flows are thickest above the major steeply dipping faults; evidently linear depressions, appearing as synclines, formed during movement on these faults and were later infilled. We found that folding is consistent from exposure to exposure and is thus also important evidence for recognizing the sequence of events.

One sample of wood from a debris flow deposit and 21 samples from peat layers deformed by the last five earthquakes were dated by conventional radiocarbon analyses (Table 1). Most of these peat layers are only a few centimeters thick and probably formed over a period of several decades (*10*). Across much of the site a key unit, peat 135, occurs as a single layer up to 22 cm thick. In the vicinity of the gully it splits into seven subunits (135a–g). We have nine dates on five of these subunits of peat 135; we use these nine dates along with three dates for the upper 2 cm of peat 130 to determine most precisely the timing of the latest five events (Fig. 3). The interpretations based on these dates are supported by seven additional dates from samples of the entire thickness of peats 135 and 130. All 19 dates for peats 130 and 135 are stratigraphically consistent. The two dates on peat 140 appear to be at about 200 to 300 years too old; samples of this peat were collected from the half-graben in the secondary zone and may be contaminated by peats exposed in the fault scarp or old wood washed into the depression.

Earthquakes in the main fault zone. The most recent large earthquake at the study site was the 9 January 1857 Fort Tejon event (magnitude, $M = 7.9$). In the area of the gully exposure, displacement occurred primarily on the fault trace to the left of meter 2 (Fig. 4). This rupture produced a large fissure at the ground surface that was subsequently filled by a debris flow (unit 148). In trench 5 (Fig. 2A) this unit contains artifacts (horseshoes, ceramics, and so forth) dating from about A.D. 1890 ± 20 (*15*). About 20 m to the southeast of the gully wall (trenches 14 and 15), a small graben formed between two splays of the main fault. Several narrow sand dikes that cut to the base of unit 148 also formed during this event.

The next youngest event either ruptured the same trace as the 1857 event or did not produce any surface rupture on the main fault zone at the gully exposure. The primary evidence for this earthquake on the main fault zone is the folding of units 139 to 142. This folding is best preserved on the northwest wall; on the southeast wall, erosion of the top of this fold before the deposition of unit 144 resulted in the prominent unconformity near the center of Fig. 4. This unconformity demonstrates that this folding predates the 1857 earthquake. We infer that this is the 8 December 1812 San Juan Capistrano earthquake. Dendroseismological data from the Wrightwood area (*16*) demonstrate that this event occurred on the San Andreas fault and that at least 12 km of the fault, including our site, ruptured during this earthquake.

We have evidence for two events during the accumulation of peat 135. The youngest of these events (event 3) produced rupture on at least two faults (shown near the center of Fig. 4) that affect only units up to the base of peat 135f. The fault to the right of meter 2 produced a small scarp that was subsequently buried by colluvium derived largely from units 135e and 138. The overlying peat, 135g, formed before the 1812 earth-

Table 1. Radiocarbon analyses of peat samples. US is the U.S. Geological Survey, Menlo Park, California. B is BETA Analytic Inc., Coral Gables, Florida. QL is the Quaternary Isotope Laboratory, University of Washington, Seattle, Washington. ^{14}C ages have been adjusted for $^{13}C/^{12}C$ ratio. This ratio was measured for each B sample; a $\delta^{18}O_{SMOW}$ value of −27 per mil was used for US samples. The standard deviations reported by QL are based on counting statistics alone. Repeat measurements and intercalibration studies indicate a slightly higher total error with an upper limit of 1.5 times the reported values. US and B suggest error multipliers of 1.0 for calculating calendar ages [see (*14*)]. Averages were calculated using the method of Ward and Wilson (*11*). Radiocarbon ages were calibrated with the use of CalibETH (*12*) with curve of Stuiver and Pearson (*13*).

Sample	Lab no.	Stratigraphic unit	^{14}C age (yr B.P. ± 1σ)	Mean ^{14}C age (yr B.P.)	Calendar age (yr A.D. ± 2σ)
6T4	US-2730	140	565 ± 40		1297 to 1368 1371 to 1426
6T4	B-25595	140	340 ± 60		1446 to 1651
	B-22339	139u (wood)	290 ± 60		1445 to 1676 1747 to 1799
7T1 10T5	US-2731 QL-4396	135 (upper 2 cm) 135g	130 ± 40 116 ± 15	119 ± 20	1682 to 1741 1804 to 1893 1905 to 1935
10T8 10T31	QL-4398 US-2788	135e 135e	137 ± 15 205 ± 50	148 ± 21	1670 to 1706 1715 to 1780 1793 to 1881 1915 to 1946
10T9 10T32	QL-4399 US-2789	135d 135d	302 ± 15 270 ± 50	297 ± 21	1514 to 1601 1616 to 1650
10T6 10T34	QL-4397 US-2798	135b 135b	334 ± 14 275 ± 40	321 ± 19	1497 to 1638
10T33	US-2790	135a	375 ± 50		1441 to 1634
5T2	US-2732	135 (lower half)	400 ± 40		1429 to 1525 1561 to 1631
5T2	B-	135 (lower half)	345 ± 60		1445 to 1649
2T1	B-22347	135	300 ± 60		1450 to 1671 1764 to 1795
7T2 5T20 7T15	US-2733 US-3121 US-3141	130 (upper 2 cm) 130 (upper 2 cm) 130 (upper 2 cm)	430 ± 45 430 ± 35 450 ± 35	438 ± 22	1427 to 1472
5T3A 5T3B 2T2	US-2631 US-2632 B-23346	130 130 130	555 ± 30 580 ± 30 590 ± 60	575 ± 20	1307 to 1359 1379 to 1410
5T3	B-25588	130	420 ± 70		1404 to 1638

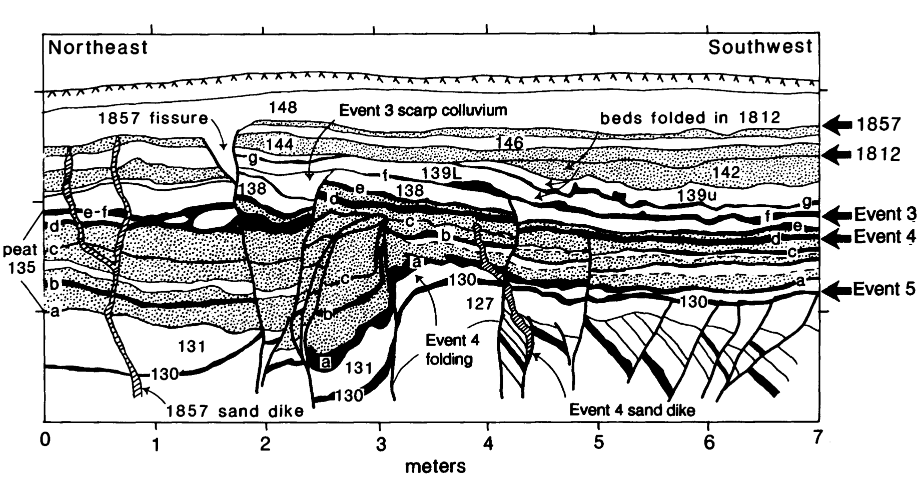


Fig. 4. Composite log of Swarthout Creek exposures at northwest corner of site showing deformation on the main fault zone associated with past five earthquakes. Fault strands shown by heavy lines. Peat layers are black, stippled units are granitic alluvial deposits. All other units are debris flows. Numbers shown for units mentioned in text. Earthquake horizons are shown by broad arrows.

quake because it was folded during that event. Thus, of the three calibrated age ranges for this peat, only the oldest, A.D. 1682 to 1741 (Table 1 and Fig. 3), is possible. Because peat 135e is older than peat 135g, and considering that peat 135f, which is about 5 cm thick, accumulated between peats 135e and 135g, only the oldest of the five calibrated age ranges for peat 135e, A.D. 1670 to 1706, is possible. Averaging the weighted means of these calendar age ranges gives a date (1711 ± 16 or 1686 ± 8) for event 3 of about A.D. 1700 (1680 to 1730).

The older of the two earthquakes that occurred during accumulation of peat 135 (event 4) produced ruptures on several faults (shown near meters 3 and 5 in Fig. 4), the tight fold near the center of the exposure, and sand dikes near the axis of the fold. All of these structures terminate at or below the base of peat 135d. The date of event 4 is thus bracketed by the ages of peats 135d and 135b. Peat 135d has two possible age ranges: A.D. 1514 to 1601 and A.D. 1616 to 1650. We prefer the younger of these because the older range requires that peat 135d accumulated much more slowly than the other peat layers in unit 135. Event 4 postdates the accumulation of peat 135b and 135c. Peat 135b has an age range of A.D. 1497 to 1638. We prefer the middle part of this range (about A.D. 1540 to 1610) because it does not require an unusually fast or slow rate of peat accumulation (Fig. 3). Our best estimate of the date of event 4 is A.D. 1610 (1500 to 1650).

The oldest earthquake that we have been able to resolve on the main zone (event 5) produced a series of ruptures that consistently offset peat 130 but did not deform the overlying units (lower right hand corner of Fig. 4). The date for the upper 2 cm of peat 130 is A.D. 1450 (1430 to 1470) (Table 1 and Fig. 3). The earthquake occurred at least a decade and perhaps several decades after this date; our best estimate for the date of event 5 is A.D. 1470 (1450 to 1490). Although it is apparent in Fig. 4 that the units below unit 127 are highly deformed, we have not been able to resolve individual events on the main fault below this angular unconformity.

Earthquakes in the secondary zone. Effects of these five earthquakes are also evident in the secondary fault zone (Fig. 2A). The four most recent events produced deformation along the scarp-forming fault zone at the southwestern margin of the site. Slip during the 1857 earthquake occurred primarily along the southwesternmost faults of the secondary zone. The 0.5-m-high scarp that formed during this event is partly buried by unit 148, which contains late 19th century artifacts. This event also produced fissures along secondary faults northeast of the scarp outside of the half-graben.

The next youngest earthquake occurred during the formation of peat 140. This event resulted in a depression into which the laminated sand and fine gravel composing units 143 and 146 were deposited. This event did not result in an appreciable scarp; in trenches 4 and 5, however, a large fissure cuts the upper part of unit 139. The upper few centimeters of this fissure are filled with organic matter derived from the lower part of peat 140, but the upper surface of this peat is not deformed. As noted earlier, the dates for this peat appear to be several hundred years too old. This event is at the same strati-

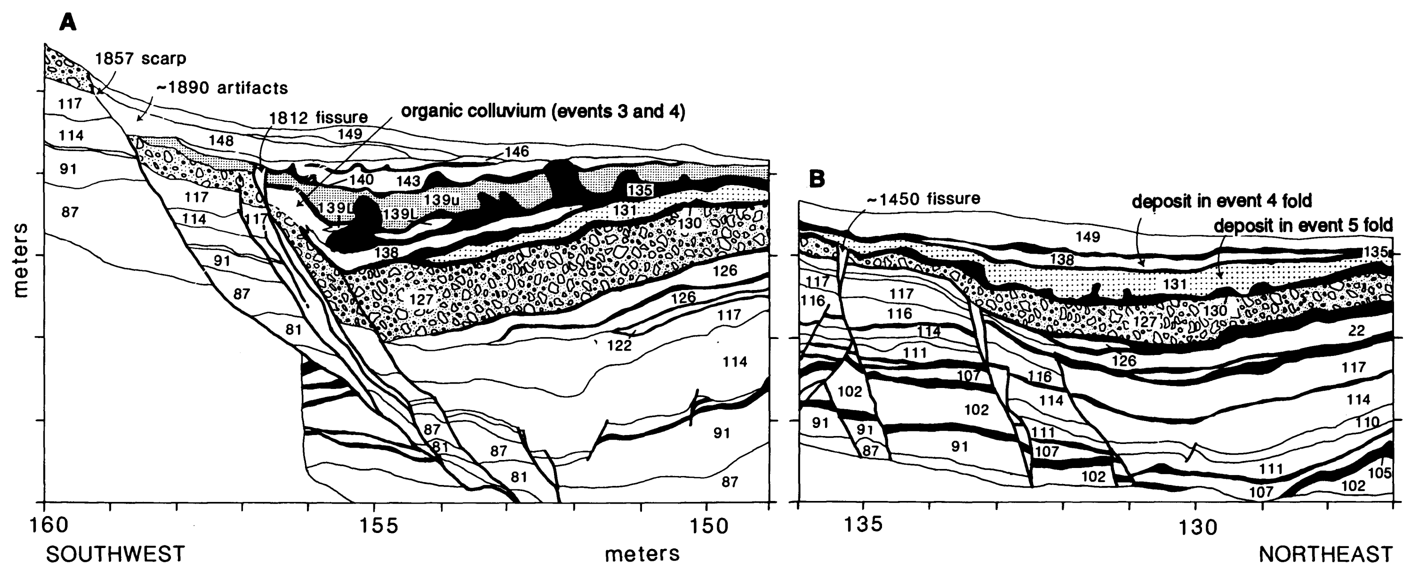


Fig. 5. Cross sections showing (**A**) scarp-forming fault zone and associated half-graben and (**B**) buried fault zone and associated growth syncline. Meter marks keyed to Fig. 2B. Vertical exaggeration is 1.25.

graphic horizon (post unit 139u, but before 1857) as event 2 on the main trace; we infer that this event occurred in A.D. 1812.

As in the main fault zone, there is evidence in the secondary zone for two earthquakes during the accumulation of peat 135. Only two thin sandy debris flows units, 138 and 139L, were deposited in the secondary fault zone during this time; thus, it is difficult to resolve events. In the secondary zone, unit 138 was deposited only in the half-graben and in the linear depressions along several secondary faults intersected by trench 5 (Fig. 2A). These depressions formed during an event that occurred during the accumulation of the lower part of peat 135; this was the same as event 4 in the main fault zone. A small scarp formed along the southwest margin of the half-graben during event 4; organic-rich colluvium shed from this scarp interfingers with unit 138 (Fig. 5A). The top of unit 138 is tilted more than the top of unit 139u, which has been affected only by the 1812 and 1857 events. This relation indicates that an event occurred during the accumulation of the upper part of peat 135, probably before the deposition of unit 139L, in that this unit appears to be less deformed than unit 138. This event must therefore be the same as event 3 in the main fault zone. Colluvium from the fault scarp also interfingers with unit 139L. It is possible that the entire scarp was produced during event 4, but this requires that the 50-cm-high scarp shed colluvium for at least 50 and perhaps as long as 240 years (difference between dates of event 4 and peat 135g). Unit 139L is very thin and so only partly filled the depression produced by event 3; this depression was later filled by unit 139u.

The organic-rich upper 20 to 30 cm of unit 127, a coarse debris flow, is the A horizon of a soil formed during a period of slope stability. During this time, secondary faults near the center of the site were the active southwest margin of the basin. Unit 131 pinches out against the paleoslope (Fig. 5A) and fills several linear depressions formed during an earthquake that occurred when the top of peat 130 was the surface of the marsh. In places, peat 130 is oxidized, indicating the marsh dried out and was burned over; it is likely that at least several decades elapsed between our date for peat 130 (A.D. 1450) and deposition of unit 131. A large fissure near meter 135 that cuts the top of peat 130 (Fig. 5B) formed during this event and was filled before deposition of unit 131. This history is consistent with the timing for event 5 in the main fault zone, about A.D. 1470 (1450 to 1490).

Implications for fault behavior. We have presented evidence for five large earthquakes at Wrightwood during the past 500 years. Sieh *et al.* (*3*) reported only three events (V, X, and Z) at Pallett Creek during the same interval; the dates of these events can be matched with those of three of the events at Wrightwood. Our excavations show that the 1857 earthquake (event Z) produced surface faulting at Wrightwood. Event 5 at Wrightwood occurred about A.D. 1470 (1450 to 1490) and therefore is probably the same earthquake as event V at Pallett Creek, A.D. 1480 (1465 to 1495). Sieh *et al.* (*3*) reported two possible calendar ages for event X, A.D. 1785 (1753 to 1817) and A.D. 1688 (1675 to 1701); it could match either the 1812 event or the event 3 at Wrightwood. They rejected the older age range on stratigraphic grounds and correlated event X with the 1812 earthquake. Jacoby *et al.* (*16*) inferred that the 1812 earthquake ruptured the San Andreas fault northwest of Cajon Creek on the basis of shaking reports from missions (Fig. 1). However, a rupture largely to the southeast of Wrightwood may better explain the observed damage in 1812. About 6 m of slip occurred during event X at Pallett Creek (*18*). At Wrightwood, event 3 produced larger vertical deformation and bed-thickness changes across faults than occurred in 1812 (Fig. 4). Therefore, we prefer the A.D. 1688 (1675 to 1701) age for event X at Pallett Creek and correlate it with event 3 at Wrightwood.

Although there remains uncertainty in correlating earthquakes, the important observation is that the Wrightwood record contains two events during the past 500 years not observed at Pallett Creek. It is plausible that surface faulting during an earthquake may occur at both sites but go undetected at one or both locations because too little sediment was deposited to record the deformation. However, if the paleoseismic record at each site for the past 500 years is complete, different sections of the fault have been involved in the earthquake ruptures. A number of speculative rupture segmentation models have been proposed for the southern San Andreas fault based on limited paleoseismic data (*2*, *4*). Although our new recurrence data cannot be used to define precisely the lateral extent of individual surface ruptures, the absence at Pallett Creek of event 4 and either event 3 or the 1812 event suggests that these earthquakes ruptured the fault in the general region of San Bernardino.

If our inference is correct that the 1812 event occurred on the part of the fault shown on Fig. 1, then for a slip rate of 24.5 ± 3.5 mm/yr (*4*), 4.4 ± 0.6 m of slip has accumulated since 1812, which is about the estimated slip per event of 4 m (*4*). In addition, this is the section of the fault for which some models of static stress change from the 1992 Landers earthquake suggest that horizontal shear stress has increased (*19*). The Working Group on California Earthquake Probabilities calculated a 30-year conditional probability of 0.2 for a San Bernardino Mountain segment (*20*) but stressed uncertainty in recurrence data and assigned the estimate with the lowest level of reliability. Our data show that for the past five earthquakes on the southern San Andreas fault northeast of Los Angeles, the recurrence interval has averaged about 100 years, significantly shorter than the 132 years reported by Sieh *et al.* (*2*) and the elapsed time of 135 years since 1857. These new observations emphasize the need to reevaluate probabilistic estimates of earthquake occurrence along the southern San Andreas fault.

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21. We thank the Southern California Water Company for allowing access to their property and Joe Freitas for doing the excavating. We thank all those who assisted in the field, especially J. Alexander, M. Miller, N. Jasek, D. White, A. Fox, T. Powers, and R. Abrams, who participated in the National Association of Geology Teachers–U.S. Geological Survey summer training program. We also thank our colleagues C. Prentice and D. Morton for reviews and D. Trimble, who performed the ^{14}C analyses, and M. Dowd, who typed the manuscript. The University of Oregon work was supported by National Earthquake Hazard Reduction Program grant #14-08-0001-61986.

6 August 1992; accepted 20 November 1992