Century-long average time intervals between earthquake ruptures of the San Andreas fault in the Carrizo Plain, California

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ABSTRACT

Paleoseismological data constrain the age, location, and associated magnitude of past surface-rupturing earthquakes; these are critical parameters for developing and testing fault behavior models and characterizing seismic hazard. We present new earthquake evidence and radiocarbon analyses that refine the chronology of the six most recent earthquakes that ruptured the south-central San Andreas fault in the Carrizo Plain (California, United States) at the Bidart Fan site. Modeled 95 percentile ranges of the earthquakes prior to the A.D. 1857 earthquake are A.D. 1631–1823, 1580–1640, 1510–1612, 1450–1475, and 1360–1452. The average time interval between the last six earthquakes that ruptured the San Andreas fault in the Carrizo Plain is 88 ± 41 yr. This is less than the time since the most recent A.D. 1857 earthquake, less than all reported average intervals of prehistoric earthquakes along the entire San Andreas fault, and significantly shorter than the 235 yr average used in recent seismic hazard evaluations. The new chronological data combined with recent slip studies imply that the magnitudes of the earthquakes that ruptured the southern San Andreas fault in the Carrizo Plain since ca. A.D. 1360 were variable, and suggest that the widely held view of rare but great surface rupturing earthquakes along this portion of the southern San Andreas fault should be reevaluated.

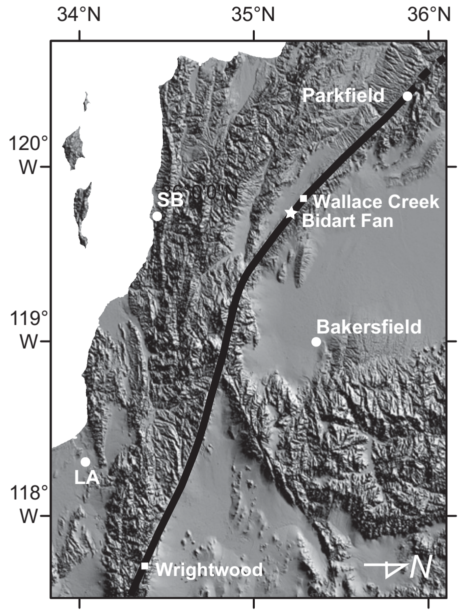

Figure 1. Shaded relief map of Southern California showing trace of A.D. 1857 Fort Tejon earthquake rupture (thick black line) and locations of selection of paleoseismic sites including Bidart Fan (white star). LA—Los Angeles; SB—Santa Barbara.

INTRODUCTION

A long-standing goal in earthquake science is to develop predictive models of earthquakes for time scales and magnitudes that affect society. Few faults have ruptured more than once during the instrumental period, thus precluding the exclusive use of seismographic data to investigate recurrence of large earthquakes on faults (e.g., Bakun et al., 2005). Absent such data, paleoseismic records of past earthquakes during the past few millennia are used to statistically characterize the behavior of active faults and estimate the likelihood of future large earthquakes along them (e.g., Working Group on California Earthquake Probabilities [WGCEP], 2008). Along the San Andreas fault, California, United States, one of the most intensely studied faults in the world, paleoseismic sites that have such data are few, far apart (WGCEP, 2008, their Appendix B), and the evidence of surface-rupturing earthquakes between them difficult to correlate (e.g., Biasi and Weldon, 2009). The lack of earthquakes along the south-central San Andreas fault since at least the early 1900s suggested (Brune and Allen, 1967; Allen, 1968) that past and future slip along the Carrizo section of the San Andreas fault may be characterized by great, characteristic slip earthquakes similar to the M7.9 1857 Fort Tejon earthquake (Zielke et al., 2010), separated by long intervals (240–450 yr) of dormancy (Sieh and Jahns, 1984). This inference was supported by three-dimensional stratigraphic reconstructions of paleoseismic excavations (Liu et al., 2004). These results influenced thinking on recurrence of large earthquakes in general (Schwartz and Coppersmith, 1984; Wesnousky, 1994). However, geochronological data from subsequent paleoseismic studies were unable to confirm this simple recurrence behavior (Grant and Sieh, 1994; Akçiz et al., 2009) and suggested greater complexity in rupture patterns (Grant, 1996; Grant Ludwig et al., 2010).

BIDART FAN

Excavations at the Bidart Fan site have provided a datable paleoseismic record for the northern end of the 1857 rupture (Fig. 1). The Bidart Fan, a composite alluvial fan, is fed by a drainage basin of ~10 km^2 on the southwestern slopes of the Temblor Range. Sediment aggradation and incision of the Bidart Fan have undergone spatio-temporal variations that are likely to have been climatically driven (Grant Ludwig et al., 2010). Its deposits along the San Andreas fault trace are dominated by debris flows, sheet flows, and channelized fluvial sediments, providing excellent conditions for preservation of earthquake rupture evidence. Data from initial excavations (Grant and Sieh, 1994), refined later by dating additional charcoal samples, showed that the penultimate earthquake in the Carrizo Plain occurred not earlier than A.D. 1640, and five earthquakes ruptured the Carrizo section since A.D. 1280–1340, indicating an average time interval of 137 ± 44 yr between ground-rupturing earthquakes (Akçiz et al., 2009). However, these data were limited because trenches were disconnected and close to channels that likely incised during the time period of the earthquake record, restricting deposition between earthquakes (Grant Ludwig et al., 2010). Since 2005, we excavated five closely spaced and connected trenches (Fig. DR1 in the GSA Data Repository[1]) away from the aforementioned deeply incised channels and thus less influenced by their incision histories. Here we present evidence for the latest six earthquakes from two trenches with the best record (Fig. 2; Figs. DR2, and DR3; Table DR1) and most precise dating (Figs. DR4 and DR5).

Earthquake Evidence

We interpret the most recent ground-rupturing earthquake at the site, event A, to be the 1857

[1]GSA Data Repository item 2010222, Figure DR1, location of trenches, Figures DR2 and DR3, complete trench logs of T5 and T11, Figures DR4 and DR5, OxCal analysis plots, Table DR1, earthquake evidence, and the code used in the OxCal analysis, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

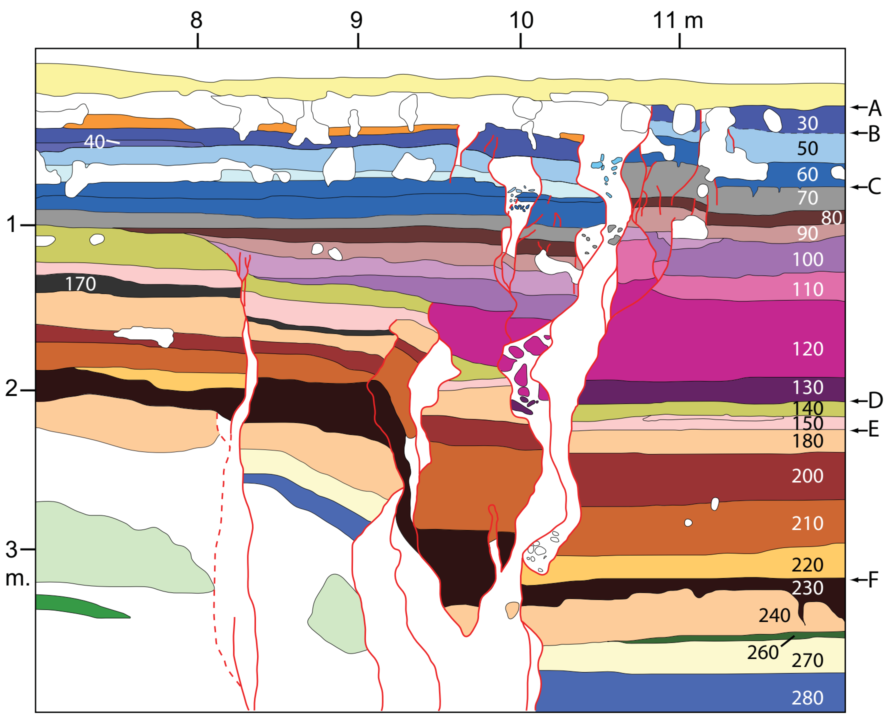

Figure 2. Portion of trench T11 (BDT11) log that shows evidence for last five earthquakes and the earthquake horizon for the sixth earthquake (not observed in this portion of the log) that ruptured Bidart Fan site in Carrizo Plain. Arrows and letters mark earthquake horizons. Colors represent different stratigraphic units identified in field.

Fort Tejon earthquake. This earthquake produced a series of fissures with significant lateral and apparent vertical offsets at the ground surface. Complex faulting for this event is spread over a zone ~10 m wide. The oldest undeformed deposit is a debris flow unit (unit 10) seen in all of the trenches.

The penultimate earthquake (event B) is distinguishable from event A in a series of fissures that occurred while unit 50 was at the surface. Significant thickness changes of some of the units across the fissure are evidence for lateral slip. Following this earthquake, the fissures were filled and the disrupted surface was overlain by unit 30, which has a variable thickness across the fault zone. Due to the limited deposition and/or erosion of sediments younger than unit 30, it is possible that 1857 earthquake ruptured some of the event B fault traces.

The third youngest earthquake (event C) occurred after deposition of unit 70. This earthquake produced ruptures along several fault traces that consistently displace unit 70 but do not deform the overlying units. Fissures filled with unit 70 blocks, and shear zones that affect units up to unit 70, are unconformably overlain by unit 60 sediments.

The fourth earthquake (event D) is the most strongly expressed event in our trenches. Evidence indicates that an ~10-m-wide and at least several-decimeters-deep sag pond was formed when unit 140 was at the surface. The depression was filled with fine-grained sediments of units 130 and 140. Additional significant evidence for this earthquake includes a blocky scarp colluvium composed of clasts derived from unit 140, and a younger moletrack within the sag pond depression at trench 11 (BDT11).

Unit 170 was at the surface when it ruptured during the fifth earthquake, event E. A filled fissure at trench 5 (BDT 5) containing pieces from units 180 and 170 is capped by sediments of unit 160 and 150. At BDT11, the main evidence is a tilted block containing unit 180 deposits and overlain by unit 150 sediments (Fig. 2).

The oldest earthquake that we have been able to resolve, event F, is only observed within our deepest trench, BDT11. The main evidence for this earthquake is a filled fissure that contains fragments from units 230 and 240. The fill material appears disturbed and is capped by unit 220, which buries a small scarp. Near the northeast end, there is an angular unconformity between the southwest-dipping units 230 and 240, and the flat-lying unit 220. This fault was reactivated during event E.

Earthquake Ages

We used 33 charcoal samples to constrain the ages of the last six earthquakes that ruptured the southern San Andreas fault in the Carrizo Plain. The radiocarbon ages were calibrated to calendar ages using OxCal software (Ramsey, 2005), following the methodology described in Akçiz et al. (2009). This software performs Bayesian statistical analysis using the Markov Chain Monte Carlo sampling process to estimate constrained probability distributions for layer and earthquake ages. The OxCal-modeled 95 percentile ranges accounting for radiocarbon calibration (causing somewhat arbitrary age separation from A.D. 1420 to A.D.1640), and stratigraphic constraints for the events and intervening layers of the 5 earlier earthquakes (and their medians) are A.D. 1631–1823 (1713), A.D. 1580–1640 (1614), A.D. 1510–1612 (1565), A.D. 1450–1475 (1462), and A.D. 1360–1452 (1417) (Fig. 3; Table 1). The intervals between these six events have a mode of ~88 yr and can be summarized by the average time interval between them of 88 ± 41 yr, or 99 ± 46 yr including the time since the last earthquake (Fig. 3, inset; Table 1).

IMPLICATIONS FOR FAULT BEHAVIOR

Chronological data from the Bidart Fan along with recently published displacement data from the Carrizo Plain (Grant Ludwig et al., 2010; Zielke et al., 2010) allow us to revisit the ideas about surface-rupturing earthquake occurrence in the southern San Andreas fault (Sieh and Jahns, 1984; Grant and Sieh, 1994; Liu et al., 2004) and fault behavior models in general (e.g., Schwartz and Coppersmith, 1984; Wesnousky, 1994; Kagan and Jackson, 1999). Data presented here suggest that earthquakes that ruptured the southern San Andreas fault in the Carrizo Plain between ca. A.D. 1360 and 1857 were more frequent (88 ± 41 yr) than previously thought (e.g., Sieh and Jahns, 1984; Grant and Sieh, 1994; Liu et al., 2004; WGCEP, 2008; Akçiz et al., 2009).

We cannot state definitely the slip and associated magnitude of all of the paleoearthquakes. A simple one to one correlation of the last five earthquake ages with the cumulative offset of ~30 m (Liu et al., 2004) measured at the Wallace Creek site yields a slip rate of 78 mm/yr. In a similar approach, if the 5 m peaks (from Zielke et al., 2010) are assumed to represent displacements occurring in successive ground-rupturing earthquakes, then the cumulative ~24.5 m yields an equivalent slip rate of 64 mm/yr. Both of those rates far exceed the ~34 mm/yr rates inferred from geodesy (Meade and Hager, 2005; Schmalzle et al., 2006) and from millennial-scale offset landforms (Sieh and Jahns, 1984; Noriega et al., 2006). One way to reconcile these results is an alternative assumption that the geomorphic offsets do not relate uniquely to the earthquakes. Such an alternative is more consistent with the geomorphology if some of the earthquakes do not contribute significantly to the accumulation of slip and channel abandonment.

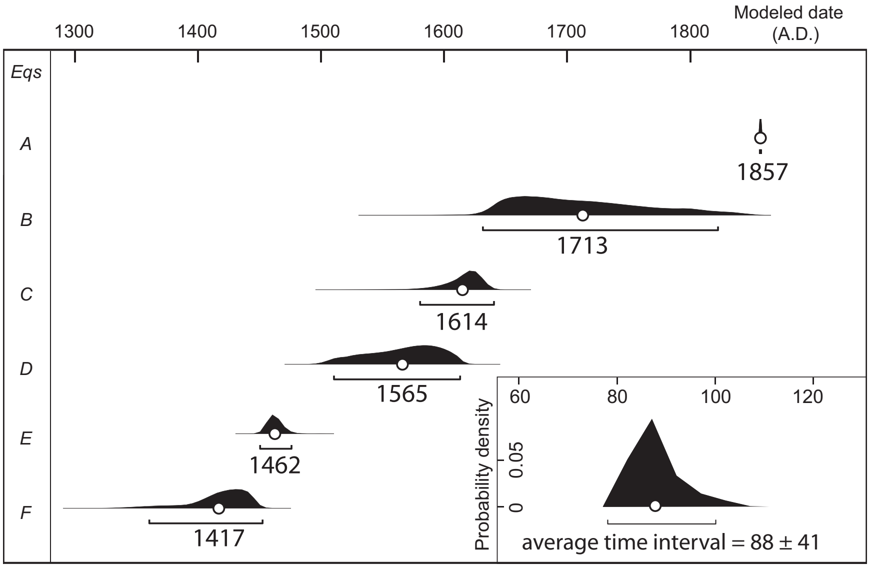

Figure 3. Probability density functions for earthquake (Eqs) ages at Bidart Fan site calculated by OxCal (Ramsey, 2005). Lines below each distribution show limit of 95.4 percentile confidence ranges for these earthquakes. Numbers below lines indicate median age. Inset shows probability density function of average time intervals between earthquakes that occurred in Carrizo Plain between ca. A.D. 1360 and 1857, as well as mean and standard error, which only account for dating uncertainties.

TABLE 1. AGE CONSTRAINTS AND TIME INTERVALS BETWEEN EARTHQUAKES THAT RUPTURED THE SAN ANDREAS FAULT IN THE CARRIZO PLAIN

EQ	Min (A.D.)	Max (A.D.)	Median	Interval Max – Min (yr)	Interval Median – Median (yr)	Interval Min – Max
	2010	2010	2010	153	153	153
A	1857	1857	1857	226	144	34
B	1631	1823	1713	243	99	–9
C	1580	1640	1614	130	49	–32
D	1510	1612	1565	162	103	35
E	1450	1475	1462	115	45	–2
F	1360	1452	1417			
Paleoseismic data alone			mean	175	88	5
			stdev	57	41	29
Paleoseismic data + open interval			mean	172	99	30
			stdev	52	46	66

Note: EQ—earthquake event (see text). Values were computed using OxCal software (see Ramsey, 2005). All dates are reported in calendar years. Min—minimum modeled age of an earthquake; Max—maximum modeled age of an earthquake; Median—value calculated by OxCal where 50% of the Probability Density Function (PDF) weight is on the other side; stdev—standard deviation. Average time interval between earthquakes is calculated using both the paleoseismic data alone, and with the inclusion of the elapsed time since the last earthquake until A.D. 2010. The intervals could be as large as the time between the maximum (youngest) age of an earthquake and the minimum (oldest) age of the prior earthquake (175 ± 57 yr), or as small as the minimum age of the earthquake minus the maximum age of the prior earthquake (5 ± 29 yr—effectively 0).

Zielke et al. (2010) and Grant Ludwig et al. (2010), suggested that ~5 m slip occurred during the 1857 and penultimate earthquake in the Carrizo Plain. The inferred incision age of a 16 m channel (ca. A.D. 1418), compared to the ages of the earthquakes that ruptured the Carrizo Plain, indicates that the three earthquakes prior to the penultimate earthquake (events C, D, and E) may have collectively produced a displacement of ~6 m in the same study area (Grant Ludwig et al., 2010). If we assume that the sag pond forming earthquake (event D) with vertical offsets ~1 m is responsible for the majority of the cumulative offset, we hypothesize that event D (A.D. 1510–1612) was also comparable to the 1857 and penultimate earthquakes in terms of magnitude and lateral displacement. That idea would help explain the preservation of a clear peak of offset at ~15 m (an additional 5–6 m more than the penultimate peak) reported by Zielke et al. (2010); its formation may have been dominated by slip in event D and the contributions from C and E are hidden within the observed offset range.

We cannot conclude whether all of the probable small slip-producing earthquakes in the Carrizo Plain (earthquakes C, E, and F) are due to moderate earthquakes rupturing locally (~M6.5–7), if they are the tail ends of large earthquakes reaching to the Bidart Fan from the southeast or northwest (e.g., Rockwell et al., 2002; Haeussler et al., 2004), or a combination of both. However, at the Bidart Fan there may be a correlation between the time intervals (approximated by the differences in median event ages computed by OxCal) between earthquakes and degree of disruption preserved on the trench walls during those earthquakes. The longest time intervals preceding earthquakes A, B, and D (144, 99, and 103 yr, respectively) correspond to the highest number and degree of earthquake deformation evidence (see the Data Repository). Likewise, the short time intervals before earthquakes C and E (49 and 45 yr, respectively) correspond to the modest earthquake evidence that we observed.

While earthquakes rupture the Carrizo Plain every 88 ± 41 yr on average, if the earthquakes with small slip in the Carrizo Plain are moderate magnitude and only slightly larger than the surface-rupture threshold (~M6.5), then 1857-like (M7.9) earthquakes may be recurring every ~150 yr (Zielke et al., 2010; i.e., time between earthquakes D and B, and B and A). Age constraints and slip estimates of the earthquakes at the Wrightwood site suggest that earthquakes B and D at the Bidart Fan might be correlative with earthquakes W3 (A.D. 1662–1700), and W4 (A.D. 1518–1542) at the Wrightwood site (Weldon et al., 2004), further supporting the possibility of these earthquakes being similar to the 1857 earthquake with ~5 m slip and >230 km rupture length. Likewise, at least one earthquake (event C) probably did not rupture the entire length of the southern San Andreas fault between the Bidart Fan and Wrightwood. Unlike the paleoseismic data from the Wrightwood site (Weldon et al., 2004), age and inferred slip per earthquake data at the Bidart Fan suggest slip-predictable earthquake behavior (Shimazaki and Nakata, 1980). There appears to be a positive correlation between the length of the interseismic period and the amount of slip in the next earthquake (with ~1 m and ~5 m offsets occurring when the time intervals between earthquakes are ~50 yr and ~150 yr, respectively).

CONCLUSIONS

Data presented here contradict previously published reports that suggest a low rupture potential for a section of the southern San Andreas fault (WGCEP, 1988, 1995, 2008). The average time interval of 88 ± 41 yr for surface-rupturing earthquakes along the southern San Andreas fault in the Carrizo Plain is the shortest average recurrence interval for any section of the San Andreas fault except Parkfield (Bakun and Lindh, 1985; Bakun et al., 2005) and similar to the recurrence interval estimates from Wrightwood, located near the southern end of the 1857 rupture (WGCEP, 2008, their Appendix B). However, in contradiction to the commonly accepted view of this section of the San Andreas fault (repetitive M7.8 earthquakes), the shorter recurrence interval corresponds to the average time interval between earthquakes of varying magnitudes in the surface-rupturing range of M6.5 and M7.9. The elapsed time since the last major earthquake (153 yr) is considerably more than the average time interval of this section of the fault, but also similar to the average time between 1857-like M7.9 earthquakes (~150 yr) if the interpretation presented here is correct.

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