Final Technical Report

RUPTURE HISTORY OF THE SAN ANDREAS FAULT IN THE CARRIZO PLAIN PRIOR TO 1200 AD

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Research conducted in collaboration with Prof. J Ramon Arrowsmith, Arizona State University, with Olaf Zielke and other students.

TECHNICAL ABSTRACT

Paleoseismological investigations of the San Andreas Fault (SAF) in the Carrizo Plain have greatly influenced general models of fault behavior and our understanding of seismic hazard in southern California. Interpretations from seven new excavations across the SAF at the Bidart Fan site in the Carrizo Plain contradict the widely accepted hypothesis that this section of the fault ruptures relatively infrequently and only during large earthquakes with large (~8 m) offsets. Preliminary interpretation of new paleoseismic data indicate that the Carrizo section of the southern SAF has ruptured six times since ~A.D. 1350. The most recent earthquake, event A, was the 1857 Fort Tejon earthquake. The penultimate earthquake, event B, occurred sometime after A.D. 1640. Four earthquakes, events C, D, E and F, occurred between A.D. 1250 and A.D. 1640. These new data from the northern section of the southern SAF indicate that since about A.D. 1350, the Carrizo section has failed more regularly and more often than previously thought. Additional paleoseismological investigations are needed to expand the record of the past earthquakes and determine the slip associated with each. This information will better constrain the past SAF rupture pattern–an essential element in the assessment of its future behavior.

NON-TECHNICAL ABSTRACT

The San Andreas fault is the most significant source of seismic hazard in California. It's proximity to densely populated and economically vital regions makes the risk associated with this fault a major threat to the nation as well as the state. Past behavior of the San Andreas fault is the best indicator of earthquake potential. This research constrains dates of past large earthquakes on the San Andreas fault in the Carrizo Plain and thereby helps to assess the potential magnitude, location, and date of future damaging earthquakes. Expected results of this research include recurrence time for large earthquakes on the San Andreas fault. This is an essential input parameter for development of National seismic hazard maps, and forecasts by the Working Group on California Earthquake Probabilities.

PUBLICATIONS

JOURNAL ARTICLE

Akciz, S.O.**,** Grant Ludwig, L., Arrowsmith, J R., 2009. Revised dates of large earthquakes along the Carrizo section of the San Andreas Fault, California, since A.D. 1310±30: *J. Geophys. Res*., 114, B01313, doi:10.1029/2007JB005285.

ABSTRACTS

Akciz, S. O., Grant L. B. and J. R. Arrowsmith**,** Revised dates of large earthquakes at Carrizo Plain section of the San Andreas fault, California, since A.D. 1280, *Multi-Hazards Around the Pacific Rim*, 2008 Association of Pacific Rim Universities Symposium, University of California, Davis, Aug. 21-22, 2008, p. 16.

Akciz, S. O., Grant Ludwig, L., Arrowsmith, J, and Zielke, O. (2008). Frequent surface rupturing earthquakes along the Carrizo section of the San Andreas Fault since A.D. 1250, *Eos Trans. AGU*, 89(52), Fall Meet. Suppl., Abstract T41A-1950.

Grant Ludwig, L.**,** and S. O. Akciz (2009). Century-long recurrence times for surface ruptures of the San Andreas fault in California (USA): Insights on earthquake potential from paleoseismology and recent large earthquakes, Session R1, Proceedings and Abstracts, IASPEI General Assembly 2009, Cape Town, South Africa.

REPORTS

This report

I. Introduction

Significance of the San Andreas fault in the Carrizo Plain

The San Andreas fault is the most significant source of seismic hazard in California (Figure 1). Its proximity to densely populated and economically vital regions makes the risk associated with this fault a major threat to the nation as well as the state. Past behavior of the San Andreas fault is the best indicator of earthquake potential.

The longest and best-dated record of large earthquakes in North America is from the Wrightwood paleoseismic site (Figure 2) near the southeastern boundary of the Mojave "segment" of the San Andreas fault (SAF) in southern California (Fumal et al., 2002; Weldon et al., 2004 and 2005). A record of 10 surface ruptures has been reported from the Pallett Creek site (Biasi et al., 2002; Sieh et al., 1989), also on the Mojave segment of the SAF in southern California. The record of ruptures from these two sites has formed the primary data set for probabilistic assessments of future southern SAF earthquakes, and for testing models of fault behavior and earthquake recurrence (Weldon et al., 2005; Biasi et al., 2002; Biasi and Weldon, 2008). Significant resources have been invested in these sites because of their proven record and rich potential.

However, there are many important questions about earthquake recurrence and fault behavior that cannot be adequately addressed with only two major sites. Figure 2 shows non-unique interpretations of space-time rupture histories for the southern SAF. Rupture scenarios are anchored by paleoseismic records at Wrightwood and Pallett Creek. The Wrightwood and Pallett Creek paleoseismic sites are only about 20 km apart (Figure 2), but correlation of specific ruptures between the two sites has been problematic (Biasi et al., 2002; Fumal et al., 2002; Sieh et al., 1989). Rupture extent and slip variation are essential fault-system parameters that can only be understood with improved spatial coverage. Several sections of the fault must be investigated to understand the potential for the largest earthquakes.

The Carrizo section of the San Andreas fault has been proposed to rupture only during the largest earthquakes, and thereby to control the occurrence of great quakes on the southern San Andreas (Schwartz and Coppersmith, 1984) with centuries-long recurrence times at Wallace Creek (Sieh and Jahns, 1984). As more data have become available, a more complex picture has emerged (Grant, 1996) with much shorter recurrence times (Table 1), comparable to other sections of the fault, and possibly clustered earthquakes (Grant and Sieh, 1994).

The Carrizo is one of the most productive sections of the San Andreas fault for paleoseismic data. Research in the Carrizo Plain has yielded multiple types of data such as slip rates from different time intervals at Wallace Creek (Sieh and Jahns, 1984) and Van Matre Ranch (Noriega et al., 2006) in agreement with geodetic measurements (Lisowski et al., 1991); measurements of slip for several ruptures (Arrowsmith and Zielke, 2009; Grant Ludwig et al., 2009; Liu et al, 2004 and 2006; Grant and Sieh, 1993; Grant and Donnellan, 1994); dates of 6-7 surface ruptures at the Bidart Fan (Akciz et al., 2009 and in prep; Grant and Sieh, 1994), and insights to channel response from tectonic offset at Phelan Creeks (Sims 1994).

Table 1. Average recurrence intervals for surface rupturing earthquakes at selected paleoseismic sites along the 1857 rupture section of the southern San Andreas fault.

Paleoseismic site *Carrizo sites in italics*	**Number of ruptures**	**Average Recurrence (years)**
Cholame LY4[1]	4	236
Wallace Creek[2]	*3*	*250-450*
Carrizo composite[3]	*6*	*235*
Bidart Fan[4a,b]	*5*	*156; 137*
Bidart Fan[5]	*6- 7*	*In preparation*
Frazier Mountain[6a,b]	2, 4	257-397, 100?
Pallett Creek[7]	10	135
Wrightwood[3]	15	98

References: [1]Stone et al. (2002); [2]Sieh and Jahns (1984); [3]Dawson et al. (2008) report composite values in WGCEP (2008) UCERF 2.0 Appendix B ; [4a]Grant and Sieh (1994), [4b] Akciz et al., (2009); [5]Akciz et al (in prep); [6a]Lindvall et al (2002); [6b]Scharer et al., 2007; [7] Biasi et al., (2002) after Sieh et al. (1989).

Most recently, analysis of paleoclimate data (Noriega, 2009) has provided a framework for interpreting tectono-stratigraphic evidence of paleo-earthquakes, as well as constraining the dates of channel incision and offset by paleo-earthquakes (Noriega, 2009; Grant Ludwig et al., 2009), in tandem with analysis of geomorphic features from high resolution LiDAR (Arrowsmith and Zielke, 2009; Hudnut et al., B4 data). In diversity of paleoseismic data, the Carrizo record rivals or exceeds both Pallett Creek and Wrightwood. We propose to exploit this record to further characterize the rupture potential of the southern San Andreas fault.

II. The Bidart Fan Paleoseismic Site

As shown in Table 1, there are only a few sites along the 1857 rupture section of the southern San Andreas fault (>500 km) that have a published chronology of at least 5 earthquakes. One of these sites is the Bidart Fan (Figure 3). The Bidart Fan site is an excellent place to develop a long chronology of earthquakes for the following reasons:

1) It has good stratigraphy for discriminating individual earthquakes and preserving material for radiocarbon dating. Sedimentation consists of areally extensive alluvial fan deposits, including debris flows, fluvially deposited sand and gravel beds, laminated silts, and clay lenses. Two *sag ponds* provide syntectonic depositional traps for preservation of paleo-earthquake evidence. The *smaller sag pond* is visible at the fan surface at Trench 4 (Figure 3). Evidence of 5 paleoearthquakes from the "T4" sag pond was the primary data set for the published record of Carrizo earthquakes (Grant and Sieh, 1994; Akciz et al., 2009). A larger, *buried sag pond*, was exposed by our field work in 2005-2008 (Figure 4). The stratigraphy in Trenches 5 and 7 – 11 preserved evidence of 6 earthquakes since 1345 A.D. (Akciz et al., in prep), and additional deeper events that we propose to date herein.

2) It has datable material. Detrital charcoal and in-situ datable organic material is commonly embedded in Bidart fan sediments. We collected hundreds of samples since 2005 field season. We collected over 300 samples just from trenches T10 and T11, which expose the older earthquake record that we propose to analyze for our next phase of work. We have successfully dated 30 samples from T11, including 4 from the older section targeted for this project (see Figure 5 box on southwest side of T11). In addition, we retain more than 100 samples collected during Grant's dissertation work in 1991. We successfully dated 36 archival samples and recently published the results (Akciz et al., 2009). We are working with John Southon and the UCI Keck AMS facility to refine radiocarbon dating methods for the semi-arid alluvial fan environment of the Bidart Fan site.

3) Geomorphic expression of the fault is clear and simple**.** With the exception of Trench 1 (excavated in 1989 and buried by a debris flow in 1991), the fault trace and all previous trenches are readily discernible on LiDAR images (Figure 3) as well as on aerial photos, and on the ground.

4) The pattern of deposition and geomorphic offsets on the Bidart Fan indicates that the active lobe of deposition has shifted around, thereby preserving ruptures at different time intervals in different places on the fan. This important feature of the Bidart fan allows us to "capture" a long record of earthquakes by placing trenches at multiple locations *along* the fault rather than by digging extremely deep trenches. The surficial pattern of sedimentation and channel incision on the Bidart fan, partly visible on Figure 3, shows that the area of active sedimentation has swept across the fan from northwest to southeast over the time period of several recent earthquake cycles (Grant and Sieh, 1994). At a specific location, there are "gaps" in the earthquake record due to lack of deposition from unfavorable climatic conditions (Noriega, 2009) and shifting locus of deposition across the fan. By examining earthquake evidence from multiple trenches across the fan and correlating chrono-stratigraphic units, we can piece together a picture of the rupture history of the San Andreas fault, analogous to putting together a jigsaw puzzle.

III. Results and their significance

In this section, we summarize our recent work and it significance in the context of improving the paleo-earthquake chronology at the Bidart Fan. A total of 14 trenches have been excavated in the SAF zone on the Bidart Fan: one by Sieh and Prentice in 1989, three by Grant and Sieh in 1991, and 10 trenches in our most recent phase of work 2005 – 2008 which includes efforts to date paleo-earthquakes and measure associated slip. Locations of 12 trenches are shown on Figure 3. In 2005 and 2006 we were funded by NSF to improve the "multi-cycle rupture history of the San Andreas fault in the Carrizo Plain" by increasing the spatial coverage of trenches on the Bidart Fan. In parallel, the Southern California Earthquake Center (SCEC) provided modest funding to cover direct costs of dating archival samples from Trenches 2, 3 and 4. We received funding from USGS grant 07HQGR0092 (this project) to dig deeper trenches and try to extend the record of earthquakes prior to 1200 A.D. All of these efforts have been productive and

have yielded significantly revised dates and recurrence intervals for Carrizo earthquakes, as described below, and displayed in Table 2 on Figure 5.

The first Bidart trench (T1) was excavated, logged and interpreted by Prentice and Sieh in 1989, but not formally published. Trench logs and summary evidence for 6 or 7 ruptures were summarized by Sieh in Yeats et al., 1997. The oldest rupture in Trench 1 occurred circa 3000 BP. The most recent rupture is assumed to be the historic 1857 Fort Tejon earthquake (Sieh, 1978). Dates of 6 previous earthquakes in Trench 1 are poorly constrained by the ages of detrital organic material in the sediments. "Gaps" in the record of earthquakes occur at different times in different trench sites. The gaps are massive, featureless zones caused by bioturbation of the fan surface while that portion of the fan was depositionally inactive. One of the gaps has been tentatively linked to a major period of drought (Noriega, 2009).

Dates of five earthquakes and evidence of 2 older, undated ruptures were compiled from Trenches 2, 3 and 4 and published by Grant and Sieh (1994). Dates are displayed in the left column of Table 2 on Figure 5. Results showed that the 5 youngest earthquakes, including the 1857 Fort Tejon earthquake, occurred since 1218 A.D. The average interval was approx. 160 years, but dates of individual events suggested possible temporal clustering, with 4 closely spaced intervals and one long interval. The data and interpretation were controversial and the relatively short recurrence interval was met with skepticism. Other workers selectively reinterpreted the results by reducing the number of earthquakes (see "CP" events in box on Fig. 2) and increasing the recurrence interval (see "Carrizo composite" in Table 1). The small number of dated earthquakes (5) and uncertainty in dates made it impossible to rigorously test the hypothesis of clustering, which has important implications for hazard analysis.

We have recently improved the paleoseismic record originally published by Grant and Sieh (1994) with additional radiocarbon dating and publication of complete trench logs (Akciz et al., 2009). Grant archived several hundred samples from T2, T2 and T4 that were too small for radiocarbon dating at the time of the original study. The original "GS94" record was based on a total of 14 radiocarbon dates, and only two samples were used to constrain the time interval during which 4 of the 5 earthquakes occurred. The ages of the intervening earthquakes were interpolated from these constraints – they were not individually dated.

With access to UCI's Keck Carbon Cycle AMS facility, we have been able to date nearly 28 additional samples, and better understand and interpret the provenance of the samples and significance of the dates. We also applied Bayesian statistical methods (OxCal, Ramsey, 2005) to reduce uncertainty in dates. We discovered systematic bias in the selection of Grant and Sieh's samples for radiocarbon dating. With limited access to radiocarbon dating resources (9 months turnaround time) and inability to date the smallest samples, Grant and Sieh (1994) consistently selected large samples to yield the highest precision measurements. These samples turned out to be older, presumably because of inherited age. At UCI, we can date much smaller samples with high precision, and we are able to examine the samples in detail before processing for the accelerator to distinguish between twigs, grasses, and detrital charcoal. This yields younger ages that are also more representative of the dates of the earthquakes. Revised dates are shown in the middle column of Table 2 (Akciz et al., 2009). Average recurrence interval for these events is 137 $\pm$ 44 years (Akciz et al., 2009), which is significantly less than the "Carrizo

composite" average recurrence time reported by Dawson et al. (2008) for the Uniform California Earthquake Rupture Forecast 2.0 (WGCEP, 2008).

In parallel with the "re-dating" effort, we excavated 10 additional trenches to improve the chronology of past earthquakes by lengthening the record and attempting to document slip associated with the last 5 or 6 earthquakes. We are beginning to write up the results for publication as we finish the last phase of funded field work in summer 2009. Data from five of these trenches (T5, T7, T8, T10 and T11 on Figures 3 and 4) have yielded significant results. As illustrated in Figure 4, these trenches revealed a paleo-sag pond which received sedimentation and recorded evidence of earthquakes for approximately the last 750 years. The partially drafted log of Trench 11, southeastern wall, is shown in Figure 5 as an example. This panel displays evidence of 6 earthquakes in the younger part of the section (focus of our current work) and additional earthquakes in the older part of the section. We collected over 300 samples from these trenches, selected 50 for radiocarbon dating, and applied statistical methods (OxCal, Ramsey, 2005) to "trim" the age uncertainty in the events. We are currently drafting the logs for publication, focusing on the younger part of the section containing 6 earthquakes.

The preliminary dates of 6 paleo-earthquakes are shown in the right column of Table 2. We are currently checking and recalculating these dates. The relatively rapid rate of sedimentation in the sag pond provided favorable conditions for "capturing" evidence of a sixth earthquake that was not reported by Grant and Sieh (1994). In addition, the sag pond sediments contained a higher proportion of in-situ plant material that yielded younger dates than reworked detrital material that predominates elsewhere on the fan outside the sag pond deposits. The overall result is a significantly younger record of earthquakes and a shorter recurrence interval. This yields a short recurrence time (approx 100 years or less) for ruptures of the San Andreas fault, and motivates re-evaluation of recurrence models such as the characteristic earthquake model (Schwartz and Coppersmith, 1984). The most recent rupture occurred in 1857, suggesting that the SAF in the Carrizo Plain has a high probability of rupture in the next few decades. Additional research is needed to find out if the short recurrence time holds for a longer time interval (i.e. prior to 1300 AD) or if the model of clustered earthquakes proposed by Grant and Sieh (1994) still holds for the Carrizo. It is important to determine the variability in time between ruptures to constrain uncertainty in probabilistic calculations of rupture potential.

Our excavations also revealed two older stratigraphic sections that are not currently tied to the younger 6 events: (1) an older section of the fan which got juxtaposed against a paleo-sag pond section of the fan which received continuous sedimentation for the last 750 years and preserved evidence for the last six earthquakes, and (2) a push-up structure bounding the aforementioned sag pond to the northwest, which remained as a high ground during the recent earthquakes, but structurally exposed potentially older earthquake evidence. Future research, including expensive field work, will be needed to document the ages of the earthquakes between the most recent six earthquakes and these older earthquakes, a case similar to our understanding of the earthquake chronology at the Wrightwood paleoseismic site. A long and complete chronology of events must be developed to find out if the short recurrence time from the 6 most recent events holds for a longer time interval (i.e. prior to 1350 AD), or if the

model of clustered earthquakes proposed by Grant and Sieh (1994) still holds for the Carrizo.

Our current knowledge of the structural and sedimentological evolution of the Bidart Fan in the last 1000 years suggest that deeper (>15 feet) section just southwest of the T11 trench (Figures 4 and 5) is the best target site for exposing the older earthquake records. Preliminary data shows this section is 3,000 to 4,000 years old. Part of this section is outlined with a box on Figure 5. Four radiocarbon dates range from approx. 800 BC to 2400 BC. Expensive excavations will be required to tie this part of the section to the younger events.

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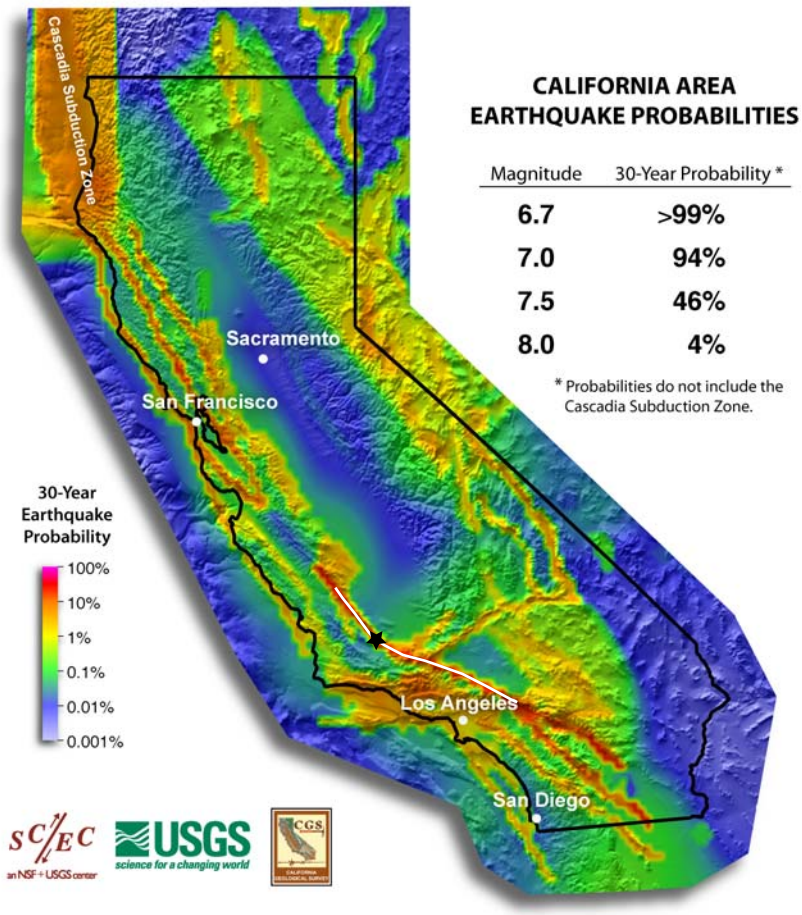

Figure 1. 30-year earthquake probabilities in California based on the Uniform California Earthquake Rupture Forecast (UCERF). The colors represent the probabilities of having a nearby earthquake rupture (within 3 or 4 miles) of magnitude 6.7 or larger in the next 30 years. As shown in the table, California has more than 99% chance of having a magnitude 6.7 or larger earthquake within this time period. The likelihood of a major earthquake of magnitude 7.5 or greater in the next 30 years is is about 46%. The location of the Bidart Fan paleoseismic site (black star) and the extent of the 1857 rupture of the San Andreas Fault (white line) are also shown.

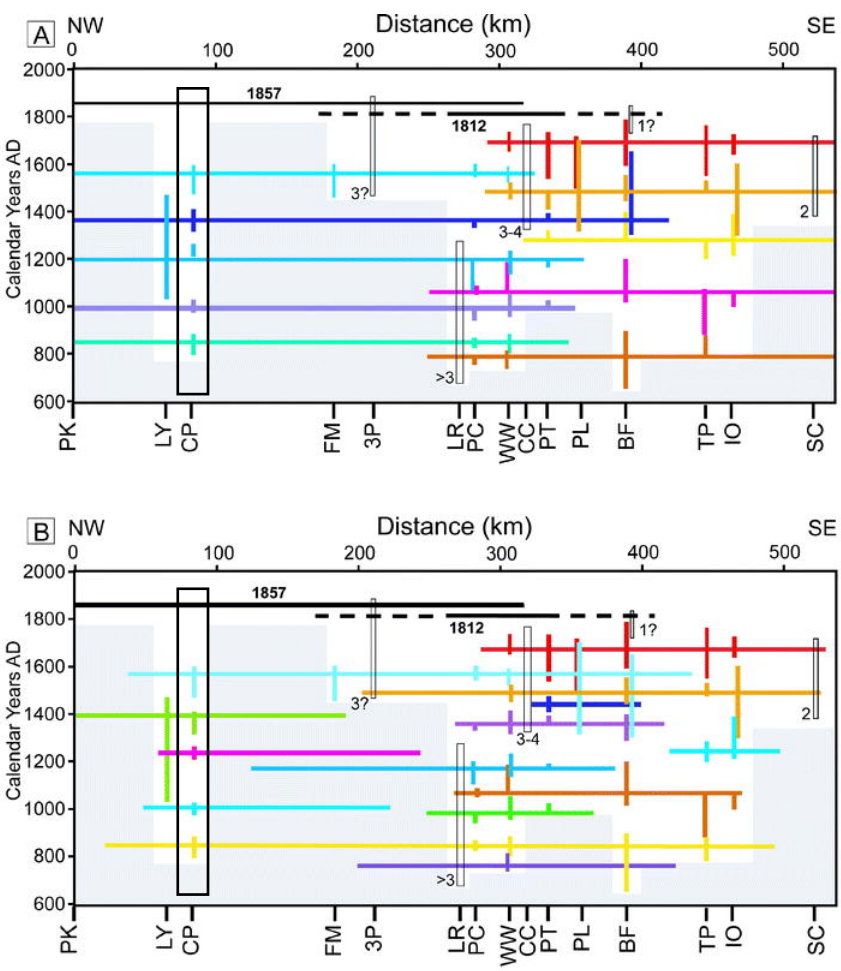

Figure 2. Two possible rupture sequences on the southern San Andreas fault (modified from Weldon et al., 2004). Vertical colored bars are ranges in age for earthquakes at the sites listed at the lower margin and horizontal bars are hypothetical rupture lengths. Open boxes represent multiple event age 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, ; CP—Carrizo Plain, (black box) ; FM—Frasier Mountain; 3P—Three Points; LR—Littlerock; PC—Pallett Creek; WW—Wrightwood; CC—Cajon Creek; PT—Pitman Canyon; PL—Plunge Creek; BF—Burro Flats; TP—Thousand Palms Oasis; IO—Indio; SC—Salt Creek.

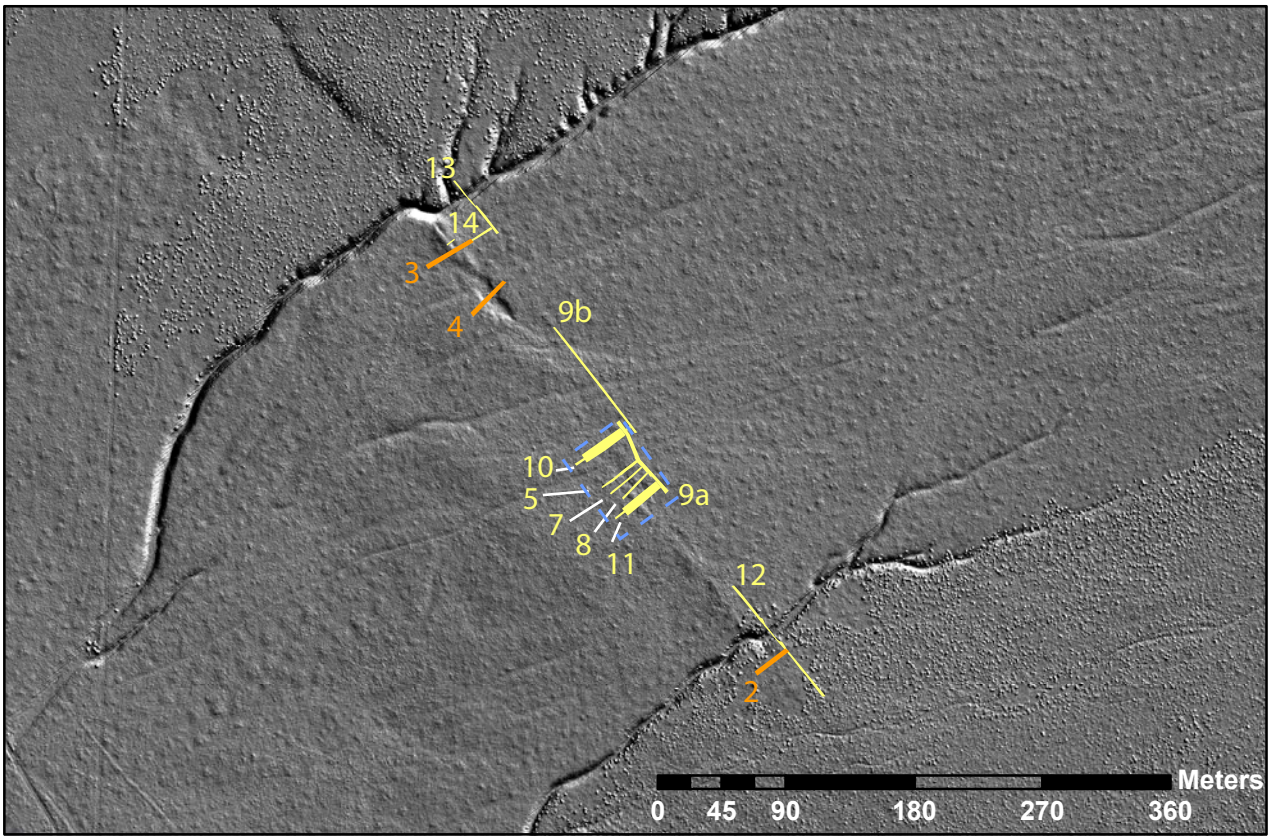

Figure 3. Locations of trenches at the Bidart Fan paleoseismic site along the Carrizo section of the southern SAF. Orange trenches (2-4) were excavated and published by Grant and Sieh (1994) and Akciz et al. (2009). Yellow trenches (5, 7-14) were excavated between 2005 and 2008. Blue box shows the area that is schematically drawn in Figure 4. The shaded relief basemap was produced by using the "B4" lidar data available from http://www.opentopography.org

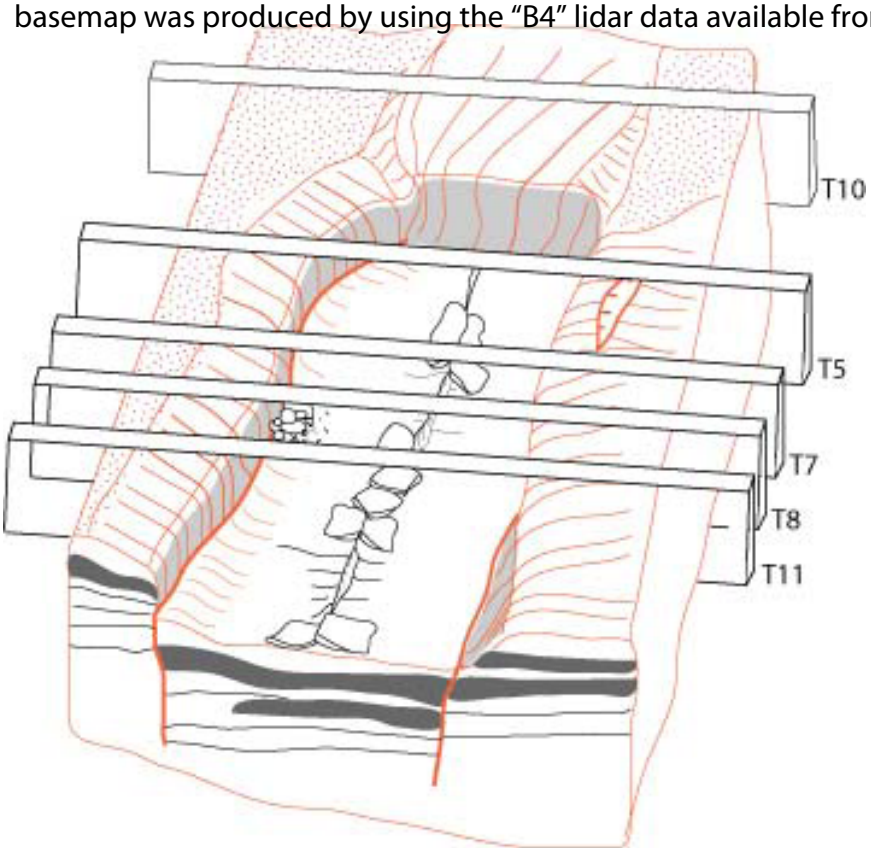

Figure 4. Cartoon diagram of what an approximately 50 m section of the SAF looked like at around A.D. 1550 (see the blue box on Figure 3 for its exact location) at the Bidart Fan paleoseismic site. All of the schematic features are based on the trench logs produced during the previous excavations. Rectengular boxes indicate the locations of the trenches that the interpretations are based on.

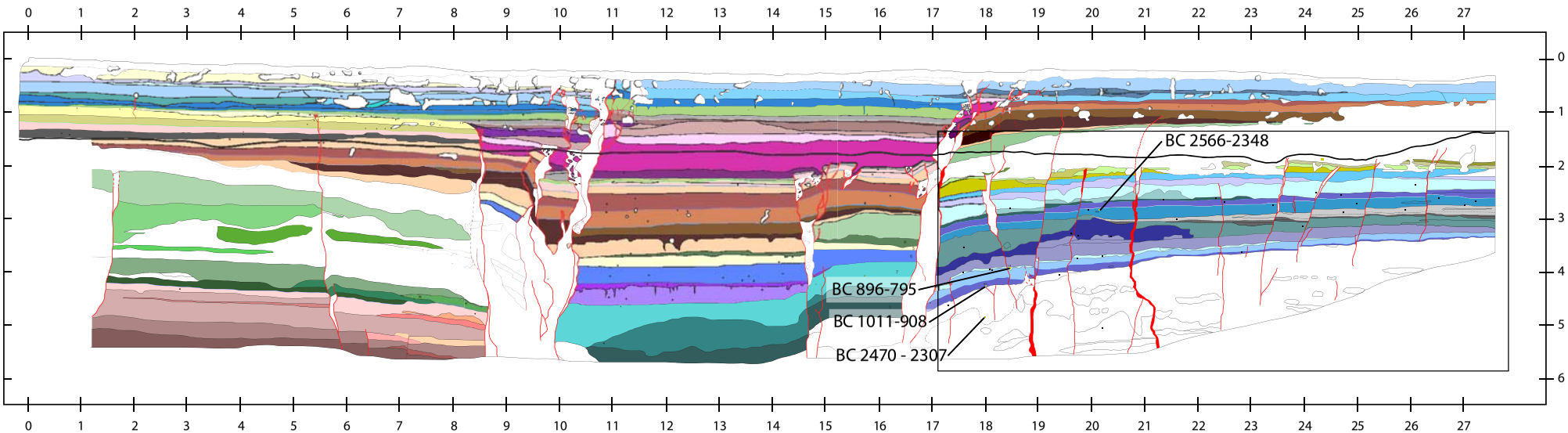

Figure 5. Trench log of the SE wall of T11 (see figures 3 and 4 for locations). The older section of the fan that is now juxtaposed against the younger (~ last 800 years) section is enclosed in a box. Preliminary radiocarbon analyses results are also shown. White areas are either bioturbated zones or fault fissures and shear zones.

Grant&Sieh, 1994	Akciz et al., 2009	Akciz et al., in prep
1857	1857	1857
1405-1510	1640-1857	1640-1840
1277-1510	1545-1630	1540-1670
1277-1510	1360-1425	1510-1640
1218-1276	1280-1340	1465-1525
after 200 B.C.		1345-1430
after 200 B.C.		

Table 2. Comparison of the ages of the earthquakes documented at the Bidart Fan paleoseismic site by various studies. Akciz et al. (2009) dated archieved samples from the original Grant & Sieh trenches. Akciz et al. (in prep) column shows the summary of the new results from the excavations conducted between 2005 and 2008 (see figures 3 and 4 for trench locations).