FINAL TECHNICAL REPORT

LATE HOLOCENEEARTHQUAKE HISTORY OF THE ANZA SEISMIC GAP CENTRAL SAN JACINTO FAULT ZONE, SOUTHERN CALIFORNIA

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Abstract

A network of deep trench exposures at Hog Lake on the central San Jacinto Fault in southern California provides evidence for 16-18 surface ruptures in the past 3.8-4 ka. This yields a long-term recurrence interval of about 230 years, consistent with its slip rate of 12-15 mm/yr and field observations of 3-4 m of displacement per event. Age control is based on nearly 150 radiocarbon ages on accumulations of annual seeds, *in situ* reed charcoal, detrital charcoal, and lacustrine gastropod shells. The seed dates are almost all in correct stratigraphic order, as are most charcoal dates, and show little evidence of reworking or vertical migration within the section, so ages of most units have been determined to within a few decades. During the past 3800 years, the fault has switched from a quasi-periodic mode of earthquake production, during which the recurrence interval is similar to the long-term average, to clustered behavior with the inter-event periods as short as 20-30 years (five surface ruptures between about AD 1025 and 1360). There are also some periods as long as 550 years during which we have recognized no evidence for any surface ruptures, and these periods are commonly followed by two or more closely-timed ruptures. Similar behavior has been observed on the San Andreas Fault at Wrightwood, where a cluster of seven surface ruptures occurred between AD 500 and 1000, the same period during which only one rupture is recognized at Hog Lake. During the San Jacinto cluster between AD 1025 and 1360, earthquake production at Wrightwood was suppressed. These observations suggest that earthquake production on a fault can be quite variable over the time frame of several earthquake cycles, and that part of this variability may be influenced by interaction with nearby major faults. This has major implications on using time-based conditional probabilities to estimate future seismic hazard unless one has knowledge on the long-term behavior of the fault in question, as well as an understanding of local and regional fault interaction.

Introduction

The Hog Lake paleoseismic site lies within a closed depression in the "Anza seismicity gap" along the central Clark strand of the San Jacinto fault in southern California (Figure 1). The site is typically inundated during the winter months, and generally dry during the summer. This section of the San Jacinto fault is very straight, and nearly all late Quaternary slip is localized along the strand that traverses through Hog Lake (Rockwell et al., 1990, Rockwell and Ben-Zion, 2007). The closed depression is largely created and

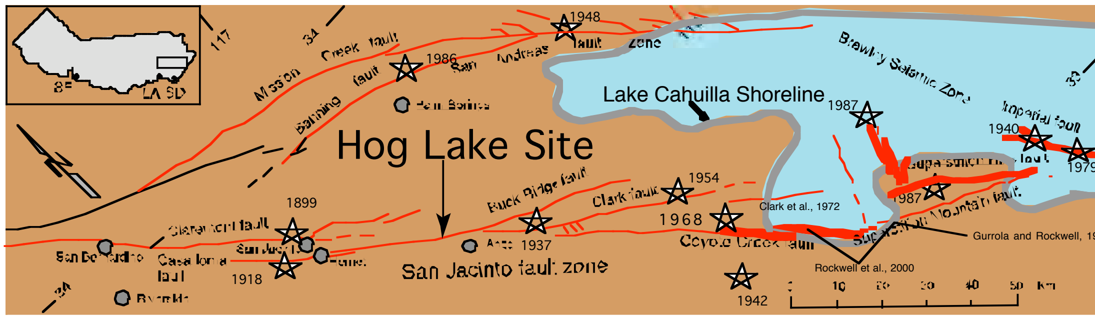

Figure 1. *Map of the San Jacinto fault zone showing the Hog Lake site near Anza, earthquakes of M6 and larger during the past century or so (stars), and known surface ruptures (thick red lines). Also shown is the shoreline of the 300 year-old Lake Cahuilla, below which several paleoseismic studies have been conducted to resolve high-resolution ages of past events on the southern San Andreas, San Jacinto and Imperial faults.*

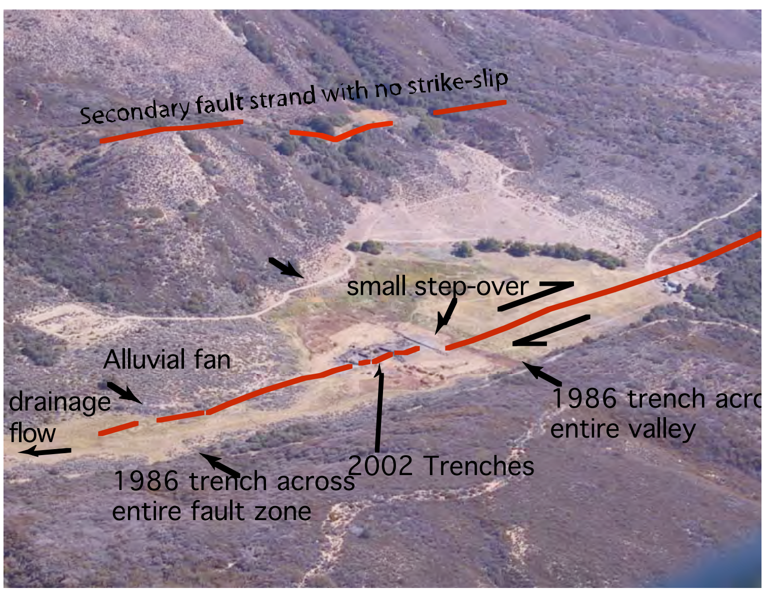

Figure 2. *Oblique air photograph of the Hog Lake site during our Fall, 2002 excavations. Note also the locations of our 1986 trenches that extended across the entire valley and demonstrated only a narrow fault zone on each side of the depression. A small step-over is present near the center of the depression. The depression is caused, in part, by blockage of the drainage to the northwest by the small alluvial fan.*

preserved by the development of two alluvial fan systems that drain Thomas Mountain, with the smaller, northwestern fan building out and blocking the northward flow of the larger fan (Figure 2). The fault has a minor southwest-side-up component of slip (Rockwell et al., 1990), thus providing an escarpment against which the alluvial fan deposits can pond. The larger fan drainage is interpreted to have flowed through a wind gap, located a few hundred meters southeast of Hog Lake, but now that drainage is beheaded due to fault slip and the dryer

Holocene climate and the entire run-off is trapped in Hog Lake.

The stratigraphy at Hog Lake is exceptional, with cm-scale resolution of individual units and the general absence of bioturbation because of the high groundwater conditions. Further, the strata contain abundant organic-rich “peat-like” deposits that contain abundant seeds, detrital charcoal, fresh water pond snails, and in-situ reed growths, all of which have yielded stratigraphically consistent radiocarbon ages. The oldest stratum exposed on the downthrown side of the fault at 6.5 meters depth is only about 2500 years old. However, older stratigraphy on the southwestern block contains an older primary strand of the fault that allows for development of a longer paleoseismic record back to about 4,000 years. All of these conditions have combined to make this an ideal site to study the occurrence of past earthquakes.

Motivation

There are two principal motivations for choosing the Hog Lake site to study past large earthquakes along the San Jacinto fault. The first, of course, relates to assessment of sesimic hazard, as accurate forecasting of large earthquakes requires a complete record and understanding of the short and long-term behavior of a fault. The other relates more to understanding the general behavior of faults, an whether they produce seismicity in a fairly “predictable” fashion (quasi-periodic, clustered) or is it largely independent of the elapsed time since the previous event (poissonian). Furthermore, the significance of fault interaction and the possible role of the San Andreas and San Jacinto faults in modulating regional seismicity are only now beginning to be addressed (Bowman et al., 2001), and the significance of these factors in regional seismic production could be key elements. In California, the earthquake cycle for individual faults is too long to make historical observations of recurrence for a fault segment or group of faults. Thus, we must rely on paleoseismology to develop observations of large earthquakes over long time periods and multiple earthquake cycles.

The San Jacinto fault is one of the primary plate boundary faults of the southern San Andreas system (Figure 1), with the second highest slip rate of any fault in southern California, accommodating about 30-40% of the total plate margin motion (Rockwell et al., 1990; Merifield, Rockwell and Loughman, 1991; Fialko, 2006). The fault has produced at least 10 earthquakes over M6 in the past 110 years, although only a few are known to have ruptured the surface (1968, 1987a, 1987b, and possibly 1918). The Hog Lake site lies along the central San Jacinto fault in the “Anza seismicity gap” ((Sanders and Kanomori, 198_) and contains a remarkably good stratigraphic record of past surface ruptures that allows for development of a long record. The "Anza gap" is a section of the fault along which the seismicity is generally deep, and what micro-seismicity that does occur is generally sparse. For fast-slipping faults, this generally implies that the fault is locked, and the lack of observations of fault creep support this interpretation. Thus, if the Anza seismicity gap indicates the presence of an asperity or strongly couple section of the fault, this is an ideal location to study the long-term patterns of strain release and test the standard recurrence models that are commonly used in hazard estimates (WGCEP, 2008).

Site Stratigraphy and Age Control

In our 2004 trenches (Figure 3), we exposed over 6.5 meters of finely stratified sand, silt, and clay on the downthrown (NE) side of the fault in trench T2 (Figure 4), with

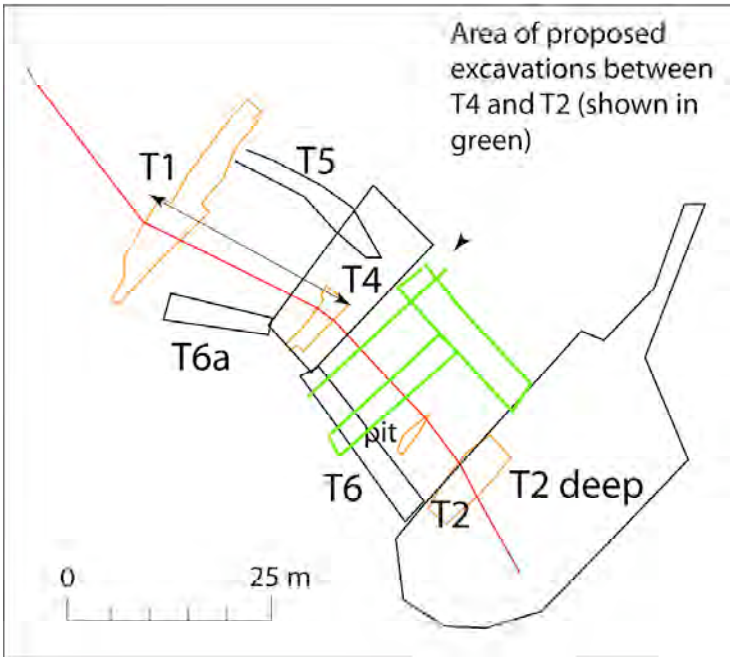

Figure 3. *Map of surveyed locations of the primary trenches from 2002 (in orange) and 2004 (in black), along with the location of trenches we plan to open in 2009 (in green).*

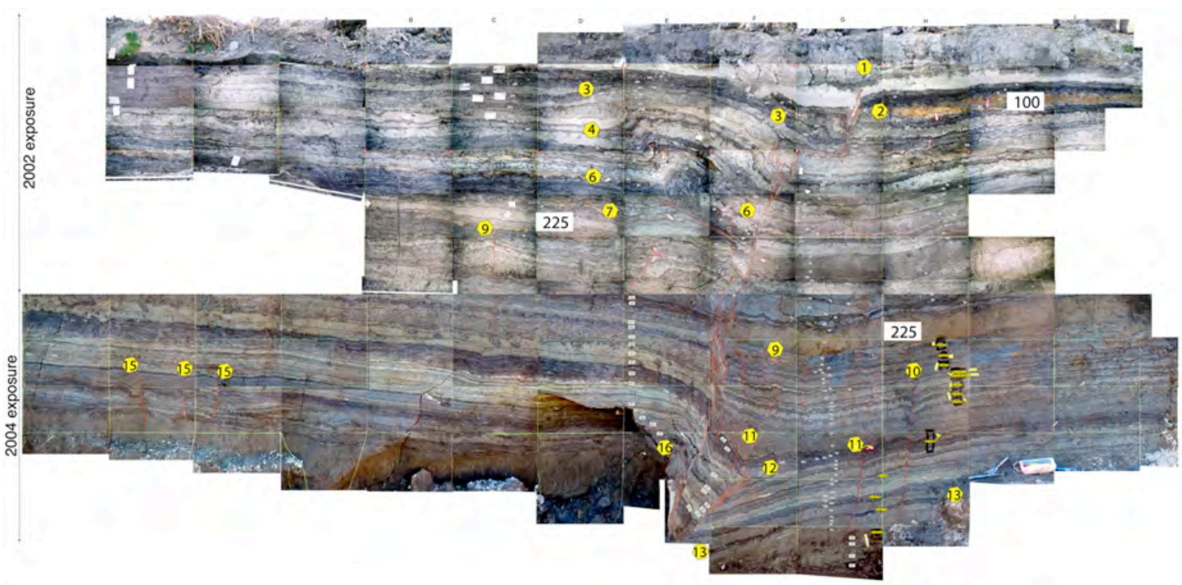

Figure 4. *Photomosaic with interpretation of trench T2N, cut 3. The stratigraphy has been wrapped through all trenches by tracing all units with fault-parallel trenches, so the unit designations here are the same as for equivalent units in T4 of figure 5. Interpretation of events are based on this and many other exposures. Note that this exposure does not have evidence for all*

the oldest section dating to about 2500 years B.P. An even older section is exposed in trench T4 on the upthrown (SW) side of the fault (Figure 5), where strata dating to as old as 4000 years are present.

The strata are dominated by quiet-water deposition of finely-laminated clayey silt with some interbeds of well-sorted sand. We numbered the strata from youngest (low numbers) to oldest (high numbers), with unit 50 near the top being the youngest mapable stratum. The distribution of some units, such as the sand and gravelly sand of units 150 and 225, indicate that the alluvial fan bounding the northern side of the depression is the primary source for the clastic material in these trenches. Exploratory pits also demonstrated that coarse clastic material is derived from the large alluvial fan on the southeastern side of the depression, but this was not the source for must clastics exposed in our trenches. We infer that the finer strata are derived collectively from both sources during large storms, during which most deposition likely occurs.

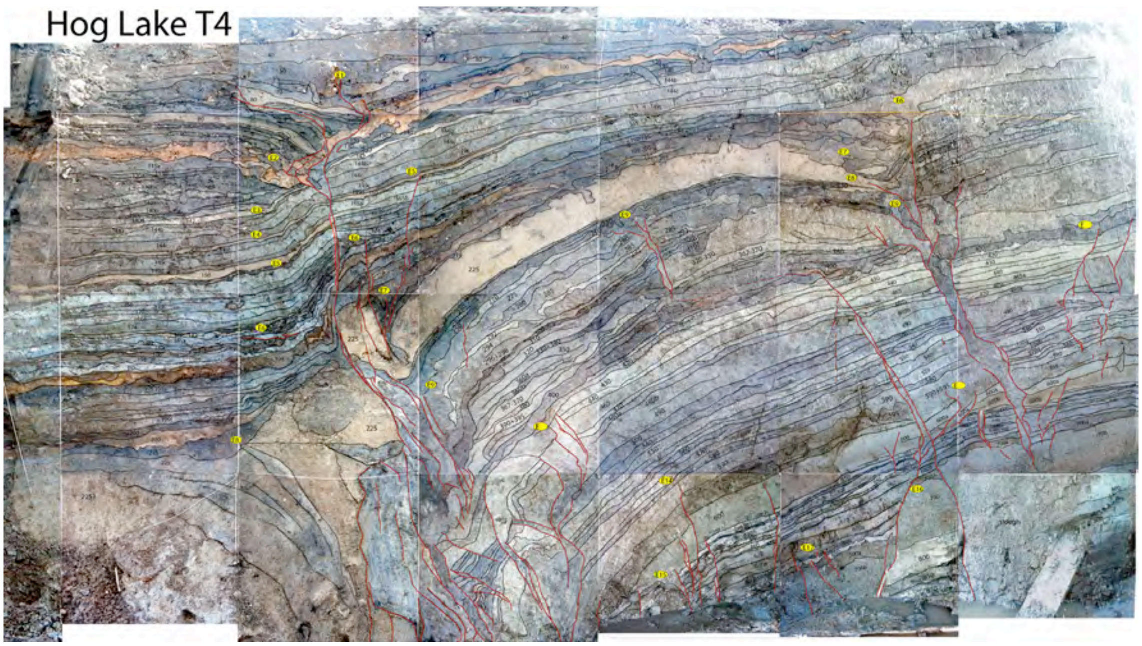

Figure 5. *The faulted portion of trench T4. Note that an older fault was exposed a few meters to the west (right in this image) that has not ruptured in the past several events. Distributed faulting is ideal for resolution of surface ruptures. Also note that evidence for some events exposed in T4 is obvious (such as for event E8, whereas evidence for this same event is obscure in trench T2S. For this and other reasons, many exposures are required to adequately characterize the earthquake history at a site.*

Some units, such as unit 100, appear to have experienced in situ burning, based on their bright orange colors and the fact that they grade to highly organic-rich peaty deposits in depressions that may have been wet during a burn. Some of these units, in combination with under- and over-lying strata, provide unique stratigraphic markers that confirmed correlation of units and sequences across faults. We also opened fault-parallel trenches (T5, T6, T6a) to "hard-correlate" stratigraphy, as many units are quite similar in appearance and texture and some of our early correlations turned out to be wrong.

The dating was conducted on a variety of materials to test consistence and variability between seeds, charcoal, in situ reeds, and shells (Table 1). In general, the shells date slightly older (couple hundred years), the seeds are remarkably consistent, and the charcoal varies from being identical to the seed dates to up to several hundred years older, presumably due to the affect of burning old wood and detrital residence. Figure 6 shows the probability distributions of the seed and reed charcoal dates for the entire section.

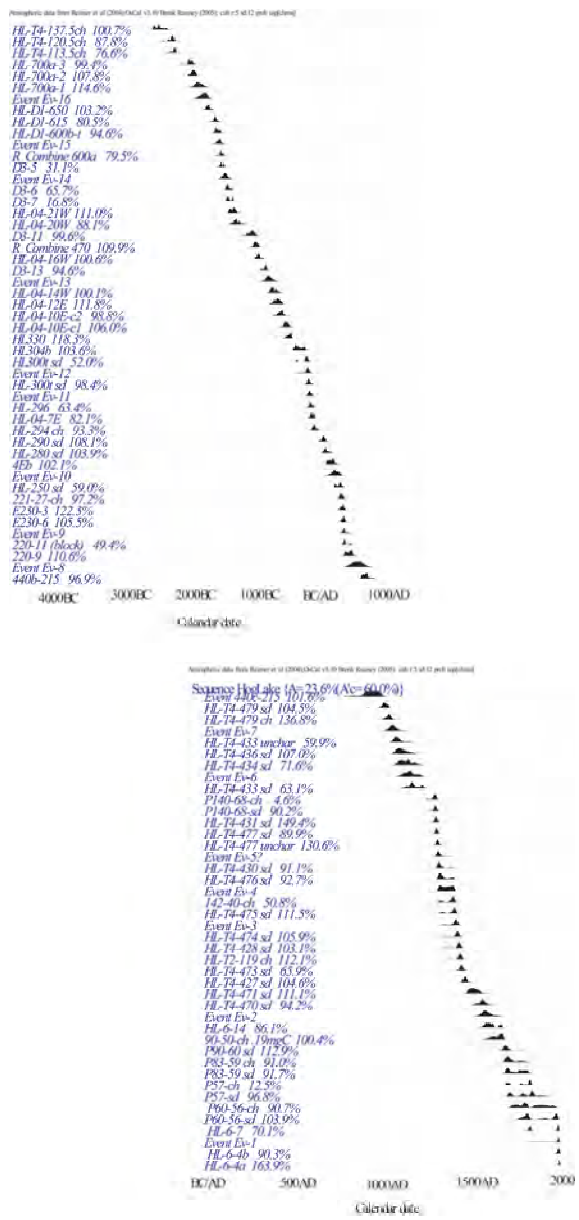

Figure 6. *OxCal output for more than 80 radiocarbon dates on seeds and reed charcoal from the strata at Hog Lake. The upper left diagram represents the uppermost part of the section, with each succesive panel downwards showing dates from progressively older strata. The upper right panel continues the dating downward to the lowest right panel, with the oldest samples yielding dates of about 4000 years.*

Earthquake Chronology

We have identified up to eighteen surface ruptures in the stratigraphy at Hog Lake, although evidence for one is weak. We used upward abrupt fault terminations and fissure fills, folding, the presence of angular disconformities, the presence of growth strata and thickened or thinned sections, and liquefaction as indicators of past surface ruptures. Although few of these criteria are convincing by themselves, the multiple lines of evidence encountered in most exposures consistently showed abundant evidence for most of the interpreted surface ruptures. We number the events from youngest (E1) to oldest (E18) for convenience at this time. Event E18 was exposed in the oldest part of the section in trench T-4, as shown in figure 4.

Events E1 and E2 ruptured on almost the same crack in the majority of exposures, overprinting some of the evidence for event E2 (Figure 7). However, in our original 1986 excavations, we exposed several trench faces that showed distinct rupture on separate cracks (see Figure 8), with E2 rupturing up through unit 100 and producing a scarp against which units 90 through 60 were deposited. Event E1 then broke on a separate crack up through unit 57 and is overlain in some exposures by undeformed unit 50. From such exposures where these two events are distinct, we know the precise event horizons, and we see much supporting evidence in other trenches, even where the relationships are less clear.

An important point here is that multiple exposures are required to adequately characterize the rupture history, even for the most recent events. In many exposures, event E1 obliterated much of the evidence of event E2, as in figures 4, 5 and 7. In spite of that, knowing from exposures where these relationships are obvious allows for recognition of the obscured evidence in other exposures.

Events E3, E4, E5 and E6 all produced progressive rupture and folding in trench T2N (Figs. 4 and 9). The fold is a minor secondary break-out structure that is only present very locally in the area of the north wall of T2. Evidence for E3 was also present in most other exposures although it is not as clear in trench T4 where it is marked by an angular unconformity (Fig. 10). E4 was marked by a clear abrupt upward termination on the south face of T2 (Fig. 11), and by upward termination and growth strata on the north face of T2 (Figure 9).

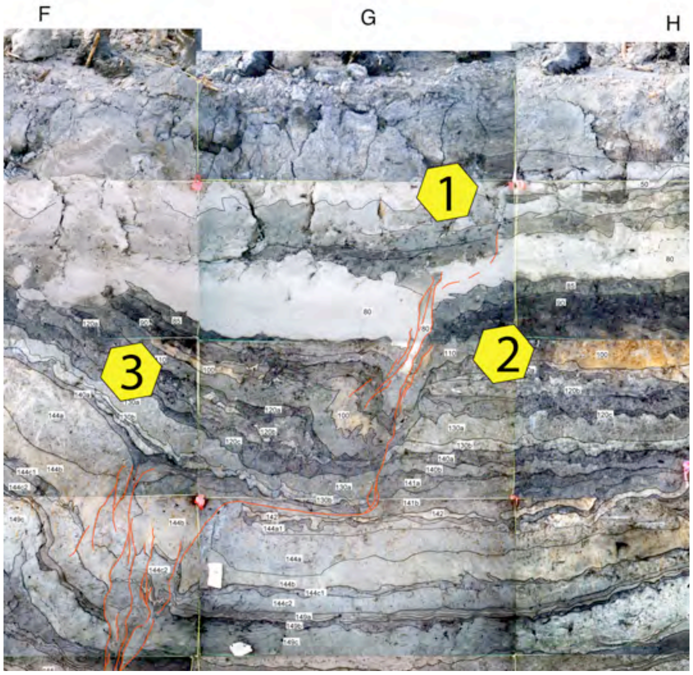

Figure 7. *Photomosaic and log showing evidence of events E1, E2, and E3 in trench T2, north wall, cut 3. Note that event E1 has partially obliterated evidence of event E2 by re-rupture along the same strand. Evidence for event E2 is still seen by the greater vertical displacement of unit 100 than unit 80, and by liquefaction and folding of units 120 through 95, overlain by less deformed unit 80. Event E3 is clear as an upward termination of multiple fault splays and an associated fissure fill, and by folding of units below unit 144.*

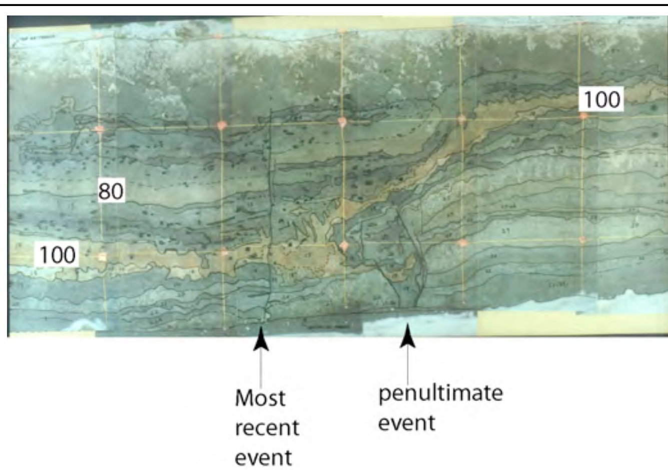

Figure 8. *Exposure from 1986 showing separation of the rupture location between the most recent event (E1) and the penultimate event (E2). Note that for E1, units are down to the right near the base of the exposure and up to the right near the top, indicating significant lateral slip.*

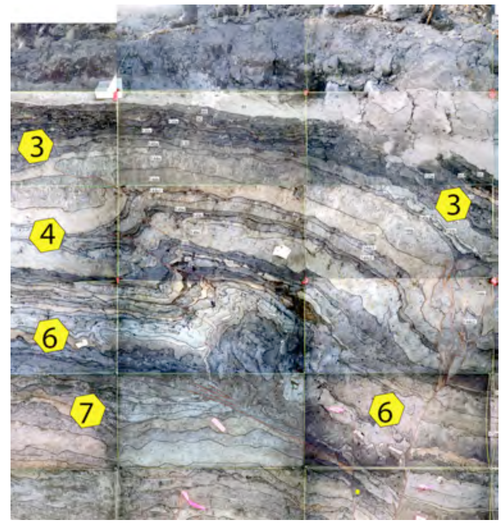

Figure 9. *Secondary break-out fold adjacent to the main trace that ruptured in events E3, E4, and E6, and possibly E5. The evidence for event E5 is in the form of growth strata, and growth strata are also associated with each of the other events. Event E7, in contrast, is indicated by minor rupture on a secondary fault, as well as clear rupture and folding in the main fault zone.*

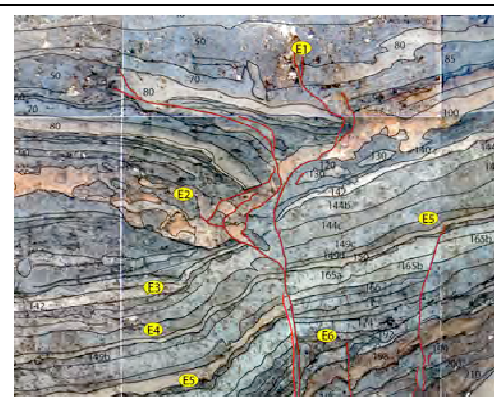

Figure 10. *Photomosaic of the south wall of trench T4, cut 3. Note the repeated section of unit 80 by event E1, which can only be resolved with strike-slip. E2 is only represented by liquefaction and disruption of unit 100, overlain by bedded section. Event E3 is represented by an angular unconformity and folding, as are events E4 and E5, but E5 is also represented by an upward termination on a secondary fault.*

Events E6 through E13 are well-expressed in various exposures, and are represented by upward terminations, fissure fills, growth section, folding, and angular unconformities. Figures 12 through 17 provide a few examples of these and other older events.

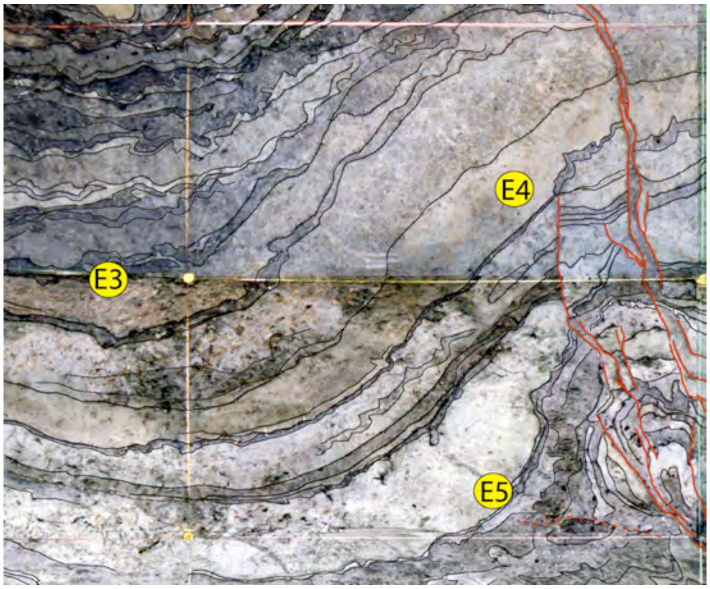

Figure 11. *Photomosaic of the south wall of trench T2, cut 2. Note the angular unconformity associated with events E3 and E5, and the clear upward termination and mismatch of units associated with event E4. Also note the growth section associated with each event.*

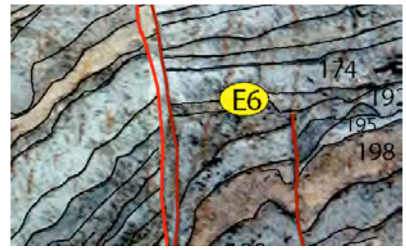

Figure 12. *An exposure in T4, cut 3 where strata of all units below 197 are warped down and then overlain by less-deformed strata of units 174 and younger. Note the fissure filled with soil adjacent to the main fault.*

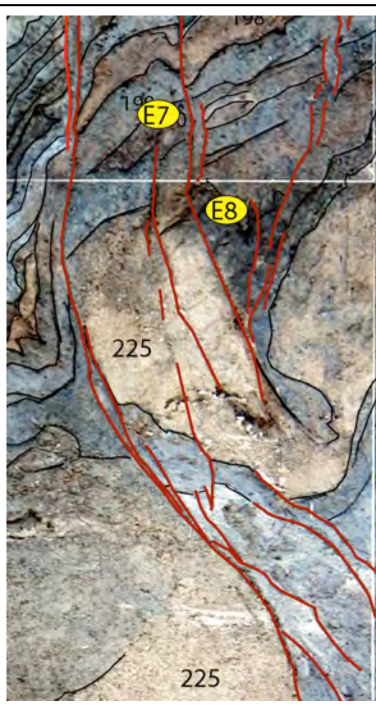

Figure 13. *Warping of unit 225 (sand) down into the fault, with associated filling of a fissure with organic soil, and upward terminations of fault strands, associated with events E7 and E8.*

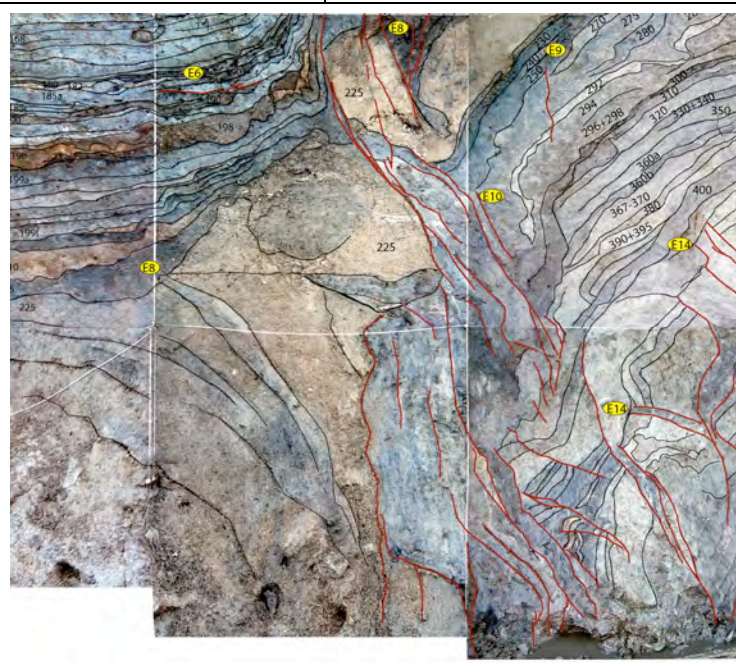

Figure 14. *Lower portion of the main fault in trench T4, cut 3. Note the warping down of unit 225 and the onlap of unit 215 resulting from event E8. Also note the filled fissures from events E8, E9 and E10, and the upward terminations and angular unconformities associated with events E6, E7, E8, E9 and E14.*

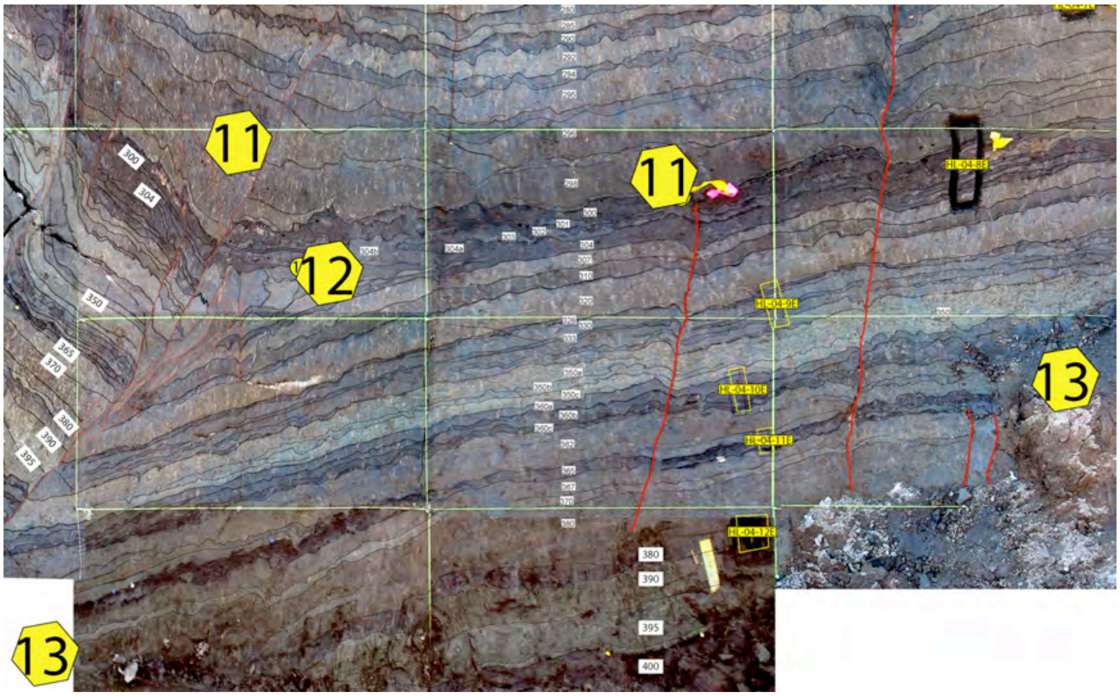

Figure 15. *Exposure of the main fault in trench T2N, cut 3. Bottom of trench is at 6.5 m depth. Event E11 has upward terminations on secondary strands and growth strata adjacent to the main fault. Event E12 is represented by the upward termination of a major strand, growth strata, warping of units east (right) of the fault down into the fault zone, and juxtaposition of dis-similar correlative strata. Event E13 in this exposure has upward terminations of secondary faults (right side of photograph), and growth strata in the main fault zone. Event E13 is the oldest event for which there is direct observation of deformation in the main fault.*

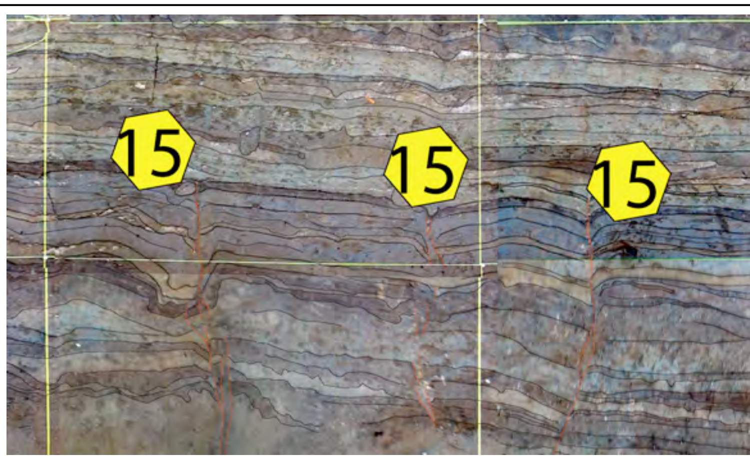

Figure 16. *Event E15 in trench T2N is represented by upward terminations on several secondary fractures. Note that there are actually two levels at which the terminations occur, suggesting that there may have been two events at about the same time.*

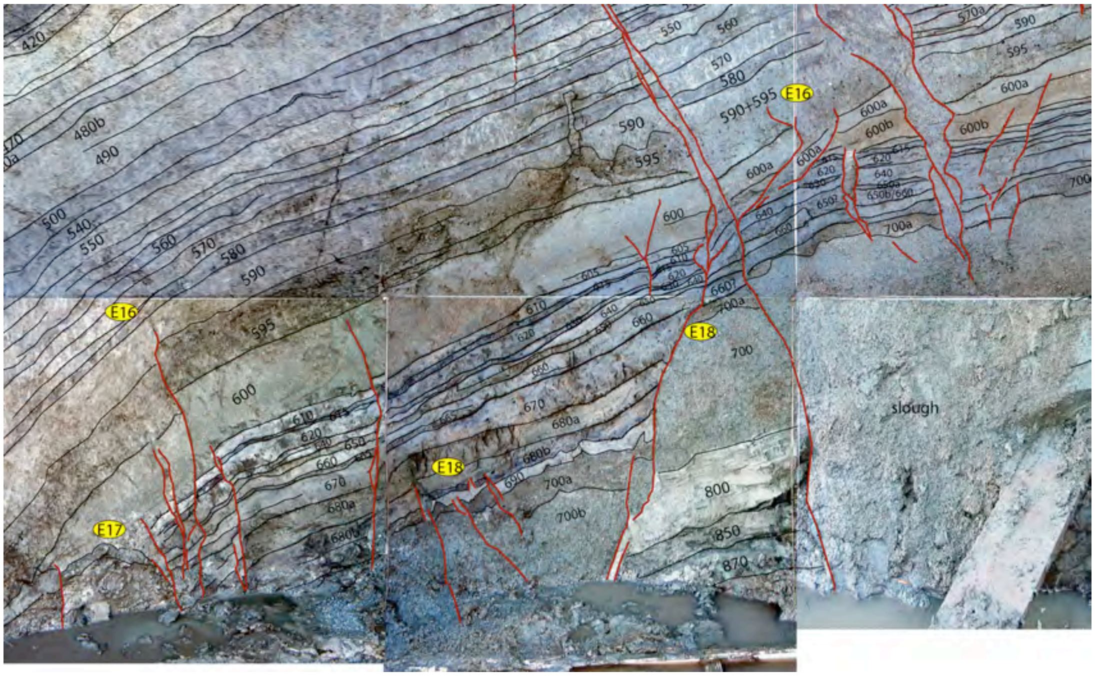

Figure 17. *Older events recorded along an older, presently inactive strand in trench T4. Event E16 is represented by upward terminations of several fault strands. Evenet E17 ruptured a significant fault (lower left) less than a meter from the currently active main strand (just out of the field of view to the left), and has an associated filled fissure. Units across this strand are mismatched. Several other strands also terminate at this level (unit 600). Evenet E18 is represented here by the upward termination of a significant strand, as well as major lithologic contrasts across the fault of correlative units, indicating significant strike slip. There also appears to be growth strata adjacent to the primary older strand, although this could also be explained with significant strike-slip and mismatch of strata.*

Figure 18 displays the probability density functions of the event ages, as plotted by the OxCal model shown in figure 6. In this plot, keep in mind that the stratigraphy in the main fault only goes as deep as event E13, so it is possible that the event history is incomplete for older events. Nevertheless, in the past 2600 years, the pattern of ruptures has apparently varied between quasi-periodic and clustered. There are apparent periods of up to 400 years during which we do not recognize evidence for any surface ruptures. There is also a cluster of three events between about AD 1300 and 1400, and the pattern for the past 500 years or so is fairly periodic.

We calculated the apparent coefficient of variation for three periods, assuming we have documented a complete record of events. Note that the recurrence interval varies by a factor of two or more, depending on which period is sampled, with the long-term recurrence interval estimated at about 210 $\pm$ 134 years. The large standard deviation is a result of the apparent variability and clustering of events for some periods. Note that our most complete record, the past 2600 years or so, includes both clusters and fairly long periods of no events. The earlier record appears more quasi-periodic. From a hazard perspective, the radiocarbon ages indicate that the most recent event occurred circa AD 1790, using AD 1850 as a prior after which there have been no large historical events that could be attributed to rupture of the central San Jacinto fault. A large earthquake in southern California is recorded in the historical record for

November 22, 1800, and this earthquake damaged both the Spanish missions at San Diego and San Juan Capistrano (Figure 19). Although the spatial coverage of damage is too sparse to confidently locate this early earthquake, its timing is consistent with the most recent event recorded in the stratigraphy at Hog Lake. Alternatively, event E1 may be pre-Mission. In either case, the lapse time since the most recent surface rupture of the Anza seismicity gap appears to be at least 208 years ago, suggesting that this section of the fault may be ripe for failure.

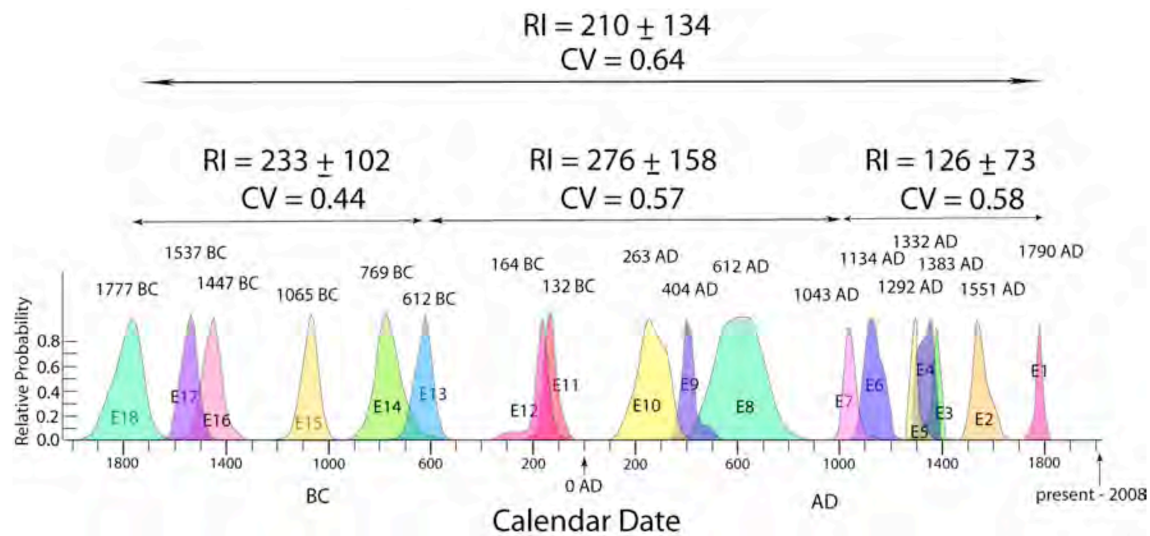

Figure 18. *Probability distributions for ages of surface ruptures recognized at Hog Lake. The dates above the probability distributions represent the peak probability year. Coeffient of variation (CV) is determined for three subsets of events, as well as for the entire sequence, and shows a factor of 2 variability. The ca 1790 event (E1) likely corresponds to the historical earthquake of November 22, 1800.*

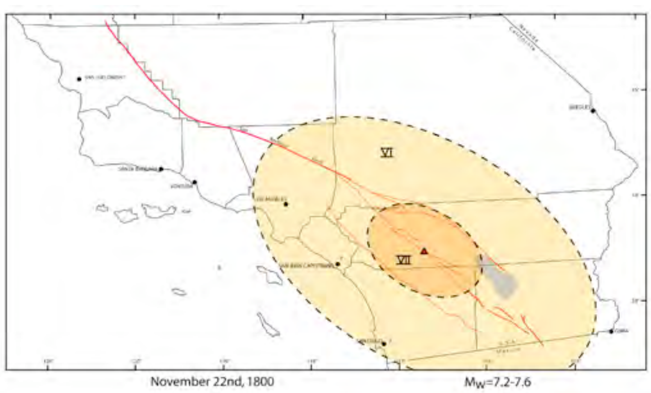

Figure 19. *Isoseismal of the November 22, 1800 earthquake (Modified from Toppozada et al., 1985)*

Comparison to the Long Record at Wrightwood on the San Andreas Fault

The only comparably long record of paleoseismic events in the southern San Andreas fault system is from Wrightwood, although the middle portion of that record is incomplete (Weldon et al., 2002). Nevertheless, we compare these two long records (Figure 20) and note that there is an apparent anti-correlation of clusters (flurries) and gaps, with the cluster of events at Anza corresponding to a lack of seismic production at Wrightwood. The Wrightwood site is along the San Andreas fault north of the juncture with the San Jacinto fault, so if this pattern of earthquakes represents actual switching of seismic activity between the two faults, this implies that this behavior should be seen along the southernmost San Andreas fault as well.

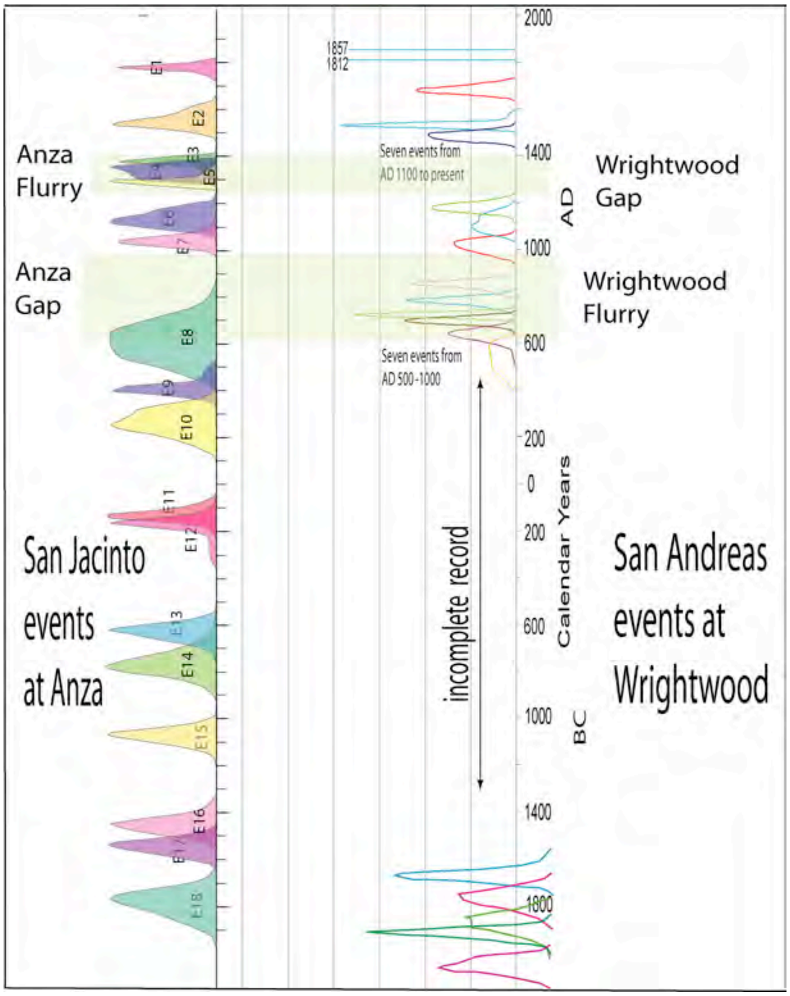

Figure 20. *Comparison of event ages at Hog Lake with the long record of surface ruptures at Wrightwood on the San Andreas fault. Note the apparent anti-correlation between clusters and gaps.*

Discussion and Conclusions

The Hog Lake record of past surface ruptures in the Anza Seismicity Gap represents one of the longest such records in the World, with recognition of 18 events during the past 3800 years. There are several major observations that have particular significance for seismic hazard analyses. First, the average recurrence interval and coefficient of variation appears to vary over time, suggesting that strain release has been somewhat variable on the timescale of the earthquake cycle. This has important implications for hazard studies, as many or most such studies base a forecast on either a short record or an assumed return period calculated from a slip rate and expected size of an earthquake. The Hog Lake record demonstrates that recurrence at a site, even one in the middle of a perceived asperity where slip has been demonstrably the greatest in past earthquakes (Middleton, 2006), can vary substantially over fairly short time frames, and that short paleoseismic records are probably inadequate to characterize recurrence.

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