FINAL TECHNICAL REPORT

# EARTHQUAKE CHRONOLOGY ON THE BIG BEND SEGMENT OF THE SAN ANDREAS FAULT: FILLING A GAP TOWARDS BETTER-CONSTRAINED RUPTURE SCENARIOS

*Prepared for*
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National Earthquake Hazards Reduction Program
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# EARTHQUAKE CHRONOLOGY ON THE BIG BEND SEGMENT OF THE SAN ANDREAS FAULT: FILLING A GAP TOWARDS BETTER-CONSTRAINED RUPTURE SCENARIOS

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## ABSTRACT

This proposal aimed to extend the paleoseismic record on the Big Bend section of the southern San Andreas fault with information from trenches excavated across the fault at Cuddy Valley. However, stratigraphy was poor at the Cuddy Valley site, and resources were shifted to the existing paleoseismic site at Frazier Mountain, about ten miles east of Cuddy Valley. Trenches excavated across a transtensional stepover at the Frazier Mountain site have provided evidence of at least eight earthquakes in the last 1000 years, with an average recurrence interval of about 122 years. One trench, T23, was excavated east of the depocenter containing the evidence of these events in hopes it would expose older stratigraphy and thus an earlier earthquake record. However, it was located in another syncline and depocenter that contained similar young sediments to those exposed in the previous trenches. Three to five earthquakes were recognized in the trench but were the same young earthquakes already identified elsewhere at the site. Although the trench did not extend the earthquake record into the past, it did provide information to clarify the detailed structure of the stepover.

## INTRODUCTION

The southern San Andreas fault (SSAF) is one of the principal plate boundary faults in southern California and carries a large fraction of the total plate motion. Large historical earthquakes such as the M 7.9 1857 Fort Tejon earthquake and the M ~7.3 December 8, 1812 earthquake have occurred on the southern San Andreas fault. Consequently, this fault dominates the seismic hazard in the region and has been the focus of intense paleoseismic studies with the purpose of characterizing the timing, extent, and size of past large earthquakes. Several key paleoseismic sites along the fault including Bidart Fan (Grant and others, 1994; Akciz and others, 2006, 2010), Pallet Creek (Sieh, 1978, 1984, 1989), Wrightwood (Fumal and others, 1993, 2002a), Pitman Canyon (Seitz, 2000), Thousand Palms (Fumal and others, 2002b), Burro Flats (Yule and Sieh, 2001) and Indio (Sieh, 1986) have provided critical information on the timing and relative size of prehistoric earthquakes on the SSAF (Figure 1). However, due to a lack of paleoseismic sites along certain sections of the SSAF, significant gaps remain in our knowledge of the frequency, extent, and size of past earthquakes. Until recently, the Big Bend section was without a paleoseismic record that spans more than three earthquakes.

The Big Bend section is defined by the 2007 Working Group on California Earthquake Probabilities (WGCEP, 2008) as a ~60 km-long section of the San Andreas fault that extends from the southern end of the Carrizo Plain to the intersection of the San Andreas fault with the Garlock fault. Previous paleoseismic studies within the Big Bend section include a trenching investigation at San Emigdio by Davis (1979) and a study by Lindvall and others (2002) at Frazier Mountain. At San Emigdio, Davis (1978) identified up to three events in trench excavation across a small stream terrace. In addition to the 1857 earthquake, two older events were identified. However, the results from San Emigdio are hampered by dating limitations and the fact that evidence for the event prior to 1857 was based primarily on liquefaction leaving uncertainty as to whether the second event occurred on the San Andreas fault. The other pre-existing Big Bend paleoseismic site, located at Frazier Mountain, had produced a limited earthquake record of two events during the past 500 years (Lindvall and others, 2002). A great deal of work has recently been carried out at this site, however, and the earthquake record has been extended to at least eight events (Gibson et al., 2010: Scharer et al., 2011). This more recent work is discussed in more detail below.

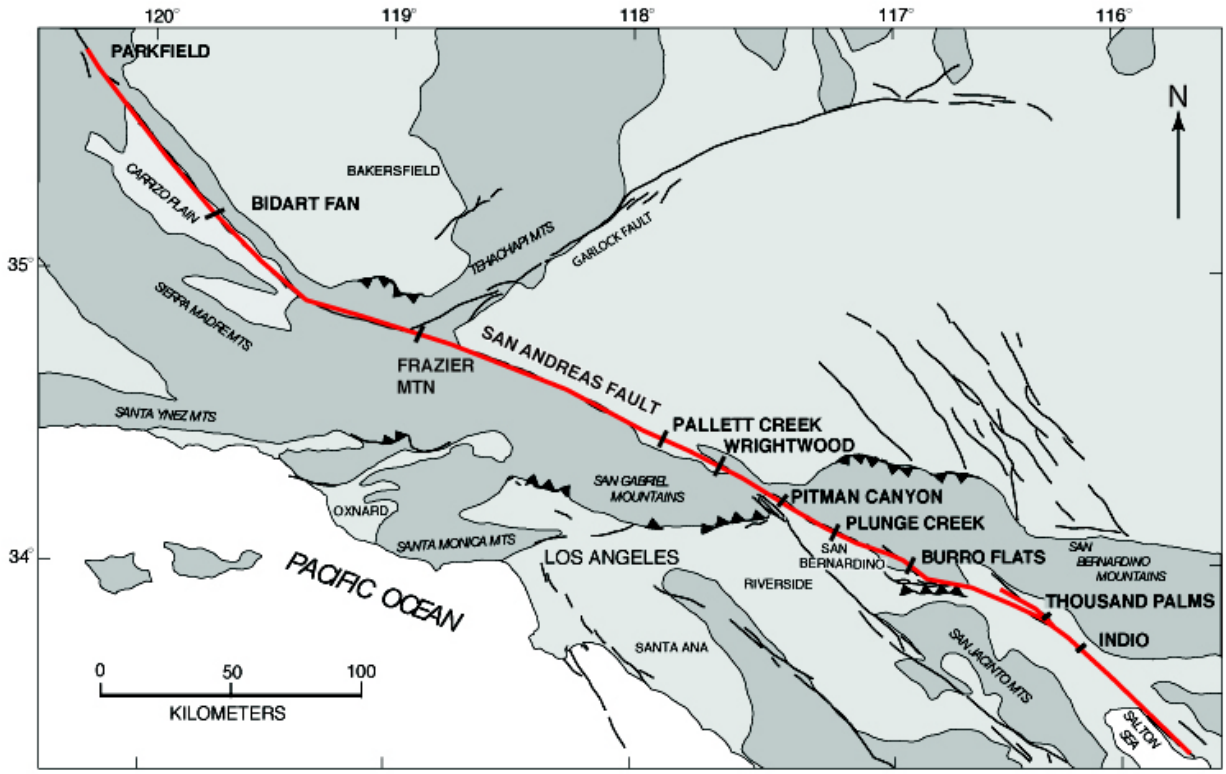


Figure 1 Map of key paleoseismic sites (bold black lines) along the southern San Andreas fault (red line). Modified from Fumal and others (2002).

Work by Akciz and others (2006; 2010) has challenged the current paradigm that the Carrizo Plain section produces large, relatively infrequent earthquakes, with past estimates of recurrence on the order of ~200 years (WGCEP 95). The Bidart Fan site, located on the Carrizo Plain section of the fault, records at least six earthquakes that occurred between AD ~1360 and 1857. The average interval between these events is now determined to be 88 ± 41 years, much less than the 200+ year recurrence interval that has been used in seismic hazard assessments (Akciz et al., 2010). At the nearby Wallace Creek site, Liu and others (2004) interpreted slip-per-event data as indicating that four of these five events were accompanied by large offsets (>5m). Scaling relationships (Wells and Coppersmith, 1994) and probabilistic estimates of surface rupture extent (Biasi and Weldon, 2006) suggest that these amounts of slip should involve >100 km of surface rupture, which would likely include the Big Bend section of the fault. If the event ages of Akciz and others (2006) and slip-per-event estimates of Liu and others (2004) are correct, then this implies that the Carrizo Plain fails in large and relatively frequent (RI= ~100 years) events in contrast to previous estimates of Carrizo Plain segment earthquake recurrence.

Another possibility is that the offsets recorded at the Wallace Creek site represent more than one event. This is an alternative that the data allow because, although the size of the offsets mapped by Liu and others (2004) are well-constrained, there is very little control on the ages of the events. More recent work by Ludwig et al. (2010) and Zielke et al. (2010) suggests that some apparent large offsets in the Carrizo Plain could actually have been produced by clusters of smaller events that occurred more frequently than offset geomorphic features were able to form. If slip during individual events were less, then some events could be smaller earthquakes restricted to the Carrizo Plain. A strategy to test this uncertainty and understand the time-space behavior of ruptures along this section of San Andreas fault is to develop a chronology of earthquakes on the Big Bend section of the fault. The goal of this work was to use paleoseismic trenching to try to extend the earthquake record on the Big Bend section.

## RESULTS

### The Cuddy Valley site

The proposed Big Bend paleoseismic site for this project was in Cuddy Valley (Figure 2). Located midway between the two nearest high-resolution paleoseismic sites (Bidart Fan and Pallett Creek, located 86 km and 110 km from the Cuddy Valley site, respectively), the site was selected as an excellent location to address the issues outlined above.

As shown in the hillshade relief image of the proposed site (Figure 3), processed from the B4 Lidar data set using the GEON workflow, the area includes, among other tectonic geomorphic features, a ~500 meter long pressure ridge that runs sub-parallel to the axis of the valley. On the north side of this pressure ridge sediment from three alluvial fans pond against it and in places partially bury this ridge. A linear closed depression on the north side of the pressure ridge was promising for being likely to record multiple earthquakes due to a relatively high deposition rate and to trap and preserve organic material for radiocarbon dating.

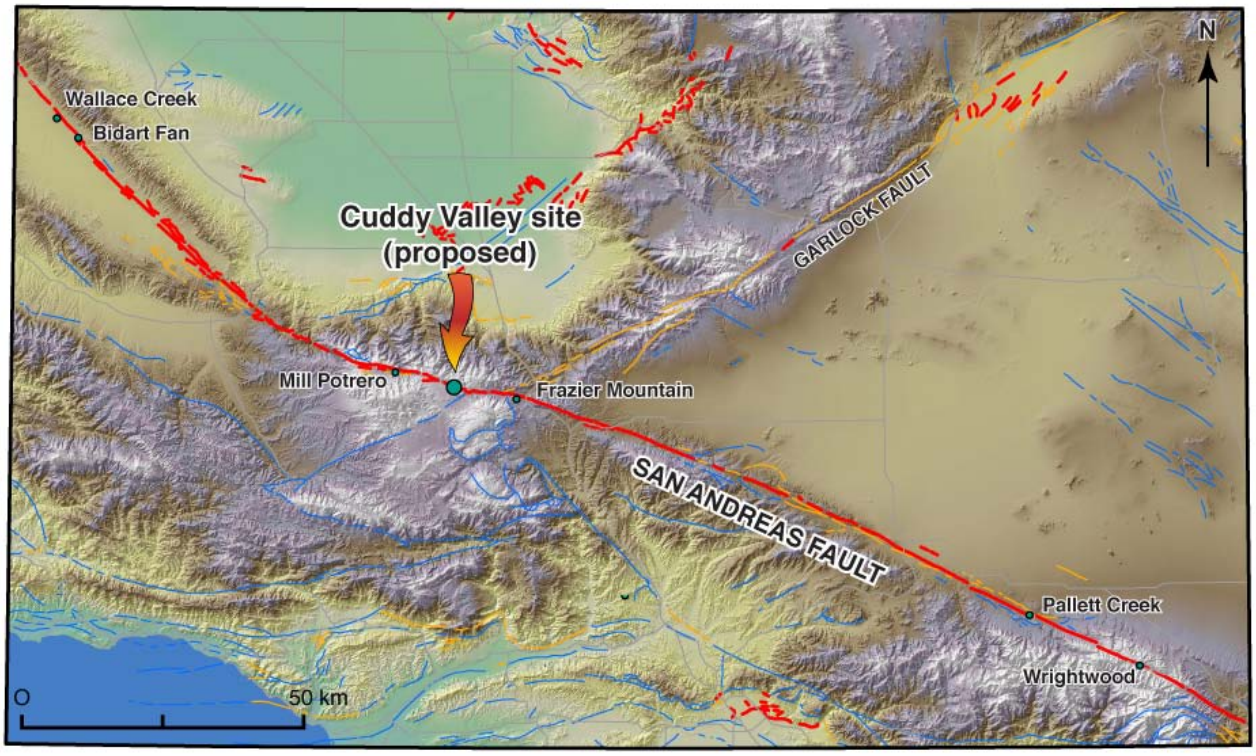


Figure 2 Map showing the location of the proposed Cuddy Valley site relative to other paleoseismic sites on the Big Bend section and high-resolution sites on the Carrizo Plain and Mojave sections of the SSAF.

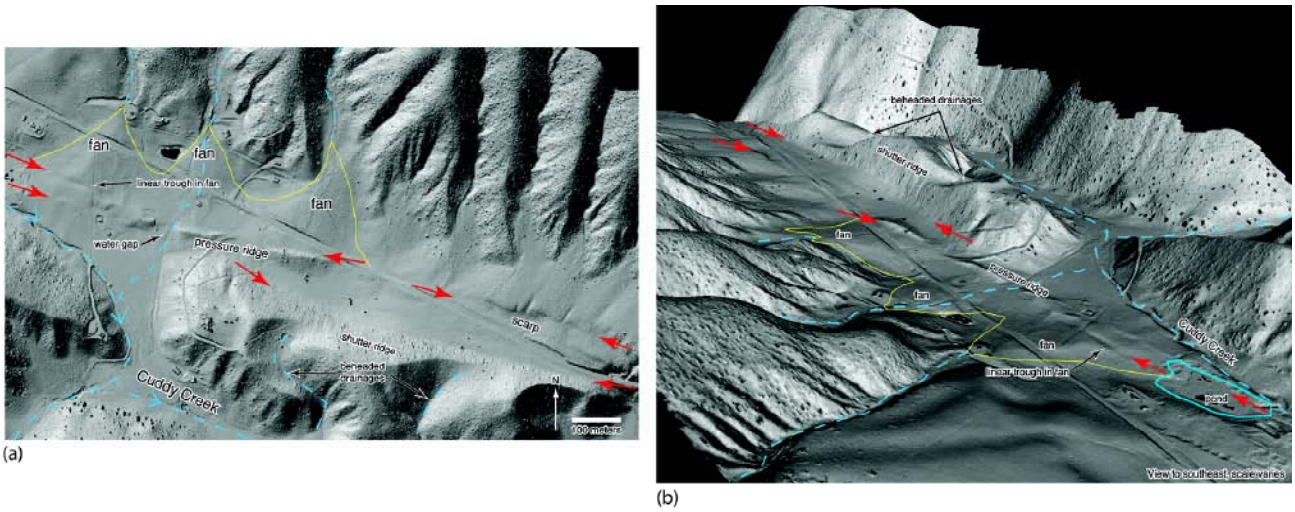


Figure 3 (a). Vertical hillshade relief processed fron B4 lidar data showing tectonic geomorphology in Cuddy Valley. (b). Oblique view looking to the south, also processed from B4 lidar dataset. Red arrows point to fault traces.

Unfortunately for the goal of building up the number of good paleoseismic sites along this section of the southern San Andreas fault, the site did not live up to expectations. Exploratory trenches were excavated across the fault at the Cuddy Valley site in 2007. In spite of the promising characteristics that led us to propose it as a paleoseismic site, the stratigraphy exposed in the trenches was coarse and not adequate to distinguish events that occur with the frequency likely on the San Andreas fault, and further work at the Cuddy Valley site was not considered profitable. Because the goals of this proposal were to address the paleoseismic record on the Big Bend section, I chose instead to participate in the large ongoing paleoseismic investigation at Frazier Mountain, about 10 kilometers east of Cuddy Valley.

**Frazier Mountain Site**

The Frazier Mountain site was first investigated by Lindvall et al (2002). It provided some information on the last two earthquakes, but investigations were hampered by a high water table. In recent years, the site has been redeveloped in great detail, a project led primarily by Kate Scharer (Appalachian State University), Ray Weldon (University of Oregon), and Tom Fumal (U.S. Geological Survey). This site has now provided a robust paleoseismic record through the last thousand or so years and is the best-developed site on the Big Bend section.

When I decided to join the efforts at Frazier Mountain, the primary investigators had already carried out a good deal of work, and they have continued to work the site since I left. This report, therefore, details only a very small piece of the larger study, and most of the site-wide results presented here were produced by many other people, including the employees and students of the above organizations as well as numerous other visiting scientists. Many of the figures shown here were produced by students of the above universities for a poster presented by Brian Gibson, a student at Appalachian State University, at the 2010 American Geophysical Union annual meeting (Gibson et al., 2010).

The recently developed Frazier Mountain paleoseismic site is located in a 250-m-long, 70-m-wide closed depression associated with a minor right step in the southern San Andreas fault. Two main fault traces cut through the site, producing a reverse flower structure (Figures 4 and 5). The faults form the boundary of a complex pull apart basin. In early field seasons, work was concentrated in the trenches on the west end of the site. Trench T1, was excavated to a depth of 6.5 meters and was centered on a large synclinal depocenter between two right-stepping traces (Figure 5). To the west, the northern trace of the fault occurs along the ridge flanking the northern edge of the site; it is primarily in bedrock.

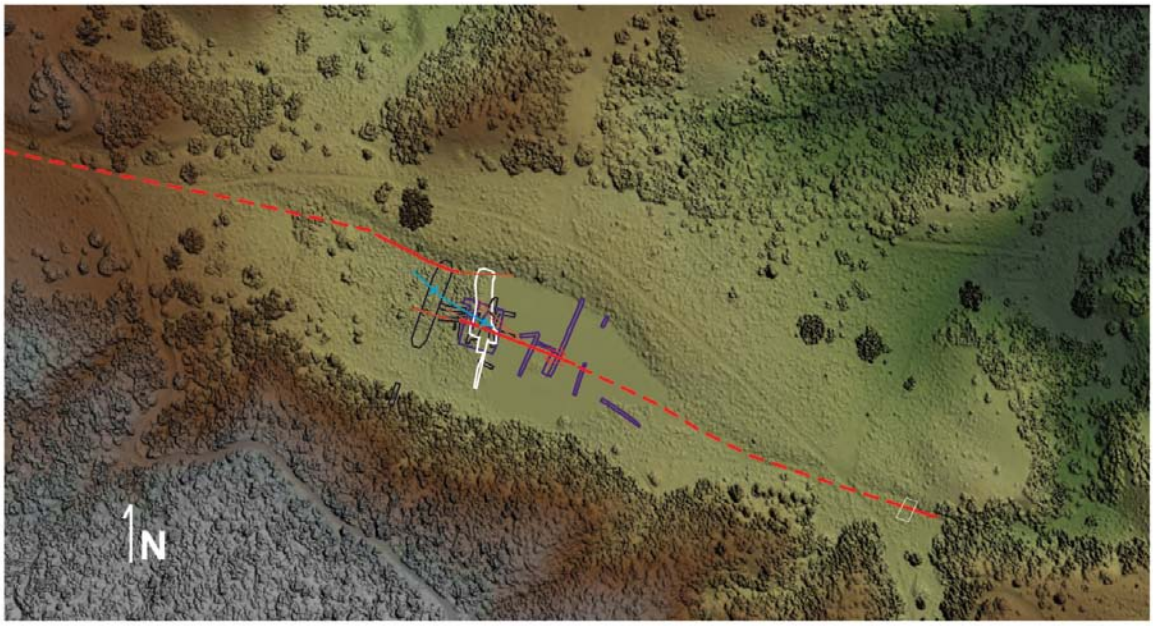


Figure 4 Frazier Mountain paleoseismic site. Figure from 2010 AGU poster of Gibson et al. (2010).

Trench T23

Trench T23 was excavated orthogonally to the fault east of the earlier trenches. The western trenches were excavated though a structural depression formed between two right-stepping traces of the fault. This depression allowed for the accumulation of well-stratified deposits and the preservation of well-defined event stratigraphy, providing constraints on the timing of events with short inter-event times. The structural depression centered on Trench T1 tapers closed the east and the strata thin in that direction. The goal in excavating Trench T23, through thinner strata, was to expose older deposits for a given depth of trench and thus extend the earthquake record back in time from the fairly well-constrained history obtained from the western trenches.

Trench T23 was about 2.5 m deep, and 50 m long. It extended from the ridge on the north side of the site south past the projection of the faults mapped to the west (Figure 5). At the north end of the trench, there is a fault at the base of the northern ridge but it is primarily in colluvium and Holocene faulting relationships are not well expressed. The 25-30 m of the trench from the northern fault zone southward exposed flat, undisturbed stratigraphy where it crossed Quaternary deposits. The discussion and trench log presented here are limited to the southern half of the trench.

The trench walls were scraped, gridded with a 1-meter-wide by half-meter-high string grid and photographed. Logging was done on printouts of the photographs. The photographs were then rectified to the grid and the photo logging transferred to the resulting rectified photomosaic. The trenches and key markers within them were also surveyed in.

The log of the southern half of the eastern wall of T23 is shown in Figure 6. The image is a gridded photomosaic of the wall with faults and key stratigraphic marker horizons highlighted in different colors.

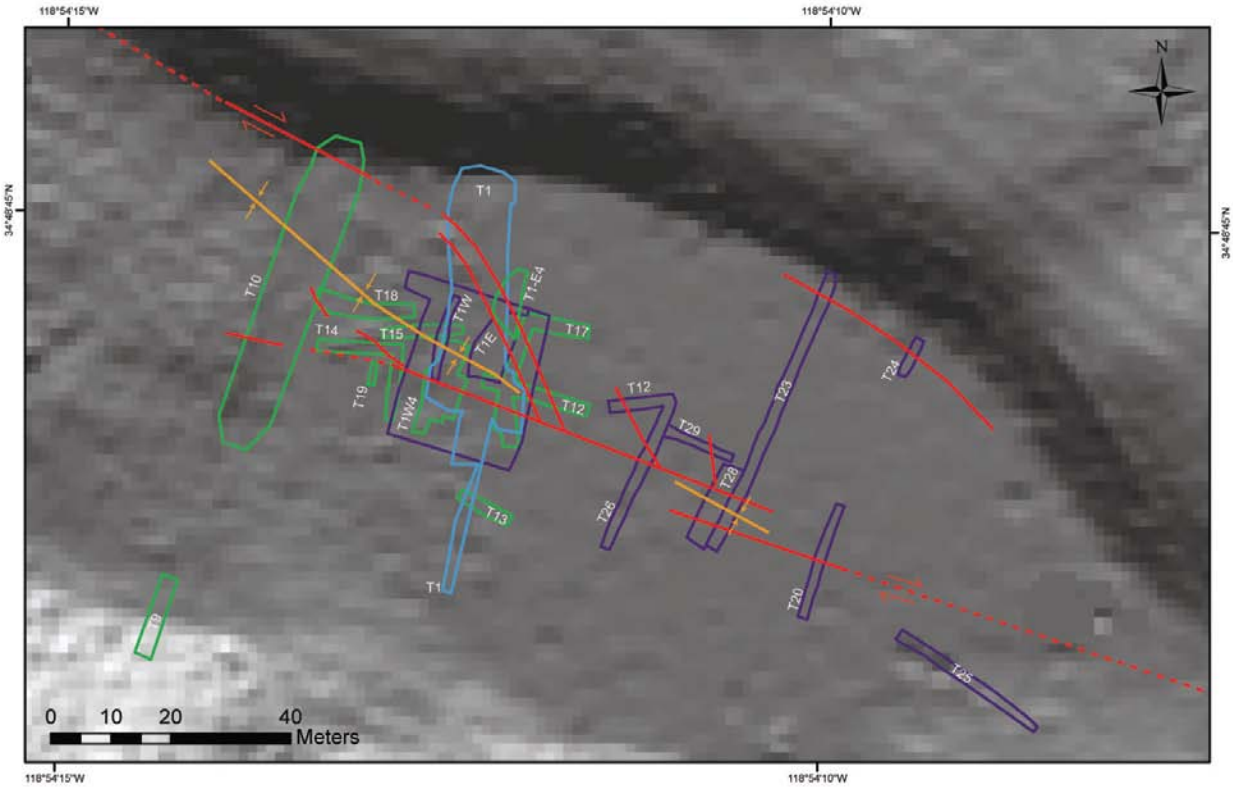


Figure 5 Map of trenches at Frazier Mountain site. Figure from 2010 AGU poster of Gibson et al. (2010). Red lines mark faults, orange lines mark the axes of synclines, and other colors depict the outlines of trenches. This report focuses on Trench T23.

*Stratigraphy*

Most of the deposits exposed in the trench comprise tan to brown and grey sand and silt in different proportions with varying amounts of clay. Distinctive marker horizons include fine and fine-medium relatively clean sand layers as well as thin clay beds. The sediments include calcareous blebs scattered throughout the deposits as well as nodules that often form in horizontal stringers that can highlight fault offsets. The upper half-meter to meter is extensively bioturbated, which has obscured the stratigraphy in the upper part of the trench.

Key marker horizons include:

- A thin, discontinuous layer of light brown to tan fine to very fine sand with occasional orange staining, marked in Figure 6 with yellow. It was mappable only between meters 35 and 43,where it appears within a graben structure (see below). Elsewhere, compression of stratigraphy and extensive bioturbation have obscured this layer

- A very distinctive light-brown to tan, with orange staining, very fine to medium sand layer is shown in light green in Figure 6. This sand layer is characterized by numerous fissures extending downward from the base of sand into the underlying layers. This layer is the same as a distinctive layer found in trenches to the west that has been shown to represent the third earthquake back at the site (Gibson et al., 2010). This sand is, in many places, immediately underlain by a light grey clay layer (shown in Figure 6 in darker green). The fissures extend through this layer and into the underlying deposits.

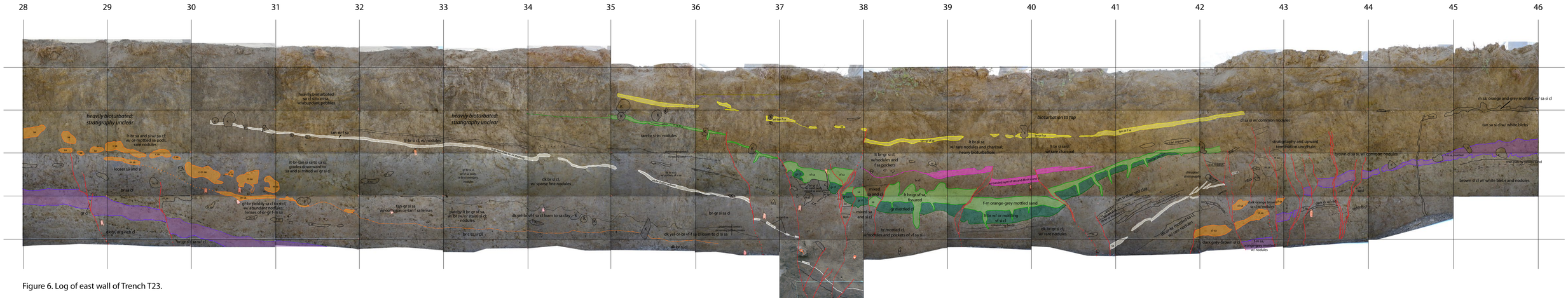


Figure 6. Log of east wall of Trench T23.

- A very thin layer of light tan, with orange staining, very fine to fine sand, marked in white in Figure 6. It is exposed at a depth of almost 2.5 meters between meter lines 37 and 38, in the graben, rising to about 1 meter depth at meter 30. Fairly continuous through the graben, the layer becomes hard to distinguish outside of it, especially to the south. On the north side, it is mappable to about meter 30, where it becomes indistinguishable in the bioturbated sand and silt in the upper meter of the trench.

- A fairly thick (ca. 20 cm) grey-orange mottled fine-medium sand with nodules. This is the deepest clean sand layer exposed in the trench.

*Fault Zone*

The main fault zone in the trench forms a broad graben, consistent with the local transtensional setting of site. The graben is deepest between meters 38 and 41, and the main fault zone exposed in the trench is between meters 36 and 45, although faults occur to the north at about meters 29 and 30 as well. The fault zone includes numerous individual traces that affect strata at least up to the uppermost sand layer (in yellow in Figure 6). The variation in thickness of deposits across the graben reflects the continued development of the graben and associated faulting during deposition of the sediment. During earthquake ruptures, extensional faulting in the graben produces a depression in the surface across the graben. Inter-event sedimentation fills in the depression, producing the growth strata evident in the trench exposure, with deposits thickest in the center of the graben and thinner to the sides.

*Event Stratigraphy*

We recognized three to five events in trench T23. In the descriptions below, distinguished sand layers are labeled based on their colors in Figure 6, e.g. "yellow", "green", etc. The event stratigraphy in this trench is not particularly well defined; upward terminations are not always clear and the extensive bioturbation in the upper meter obscures stratigraphic and fault relationships. Evidence is largely restricted to the central graben area.

- Most recent event: The most recent event recognized in the trench extends at least through the uppermost sand (yellow). The upward termination of the traces that affect yellow nail is uncertain due to pervasive bioturbation in the upper part of the trench. Thus whether this represents only one event or more than that is uncertain. However, clear offsets of the sand where it had been continuous (e.g. at m 38), indicate that at least one event postdates this sand.

- Second (and third?) event: The "green" sand layer has been extensively affected by faulting and fault-related fissuring. At least some of this faulting occurred prior to deposition of the overlying "yellow" sand. The patchiness of the yellow sand in this wall makes the relationship of the "green" and "yellow" sands somewhat uncertain, the apparent lack of offset of the thin "yellow" sand above the large offset of "green" fissured sand around meter 40 supports this contention. Relationships on the other side of the trench, not shown here, also support this. Furthermore, the greater degree of folding of the "green" sand layer than the "yellow" sand layer indicates an event between the two deposits. Faults affecting the "green" but not the "yellow" sand extend in many cases slightly above the top of the "green" sand. Furthermore, in the center of the graben (meters 38-41), the "green" sand is overlain by a tri-banded layer of tan and dark, organic-rich silt and clay, shown in pink. This "pink" silt has also been offset, and the offset looks similar to that of the underlying "green" sand. At the southern end, however, the "pink" silt is not parallel with the underlying sand, suggesting there may have been offset between "green" and "pink". Furthermore, there is some question whether the character of the fissuring and deformation of the "green" sand demand that it have been at the surface when it was faulted, or if that deformation could have occurred when it was buried by up to 20-30 cm of silt. Thus, the faulting and

deformation that affects the "green" but not the "yellow" sand may represent one event, when the green sand was near but not at the surface; or it may represent two events, one when green sand was at the surface and another when it was buried, perhaps when the "pink" silt was at or near the surface.

- Third (or fourth) event: At least one event occurred between deposition of the thin "white" sand and the "green" fissured sand. The much greater degree of folding of the "white" than the "green" sand supports this (see the dugout exposure between meters 37 and 38 in Figure 6), as do the several fault traces that offset the "white" sand but have no effect on the overlying "green" sand (e.g. around m 41).

- Fourth? (or fifth) event: An older event is uncertain. North of the main part of the graben, between meters 28 and 30, the deepest "purple" sand layer is faulted. The overlying "white" sand layer is not evident over these traces, so it is unclear whether the faults affect it. Furthermore, there is almost no overlap of "white" and "purple", and little of the purple is exposed in the graben, so the relative degree of folding in each is uncertain. We were unable to map them above about 1 m depth because of poor stratigraphy. Overlying units are massive, gray-brown, primarily sandy silt and silty sand with some clay and abundant nodules and have a large degree of lateral variability. A poorly defined "layer" of sand and silt that contains numerous irregularly shaped pods of orange-mottled sand lies between the "purple" and "white" sands layers. This layer does not appear to be affected by the faulting that offsets the underlying "purple" sand, suggesting at least one event occurred between "white" and "purple". However, this possible event is poorly defined and uncertain given the exposure and the stratigraphic control.

*Relationship to other trenches*

Following the excavation and logging of trench T23, and after I had left the site, additional trenches between T23 and the depocenter to the west were excavated. T28 extended the T23 exposure westward by cutting back the west wall of T23. T26 was excavated across the fault about halfway between T23 and the western trenches. T29 was cut parallel to the fault as a linking fault to help clarify stratigraphic relations between trenches. The further excavations clarified the exposures in T23.

The new trenches revealed that T23 did not, in fact, expose older stratigraphy than had been uncovered in the trenches to the west. Rather than tapering out steadily to the east, the western depocenter shallowed well west of T23. A second syncline and depocenter occur around T23, with a structural high existing between the two depocenters (Figure 5). Thus the deposits in the western depocenter, centered on T1, thin to the east, near T26, then thicken again in the region of trenches T23 and T28. T28 was cut through a deeper part of the depocenter than T23 and thus exposes the same stratigraphy as T23 but in greater detail because of the greater depth. The log of the western wall of T28 is shown in Figure 7. This trench exposed evidence of the five most recent events as reflected by growth strata. In T28, as in T23, individual event stratigraphy is not that well expressed. However, the trenches revealed that the extensively fissured "green" sand in T23 is the same as the extensively fissured "purple" sand exposed in T28 and elsewhere at the site (located at about 1.5 m below the log surface in the center of the graben as shown in Figure 7). Relationships in other trenches confirm that this unit was at or near the surface during the third event back, which occurred at about 1640 AD (Gibson et al., 2010). It was preceded by a short interval of about 25 years and followed by a longer interval of about 150 years. The time between the fourth and fifth events is also short, on the order of 25 years (Gibson et al., 2010).

That the fissured sand ("green" in T23 and purple in T28) has been affected by three events is consistent with what was observed in trench T23, although details of the temporal distribution of those three events

was not revealed in that trench. The fairly large amount of fine sedimentation that occurred between the "green" sand and the underlying "white" and "purple" sand in T23, however, is not consistent with very short inter-event periods, suggesting that the older events in T23 are not the fourth and fifth events exposed elsewhere at the site, and thus the event stratigraphy as reflected in recognized event horizons, is incomplete in T23.

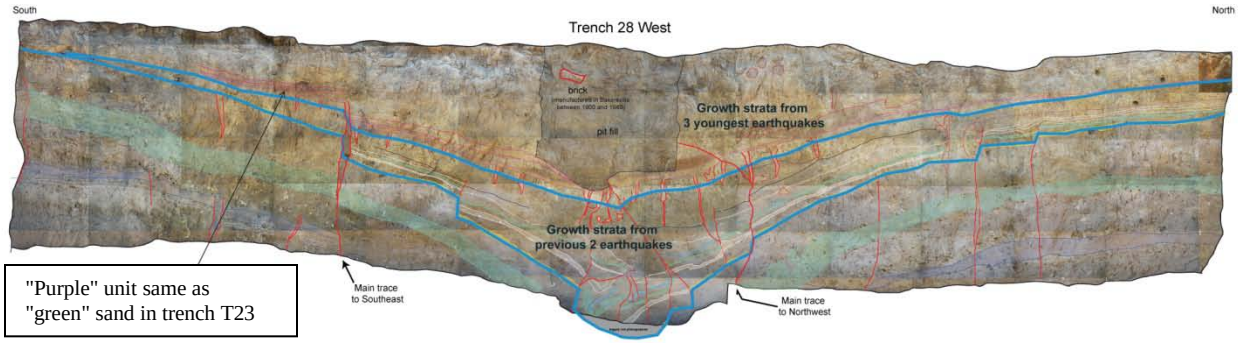


Figure 7. Log of Trench T28, and extension to the west of trench T23. Figure from 2010 AGU poster of Gibson et al. (2010).

Because of the structural setting exposed with the later trenches, it became clear that T23 was not revealing older stratigraphy than that which had already been exposed in other, deeper trenches to the west. It was decided that as T23 would not reveal new event stratigraphy, we would not expend resources on dating the radiocarbon samples from the trench. Event stratigraphy and age control has thus been obtained from other trenches than T23.

*Summary of results to date from Frazier Mountain Site*

Although trench T23 has been more useful in revealing the structural details of the site than in further constraining paleoseismic event history, the Frazier Mountain site as a whole has provided necessary new information about the frequency of earthquakes along the Big Bend section of the fault. As shown in Gibson et al. (2010), the work at the site to date indicates that eight earthquakes have occurred over the last 1000 years, with an average interval of about 122 years, with individual intervals ranging from ~25 to ~325 years. The five most recent events have been associated with normal faulting in this transtensional stepover. However, older events appear to have a reverse component suggesting a slightly different localized structural environment, either because of a change in setting or because of very localized variations in the expression of a complex stepover region.

## SUMMARY AND CONCLUSIONS

The goal of this project was to use paleoseismic trenching to extend the record of paleoearthquakes in the Big Bend section of the southern San Andreas fault. The original proposed site, in Cuddy Valley, turned out to have poor stratigraphy, and it was abandoned. The resources of this project were then shifted to the larger, multi-year, multi-institution efforts at the Frazier Mountain paleoseismic site, about 10 km east of Cuddy Valley. Because this project is so extensive, and extends far beyond the contributions of this project, this report is limited to describing only one of many trenches at the site, and one which, while shedding light on the local structure, did not provide much new information regarding the earthquake history of the site. However, the Frazier Mountain site overall has yielded a wealth of information about the Big Bend section, including a 1000-year record of events, with an average recurrence interval of about 122 years. Age constraints are beginning to allow some comparisons of the Big Bend paleoseismic record with those on the Carrizo and Mojave sections. Further work to constrain slip per event should permit further comparisons to assess which earthquakes have been large and ruptured through multiple sections

and which have been more moderate and limited to smaller sections of the fault and will likely be reported in future publications.

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