FINAL TECHNICAL REPORT

RECURRENT FAULTING ALONG THE SAN ANDREAS FAULT

U.S. Geologic Survey National Earthquake Hazards Reduction Program
External Grant Award Number **04HQGR0054**

Recipient
Division of Geological and Planetary Sciences 100-23
California Institute of Technology
1200 E. California Blvd.
Pasadena, CA 91125
Tel: (626) 395-8439 Fax: (626) 395-1740

Principal Investigator
Dr. Kerry Sieh
with
Jing Liu and Christopher Madden

Program Element I
Key Words
Paleoseismology, Recurrence Interval, Rupture Characteristics

October 2005

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number (Recipient, insert award number). The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

TABLE OF CONTENTS

ABSTRACT

For the first part of this project, we completed two manuscripts based on our recent work at Wallace Creek (WC). The shorter manuscript summarizes slip-per-event at WC for the last 6 paleoearthquakes and was published in the journal *Geology*. A longer manuscript that fully details our findings at the WC site was submitted to the *Journal of Geophysical Research,* where it is currently in final review. The second part of this project focused on exploratory paleoseismic investigations at an offset stream channel located approximately 4 km northwest of WC. The purpose of this investigation was to see if this site could constrain better the timing of the 6 events identified at WC, and millennial scale slip rate variations along the Carrizo segment of the San Andreas fault. Two fault-parallel trenches and one fault-perpendicular trench excavated at the site showed that the thalweg of the offset stream channel, which we call Branden Creek (BC), is offset about 42 to 48 meters. Stratigraphic relations in the fault-parallel trenches suggest the first earthquake to offset the creek occurred shortly after AD 250 to AD 570. Comparison of the ~45 meter offset of BC to the total ~36(+?) meter offset resulting from six events at WC, strongly suggests the offset of the BC channel resulted from seven and possibly more slip events. Assuming that the BC channel incised shortly after the event that occurred prior to the first event to offset the channel, we calculate a best-estimate slip rate of 26.1 to 37.2 mm/yr for the San Andreas fault at the BC site. The actual slip rate could be slightly higher or lower, however, due to uncertainties in the total offset of the creek, and poor constraints on the timing of channel incision. Our trenches yielded evidence for a minimum of four clearly defined events in the last ~1,450 years, suggesting that additional events documented during this period at WC, and inferred from the large offset of BC, were not recorded in the channel stratigraphy at the BC site. Thus, the site did not prove useful for constraining the timing of recent events. Comparison of our findings to other paleoseismic data from the Carrizo segment of the San Andreas fault suggests that late Holocene strain accumulation in the area was relatively constant, while strain release during the same period was irregular.

1.0 INTRODUCTION

During the first 28 years of the NEHRP, both theoretical and the observational aspects of earthquake science made significant contributions to understanding the nature of earthquakes. One practical result has been probabilistic hazard maps for the United States. [1,2,3] Ironically, these attempts to quantitatively and probabilistically characterize earthquake hazard evoke both feelings of pride *and* of embarrassment. For these maps represent not only the synthesis of much of what we know about earthquake phenomenology and physics, but they also highlight important deficiencies in our understanding.

One deficiency is our poor understanding of recurrent fault slip through many earthquake cycles. One widely recognized limitation of current probabilistic forecasts (and of theoretical models, as well) is our reliance on tenuous concepts of source recurrence. These include the notions that 1) seismicity on a fault can be represented realistically by a repeating characteristic rupture and that 2) slip patterns along large historical ruptures reflect along-strike differences in fault friction.[4,5,6]

In reality, we have only very sparse data to support these ideas.[7] As far as we are aware, the best two cases of an historical rupture mimicking a prior rupture are the Superstition Hills rupture of 1987 and the Borah Peak earthquake of 1983.[8,9] The Imperial fault ruptures of 1940 and 1979 support a more complicated view of serial fault rupture. That is, a “slip patch” model of faulting, whereby individual patches of a fault have a characteristic frictional resistance that does not change appreciably through many earthquake cycles[7]. This leads to similar magnitudes of slip from one earthquake to the next on an individual patch. For faults consisting of two or more patches, individual patches may fail individually, as in 1979, or together, as in 1940.

Ward[10] tested this idea by constructing a quasi-dynamic model of the Imperial fault, in which he assigned strength to three segments of the fault, as suggested by the historical slip data and by paleoseismic information.[11] His synthetic rupture histories contain considerable variation in slip functions, but consist of three basic types of events: 1940-like events that involve rupture of all three patches, 1979-like low-slip events on the northern patch and low-slip events on the southern patch. The degree to which individual localities on the fault experience similar slip from event to event depends upon the particulars of Ward’s parameterization of the fault patches. Even so, he suggests that low slip on the northern patch in 1940 is not typical for the larger events and that, instead, slip in such events varies greatly. The investigations we propose to continue herein are an empirical test paleoseismic test of Ward’s model.

The concept of a "characteristic earthquake," in which the failure of a fault occurs repeatedly in events with nearly identical rupture lengths, locations and slip magnitudes, arose nearly two decades ago, from paleoseismic studies along the Wasatch fault.[12] The characteristic-earthquake concept had already been dismissed as improbable for the San Andreas fault several years before it was proposed.[13] Then, as now, sparse data suggested, instead, that the fault consists of several characteristic-slip patches, or segments, that sometimes fail separately and sometimes fail together. Extreme variability in the intervals between large ruptures also casts doubt on the characteristic-earthquake hypothesis. In the Carrizo Plain, for example, along the northwestern half of the great 1857 rupture (Figure 1), geomorphic analyses of offset stream channels suggest that dextral slip during the last two prehistoric ruptures was nearly identical to that of 1857.[14,15] This is a curious finding, however, because more recent paleoseismic work[16] has shown that the times between large ruptures here has been highly irregular (Figure 2).

Figure 1. Map of Wallace Creek site in relation to major active faults of California.

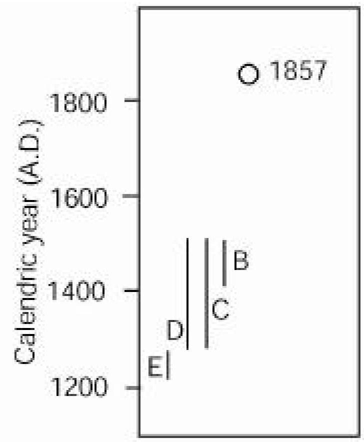

Figure 2. Dates of latest large ruptures of the San Andreas fault at the Bidart site, Carrizo Plain. The latest two events (1857 and event B) appear to be associated with similar amount of dextral slip. The slip associated with the prior three closely timed events is unknown

At the Bidart site, a few km southeast of Wallace Creek, the latest full interval is about 3 centuries, but a flurry of 4 large events occurred between about AD 1200 and 1500 (Figure 2). If all of these events involved offsets similar in size to those of 1857, then either strain accumulated faster between AD 1200 and 1500 or large strains were stored in the centuries prior to this cluster. Another possibility is that the inter-event rate of strain relief is roughly constant, in which case the closely timed events would have had much smaller offsets. Resolution of this issue is important for understanding both the past and the future behavior of faults.

This report summarizes data from recently completed work at Wallace Creek and details new work at a promising paleoseismic site that helps answer this puzzle.

1.1 Background

Work completed at the Wallace Creek paleoseismic site

One of the best places to determine whether or not a fault segment experiences similar amounts of slip through many earthquake cycles is that portion of the San Andreas fault known as the Carrizo segment. Along much of this segment, the fault trace is geometrically simple and unusually well expressed. It was here that Wallace[17] first noted and interpreted 10-meter-scale channel offsets as resulting from serial great earthquakes. Sieh[18] refined this work and demonstrated that the most recent large earthquake, in 1857, involved dextral offsets of about 8 to 10 meters. Grant and Sieh[19] showed with a 3-D excavation that slip across a narrow aperture during the 1857 earthquake locally was as small as 7 m. But Grant and Donnellan[20] confirmed an 11 ± 2 meter 1857 offset across a broad aperture nearby by comparing an 1855 survey of a fault-crossing section line with a GPS measurement of the same section line.

Attempting to understand the strain budget for earthquake production, Sieh and Jahns[14] used the 130-m offset of Wallace Creek to determine a 34 mm/yr slip rate there, averaged over the past 3,700 years. At this rate, 10-m offsets would accrue on average about every 300 years. They also interpreted offsets of small drainages as evidence for about 9.5 to 12.3 meters of offset during the past three great earthquakes. Assuming a slip-predictable model they then estimated past recurrence intervals of 240 to 450 years. Not surprisingly, theoretical models, beginning with those of Stuart[4] and Rundle[5], which use the magnitude of slip in 1857 as an indication of fault friction, bolster these geologic findings by producing model rupture sequences with quasi-periodic slips that do not vary greatly in amount from one event to the next.

The highly irregular recurrence intervals documented by Grant and Sieh,[16] however, show that fault rupture here is not quasi-periodic (Figure 2). Such a pronounced deviation from periodic behavior suggests that slip per event might also vary by a factor of 3 or more. For, if slip were the same in each event, strain relief rates would vary by a factor of 3 or more.

We have now completed collection of data along a particularly interesting 60-meter section of the fault just a few hundred meters southeast of Wallace Creek. At this locality, very small channels are cut by a very simple, narrow trace of the San Andreas fault (Figure 3). Upstream from the fault is a late Pleistocene alluvial fan, cut by a small channel. Downstream from the fault, several small gullies appear to be dextrally offset from this upstream channel. The youngest offset gully is the clearest. This appears from its geomorphic expression, alone, to have been offset 7 to 9.5 meters during the 1857 earthquake.[14,16,18,19] Older offset gullies, farther northwest from the source channel, are more subdued, but nevertheless, are still clearly visible downstream from the fault scarp. Colluviation at the base of the scarp has buried these small gullies partially, and so their precise geometry near the fault is obscure. Thus, various authors have measured different values for these offsets.

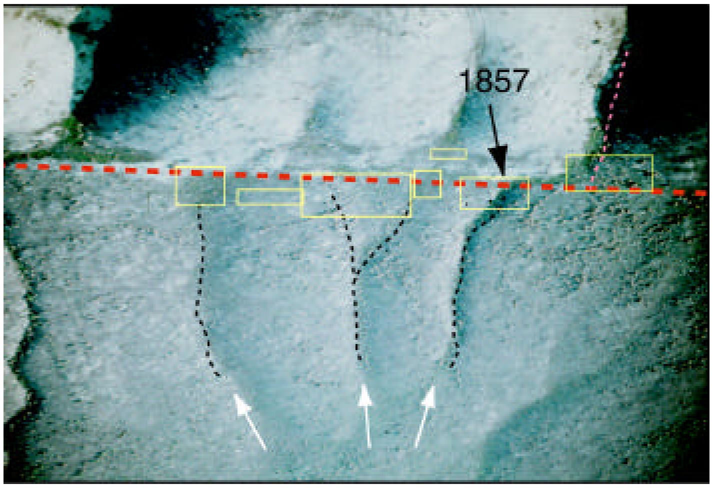

Figure 3. Aerial oblique view of the series of small downstream channel segments (black dashes) and the plausible upstream source (thin red dashes in upper right). Thick red line is the fault trace. The yellow boxes indicate volumes we had excavated early in the study. Southeast is to the right.

In our program of 3-D excavations, the first cuts were made farthest from the fault. Subsequent faces were cut progressively closer to the fault. In this manner, we carefully followed each potential piercing line into the fault zone.

Most exposures downstream from the revealed singular channels with repeated scours and fills. In some cases, however, superimposed channels appeared in the downstream exposures. Downstream channels cut into a bioturbated sequence of gravelly and sandy lenses. The presence of a pedogenic carbonate horizon in these older alluvial deposits suggests an early Holocene or older age.[14] Radiocarbon dates of about 15,000 years on charcoal within the deposits confirms this. At an average slip rate of 34 mm/yr[14] these deposits would now be separated about 500 meters from their upstream correlatives.

As one would expect, the upstream exposures were far more complex. They consisted of a broad V-shaped scour in the late Pleistocene "bedrock," filled with a complex scour-and-fill sequence. Figure 4 is a typical upstream exposure. It shows 8 of the 9 distinct channel scour-and-fill sequences. Several of these are topped by distinctive, laminated silt beds, which represent ponding of in the upstream channel following large ruptures that placed shutter ridges in front of the channel at the fault.

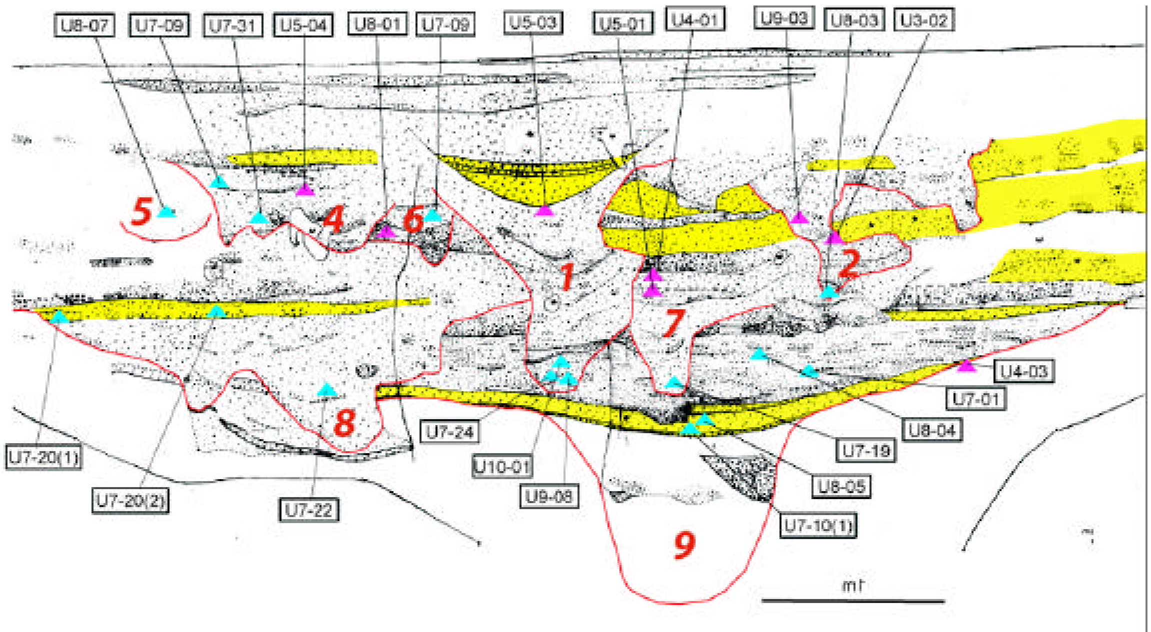

Figure 4. This example shows 8 of the 9 nested channel scours and fills exposed in cuts made upstream from the fault. Alluvial and colluvial sediment are uncolored. Suspended-load silts in yellow represent the temporary ponding of the drainage behind sequential shutter ridges. Channel margins and names are in red. The triangles show the stratigraphic position of radiocarbon samples. View is upstream.

Figure 5a is a map of the thalwegs of all the channels at the site. Each dot represents the exposure of a thalweg in an exposure. (Yes, that means we exposed and mapped a lot of exposures!) Determining the trajectory of a channel was principally just a matter of connecting the dots. The thalwegs are color-coded to indicate demonstrated correlations of upstream and downstream channels. The correlations are based principally on six factors: Stratigraphic position in the upstream cuts, geographic position on the downstream side of the fault, shape of the channels, strata within the channels, angle of channel entry and exit and radiocarbon analyses. Figure 5b shows representative cross-sectional shapes of each channel, both upstream and downstream from the fault.

Several of the upstream channels (7, 8, and 9) and downstream channels (e, f, i, j, k, and l) have no correlatives within the volume of the excavations.

Space does not allow us to defend each of the correlations, but one example gives an idea of the basis and quality of the correlations. Figure 6 shows basis for correlation of upstream channel 2 with downstream channel b.

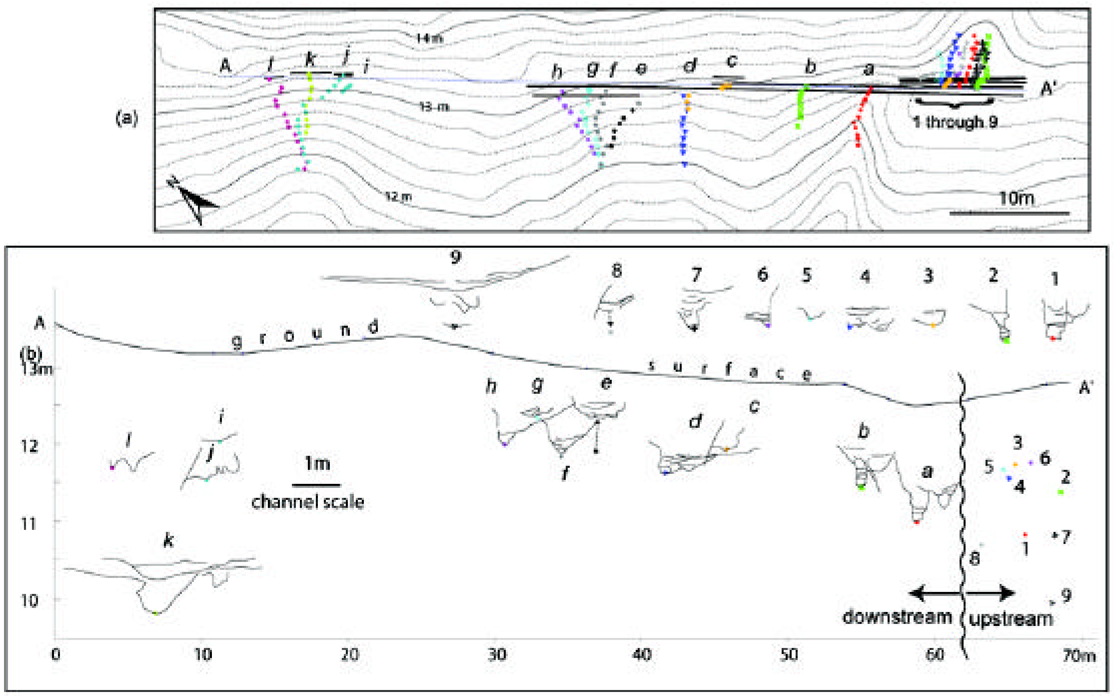

Figure 5 Upstream and downstream channel thalwegs. (a) Map of the channel thalwegs in the excavated area. Colors indicate correlations across the fault. Downstream channels e, f, i, j, k, and l do not have upstream correlatives within the excavated region. Nor do upstream channels 7, 8 and 9 have downstream correlatives. (b) Fault parallel cross-section shows relative position of the upstream and downstream channels and the cross-sectional shapes of their channels. Cross-sections of upstream channels are spread out above the ground surface, because they are too tightly grouped in the upstream channel to show them *in situ*.

Figure 7 depicts the sequence of six discrete offset events. Three offsets of 7.5 to 8 meters constitute half of the sequence. This suggests that there is either a static mechanical property of the fault or a controlling dynamic property of successive ruptures that is invariant for at least half of the events. Two smaller events in the middle of the sequence, however, indicate that the story is not quite so simple. The third and fourth events produced only 1.4 and 5.4 meters of dextral offset, respectively. It is curious that these two consecutive offsets sum to almost 7 meters. Due to this coincidence, some of our colleagues have suggested that we have misinterpreted our data and that these two are just one event. Page limitations prevent us from demonstrating it here, but the details of the stratigraphy show that these are, indeed, two separate ruptures. The basic evidence is that channels 4-d and 3-e in Figure 5a are separate channels and that channel 3-e is offset 1.4 meters less than channel 4-d.

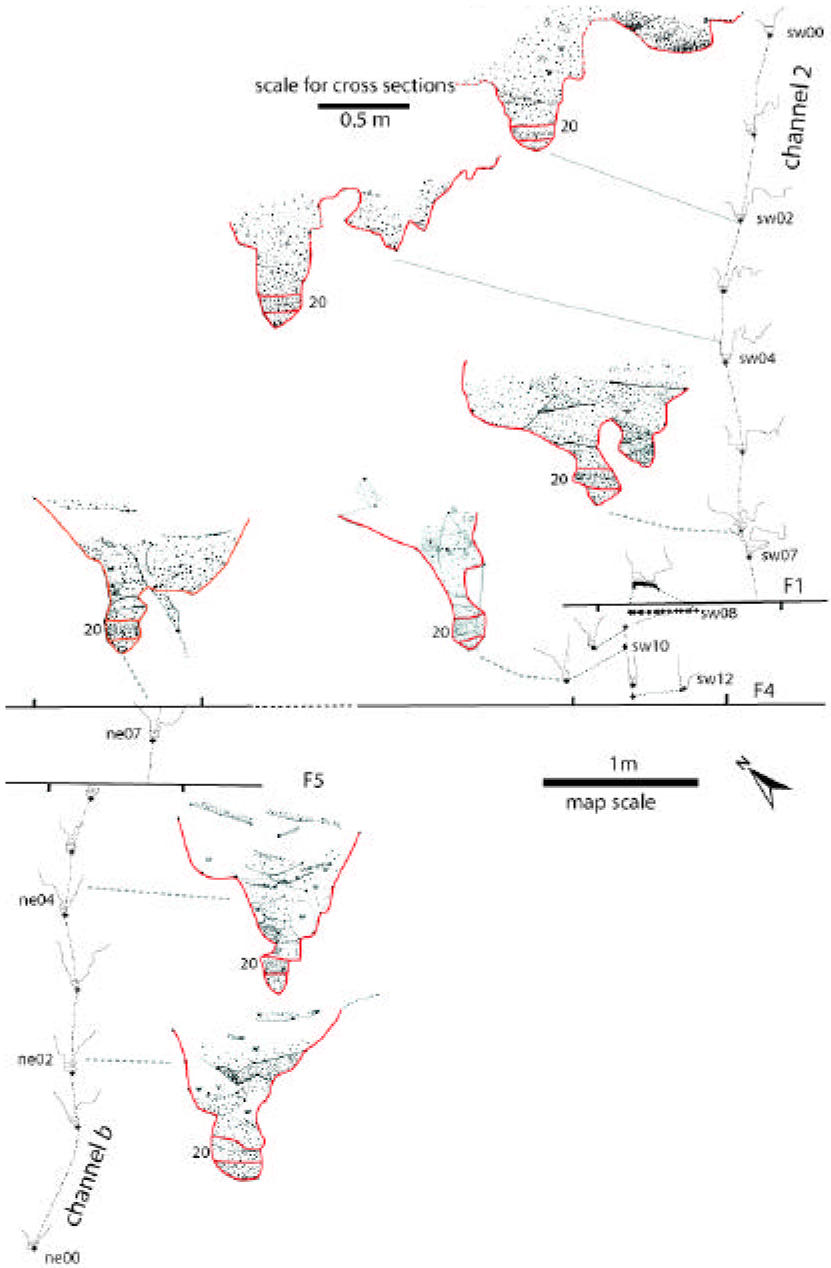

Figure 6. Summary of data used to map channels 2 and b and to correlate them across the fault. Note the narrowness of the channel and the similar stratigraphy in the channels. Dashed segment of main fault indicates removal of several meters along strike, so that both upstream and downstream channels can be shown in the same figure. Total dextral offset of channel 2 from channel b is 15. 5 meters. This occurred in two, nearly identical events of about 7.6 and 7.9 meters.

We wonder, though, if the 1.4- and 5.4-meter events were closely spaced in time and, thus, part of a rapid-fire sequence. Perhaps the initial 1.4-meter event was a rupture whose terminus was very close to the site, and the subsequent 5.4-meter event overlapped its "tail" and continued on into unruptured ground. This hypothesis may one day be tested by paleoseismic data from other sites.

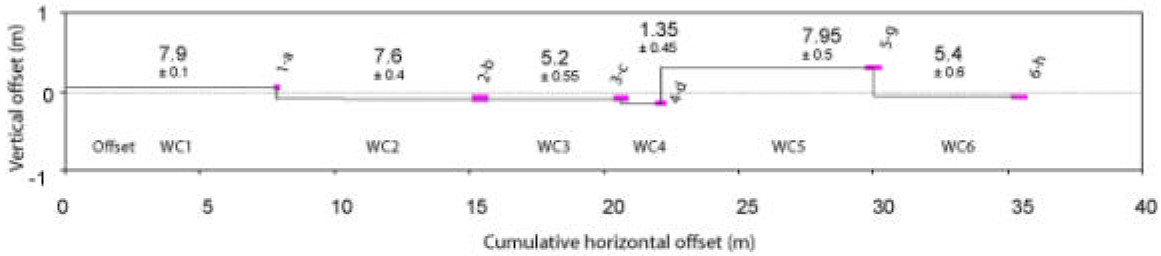

Figure 7. About 36 meters of right-lateral offset and no vertical offset has accumulated in 6 discrete offset events. Offsets of 7.5 to 8.0 meters account for at least half the record, but two smaller slippages occurred in the middle of the sequence. Uncertainties in the horizontal measurements appear as purple bars. I view the offset shown for the first event (WC6) as a minimum constraint.

Dating of the rupture sequence at Wallace Creek has proved problematic. The results from radiocarbon analysis are ambiguous, because some channels contained samples that differed in age by up to a thousand years. This showed clearly a severe problem with inherited carbon. That is, the samples from some strata had ages that ranged over as much as a millennium. This indicated that some of the samples were up to a thousand years older than the stratum in which they resided. An attempt at dating the silt lens produced by the 1857 shutter ridge by thermoluminescence was also disappointing. The date of about 4,000 years showed that the sample was not completely reset during transport.

The radiocarbon analyses of samples within channels older than channel 6 on the upstream side and channel h on the downstream side are between 2,500 and 15,000 years old. These support our interpretation that they have correlatives well outside the perimeter of our excavations.

The younger channels have dates that constrain the offset history as shown in Figure 8. It is disappointing that this site, which has exceptional constraints on offset magnitude, provides such poor temporal control on the offsets.

Radiocarbon analyses from a paleoseismic site a couple kilometers to the southeast may help reduce the uncertainties. At the Phelan site, Sims and colleagues[21,22,23] were able to constrain rather well the depositional periods of several discrete alluvial deposits. Since the deposits likely were the product of either severe winter storms or summer cloudbursts, it is not unreasonable to assume that the deposits of these two sites are correlative. If we make this assumption, we constrain the dates of the offsets at the Wallace Creek site much more tightly (Figure 9). The dates of the first 4 events in this construction are also consistent, though barely so, with Grant and Sieh's interpretation of the nearby Bidart site (Figure 2), which has four large events occurring within the period AD 1215 to 1500.

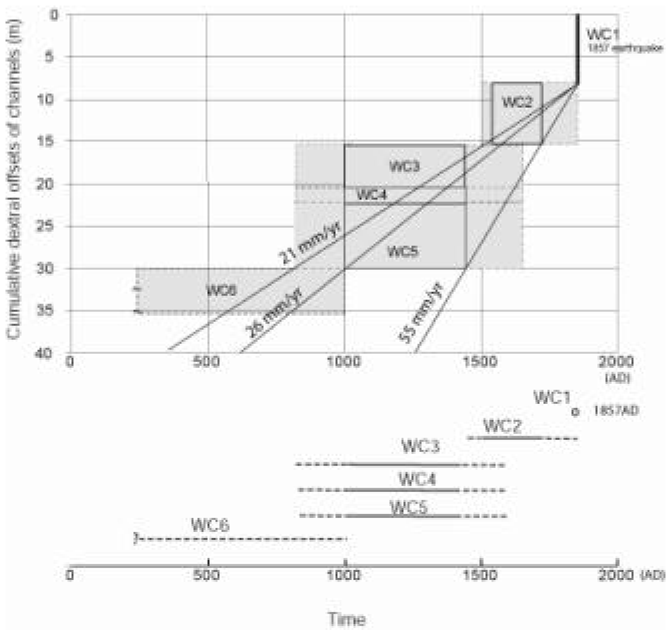

Figure 8. Slip history of the San Andreas fault through the past six events, based solely on data from the Wallace Creek paleoseismic site. Note that the magnitude of slip for each event (except WC 6) is very well constrained, but that the dates of most of the events are poorly constrained. Average slip rates are drawn through the data only for reference.

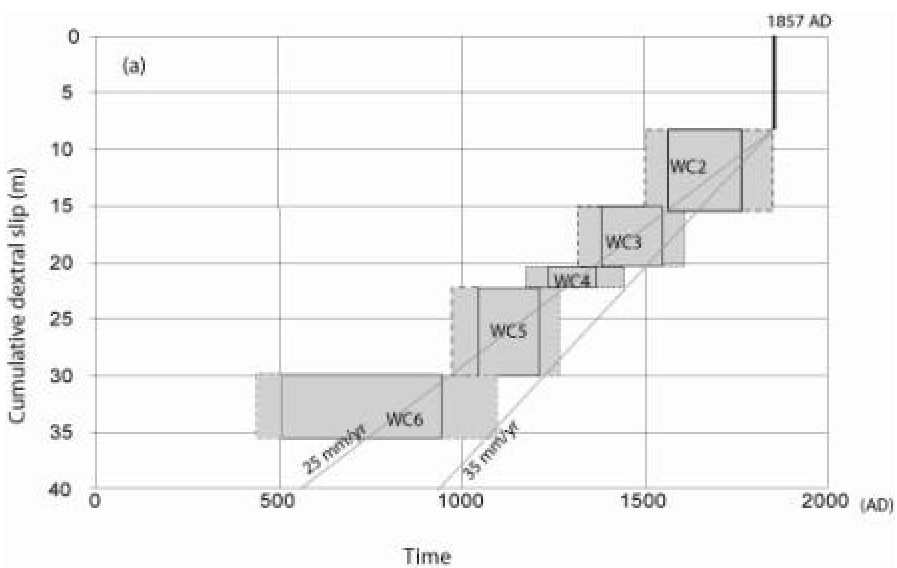

Figure 9. Revised event history, based upon correlation of WC stratigraphy with well-dated stratigraphy at Phelan site, about 2 km to southeast. Tighter and more reliable age constraints will be important for understanding any relationships between slip amount and recurrence interval and other aspects of fault behavior.

2.0 SCOPE OF CURRENT WORK

Publication of Recent Wallace Creek Results

For the first part of this project, we prepared two manuscripts for publication based on Jing Liu's PhD. thesis. The shorter manuscript, entitled: Six similar, sequential ruptures of the San Andreas fault, Carrizo Plain, California[24], briefly summarizes our findings at Wallace Creek for the general geoscience community. We published this paper in the journal *Geology* and present the abstract of the article in Appendix A of this report.

The longer manuscript, entitled Serial Ruptures of the San Andreas Fault, Carrizo Plain, California, Revealed by Three-dimensional Excavation[25] offers a more detailed description of our work at WC and the implications of our results for modeling rupture behavior on the San Andreas fault. We submitted this longer manuscript to the Journal of Geophysical Research and responded to first reviews. The revised manuscript is currently in review.

Investigations to Answer Questions from Wallace Creek Work

The second part of this project focused on answering questions that have arisen from the work at the WC paleoseismic site; most notably, what are the dates of the last five prehistoric events? Although we succeeded in determining the sequence of six offsets that produced the latest 36 meters or so of offset at the WC site, we failed to constrain well the dates of most of these events, especially the earlier ones. For example, event WC6, the oldest pre-historic earthquake identified in the WC trenches could have occurred anytime within the period AD 300 to 1000. Event WC5 could have occurred anytime between AD 1000 and 1500, although we may have constrained both WC5 and 6 to between 400 and 1250 by correlating our strata with those of the Sim's Phelan Creek site, a few kilometers to the southeast. And, if both events correlate to the fifth and sixth events seen by Grant and Sieh at the Bidart site, they could both actually post-date AD 1200. These poor constraints prohibit any reliable or useful constraints on the 1) variability of slip rate at millennial scales, 2) variability in recurrence interval and 3) correlations of slip magnitude with length of recurrence interval.

To better constrain the timing of the WC events, we conducted exploratory paleoseismic investigations at a promising site 4 kilometers northwest of WC that records at least the last six events on the San Andreas fault. (Figure 10). We call this site Branden Creek (BC). A channel at the BC site exhibits a geomorphic offset of over 40 meters, equivalent to the cumulative slip for at least the last six events at WC. Because the large events that offset the creek would have created several high shutter ridges that blocked flow in the upstream channel, we hoped that the collapse of these shutter ridges into the deep upstream channel of BC would be much more obvious than in the shallow channels of WC, and would be less obscured by bitourbation. We anticipated that the interbedding of these collapse deposits with ponded alluvium would be clear enough to resolve individual events within the thick section of ponded alluvium (Figure 11). Most importantly for dating the events, we anticipated finding in-situ organic material in A horizons developed in the ponded deposits, or short-traveled detrital organic material such as grass mats that had fallen into the channel during collapse of the shutter ridges

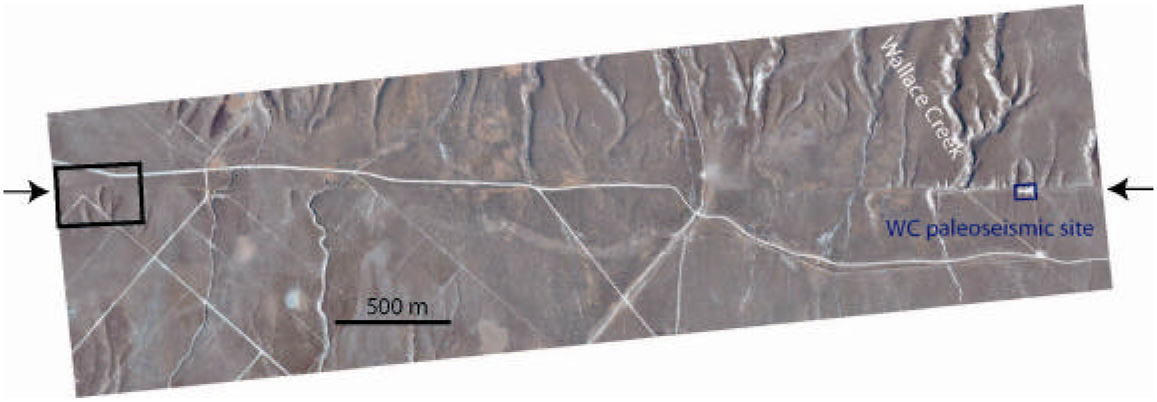

Figure 10. Branden Creek crosses the fault about 4 km northwest of Wallace Creek.

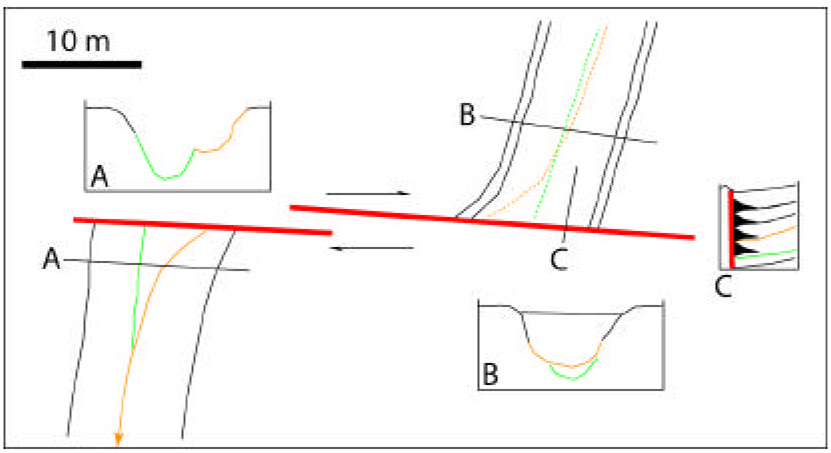

Figure 11. Sketches of Branden creek at the fault crossing.

The upstream channel is almost full of channel sediment, which contains ponded deposits and colluvial wedges.

The BC site also offered the possibility to obtain another slip rate measurement for the fault, and a chance to constrain better the magnitude of slip for event WC6. We felt it necessary to obtain another slip measurement for this event because the 5.4 meter offset at the Wallace Creek site may only be a minimum. Since the magnitude of slip for this event should equal the difference between the pre and post WC-6 downstream channel thalwegs, the site provides an opportunity to obtain a precise measurement for this event (Figure 11). Although, this latter task requires extensive 3-D excavations, we hoped limited excavations for this exploratory investigation could help us evaluate the usefulness of the site for further study.

3.0 EXPLORATORY PALEOSEISMIC INVESTIGATIONS AT BRANDEN CREEK

3.1 Geomorphology of the Branden Creek Site

Branden Creek is an approximately 20-meter-wide, southwest-trending ephemeral stream that has incised into late Pleistocene alluvial fan deposits shed from the Temblor Range, northeast of the site. As mentioned above, surficial observations show that Branden Creek has been offset over 40 meters by the San Andreas fault, resulting in the channel upstream of the fault no longer connecting directly to the downstream channel. Figure 12 shows offset legs of the creek, hereafter referred to as the upstream and downstream channels. A narrow fault-parallel drainage has developed between the two channels.

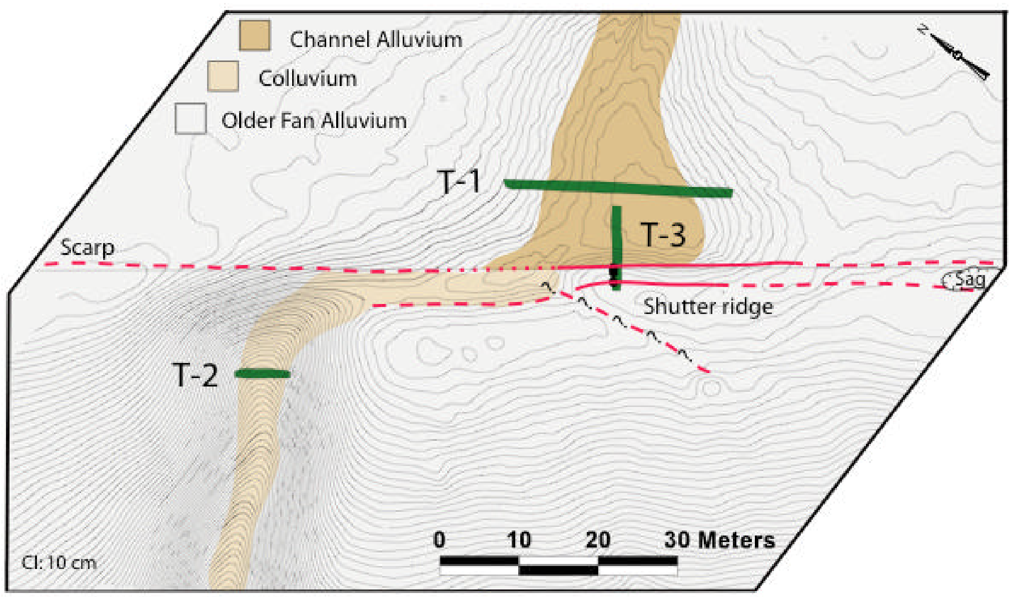

Figure 12. Detailed contour map of the Branden Creek site showing the surface expression of the San Andreas fault and the >~40+ meter geomorphic offset of the creek across the fault. Ponded alluvial sediments nearly fill the dammed upstream channel while the downstream channel is only partially filled with colluvium. The contour interval for the map is 10 centimeters.

The San Andreas fault is well expressed across the Branden Creek site. Immediately southeast of the creek, the fault is marked by a subtle closed-depression, labeled “sag” on Figure 12, which merges northwestward into a 60 centimeter-high shutter ridge that blocks the upstream channel. At the northwest edge of the channel, the shutter ridge steps a couple meters to the left (southwest). Here a small north-trending rill, oriented about 30 degrees to the strike of the San Andreas fault has incised obliquely across the shutter ridge. The rill intersects the connector channel at the left step in the shutter ridge, suggesting the presence of a secondary fault splay.

Beyond the step, the linear connector channel marks the general location of the fault between the two legs of BC. Northwest of the connector channel, the abrupt termination of the downstream channel marks the fault location. Northwest of the downstream channel, the fault is expressed along a prominent northeast-facing scarp.

The downstream channel is currently about 3 meters deep, with steep upper walls that shallow abruptly towards the base of the channel. This suggests the downstream channel is partially filled with colluvium, and that the channel incision extends several meters beneath the ground surface.

The upstream channel has a flat bottom that is only about a meter below the crest of the channel walls. This portion of the channel has obviously been filled-in with ponded alluvial and colluvial material deposited after the San Andreas fault offset the creek. The connector channel between the upstream and downstream legs is similarly filled with colluvium.

3.2 Methodology

We excavated two fault-parallel and one fault-perpendicular trench at the Branden Creek site. We placed one fault-parallel trench (T-1) and the fault-perpendicular trench (T-3) in the upstream channel, and the other fault parallel trench (T-2) across the downstream channel (Figure 12). Trench T-1 was placed approximately 7.5 meters upstream of the shutter ridge to provide a typical exposure of the Branden Creek channel stratigraphy and morphology, well upstream of any fault deformation or scarp-derived colluvium. This allowed us to better understand channel and fault relations in the subsequent trenches at the site.

Trench T-3 was located between trench T-1 and the top of the shutter ridge to the south. We carefully oriented the trench to expose the deep center portion of the channel, which stood the best chance of "collecting" and preserving obvious event stratigraphy. We were careful, however, to not disturb the channel thalweg, and northwestern channel margin, so as to preserve these areas for any future 3-D excavations at the site.

We placed trench T-2 across the downstream channel, nearly 10 meters southwest of the San Andreas fault. The purpose of this trench was to more precisely measure the total offset of Branden Creek using the channel thalweg of the main upstream and downstream channels as a piercing line. Furthermore, we hoped to find other downstream channel incisions that could be used to measure slip from individual events in future 3-D excavations.

Prior to excavating the trenches, we conducted a detailed total station survey of the entire study area. We surveyed over 3000 data points in and around the upstream and downstream channels and used this information to create a detailed topographic base map with a 10-centimeter contour interval for the site (Figure 12). We marked five of the survey points with large nails and covered each nail with a rock cairn to preserve it for future surveys at the site.

All geologic contacts exposed in the trench walls were marked with small nails and then surveyed with the total station. We placed these data in the same reference frame as the topographic survey using the five permanent reference points, which allowed us to precisely measure offset of Branden Creek in 3-D.

3.3 Stratigraphy

Older Fan Deposits

The older fan deposits into which Branden Creek is incised consist predominately of massive, light brown sandy to gravelly silt with interbeds of well-sorted gravel, sand and clay. Beds are generally tabular in shape, and slope very gently southwestward. The sand and gravel in the coarser beds is typically coated with carbonate, whereas silt and fine sand in the finer beds is slightly to moderately oxidized. The alluvium within about 2 meters of the ground surface is highly bitourbated. Although we didn't date the older fan alluvium directly, these deposits appear to be part of the same late Pleistocene fan complex dated by Sieh and Jahns at Wallace Creek[14]. The similarity of the provenance, color and induration of the substrate at BC to correlative deposits at WC suggest that these deposits are also Late Pleistocene in age.

Channel Fill

The upstream channel is filled with distinctive, laterally continuous alluvial and colluvial deposits that we divide into four primary units (100-400) based on depositional style, and several subunits based on composition. The downstream channel is filled only with units 300 and 400. Figure 13 shows the distribution of these units in the deepest portion of the upstream (trench T-1) and downstream (trench T-2) channels. Plate 1 at the back of this report includes complete logs of trenches T-1 and T-2.

Several localized wedges of colluvium derived from the substrate and units 100 and 200 were observed in the immediate vicinity of the fault zone and are shown on Figure 17, in Section 3.6, below.

Unit 100, the uppermost deposit in the upstream channel consists of well-sorted, fluvial sandy gravel that is approximately 1.25 meters thick in the deepest part of the channel and pinches out toward the channel margins. This gravel does not resemble any of the other deposits that fill Branden Creek and probably came from a distinctive sediment source such as a landslide in the Temblor Range.

Unit 100 has incised into the finer grained sediments of unit 200, which includes a ~10 centimeter thick upper silt bed (210) and ~25 centimeter thick lower sandy silt bed with scattered gravel (220). Trench T-3 shows that unit 100 thins and unit 200 pinches out toward the San Andreas fault (See figure 17 in Section 3.6). The presence of units 100 and 200 only in the upstream channel indicates that stream flow across the fault had been completely cut off when these units were deposited. This explains the depositional environment for the beds of unit 200, which likely settled out of suspension as water ponded against the shutter ridge blocking the upstream channel.

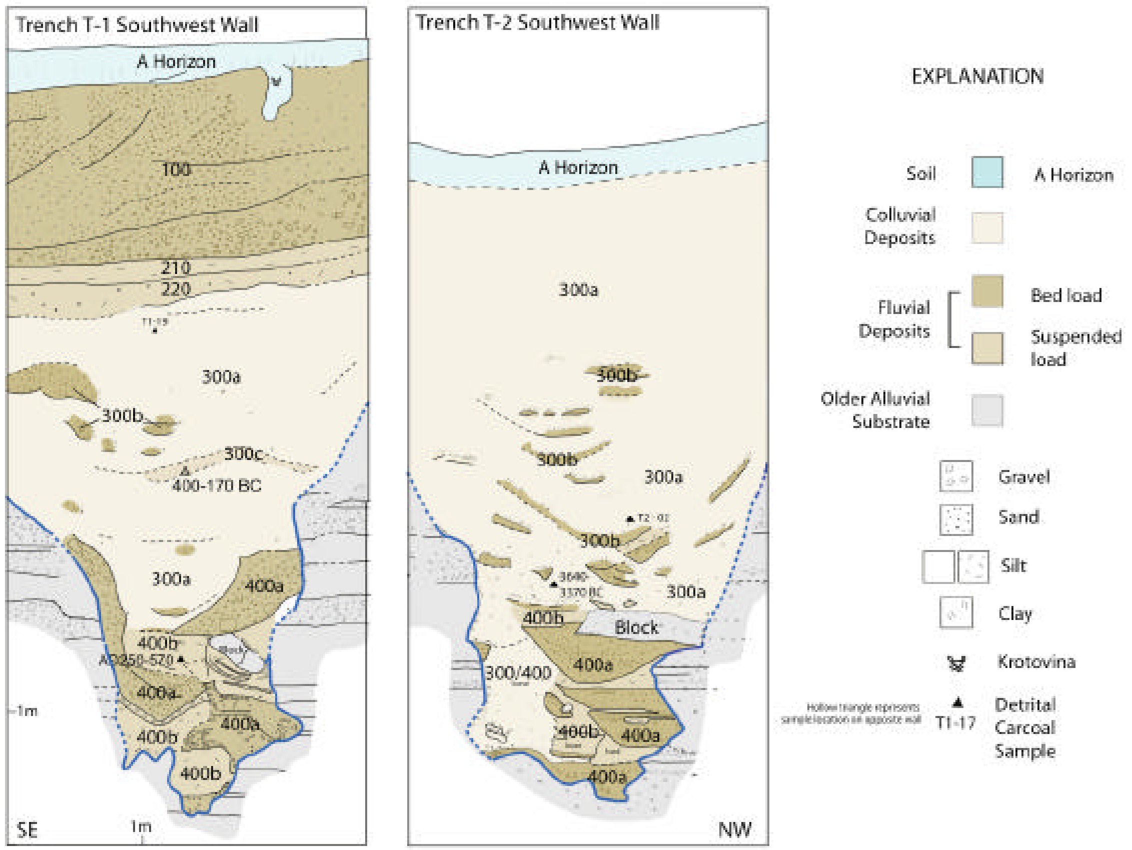

Figure 13. Stratigraphic profiles through the middle of the upstream and downstream channels. See Plate 1 for complete logs of trenches.

Unit 300 consists of massive, poorly sorted colluvial and alluvial deposits (300a) interspersed with small gravel-filled channels (300b) and lenses of silt (300c). Unit 300 is a maximum of about three meters thick in the downstream channel, and just over two meters thick in the upstream channel, having been partially eroded away prior to deposition of units 100 and 200. The massive alluvial/colluvial fraction (300a) consist primarily of sandy silt with scattered gravel and was probably derived locally from sloughing of the channel walls, as suggested by the poorly defined channel margins between unit 200 and the underlying substrate (shown by dashed lines on Figure 13). Another indicator that unit 300 is derived largely from channel wall material is that the unit exhibits nearly the same thickness on both sides of the fault, even though the sediment supply was trapped upstream behind a shutter ridge after the first event.

The channels comprising sub-units 300b and c are much better developed in the downstream channel, suggesting this area experienced more incision than the upstream channel during the deposition of unit 300. In general, however, unit 300 represents long-term aggradation, punctuated by short episodes of minor independent channel incision on both sides of the fault.

A series of cut and fill channels at the base of the upstream and downstream channels comprise unit 400. Individual channels within unit 400 typically consist of gravel (400a) and silt couplets (400b), locally interbedded with blocks of substrate or reworked colluvium that has fallen into the channel.

All units at the site are capped by 20 to 50 cm of topsoil. This A horizon consists of fine sandy silt and is in sharp contact with the older fan deposits and unit 100 in the upstream channel. The base of the soil is more gradational where it overlies unit 300 in the downstream channel. In the upstream channel, a thin distinctive clay layer can be observed at or near the top of the soil.

Age of Channel Deposits

Calibrated 2-sigma radiocarbon dates of 440–170 BC and 3640-3670 BC provide maximum age constraints for unit 300 in the upstream and downstream channels respectively. A charcoal sample from one of the silt beds near the top of unit 400 yielded a younger calibrated radiocarbon date of AD 250-570. This date constrains the age of all units overlying unit 400, and shows that charcoal samples dated from unit 300 have a large inheritance problem. We found no evidence of burrowing or other bioturbation in the vicinity of the younger date and are confident that it was in place.

Dates were calibrated with the computer program Oxcal 3.1, which uses long-term atmospheric data sets from Reimer et al.[26] and Ramsay[27]. The original report from the lab that processed and dated the samples is included in Appendix B of this report.

3.4 Channel Morphology

Main Channel

The margins of the upstream and downstream channels were clearly defined in our trenches by differences in the color, lithology and induration of the channel fill with respect to the underlying older alluvial substrate. The most striking differences occurred in units 100, 200 and 400, which were darker in color, less oxidized and contained less pedogenic carbonate than the underlying substrate. The channel margins are poorly defined between unit 300 and finer-grained substrate, likely because unit 300 is largely composed of material eroded or sloughed from nearby channels walls.

The upstream channel has steep basal walls that generally shallow upward in two distinct increments, represented by inflection points a and b on the cross-sectional profile of the channel in Figure 14,. About 2 to 2.5 meters above the base of the channel, the slope of the walls shallows from nearly vertical (red lines on Figure 14) to between 45 to 60 degrees (blue lines). This transition directly above or below the contact between units 300 and 400 (Figure 13). About 3.2 to 3.6 meters above the base, the channel walls shallow to 30 degrees or less (green lines).

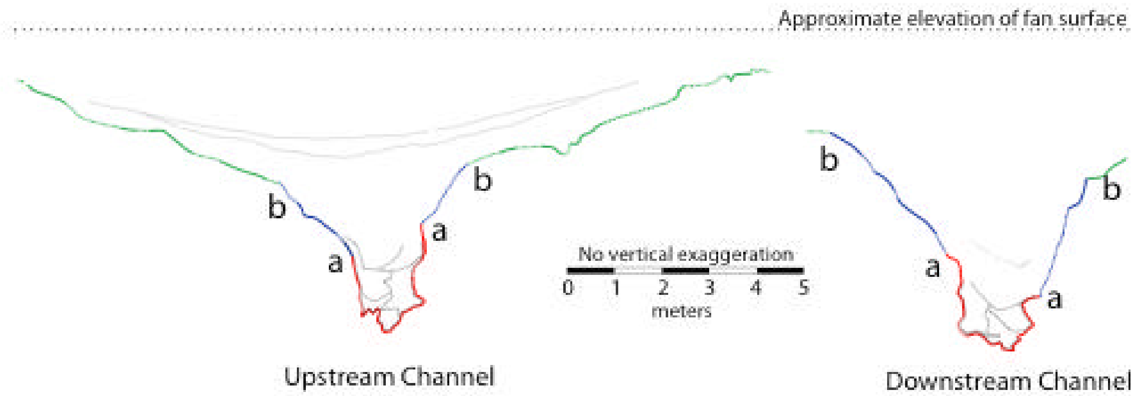

Figure 14. Cross-section of upstream and downstream channel margins. Colored lines mark angle of channel wall slopes: red > 80 degrees, blue 45 – 80 degrees, and green < 45 degrees. Letters a and b mark inflection points between slope segments. Black lines define margins of significant internal channels.

The steep 1- to 1.5-meter-wide basal portion of the main channel is probably a morphological remnant from the initial incision of the channel, when the creek was a steep narrow gully with nearly vertical walls extending to the surface. Similar steep gullies still form on the Carrizo plain today. We found large blocks of the substrate in the basal channel section that suggest the upper channel walls were unstable and often collapsed into the channel. The first offset of the creek cut off the fast, through-going stream flow that had created and maintained the steep gully walls, ushering in a period of colluviation that gradually lowered the slope of the walls.

The downstream channel is also characterized by a narrow steep-walled lower section and more shallow-sloped central section (Figure 14). Trench T-2 was not long enough to expose the upper portion of the channels walls.

Internal Channels

Very broad shallow channels in the upper ~2 meters of the upstream channel probably represent debris flow scours into the colluvium of the nearly filled upstream channel (Figure 14). The small cut and fill channels preserved at the base of the main upstream and downstream channels are defined by sharp erosional contacts and clay layers at the base of some channel bottoms. Both upstream and downstream channels contain 4 to 5 nested channels, each typically less than a meter in width, and deeper than they are wide (Figure 15). We designate these small channels 1 through 5 in the upstream channel and a through d in the downstream channel, ordered from youngest to oldest based on cross-cutting stratigraphic relations.

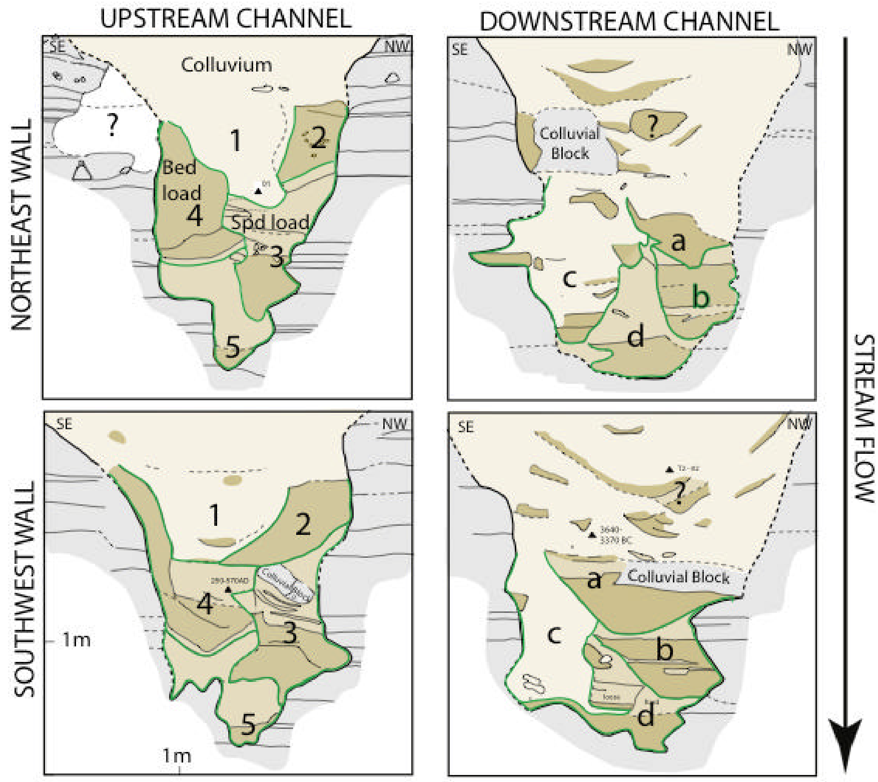

Figure 15. Green lines mark individual cut and fill channels at the base of Branden Creek. We identified five distinct scours in the upstream channel (1-5) and four in the downstream channel (a-d). Channels can be readily matched between trench walls, but do not correlate well across the fault.

In most cases these small channels can be roughly correlated across each trench based on similarities in stratigraphy and channel shape. Figure 15 shows that numbered (upstream) channels cannot be readily correlated to lettered (downstream) channels, however. The only feature that correlates well between these channels is the coarseness of their internal stratigraphy.

The lack of correlation between the two trenches probably results from localized variations in stream flow due to blocks of colluvium that have fallen into the channels. Channel obstructions can produce changes in channel morphology, even over distances as short as 1 meter (the width of the trenches), as can be seen in the northeast wall of trench T-2, where several small channels are deflected around a block of colluvium that has fallen in and lodged against the southeast channel wall. The cumulative effect of such minor deflections offers the best explanation for the lack of correlation of the nested channels between our trenches.

3.5 Channel Offset

Cumulative Offset of Main Channel

The similar stratigraphy and shape of the upstream and downstream channels clearly shows that the main channel of Branden Creek correlates across the fault, allowing us to unambiguously determine the total offset of the creek. We measured the lateral offset of the creek by projecting the thalwegs of the main upstream and downstream channels into the fault zone and then measuring the separation of these intersection points along strike of the fault. A simple straight-line projection of each thalweg to the fault, using orientations measured in the trenches, results in a total lateral offset of about 48 meters (Figure 16).

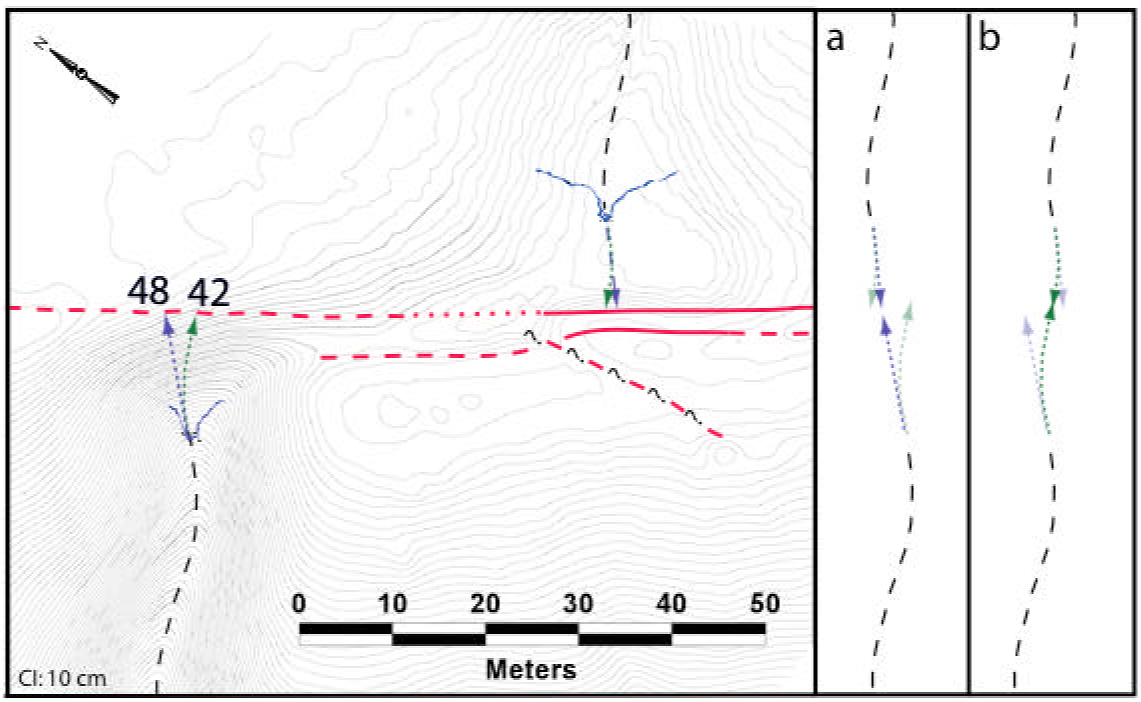

Figure 16. Colored lines depict possible end member projections of the channel thalweg to the fault zone: Blue dotted lines show a straight-line projection using thalweg orientations obtained in trenches. The green dotted line assumes the channel is more sinuous near the fault zone. Numbers above downstream channel represent possible offsets values in meters. Insets a and b show channel reconstructions using each projection.

Inset a in Figure 16 depicts a reconstruction of the channel after the ~48 meters of slip has been removed. This reconstruction shows that the orientations of upstream and downstream thalwegs correlate well across the fault. Furthermore, in map view, the sinuosity of the reconstructed channel generally matches across the fault.

Because our trenches are 7 to 10 meters away from the fault zone, slight variations in the trend of the thalweg could result in a deviation of several meters from the offset measured using the straight-line projection. For example, if the creek channel were locally more sinuous, perhaps due to a change in the fan gradient due to deformation near the fault zone, the stream offset could be as low as about 42 meters (Figure 16b). Stratigraphy in the southeast wall of Trench T-3 and the morphology of the northwest wall of the downstream channel constrain the location of the channel thalweg, limiting the maximum offset of the creek to no more than about 48 meters. We therefore estimate the total offset of Branden Creek as about 45 +/-3 m. Sequential excavations of each channel to the fault zone would probably reduce this uncertainty to tens of centimeters or less.

Possible Offset of Internal Channels

At Wallace Creek, the repeated incision of new fault-perpendicular channels across the San Andreas fault allowed for the determination of slip per event. At Branden Creek, a distinctive right deflection at the head of the downstream channel suggests that there may have been similar high-angle incision across the fault after at least the first event. An interesting channel cut into a terrace on the northwest wall of the upstream channel could reflect post-event incision. This channel is marked with an X on Plate 1. Without knowing the age of this channel or its location, trend, or morphology closer to both sides of the fault, we cannot resolve slip on this feature. This feature provides a good target for future investigations to determine the slip for the first event to offset Branden Creek.

The lack of other fault-perpendicular channels across the fault between the upstream and downstream channel shows incisions after the second event, if any, occurred at low angles to the fault, which would make it difficult to resolve slip for these features.

3.6 Paleoiseismic Investigation

Fault Zone Structure

Trench T-3 exposed a 1.5- to 2-meter wide zone of faulting beneath the shutter ridge immediately southwest of the upstream channel. The fault zone could in fact be wider because we were not allowed to extend trench T-3 further to the southwest due to ecological constraints. Figure 17 shows that the fault zone includes several continuous to discontinuous sub-vertical fault strands.

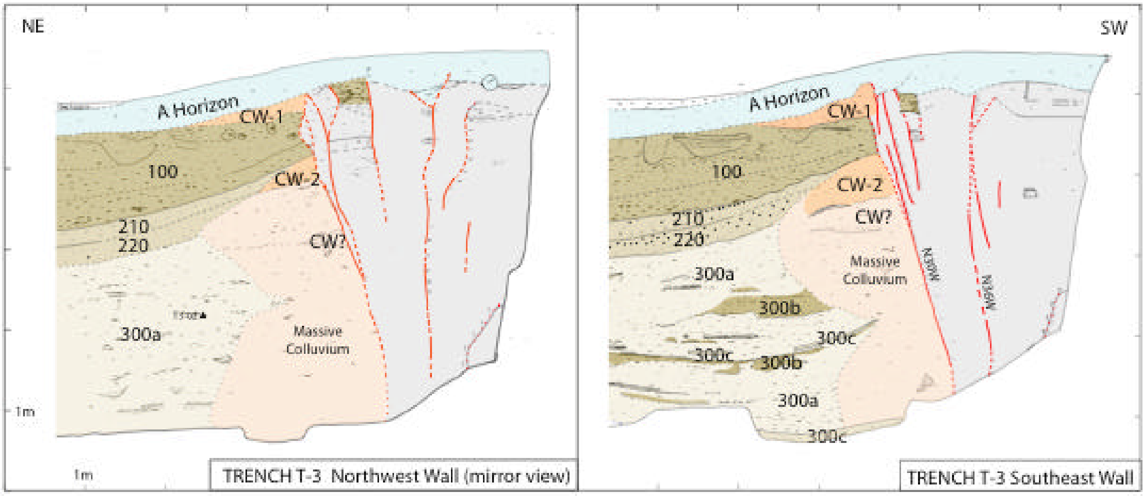

Figure 17. Logs of the San Andreas fault zone as observed in a portion of trench T-3 (The trench logs are presented in their entirety on Plate 2 at the end of this report). The dark orange wedges near top of the trench overlie distinct event horizons. The underlying lighter orange material is probably also scarp or shutter-ridge-derived colluvium; events in this material cannot be resolved because of the lack of stratigraphy.

The northeastern edge of the fault zone is defined by what we call the main fault, which strikes N30W and juxtaposes the upstream channel deposits against older alluvial fan deposits to the southwest. The main fault is locally lined with sheared clay and branches upward into several secondary fault splays that bound lenses of older alluvium and younger channel deposits. These splays extend to the base, or in some cases, just above the base of the topsoil.

Faults to the southwest of the main strand are typically discontinuous, cutting older fan deposits and truncating silt or sand beds near the surface before terminating at the base of or within the topsoil. These faults are locally lined with carbonate, sand or clay. Several of the strands die downward into the massive older alluvial deposits. A carbonate-lined silt bed exhibits about 0.4 meters of vertical separation southwest of the main strand. Only the main fault and one of the secondary strands can be correlated across the trench.

Evidence for Earthquakes

The multiple large strike-slip offsets that produced the cumulative ~45 meter offset of Branden Creek created several high shutter ridges that blocked flow in the upstream channel. We anticipated that the collapse of these shutter ridges into the upstream channel shortly after each earthquake would produce distinctive colluvial wedges separated by beds of alluvium deposited between events. Furthermore, we hoped that organic material in each wedge and ponded deposit would bracket the timing of the events. To our surprise, trenches T-1 through T-3 revealed evidence for at least four events, only two of which were clearly delineated by colluvial wedges; none of the wedges contained datable organic material (Figure 17; CW-1 and CW-2). Other wedge-like features and colluvial deposits may have represented additional events, but a lack of stratigraphy below unit 200 kept us from resolving the number or the relative timing of these earthquakes. We describe the evidence for these events below, from oldest to youngest:

The first event to offset Branden Creek is marked by the abrupt transition from the high-energy erosional environment in which unit 400 was deposited, to the sluggish, aggradational environment of unit 300. The primarily massive sediments of unit 300 upstream of the fault indicate that the upstream channel was blocked by a shutter ridge during this event and filled with ponded alluvium and colluvium. Numerous small channels in unit 300 downstream of the fault, indicate that this portion of the channel adjusted to the lower stream gradient of the offset channel through incision.

Alternatively, the transition to lower energy stream flow between units 400 and 300 could have been caused by an abrupt climatic shift that produced less rainfall on the Carrizo Plain. We believe this is unlikely, however, because our investigations at Wallace Creek, and studies by Sims at Phelan Creek show that storms in the past couple millennia produced enough precipitation to cause repeated channel incision at both sites[21,22,23,24,25]. We therefore believe that there was enough precipitation to continue incision of the Branden Creek channel. Furthermore, a change in climate does not explain why channels in unit 300 occur primarily downstream of the fault. A large earthquake that significantly altered the creek channel is the most reasonable explanation for the radical change in the style of sedimentation between units 300 and 400..

A charcoal sample in unit 400 constrains the maximum age of this earthquake to between 250 to 570 AD. Assuming that channels in unit 400 incised and filled rapidly during each storm, this earthquake likely occurred only shortly after this piece of charcoal was deposited.

Crudely wedge-shaped gravel and sand layers on the northwest wall of trench T-3 (CW? on Figure 17) and a large massive pod of colluvium in the lower two thirds of both trench walls could represent one or more events within unit 300. As mentioned above, we cannot constrain the number or timing of these events due to the lack of stratigraphy in unit 300.

The next youngest clearly resolvable earthquake produced a distinctive wedge of loose, porous, carbonate-coated sand and silt beneath units 210 and 220 and immediately southwest of the main fault strand. This colluvial material probably collapsed off of the adjacent shutter ridge, burying the top of unit 300, the event horizon, during or immediately after this earthquake. Units 210 and possibly unit 220 pinch out against the colluvial wedge while a gravel bed at the base of unit 100 thins only slightly across the wedge, suggesting units 102 and 103 had largely filled in the topographic expression of the shutter ridge prior to the deposition of unit 100.

The next youngest event is marked by another wedge of loose silty gravel above unit 100 and bounded by the main fault. This wedge is apparent in both walls of trench T-3, and appears to have been derived from both unit 100 and surface soil at the time. The topsoil on the southeast wall of trench T-3 thins above this wedge.

Detrital charcoal collected from the base of unit 220 could provide a lower bounding age for both events. Due to budget constraints for this project, we focused on dating earlier events at the site, and did not date any samples from unit 220. The lack of charcoal in the colluvial wedges, or above unit 220 limits our ability to determine an upper bounding age for these events.

The most recent event at the site is clearly marked on both walls of trench T-3 the upward termination fault strands into the topsoil. Although we couldn't directly date this event, the close proximity of fault strands to the ground surface, suggests this event is the historical1857 earthquake.

4.0 DISCUSSION

4.1 Constraints on Branden Creek Earthquake Record from Slip Measurements at Wallace Creek

At Wallace Creek, we determined that the last six earthquakes on the San Andreas fault had produced a maximum cumulative slip of about 36 meters, with slip for typical events ranging from 7.5 to 8 meters. For some events, however, slip was as low as 5.2 to 1.4 meters. If we assume that the fault experienced exactly the same amount of slip per event at BC and WC, the ~45 meter offset we see at our site must have been produced by more than six events. Using this simple model, we can further assume the additional ~9 meters of slip at Branden Creek occurred prior to the sixth event at Wallace Creek (Figure 18).

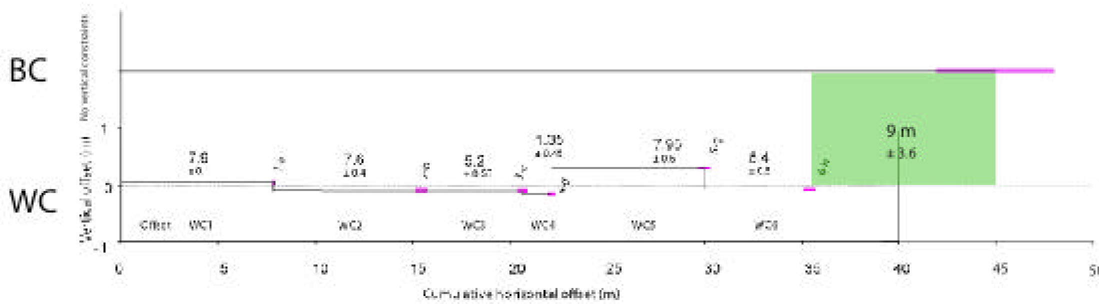

Figure 18. Approximately 9 meters of slip is unaccounted for when comparing the slip from six events at the WC site to the ~ 45 meter offset of Branden Creek. The additional 9 meters probably represents slip from an event prior to WC6.

If the 36 meters of slip at the Wallace Creek site is a minimum value (which we have reason to believe) and a "typical" 7.5 to 8 meter WC slip event accounts for the remaining Branden Creek offset, seven events must have occurred since BC was incised. If, however, slip for the seventh event back was similar to that of the 5.2 or 1.4 meter slip events at WC, the ~45 meter offset of BC could have resulted from eight, or even more events. Conversely, if the 1.4 meter WC4 slip event at WC marked the tail end of a rupture that died out northward before BC, the ~45 meter offset could have occurred in as little as six very large events. The single radiocarbon date constraining the maximum age of the earliest BC event to AD 250 to 570, does not shed much light on these uncertainties because this date falls within the maximum age range of event WC6 (AD 300 to 400). Our best guess, based on the typical occurrence of large events at WC, and the likelihood that the 36 meter total offset at that site is a minimum value, is that first event to offset BC was large (7.5 – 8 meters), and that Branden Creek has probably experienced seven events. Despite these uncertainties, the WC earthquake record shows that several events were not recorded clearly in the stratigraphy of our fault-perpendicular trench.

4.2 Slip Rate

The 45 ± 3 meter total offset of Branden Creek and maximum age of AD 250 to 570 for the first earthquake to offset the channel, allows us to calculate a crude minimum slip rate of 26.1 to 37.2 mm/yr for the San Andreas fault at our site [45 ± 3 m/1,447 ± 160 yr]. This rate assumes that the first event to offset Branden Creek occurred immediately after the deposition of the ~1,450 year old charcoal sample, and that the creek incised immediately after the earthquake that occurred prior to the AD 250 to 570 event, and thus accumulated all the strain of that earthquake cycle. Because we cannot preclude that the creek incised immediately before the first event to offset the channel, our slip rate may be too high by up to one cycle of strain accumulation. If we assume Branden Creek has experienced six earthquake cycles in the past 1,447 ± 160 years, we get a recurrence interval of about 215 to 270 years. Our calculated slip rate could therefore be a maximum of 21 percent (the percentage of the dated earthquake record at the site comprising one recurrence interval) lower, providing an extreme minimum slip rate of 20.6 to 29.4 mm/yr. Conversely, if the creek incised shortly before the first event to offset the channel, and the event occurred a couple hundred years after AD 570, the rate would be higher. Because the creek likely incised in response to deformation from the event prior to the first event to offset the creek, we prefer the 26.1 to 37.2 mm/yr rate estimate.

4.3 Implications of Findings

Despite uncertainties in the slip rate and event timing at the Branden Creek site, our work offers new insights into variations in the late Holocene slip rate and patterns of earthquake recurrence for the Carrizo segment of the San Andreas fault.

One of the key questions that arose from our work at the Wallace Creek site was whether the slip rate of the San Andreas fault varied through time. Results from recent work in the Elkhorn Hills area of the Carrizo Plain, the work documented in this report, and our original work at Wallace Creek now offer slip rates in three different millennia. From youngest to oldest, these documented rates are 29.5 to 35.8 mm/yr since AD ~1160 at the Elkhorn Hills site[28], 26.1 to 37.2 mm/yr since AD ~250 to 570 at Branden Creek, and 31.0 to 36.8 mm/yr since ~1800 BC at Wallace Creek[14]. The very broad agreement of these slip rates suggests that the long-term slip rate for the Carrizo Plain segment has varied by less than 30% over the last four millennia.

Earthquake recurrence may have been quite irregular over the last three millennia, however. This best illustrated by comparing our BC results to the event record at the Bidart site approximately 18 km southeast of Wallace Creek. The BC data show that probably seven and possibly more events have occurred over the last ~1,450 years. Ongoing studies at the Bidart site reveal evidence for a minimum of 10 events over the last 3,000 years[29]. Assuming that the entire Carrizo segment has experienced a relatively similar rupture history, the Branden Creek site shows that at least two-thirds of the large slip events on the San Andreas fault occurred in last ~1500 years. Furthermore, previous work at the Bidart site shows that at least four of these events occurred between 500 to 800 years ago. These data imply that the paleoseismic record for the first 1,500 years of the 3,000-year Bidart record is incomplete, or that strain release varies significantly through time. If so, average earthquake recurrence is not a useful tool for estimating seismic hazard along this portion of the San Andreas fault.

4.4 Potential for Future Work at Site

Contrary to our expectations before starting this reconnaissance investigation, the Branden Creek site did not yield a clear, datable record of the last six or seven events on the San Andreas fault. There is a strong possibility, however, that further 3-D excavations will provide good constraints on slip from the sixth or seventh events back, thus constraining, or extending the Wallace Creek paleoseismic record. We did not see evidence of re-incision across the fault zone after the first few events, making slip determinations for later events difficult. Unfortunately, this will limit our ability to characterize the post-incision event record at the site, hampering strong event correlations between BC and WC.

Dating additional charcoal samples collected during this investigation can also provide a maximum age for the third event back.

5.0 SUMMARY OF RESULTS FROM EXPLORATORY PALEOSEISMIC INVESTIGATIONS

Paleoseismic investigations at the Branden Creek site show:

- Branden Creek is offset a total of 42 to 48 meters by the San Andreas fault.
- This offset probably resulted from seven, or perhaps more events.
- The first event to offset the creek occurred shortly after AD 250 to AD 570.
- Our best-guess slip rate for the San Andreas fault at Branden Creek is 26.1 to 37.2 mm/yr.

Our preliminary investigations show that additional studies at the Branden Creek site have a good chance of constraining further the slip rate and timing of the first event to offset the creek. Furthermore, there is a possibility that additional work could constrain the slip for the second event to offset the channel. Unfortunately, site conditions preclude precise dating or determination of slip per event for most of the prehistoric earthquakes that have occurred since Branden Creek was incised.

ACKNOWLEGMENTS

First and foremost, we thank Mr. Benjamin Fortun and Ms. Lynn Kleiner, who graciously allowed us access to their properties to conduct paleoseismic investigations at the Branden Creek site. Once the trenches were open, Branden Maehr, after whom we named the creek, provided invaluable help hand digging in the base of the trenches to search for sometimes elusive channel thalwegs. Graduate students Brian Gray from Central Washington University, and Emily Schultz and Celia Shiffman from Oregon State University helped during various stages of the fieldwork, and Brian drafted several trench logs for this report. Ramon Arrowsmith of Arizona State University, Tempe, and Kathy Sharum of the Bureau of Land Management gave us valuable advice on how to avoid impacting endangered species with our trenching endeavors. The Southern California Earthquake Center provided trench shores for this investigation. Finally, Jim Nye allowed us to stay at his house near the trench site, sheltering us from one of the wettest years we can remember on the Carrizo Plain.

REFERENCES

1. E.g., W. G. o. C. E. Probabilities, *Bull. Seismol. Soc. Amer* **85**, 379-439 (1995).
2. W. G. o. C. E. Probabilities, "Probabilities of Large Earthquakes Occurring in California on the San Andreas Fault" *88-398* (U.S.G.S., 1988).
3. R. Yeats, K. Sieh, C. Allen, *The Geology of Earthquakes* (Oxford University Press, New York, 1997).
4. E.g., W. D. Stuart, *J. Geophys. Res.* **91**, 13,771-13,786 (1986).
5. J. B. Rundle, *J.Geophys.Res.* **93**, 6255-6274 (1988).
6. S. Ward, S. Goes, *Geophys.Res.Lett* **20**, 2131-2134 (1993).
7. K. Sieh, *Proc. National Academy of Sciences* **93**, 3764-3771 (1996).
8. S. Lindvall, T. Rockwell, K. Hudnut, *Bull. Seismol. Soc. Am.* **79**, 342-361 (1989).
9. S. Salyards, Patterns of offset associated with the 1983 Borah Peak, Idaho, earthquake and previous events, R. S. Stein, R. C. Bucknam, Eds., Proceedings of Workshop XXVIII on the Borah Peak, Idaho, Earthquake (United States Geological Survey, 1985).
10. S. Ward, *Bull. Seismol. Soc. Amer.* **87**, 1422-1441 (1997).
11. A. Thomas, T. Rockwell, *J.Geophys.Res.* **101**, 5987-5997 (1996).
12. D. P. Schwartz, K. J. Coppersmith, *J. Geophys. Res.* **89**, 5681-5698 (1984).
13. K. Sieh, *J. Geophys. Res.* **83**, 3907-3939 (1978).
14. K. Sieh, R. H. Jahns, *Geol. Soc. Am. Bull.* **95**, 883-896 (1984).
15. K. Sieh, in *International Research Conference on Intraplate Earthquakes, Sept. 17-19, 1979* J. Petrovski, Ed. (Ohrid, Yugoslavia, 1981) pp. 209-218.
16. L. Grant, K. Sieh, *J.Geophys.Res.* **99**, 6819-6841 (1994).
17. R. Wallace, Notes on steam channels offset by the San Andreas fault, southern Coast Ranges, California, W. R. Dickinson, A. Grantz, Eds., Conference on Geologic Problems of the San Andreas Fault System, Proceedings, Stanford, California (Stanford University Publications in the Geological Sciences, 1968).
18. K. Sieh, *Seismol. Soc. Am. Bull.* **68**, 1421-1428 (1978).
19. L. Grant, K. Sieh, *Bull.Seism.Soc.Am.* **83**, 619-635 (1993).
20. L. Grant, A. Donnellan, *Bull. Seismol. Soc. Amer* . **84**, 241-246 (1994).
21. J. D. Sims and J.C. Hamilton, *Abstracts with Programs Geological Society of America*, *21*, (1989).
22. J. D. Sims, *Proceedings of the workshop on paleoseismology, U S Geological Survey Open-file Report 94-568, C. S. Prentice, D. P. Schwartz and R. S. Yeats (editors)*, 170-172 (1994).
23. J. D. Sims, T. Ito, J. Hamilton, A. J. Foss, C. D. Garvin and D. B. Meier, *unpublished manuscript* (1994).
24. J. Liu, Y. Klinger, K. Sieh, C., Rubin, *Geology*. **32**, 649–652 (2004).
25. J. Liu-Zeng, Y. Klinger, K. Sieh, C. Rubin, and G. Seitz, JGR, in review.
26. P.J. Reimer, M.G.L Baillie, E. Bard, A. Bayliss, J.W., Beck, C. Bertrand, P.G., Blackwell, C.E., Buck, G. Burr, K.B. Cutler, P.E. Damon, R.L. Edwards, R.G. Fairbanks, M. Friedrick, T.P. Guilderson, K.A. Hughen, B. Kromer, F.G. McCormac, S Manning, C. Bronk Ramsay, R.W. Reimer, S. Remmele, J.R.

Southon, M. Stuiver, S. Talamo, F.W. Taylor, J. van der Plicht and C.E. Weyhenmeyer, *Radiocarbon*. **46**, 1029-1058.

27. C. Bronk Ramsay, Radiocarbon Program *OxCal*, Version 3.1 (2005).
28. G. Noriega, J.R. Arrowsmith, L. Grant, J. Young, *Proceedings and Abstracts, Southern California Earthquake Center Annual Meeting.* 160 (2005).
29. L. Grant, J.R. Arrowsmith, S. Akciz, *Eos Transactions of the American Geophysical Union* **86** (52), Fall Meet. Suppl., Abstract U42A-07 (2005)

PLATES

PLATE 1 - LOGS OF TRENCHES 1 AND 2
PLATE 2 - LOGS OF TRENCH 3


SE
NW
N36W
Figure 13a
Figure 13b
A Horizon
100
210
220
300a
300b
300c
400a
400b
300/400
Block
X
T1-17
T1-19
T1-21
T1-22
T1-03
T1-23
T2-02
400-170 BC
AD250-570
3640-3370 BC
Massive Homogeneous
1m
DEPOSITS
Soil
A Horizon
Colluvial Deposits
Fluvial Deposits
Bed load
Suspended load
Older Alluvial Substrate
SYMBOLS
Gravel
Sand
Silt
Clay
Krotovina
Detrital Carcoal Sample
(Hollow triangle marks sample projected from opposite wall)
UNITS
100 - Channelized Gravel, locally with Sand
210 - Lense of Massive Silt
220 - Lense of Massive Sandy Silt with Gravel
300 - Massive Silt with scattered Sand and Gravel (a) locally with lenses of Gravel (b) and Silt (c)
400 - Channelized Gravel (a) and Sandy Silt to Silt (b)
TRENCH T-1 UPSTREAM CHANNEL
Southwest Wall (View down stream)
TRENCH T-2 DOWNSTREAM CHANNEL
Southwest Wall (View down stream)

PLATE 1

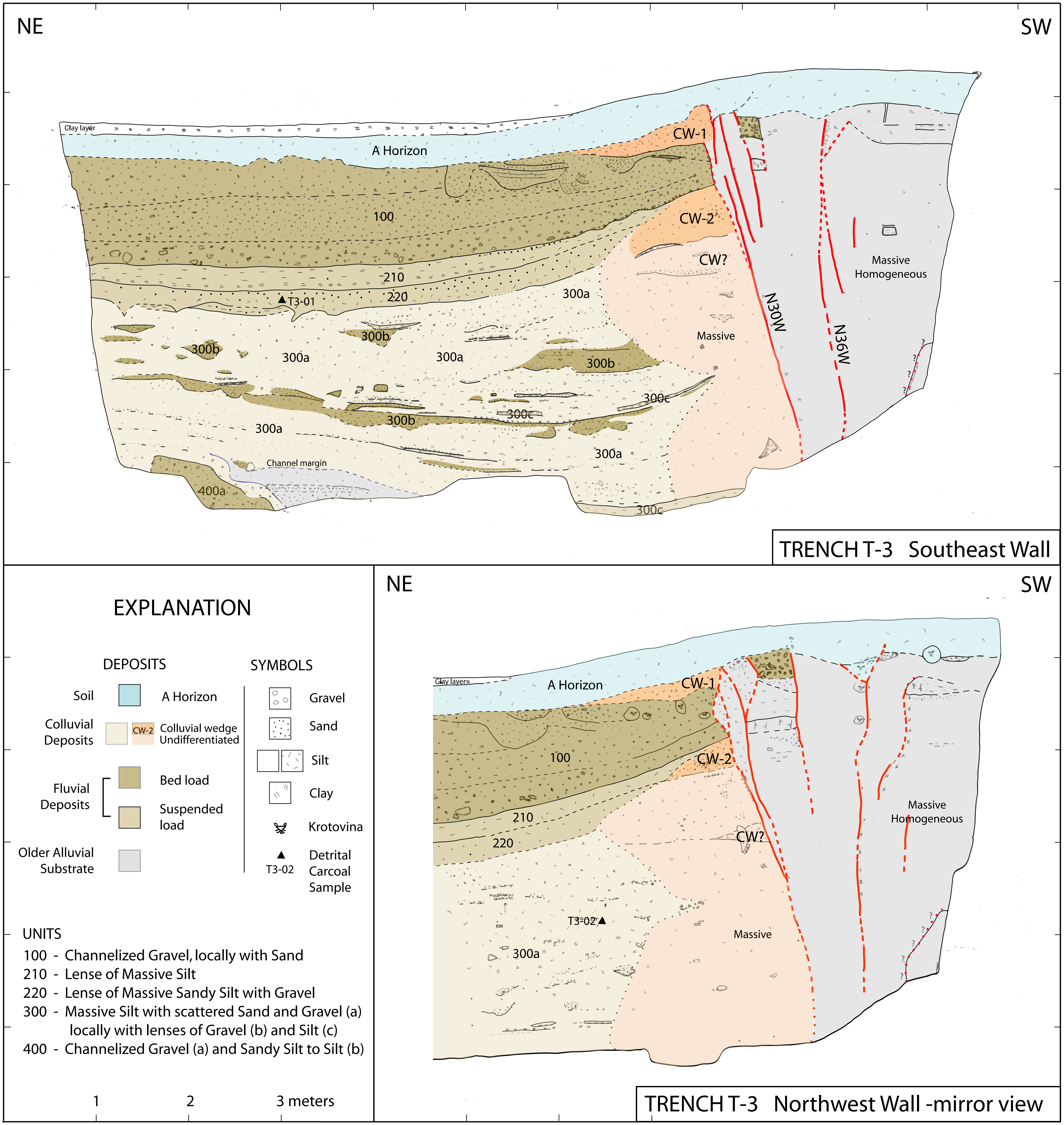
NE
SW
Clay layer
A Horizon
CW-1
100
CW-2
CW?
210
220
T3-01
300a
Massive
N30W
N36W
Massive
Homogeneous
300b
300b
300a
300a
300b
300c
300c
300b
300a
300a
Channel margin
400a
300c
TRENCH T-3 Southeast Wall
EXPLANATION
DEPOSITS
Soil
A Horizon
Colluvial Deposits
CW-2
Colluvial wedge Undifferentiated
Fluvial Deposits
Bed load
Suspended load
Older Alluvial Substrate
SYMBOLS
Gravel
Sand
Silt
Clay
Krotovina
T3-02
Detrital Carcoal Sample
UNITS
100 - Channelized Gravel, locally with Sand
210 - Lense of Massive Silt
220 - Lense of Massive Sandy Silt with Gravel
300 - Massive Silt with scattered Sand and Gravel (a) locally with lenses of Gravel (b) and Silt (c)
400 - Channelized Gravel (a) and Sandy Silt to Silt (b)
1
2
3 meters
NE
SW
Clay layer
A Horizon
CW-1
100
CW-2
210
220
CW?
T3-02
300a
Massive
Massive
Homogeneous
TRENCH T-3 Northwest Wall -mirror view

PLATE 2

APPENDIX A - Abstract from *Geology* Article

Six similar, sequential ruptures of the San Andreas fault, Carrizo Plain, California

Jing Liu, Yann Klinger
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA, *and* Laboratoire de Tectonique, Institut de Physique du Globe de Paris, 4 place Jussieu, 75252 Paris cedex 05, France

Kerry Sieh*
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA

Charles Rubin
Department of Geological Sciences, Central Washington University, Ellensburg, Washington 98926, USA

*Corresponding author; e-mail: sieh@gps.caltech.edu.

ABSTRACT

We document the precise sizes, but not the dates, of the six latest offsets across the San Andreas fault at Wallace Creek, California. Three and perhaps four of these, including the latest, in 1857, show dextral offset of 7.5–8 m. The third and fourth offsets, however, are just 1.4 and 5.2 m. The predominance of similar offsets for the latest six events suggests that the fundamental properties of the fault system that control slip size do not vary greatly from event to event. The large offsets imply that ruptures involving this site are typically more than 200 km long.

APPENDIX B - Radiocarbon Dating Lab Report

CENTER FOR ACCELERATOR MASS SPECTROMETRY

Lawrence Livermore National Laboratory

^{14}C results

Submitter: Madden/Kashgarian DATE: March 23, 2005

CAMS #	Sample Name	Other ID	$\delta^{13}C$	fraction Modern	±	$D^{14}C$	±	^{14}C age	±
114455	BC-T1-13 CLM		-25	0.8178	0.0053	-182.2	5.3	1620	60
114456	BC-T1-18 CLM		-25	0.7584	0.0046	-241.6	4.6	2220	50
114458	BC-T2-04 CLM		-25	0.5535	0.0023	-446.5	2.3	4750	35

1) $\delta^{13}C$ values are the assumed values according to Stuiver and Polach (Radiocarbon, v. 19, p.355, 1977) when given without decimal places. Values measured for the material itself are given with a single decimal place.

2) The quoted age is in radiocarbon years using the Libby half life of 5568 years and following the conventions of Stuiver and Polach (ibid.).

3) Radiocarbon concentration is given as fraction Modern, $D^{14}C$, and conventional radiocarbon age.

4) Sample preparation backgrounds have been subtracted, based on measurements of samples of ^{14}C-free coal. Backgrounds were scaled relative to sample size.