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Characterizing the Timing of Ruptures Crossing the Boundary between the Provo and Salt Lake City Segments of the Wasatch fault.

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Project Abstract

The Wasatch fault zone (WFZ) is a ~350 km-long normal fault that dips beneath the Salt Lake-Provo-Ogden metropolitan area, posing the greatest seismic risk within the Intermountain West region of the United States. How earthquake behavior is modulated by segment boundaries is an important scientific question, especially for the WFZ where the urban area extends along multiple fault segments. This investigation aimed to establish an earthquake chronology at the Traverse Ridge paleoseismic site (TR site: 40.492°, - 111.805°) along the 7 km-long Fort Canyon fault, which links the Salt Lake City (40 km) and Provo (59 km) segments of the WFZ and to evaluate rupture models for the segment boundary. We re-excavated two trenches that were originally dug by consultants at the TR site across two parallel traces (northern and southern) of the Fort Canyon fault. The north trench exposed Tertiary volcanic rock within the footwall and three scarp-derived colluvial wedges that were deposited across the fault zone. The south trench exposed a fault zone with Tertiary alluvial fan units in the footwall and one distinct colluvial wedge overlying a massive deposit of fault-derived colluvium in the hanging wall. Colluvial wedge heights, ranging from 0.5-1.2 m, provide a lower limit for vertical displacement in these events. Given this displacement minimum, and considering empirical relationships among rupture parameters and magnitude, we infer that these events were greater than M 6.5, with surface ruptures extending well beyond the Fort Canyon fault. Two to four earthquakes have ruptured the Fort Canyon fault at this site during the Holocene. Radiocarbon results constrain the age of the most recent event (MRE) along the southern trace to 0.2-0.5 ka, the MRE on the northern trace to 0.4-3.5 ka, and an older event on the northern trace to between 7.4 and 8.2 ka. We infer that another event may have occurred along the southern fault trace prior to the MRE and after 6.2 ka. Soil development within the most recent colluvial wedges on the south and the north fault traces is similar, but fault trace morphology leads us to infer that they are more likely separate events. Initial comparisons with published paleoseismic data on the southern Salt Lake City and northern Provo segments show that the TR site records about half the number of earthquakes that have occurred on the adjacent segments since the mid Holocene. The MRE on the southern trace at the TR site overlaps with the youngest event identified on the northern Provo Segment, providing evidence of a Provo rupture extending into the segment boundary. The youngest event on the northern trace at the TR site overlaps with event ages on both the southern Salt Lake City and northern Provo segments, and could be evidence of a rupture spanning portions of both fault segments. The currently published data permit a range of rupture models across this segment boundary including spill-over, segment-boundary, single-segment, and multi-segment ruptures. The forthcoming published records from nearby sites on the northernmost Provo (Alpine site) and southernmost Salt Lake City (Corner Canyon site) segments will enhance the ability to evaluate rupture models at this segment boundary.

Table of Contents

List of Tables

List of Figures

Introduction

The central portion of the Wasatch fault zone (WFZ) including the Provo, Salt Lake City, and Weber segments (Figure 1) pose the most significant seismic risk within the Intermountain West region of the United States (e.g., WGUEP, 2016). Along the entirety of the Salt Lake-Provo-Ogden metropolitan region the WFZ outcrops on the western piedmont of the Wasatch Range, striking parallel to the urban corridor (north-south), and dipping west beneath the region's cities (Figure 1). This geometry indicates that the fault's seismogenic zone lies directly beneath the urban centers and future surface rupturing earthquakes along any of these segments would produce damaging ground motions, with accelerations greater than 1G experienced across a widespread area (e.g., Wong et al., 2003; Petersen et al., 2014). Because the WFZ is among the most active fault zones within the Basin and Range and because of its situation beneath a major urban center, numerous paleoseismic sites have been documented along it with the overarching goal of characterizing the size and frequency of earthquakes along each of the various fault segments (See DuRoss et al., 2016 for a review of site locations and a compilation of event data).

Because the Salt Lake City-Provo-Ogden metropolitan region extends across multiple WFZ segments, an important goal towards better characterizing seismic hazard is to determine how earthquake ruptures behave at segment boundaries. Accurately modeling ground shaking, losses, and potential response scenarios for future earthquakes requires the community to examine the spatial extents of past earthquakes and evaluate the likelihood of possible rupture scenarios that may occur in the future, such as *single-segment* ruptures, *multi-segment* ruptures, *partial-segment* ruptures, *spill-over* ruptures, *segment-boundary* ruptures and other combinations of these scenarios (e.g., DuRoss et al., 2016). In this study we conducted a paleoseismic investigation at the Traverse Ridge site (TR site: 40.492°, - 111.805°) along the 7 km-long Fort Canyon fault (FCF), which links the Salt Lake City (40 km) and Provo (59 km) segments of the WFZ. Evidence from this site leads us to infer an event chronology of three earthquakes along the FCF segment boundary since ~8.2 ka.

In the next section of the report we present information about the fault zone at the TR site (Figures 1-2) and the methods employed in this paleoseismic investigation. Then we present the stratigraphic, structural, and geochronologic results (Tables 1-2 and Figures 3-6) which lead us to infer the record of earthquakes at this site. In the discussion section we present two plausible earthquake chronologies permitted by the data, including a rationale for our preferred earthquake chronology. Then we discuss colluvial wedge heights and the constraints that puts on rupture lengths and magnitudes (Table 3). Finally we present a discussion of how the TR site earthquake chronology may correlate with the published record of earthquakes at nearby sites on the Salt Lake City and Provo segments of the WFZ.

Traverse Ridge Site and Methods

The TR site includes seven ~500 m-long previously excavated trenches across the Fort Canyon fault zone near the crest of Traverse Ridge (Figure 2). These trenches were originally excavated in preparation for a potential housing development within the city of Draper, Utah. However, those plans were abandoned and the trenches have been left open since the winter of 2005-2006. We identified the TR site as an good target for investigating the earthquake chronology at this segment boundary because it is situated midway along the Fort Canyon fault between the southern endpoint of Salt Lake City segment and northern endpoint of the Provo segment, just ~3.5 km from both of these neighboring fault segments (Figure 2). At this position, paleoseismic events documented at the TR site should correlate with paleoearthquakes documented at nearby sites on the adjacent fault segments, providing data which enables the evaluation of earthquake rupture scenarios.

We conducted reconnaissance mapping of the Fort Canyon fault utilizing the 2006 and 2013-2014 State of Utah AGRC lidar datasets for field and remote mapping of fault traces (Toke et al., 2017). Along the Fort Canyon fault we found that the WFZ is more complex than on the neighboring fault segments. The FCF has a higher density (~10 scarps per km) of short fault scarps (~140 m/scarp) and numerous stretches of the fault with overlapping fault traces. Within this complex array of faults we identified the crest of Traverse Ridge as one of the least complex portions of the FCF (Figure 3). Here, two prominent fault scarps (a north and south trace) were clearly crossed by the westernmost of the seven TR site trenches (hereafter we refer to this as trench 1). Furthermore, reconnaissance hand excavations of the outcrops in trench 1 revealed fault-derived colluvial wedge deposits composed of infilled dark soil a-horizon material mixed with footwall clasts, which we inferred to be strong evidence of Holocene earthquake ruptures along the FCF (e.g., Toke et al., 2013).

In early August, 2016, with funding from the USGS (This award) and permission from the City of Draper, we employed a track-hoe operator to re-excavate two sections of trench 1 along the north and south traces of the Fort Canyon fault at the TR site (Figures 3-6). The trench across the north trace of the fault (T1N) was re-oriented from the existing exposure to be fault-perpendicular. The trench across the south trace of the fault (T1S) involved widening the existing trench. Both trenches were benched for safety. Each re-excavation extended for more than 14 m, reaching depths of 1.5-2.5m below the ground surface. A 0.5 m grid of labeled nails was placed on the trench exposure for reference during paleoseismic logging.

The re-excavated faces of T1N and T1S were documented with 16 megapixel digital photographs from an Olympus Stylus Tough camera and a Panasonic Lumix DMC-FZ70. Photographs were taken perpendicularly at various distances from the trench wall (ranging from 0.5-4.0 m). Each photographic set (camera type and distance) was taken with more than 50% overlap. Photographs were processed with Agisoft Photoscan to produce point clouds, and three-dimensional models of the trench walls (e.g., Bemis et al., 2012). Photomosiac 'textures' were processed and co-registered with the three-dimensional models enabling us to produce and print orthophoto mosaics of the trench walls. We logged the walls using 8.5 x 11" prints of these orthophoto mosaics at ~1:5 scale in the field, mapping lithologic units, soils, faults, burrows, clasts, and other trench features such as trench floors, benches, and spoils piles. Every field participant completed some portion of the paleoseismic logging. The continuity of all contacts was verified by the project PI. A trench review was conducted on August 31st with participants from the Utah Geological Survey, Utah Valley University, local consultants, and other government employees. The re-excavated portions of trench 1 were in-filled on September 28th, 2016. Our logging was digitized from scans of the field logs using ArcGIS.

Twenty eight samples (charred plant material and bulk soil samples) were collected for potential radiocarbon analysis and two samples were collected for potential optically-stimulated luminescence (OSL) analysis (Figures 3-6). The OSL samples were not been analyzed because they were collected less than 1 meter from the ground surface and the sample material was composed mostly of clay, rather than sands or silts - which are the desired OSL target materials. Seventeen radiocarbon samples were analyzed at the NOSAMS lab in Woods Hole, Massachusetts. Ten of these were preprocessed from six bulk soil samples at PaleoResearch Lab in Golden, Colorado. Radiocarbon ages were calibrated using the IntCal13 model in the program OxCal v. 4.3 (Tables 1-2) and earthquake event ages were inferred using the radiocarbon data in the context of the stratigraphic and structural relationships (Table 3).

Results: Stratigraphy, Structures, Geochonology, and Events

Trench 1 North (T1N) Stratigraphy and Faulting

The northern trench (T1N: Figures 2-4 and Table 1) was situated along a 390 m-long trace of the Fort Canyon fault which trends 260 degrees with a scarp that dips to the southeast (Toké et al., 2017). T1N was cut roughly perpendicular to the fault trace extending for ~14 m along a ~350 degree trend from a point at the edge of the pre-existing trench footprint (approximately 40.49254°, - 111.80467°). The footwall lithology within T1N is composed of Tertiary volcanic rock including a range of deposits from welded block and ash flows and angular alluvium composed of reworked volcanic material (Biek, 2005).

Paleosol development was apparent between some of the footwall Tertiary units and one thin package of fault-derived colluvium (C_0) was deposited across a fault zone within the footwall (FZ1). The hanging wall lithology is composed of scarp-derived, matrix-supported colluvium. Three distinct packages of colluvium were identified within the hanging wall of the T1N exposure (C_1-C_3). The lowermost of these matrix-supported units (C_1) was massive, highly-weathered, clay-dominant colluvium with sparse, angular pebble to cobble-sized volcanic clasts. This unit had the highest plasticity of the three colluvial packages. It is likely that the C1 colluvium may be associated with a paleoearthquake, but C_1 extends below the depth of the trench, so its relationship to a faulting event is uncertain. Two additional hanging wall packages of colluvium were deposited above C_1. Both of these younger colluvial packages (C_2 and C_3) were derived from eroded fault scarp free faces and each was overprinted with soil development, including a prominent a-horizon indicating a period of relative slope stability after the packages of colluvium were deposited across the fault zone.

In total, three fault zones containing evidence for recent earthquakes were identified within T1N, at meters 9.5-10 (FZ1), meter 6 (FZ2), and meter 7 (FZ3). Each of these fault zones extended into discrete fault scarp-derived colluvial packages (C_0, C_2, and C_3) which we infer to be colluvial wedge deposits following surface ruptures of the FCF (Table 3). The colluvial wedge overlying FZ1 (C_0) is thin (0-50 cm), located within the footwall stratigraphy, and is composed of angular clasts ranging from coarse sand to small cobbles in size. Unlike the colluvial wedges identified within the hanging wall, C_0 is clast-supported and does not include a-horizon soil development. The colluvial wedges overlying FZ2 and FZ3 (C_2 and C_3, respectively) are filled with colluvium that is generally darker in color than the C_0 colluvial wedge. C_2 and C_3 are matrix-supported and contain angular clasts of volcanic rocks, ranging in size from pebbles to cobbles. The larger clasts within C_2 and C_3 are generally more abundant near the base of the deposits. The upper portion of C_2 retains some character of a buried soil a-horizon, which helps distinguish the unit from the base of C_3. Additionally, C_2 is greyer in color than that of the overlying C_3 deposit. C_3 is close in color to the dark modern a-horizon of the mollisol on the footwall side of the fault scarp. The top of C_3 grades into the modern soil a-horizon.

Fault Zone 1 strikes 279° and dips 84° to the southwest. An earthquake along FZ1 resulted in the deposition of the C_0 colluvial wedge. We attribute the lack of obvious soil a-horizonation within the C_0 colluvial wedge to its position above the recently active portion of the fault scarp. Because of this position, and a clear unconformity at the top of C_0, we infer that any a-horizonation that had previously developed was eroded away with recurrent uplift and erosion across the footwall side of the fault scarp. Today, C_0 is overlain by ~40-50 cm of younger slope-derived colluvium which has a well-developed soil a-horizon. A single bulk soil sample was collected from the C_0 colluvial wedge and processed at PaleoResearch labs, but this sample did not yield any datable material, so we are unable to constrain the timing of the Earthquake responsible for C_0. However, given its position within the footwall, directly overlying reworked Tertiary volcanic rock, we infer that it is significantly older than the events associated with C_2 and C_3.

The oldest event constrained within T1N occurred along FZ2 and resulted in the deposition of the C_2 colluvial wedge. FZ2 strikes 277° and dips 76° to the southwest. This fault zone presents evidence for shear due to faulting from the trench floor to about ~10 cm above the contact between C_1 and C_2. Above 10 cm, the fault scarp free face was eroded back and progressively buried by the C_2 colluvium. Radiocarbon sample TR-A (charcoal pieces) was collected within the faulted paleosol along a small fissure at the boundary of the C_1 and C_2 colluvial deposits. This sample was collected within the reconnaissance study of Toké et al., 2013. We infer that this charcoal originated from the soil which existed at the time of the penultimate event and constrains the maximum age of C_2 to 8,239 years before present (years BP). Radiocarbon sample TR10a was collected within the middle of C_2, about 40 cm above the base of the colluvial wedge, indicating that it accumulated within the soil after the occurrence of the penultimate event and constrains the minimum age of C_2 to before 7,406 years BP (Table 1).

The youngest event constrained along the northern fault trace occurred along FZ3. This fault strikes 288° and dips 70° to the southwest. FZ3 juxtaposes the footwall units against the C3 colluvium. There is evidence for shear along the fault surface for ~50 cm above the base of C_3, beyond which the scarp is eroded back and buried by the C3 colluvium which overlies the paleosol at the top of C_2. Radiocarbon samples TR13a and TR13b were extracted from a bulk sample within this paleosol and constrain the maximum age of C_3 to after 3,516 years BP. Three charcoal samples were collected from within the C_3 colluvial wedge (TR7, 16 and TR17: Table 1). TR16 constrains the minimum age for the deposition of the C_3 colluvium which was shed from the fault scarp sometime before 363 years ago.

Trench 1 South (T1S) Stratigraphy and Faulting

The south trench (T1S: Figures 2, 5-6, and Table 2) was re-excavated along a ~215 m long fault scarp just south of T1N (Toké et al., 2017). This fault trace trends 290 degrees and the scarp slopes to the southwest, it intersects and appears to topographically displace the northern fault trace just to the west of the TR site. Two primary fault zones (FZa and FZb) were observed within T1S. FZa outcrops at meter 11, strikes 304°, dips 64° to the southwest, and juxtaposes footwall Tertiary alluvial fan stratigraphy (Biek, 2005) against massive fault scarp-derived, matrix-supported, colluvium in the hanging wall (C_A). The Tertiary alluvial fan stratigraphy contains a significant component of soil carbonate which has coated some clasts completely. $CaCO_3$ has impregnated pre-existing ground cracks within the footwall stratigraphy and also occurs as nodules within the matrix of the footwall lithology. The massive hanging wall C_A colluvium is faulted by FZb at meter 9.5. Here, FZb strikes 294° and is nearly vertical, dipping more than 85° to the southwest. A fissure is filled with soil a-horizon material along FZb. The fault zone extends from the base of the trench to ~70 cm below the present day ground surface. Clasts from the footwall units and near surface soil a-horizon material were deposited across the displaced paleo ground surface forming a prominent colluvial wedge (C_B), the T1S most recent event (MRE). Bulk soil samples were collected from the filled fissure (TR29), the paleosol a-horizon below the MRE colluvial wedge (TR28), and from within the colluvial wedge (TR25) to constrain the age of the MRE the southern fault trace. The bulk samples were processed to identify and extract datable material at PaleoResearch Labs in Golden, Colorado. Four separate samples of charred material were dated from within the MRE colluvial wedge (TR25a-d: Table 2). These samples constrain the age of the C_B colluvial wedge formation to before 212 years ago. Two separate pieces of charred plant remains were dated from within the pre-MRE paleosol (TR28a and TR28b). TR 28a constrains the age of the MRE along the southern fault trace to after 540 years BP. The dated material from within the fissure yielded a much older date than the pre-MRE paleosol (Table 1). Interestingly, while it is clear that recurrent faulting has occurred across the T1S fault scarp, no good evidence capable of constraining additional events was observed.

Discussion

Interpretations of the Earthquake Record at the TR Site

The TR site presents evidence for four earthquake-derived colluvial wedges within two paleoseismic exposures on parallel fault traces that cut footwall lithologies of disparate age and origin (Table 3). This presents an issue to address for event correlations between the two trenches. T1N presents evidence for three separate earthquake events, two along the main fault zone and one older, undated, event that is preserved within the footwall stratigraphy of the fault zone. T1S presents evidence constraining one recent Holocene event, but the morphology of the fault scarp hints that other Holocene events likely ruptured this fault trace and are not well-preserved in the TR site paleoseismic record.

Two distinct paleoseismic events are constrained with certainty by the TR site's record. The most recent event occurred between 212 and 540 years BP on the southern fault trace and an older event occurred on the northern fault trace between 7,406 and 8,239 years BP. The northern fault trace also preserves excellent evidence for a younger event between 363 and 3,516 years BP, however, with no stratigraphic correlations between T1S and T1N and relatively poor radiocarbon age bracketing of this event, we cannot claim with certainty whether this event is evidence of the same event that recently ruptured the southern fault trace or if the event is a separate penultimate event at the TR site.

Our preferred interpretation is that the younger event along the northern fault trace is a separate event from the MRE along the southern fault trace. We suspect this is the case for four reasons. First, the radiocarbon ages originating from the C_3 colluvial wedge along the northern trace are generally older than those of the C_B colluvial wedge along the southern fault trace. Second, the ages within C_3, which are event minimum ages, are similar to the ages constraining the pre-MRE paleosol on the southern fault trace, which are event maximum ages. Third, the age gap between radiocarbon samples within the paleosol developed prior to the C_3 colluvial wedge and the radiocarbon samples from within C_3 is approximately three thousand years. This means that there is much greater probability that the event ages on these separate fault traces do not correlate. Finally, where the two fault traces intersect, to the west of trench 1, it appears that the southern fault trace cross cuts the northern fault trace (Figure 2a). Thus, we strongly suspect that the last rupture along the northern fault trace occurred before the rupture along the southern fault trace. If this is true, one may further infer that the older sample from within the C_3 colluvial wedge better constrains the minimum timing of the penultimate event at the TR site to between 591 and 3516 years BP. In summary, our preferred interpretation for the event chronology at the TR site is (Table 3):

- Most Recent Event: 212-540 years BP
- Penultimate Event: 591-3,516 years BP
- Older Event: 7,406-8,239 years BP

Note that we refer to the third event as simply an ‘older event.’ We describe it this way, rather than antepenultimate event, because we suspect that other event(s) may have occurred along the southern fault trace that were not preserved in the stratigraphy. The southern fault scarp at the TR site is among the most prominent within the segment boundary (Toké et al., 2017). With more than 12 m of topographic relief, maximum scarp slope exceeding 20 degrees, and more than 20 m of apparent geomorphic surface displacement (Figure 2b). We infer that it is unlikely that only one Holocene event occurred on this trace of the fault. Furthermore, the soil a horizon material that was dated within the FZb’s fissure yielded an age of 6234-6381 years BP. No corresponding source for paleosol material of this age was observed within the T1S trench. An explanation for this otherwise missing older paleosol is that it was likely faulted and eroded away prior to the development of the most recently faulted paleosol below C_B. Therefore, we infer that evidence that constrains the age of this antepenultimate event may be preserved elsewhere along the FCF.

Colluvial Wedge Heights and Estimates of Fault Rupture Lengths

Colluvial wedge heights (Table 3 and Figures 3-6) provide lower limits for vertical displacement in past earthquakes along the Fort Canyon fault within the Provo to Salt Lake City segment boundary. The four colluvial wedges identified within T1N and T1S ranged in height from 0.5 to 1.2 meters. Given these displacement minimums, and considering the empirical relationships among rupture parameters and magnitude (e.g., Wells and Coppersmith, 1994; Stirling et al., 2002), we infer that all of these events were equal or greater than M_w 6.5 and the largest of these colluvial wedges might be indicative of paleoearthquakes equivalent to or exceeding M7 (Table 3).

Normal faulting earthquakes of these magnitudes (M6.5-M7) should be associated with rupture lengths ranging from at least 8 to more than 40 km (e.g., Wells and Coppersmith, 1994; Stirling et al., 2002) which indicates that all of these ruptures should continue on to one of the neighboring recent paleoseismic sites at Alpine (Bennett et al., 2015) and Corner Canyon (DuRoss et al., 2015) which are within 4 km of the TR site and the largest ruptures would likely be recorded beyond the next closest sites such as the South Fork Dry Creek site (12 km north of the TR site along the Salt Lake City segment:

Black et al., 1996) and the American Fork site (~10 km south of the TR site along the Provo segment: Forman et al., 1989).

Comparison of the TR Site with Nearby Records

The record at the South Fork Dry Creek site which is located on the southern Salt Lake City segment includes four events over the last six thousand years (1.1-1.5, 1.5-2.4, 3.1-4.3, and 4.5-5.5 ka: Black et al., 1996, compiled in DuRoss et al., 2016) , the record at the American Fork site on the northern Provo segment includes four events over the last seven thousand years (0.2-0.6, 1.4-2.8, 2.9-4.8, and 5.2-7.2 ka: Forman et al., 1989, compiled in DuRoss et al., 2016), and the TR site along the Fort Canyon fault records three events over the last eight thousand years (0.2-0.5, 0.4-3.5 ka, and 7.4-8.2 ka). The TR site records fewer earthquakes than have occurred on the neighboring fault segments since the mid Holocene. In even greater contrast, the preliminary records from the Alpine Site (e.g., Bennett et al., 2015) and Corner Canyon Site (e.g., DuRoss et al., 2015) indicate an even greater frequency of events at the endpoints of the neighboring segments over this time span (5-6 events since the mid Holocene).

There are at least three possible explanations for fewer earthquakes at the TR site since the mid Holocene. First, faulting within the segment boundary between the Provo and Salt Lake City segments of the WFZ is complex with numerous stepping fault traces and fault scarps that occur more than a kilometer away from the main Fort Canyon fault traces. Therefore it is possible that ruptures have crossed through the segment boundary without rupturing the TR site. Second, the Fort Canyon fault has less total displacement than the adjacent fault segments, which could mean that less total slip occurs at the surface when this portion of the fault ruptures. Therefore, some unrecorded events may have had small surface displacements (i.e., less than 50 cm) through the high topography of Traverse Ridge which includes numerous landslides. This small scale of surface rupture would be challenging to preserve in this erosion-dominant part of the landscape. Third, ground rupturing earthquakes sometimes have large gaps in their surface ruptures (e.g., Biasi and Wesnousky, 2016). Therefore, it is possible that ruptures may be recorded at sites on adjacent fault segments (i.e., the Alpine or Corner Canyon sites), but not within an individual paleoseismic site along segment boundary (i.e., the TR site).

At this point, the published event chronology data from the TR site and the neighboring portions of the Provo and Salt Lake City segments permits a range of rupture models across this segment boundary including spill into, spill-over, segment-boundary, single-segment, and multi-segment ruptures. For instance, it is possible that the MRE at the TR site (0.2-0.5 ka) corresponds to the youngest event at the American Fork site (0.2-0.6 ka) without a matching earthquake at the South Fork Dry Creek Site. This could be interpreted as an example of a rupture occurring on an adjacent segment and spilling into, or possibly across the segment boundary. It could also be interpreted as a segment boundary earthquake that ruptured part of a neighboring segment. The oldest rupture at the American Fork Site has no correlative earthquake at the TR site or SFDC site and may represent an example of a single or partial segment rupture. Additionally, the youngest event on the northern trace at the TR site (our inferred penultimate event) may correspond to the published penultimate events on both the southern Salt Lake City and northern Provo segments and could be an example of a multisegment rupture. Presumably, the forthcoming records from the nearby sites on the northernmost Provo (Alpine site: e.g, DuRoss et al., 2015) and southernmost Salt Lake City (Corner Canyon site: e.g, Bennett et al., 2015) segments will allow the earthquake science community to further refine the evaluation of rupture models at this segment boundary.

The Utility of Paleoseismic Sites within Segment Boundaries

The results from the TR site demonstrate that paleoseismic information may be obtained from within the high and varied terrain of normal fault segment boundaries. However, the fewer total events observed at the TR site brings into question whether or not this paleoseismic setting is adequate to record all events which rupture the segment boundary. Ideally, future attempts at utilizing segment boundary paleoseismic sites should: 1) seek out the least complex parts of the fault zone, 2) trench all parallel and sub-parallel traces of the fault zone, and 3) attempt to trench within paleoseismic sites with recent and recurrent deposition (e.g., montane basins, high alluvial fans, etc.). Finally, because of fault complexity and rupture variability it may be necessary to trench at multiple locations within the segment boundary to obtain the same quality of record as recorded on adjacent segments at a single site. This type of endeavor may require a larger than normal geochronology budget.

Conclusions

At least two, likely three, and possibly more earthquakes have ruptured the Fort Canyon fault at the TR Site since the late Pleistocene. The most recent event occurred along the southern fault trace at the TR site between 212 and 540 years BP. The northern fault trace was ruptured by an event that occurred between 363 and 3,516 years BP. This was most likely a separate event from the MRE on the southern fault trace, but simultaneous rupture of the two fault traces cannot be ruled out. An older event ruptured the northern fault trace between 7,406 and 8,239 years before present. During the Holocene about half as many earthquakes have ruptured the TR site than neighboring paleoseismic sites along the Provo and Salt Lake City segments of the WFZ. This may be due to distributed faulting, missing stratigraphy due to erosion a the TR site, gaps in the surface rupture of some paleoearthquakes, and/or because less total slip and presumably total events occurs within fault segment boundaries.

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Publications and Presentations

Results from this project have been presented at four regional and national meetings:

Toké, N. A., “Paleoseismic Investigation within the Traverse Ridge Segment Boundary: Initial Plans for Summer 2016 Field Work” Utah Quaternary Fault Parameters Working Group, Salt Lake City, Utah, February 10th, 2016.

Toké, N.A., “Investigating the History of Large Earthquake of the Wasatch Fault at the Traverse Ridge Paleoseismic Site in Draper, Utah” Utah Quaternary Fault Parameters Working Group, Salt Lake City Utah: February 8th, 2017.

Toké, N.A., C. Langevin, J. Phillips, E. Kleber, C.B. DuRoss, J.D. Wells, D. Horns, G. McDonald, and J.K. Carlson “Investigating the History of Large Wasatch Fault Earthquakes Along the Fort Canyon Fault at the Traverse Ridge Paleoseismic Site” Seismological Society of America Annual Meeting, Denver, CO: April 20th, 2017, Poster #22

J. Phillips, Toké, N.A., C. Langevin, E. Kleber, C.B. DuRoss, A. Hiscock, J.D. Wells, G. McDonald, D. Horns, and J.K. Carlson “The Traverse Ridge Site: A Wasatch Fault Example of the Challenges in Interpreting Earthquake Records and Hazards at Segment Boundaries” Abstract submitted to the 2017 Annual Meeting of the Geological Society of America Meeting in Seattle, WA: October 24th, 2017.

One paper related to this project has been published and another paper is planned for submission.

Toké, N.A., J. Thomas, M.P. Bunds, M. Arnoff, D.M. Horns, and J.K. Carlson “Inferences about Fault Segmentation from Recent Surface Breaks along the Wasatch Front from Lidar, SfM, and Outcrops from American Fork Canyon to Dimple Dell Regional Park” 2017 UGA Guidebook: Geology and Resources of the Wasatch Front and Back.

Toké, N.A., J. Phillips, C. Langevin, E. Kleber, C.B. DuRoss, A. Hiscock, M. Bunds, D. Horns, J.D. Wells, G. McDonald, and J.K. Carlson. Preliminary title: Characterizing Surface Ruptures Crossing the Fort Canyon fault between the Provo and Salt Lake City Segments of the Wasatch fault. In preparation for submission to BSSA or a similar journal.

Broader Impacts

In addition to the ongoing scientific contributions from this research, this project benefited the educational experience of undergraduate students from Utah Valley University and several other colleges and universities. Two UVU students presented results from this project at the annual meeting of the Seismological Society of America (Joseph Phillips and Chris Langevin). J. Phillips is now the lead author on an abstract for the annual meeting of the Geological Society of America and is planning to attend graduate school and complete a thesis project related to earthquake geology. In addition to C. Langevin and J. Phillips, two other students were hired as paid student assistants through UVU (J. Wells and C. Bross) and Utah Geological Survey student interns from Weber State University, the University of Utah, and Carleton College participated in paleoseismic field work at the Traversed Ridge site. Finally, the entire UVU fall 2016 geologic hazards class (GEO 3200) visited the Traverse Ridge site and adjacent portions of the Wasatch fault over multiple days and completed an extensive lab report based upon this experience. In total more, more than two dozen undergraduate students have directly benefitted from this funded grant project. Additionally, Joe and Chris presented this project at the 2017 Intermountain West AEG Annual Student Night and we plan to present the results of this project in a public lecture series at Utah Valley University.

Table 1. T1N radiocarbon data arranged by stratigraphic order. Pretreatment and analyses were performed at the Woods Hole NOSAMS lab. Italicized samples are younger or older than expected based upon stratigraphic relationships. Bold samples help constrain event ages. TR3 may be a root that died as a result of burial from the MRE wedge. TR4 may simply be a sample that laid on the landscape a long time prior to deposition.

Trench 1N Sample ID[1]	NSF-NOSA MS#	Sample Type	Trench and Coordinates (X,Y)[2]	Unit	Fraction Modern	+/- [3]	^{14}C age (years BP)	+/- [4]	2σ calibrated age (cal CE / BCE)[5]	2σ calibrated age yBP
TR7_ UVU2016	**142558**	**Charcoal Piece**	**T1N - EW (5.80, 3.47)**	**Upper MRE (C_3 wedge)**	**0.9519**	***0.0020***	***395***	***15***	**1445-1495 (88.3%) 1601-1614 (7.1%) CE**	**403-572 yBP**
TR16_ UVU2016	**142559**	**Charcoal Piece**	**T1N - WW (6.05, 3.25)**	**Upper MRE (C_3 wedge)**	**0.9653**	**0.0020**	**285**	**15**	**1522-1573 (51.8%) 1630-1654 (43.6%) CE**	**363-495 yBP**
TR17_ UVU2016	**142560**	**Charcoal Piece**	**T1N - WW (6.25, 3.16)**	**Middle MRE (C_3 wedge)**	**0.9347**	**0.0020**	**545**	**15**	**1325-1345 (17.5%) 1393-1426 (77.9%) CE**	**591-692 yBP**
TR13a_ UVU2016	**144287**	**Charred Hardwood pieces**	**T1N - WW (5.00, 2.20)**	**PRE MRE Soil, top C_2**	**0.6733**	**0.0015**	**3180**	**20**	**1499-1421 (95.4%) BCE**	**3438-3516 yBP**
TR13b_ UVU2016	**144295**	**Charred unidentified pieces**	**T1N - WW (5.00, 2.20)**	**PRE MRE Soil, top C_2**	**0.6500**	**0.0017**	**3460**	**20**	**1879-1837 (26.6%) 1831-1733 (56.7%) 1719-1694 (12.2%) BCE.**	**3711-3796 yBP**
TR6_ UVU2016	*142557*	*Charcoal Piece*	*T1N - WW (4.99, 1.86)*	*Middle PE (C_2 Wedge)*	*0.3652*	*0.0021*	*8,090*	*45*	*7287-6830 (95.4%) BCE*	*8847-9304 yBP*
TR10a_ UVU2016	**144286**	***Charred Hardwood pieces***	**T1N - WW (4.25, 1.80)**	**Middle PE (C_2 Wedge)**	**0.4440**	**0.0015**	**6520**	**25**	**5538-5467 (93.6%) 5402-5389 (1.8%) BCE**	**7406-7555 yBP**
TR4_ UVU2016	*142556*	*Charcoal Piece*	*T1N - EW (2.65, 1.43)*	*Middle of PE (C2 Wedge)*	*0.2202*	*0.0023*	*12,150*	*85*	*12313-11812 (95.4%) BCE*	*13829-14330 yBP*
TR-A_ UVU2015	**142561**	**Charcoal Piece**	**T1N-2014**	**Base of PE (C_2 Wedge)**	**0.4051**	**0.0020**	**7,260**	**40**	**6222- 6051 (95.4%) BCE**	**8068-8239 yBP**
TR3_ UVU2016	*142555*	*Charred Piece (root)*	*T1N - WW (0.80, 0.35)*	*Within C_1 Massive Colluvium*	*0.9573*	*0.0019*	*350*	*15*	*1470-1525 (43.6%) 1557-1633 (51.8%) AD*	*384-547 yBP*

(1) Assigned sample name based upon: A) the year collected, B) the site name, C) the order of collection.
(2) Samples Locations by trench number and wall and coordinates (X-Horizontal, Y-Vertical) bottom-south corner is the origin.
(3) Error value (2σ) assessed in the calculation of the modern fraction.
(4) Error value (2σ) assessed in the calculation of ^{14}C years before present.
(5) Determined using single samples in OxCal 4.2 (Bronk Ramsey, 2013) and using the calibration curve of Reimer et al., (2013).

Table 2. T1S radiocarbon data arranged by stratigraphic order. Pretreatment and analyses were performed at the Woods Hole NOSAMS lab. Italicized samples are younger or older than expected based upon stratigraphic relationships. Bold samples constrain event ages.

Trench1S Sample ID[1]	NSF-NOSAMS#	Sample Type	Trench and Coordinates (X,Y)[2]	Unit	Fraction Modern	+/- [3]	^{14}C age (y BP)	+/- [4]	2σ calibrated age (cal AD / BC)[5]	2σ calibrated age (y BP)
TR25a_ UVU2016	144288	charcoal	T1S - EW (9.90, 4.26)	MRE C_B:Middle	0.9663	0.0020	275	15	1526-1557 (27.6%) 1631-1660 (67.8%) CE	357-491 yBP
TR25b_ UVU2016	**144289**	**charcoal**	**T1S - EW (9.90, 4.26)**	**MRE C_B: Middle**	**0.9741**	**0.0028**	**210**	**25**	**1646-1684 (30.4%) 1736-1805 (48.3%) 1935 – ? (16.6%) CE**	**212-371 yBP**
TR25c_ UVU2016	144290	charcoal	T1S - EW (9.90, 4.26)	MRE C_B: Middle	0.9789	0.0020	170	15	1666-1685 (16.8%) 1731-1784 (50.8%) 17796-1809 (9.7%) 1927 – ? (18.1%) CE	208-351 yBP
TR25d_ UVU2016	144291	charcoal	T1S - EW (9.90, 4.26)	MRE C_B: Middle	0.9620	0.0020	310	15	1515-1597 (73.7%) 1617-1645 (21.7%) CE	372-502 yBP
TR28a_ UVU2016	*144292*	*charcoal*	*T1S - EW (8.99, 3.60)*	*Paleosol below MRE*	*0.8403*	*0.0017*	*1400*	*15*	*615-660 (95.4%) CE*	*1357- 1402 yBP*
TR28b_ UVU2016	**144293**	**charcoal**	**T1S - EW (8.99, 3.60)**	**Paleosol below MRE**	**0.9583**	**0.0020**	**340**	**15**	**1477-1529 (33.0%) 1543-1635 (62.4%) CE**	**382-540 yBP**
TR29_ UVU2016	*144294*	*charcoal*	*T1S - EW (9.40, 2.30)*	*Soil material in fissure*	*0.5048*	*0.0014*	*5490*	*20*	*4364-4326 (91.7%) 4284-4271 (3.7%) BCE*	*6234-6381 yBP*

(1) Assigned sample name based upon: A) the year collected, B) the site name, C) the order of collection.
(2) Samples Locations by trench number and wall and coordinates (X-Horizontal, Y-Vertical) bottom-south corner is the origin.
(3) Error value (2σ) assessed in the calculation of the modern fraction.
(4) Error value (2σ) assessed in the calculation of ^{14}C years before present.
(5) Determined using single samples in OxCal 4.2 (Bronk Ramsey, 2013) and using the calibration curve of Reimer et al., (2013).

Table 3. Events, Fault Data, and Earthquake Inferences. Refer to Tables 1-2 and Figures 3-6 for stratigraphic relationships, sample locations, and event age constraints.

	Age Constraint	Trench Observed	Colluvial Wedge	Wedge Height	Fault Zone	Rupture Length[1]	Mw Empirical[2]
Most Recent Event (MRE)	**0.2-0.5 ka**	**T1S**	$\mathbf{C_B}$	**0.7**	**FZb**	**15 km**	**6.7**
Penultimate Event (PE)	**0.4-3.5 ka**	**T1N**	$\mathbf{C_3}$	**1.2**	**FZ3**	**44 km**	**7.0**
Missing Event?	*< 6.2 ka*	*T1S*	*eroded*	*?*	*FZb*	*?*	*?*
Older Event	**7.4-8.2 ka**	**T1N**	$\mathbf{C_2}$	**1.1**	**FZ2**	**33 km**	**6.9**
Unconstrained Event	*Pre Holocene*	*T1N*	C_0	*0.5*	*FZ1*	*8 km*	*6.6*

1- Rupture lengths (L) calculated using the empirical equation related to displacement (D) from the instrumental data of Stirling et al., 2002: Log (L) = -0.81 + 0.56*Log(D), displacement is assumed to be the colluvial wedge heights presented here which are minimum estimates.
2- Moment magnitudes (Mw) calculated following the empirical equation for average displacement along normal faults: Mw = 6.45 + 0.65*Log(AD), Wells and Coppersmith, (1994)

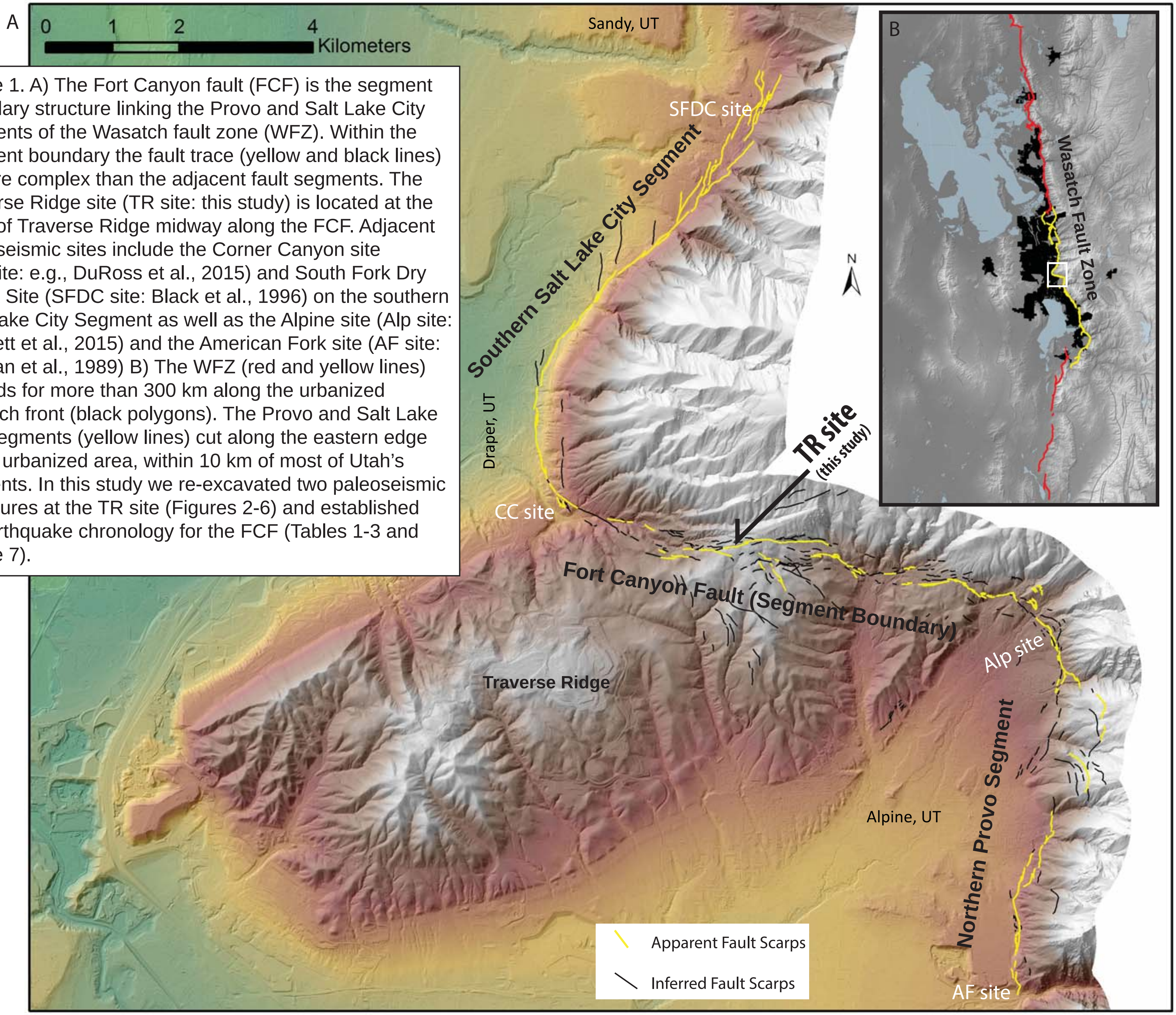


Figure 1. A) The Fort Canyon fault (FCF) is the segment boundary structure linking the Provo and Salt Lake City segments of the Wasatch fault zone (WFZ). Within the segment boundary the fault trace (yellow and black lines) is more complex than the adjacent fault segments. The Traverse Ridge site (TR site: this study) is located at the crest of Traverse Ridge midway along the FCF. Adjacent paleoseismic sites include the Corner Canyon site (CC site: e.g., DuRoss et al., 2015) and South Fork Dry Creek Site (SFDC site: Black et al., 1996) on the southern Salt Lake City Segment as well as the Alpine site (Alp site: Bennett et al., 2015) and the American Fork site (AF site: Forman et al., 1989) B) The WFZ (red and yellow lines) extends for more than 300 km along the urbanized wasatch front (black polygons). The Provo and Salt Lake City segments (yellow lines) cut along the eastern edge of the urbanized area, within 10 km of most of Utah's residents. In this study we re-excavated two paleoseismic exposures at the TR site (Figures 2-6) and established an earthquake chronology for the FCF (Tables 1-3 and Figure 7).

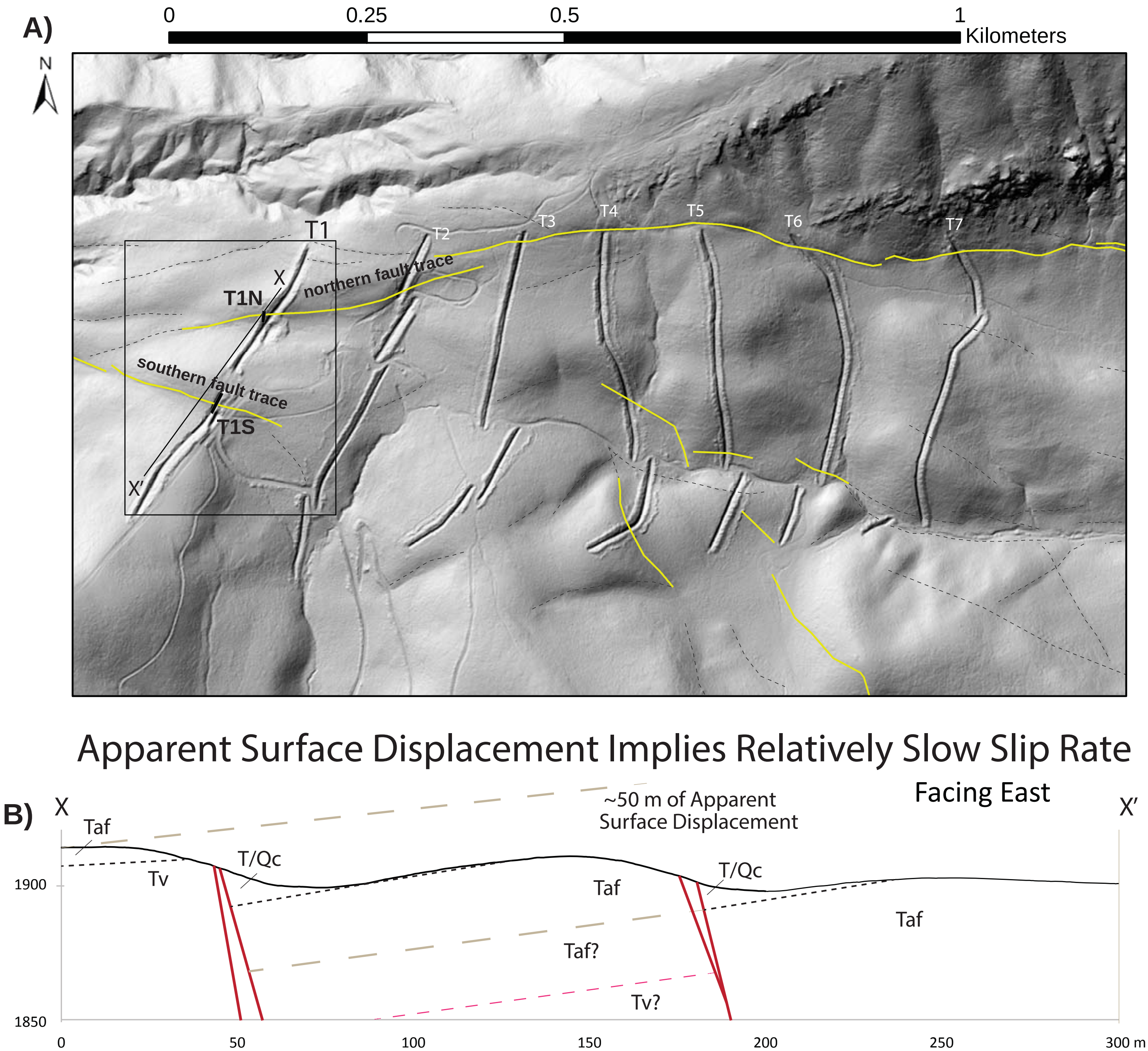


Figure 2. A) The Traverse Ridge site (TR site) consists of seven ~500 m long paleoseismic trenches that were originally investigated as part of a geotechnical investigation for a planned, but abandoned housing development. In this study we identified the westernmost trench (trench 1) as having the best potential for further paleoseismic investigation. We re-excavated two portions of trench 1 which crossed the two prominent traces of the Fort Canyon fault near this location. Trench 1 north (T1N: small black line) was cut across the northern fault trace and re-oriented, extending about 14 m along a 350° trend from the existing trench at approximately: 40.49254°, - 111.80467°. Trench 1 south (T1S) was exposed by widening the existing trench exposure without changing the trench orientation. B) The northern and southern fault scarps cut through Tertiary volcanic and alluvial fan units (Biek, 2005). There appears to be at least 50 m of apparent displacement across these two fault traces. Just west of the trench site, it is apparent that the southern fault trace cuts the northern fault trace, indicating more recent activity, which corresponds to trenching observations (Figures 3-6).

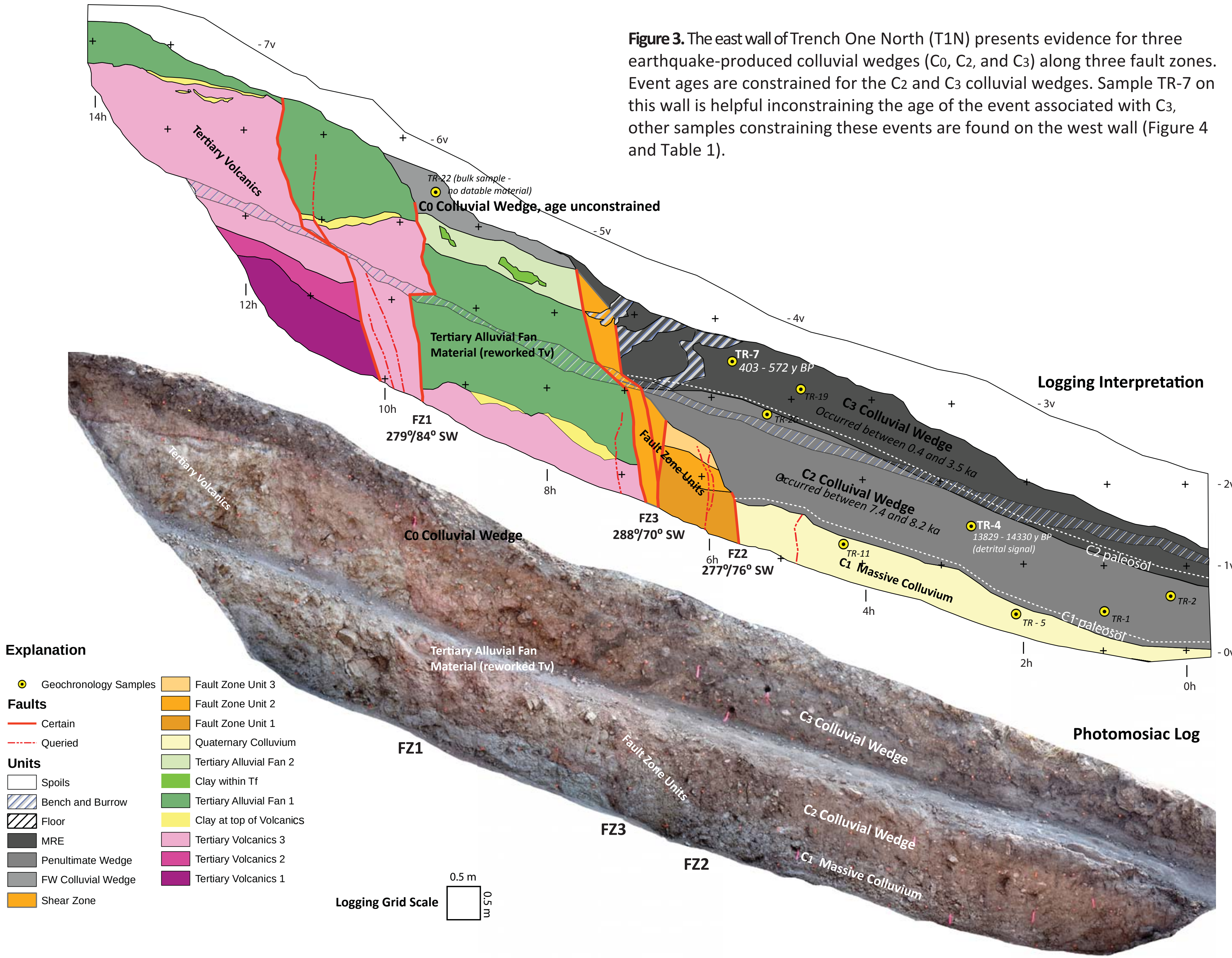
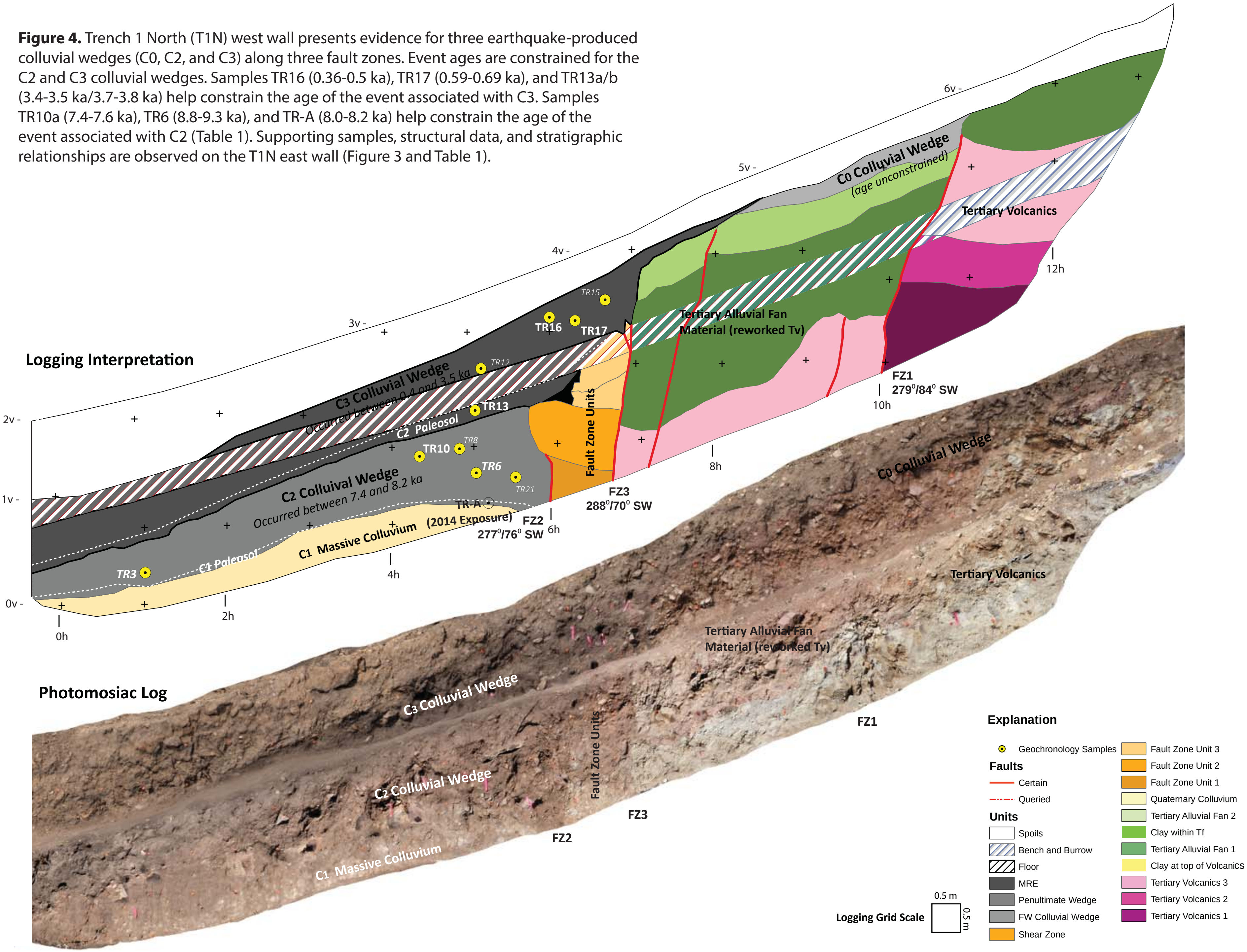


Figure 3. The east wall of Trench One North (T1N) presents evidence for three earthquake-produced colluvial wedges (C_0, C_2, and C_3) along three fault zones. Event ages are constrained for the C_2 and C_3 colluvial wedges. Sample TR-7 on this wall is helpful inconstraining the age of the event associated with C_3, other samples constraining these events are found on the west wall (Figure 4 and Table 1).

Figure 4. Trench 1 North (T1N) west wall presents evidence for three earthquake-produced colluvial wedges (C0, C2, and C3) along three fault zones. Event ages are constrained for the C2 and C3 colluvial wedges. Samples TR16 (0.36-0.5 ka), TR17 (0.59-0.69 ka), and TR13a/b (3.4-3.5 ka/3.7-3.8 ka) help constrain the age of the event associated with C3. Samples TR10a (7.4-7.6 ka), TR6 (8.8-9.3 ka), and TR-A (8.0-8.2 ka) help constrain the age of the event associated with C2 (Table 1). Supporting samples, structural data, and stratigraphic relationships are observed on the T1N east wall (Figure 3 and Table 1).



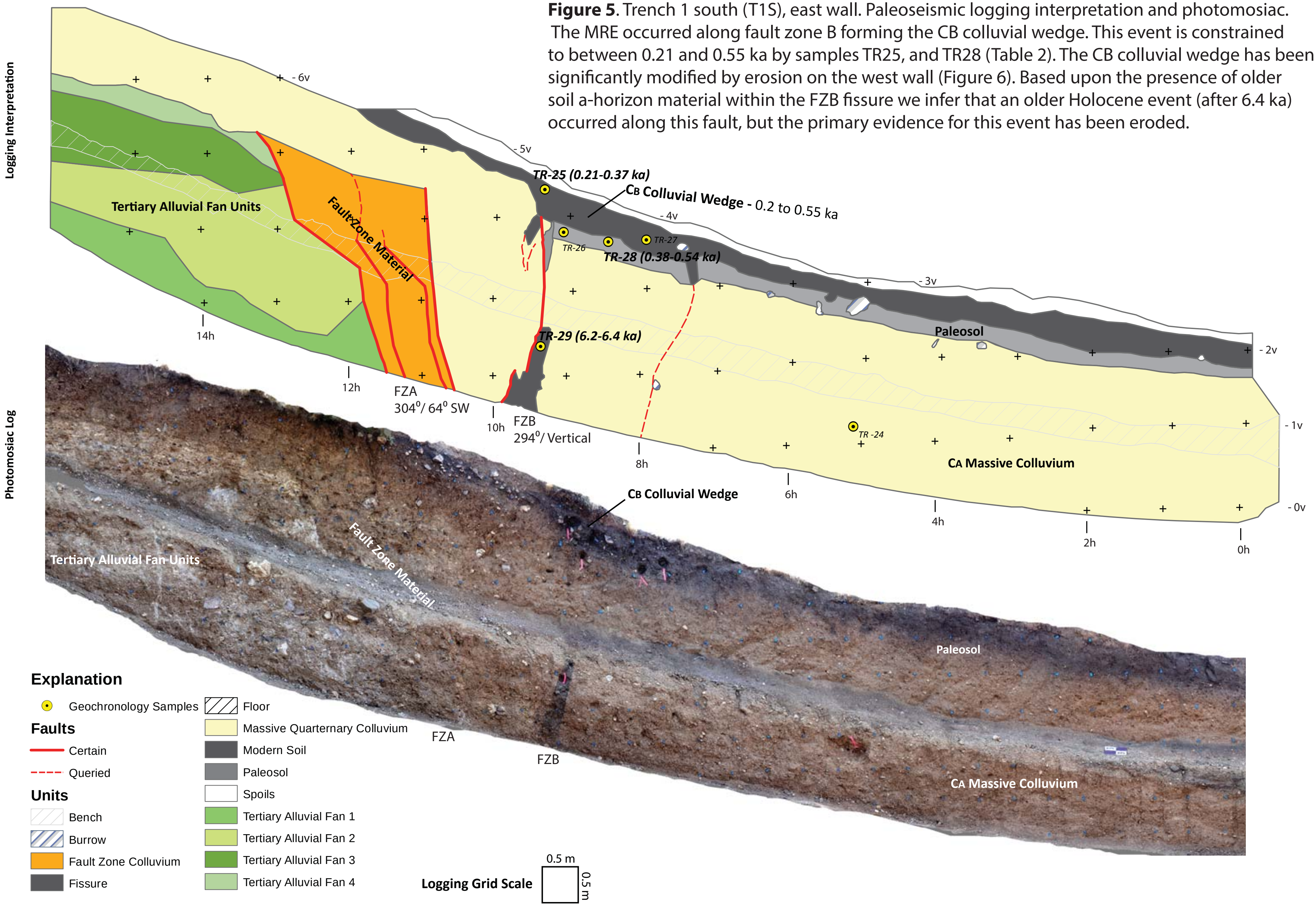


Figure 5. Trench 1 south (T1S), east wall. Paleoseismic logging interpretation and photomosiac. The MRE occurred along fault zone B forming the CB colluvial wedge. This event is constrained to between 0.21 and 0.55 ka by samples TR25, and TR28 (Table 2). The CB colluvial wedge has been significantly modified by erosion on the west wall (Figure 6). Based upon the presence of older soil a-horizon material within the FZB fissure we infer that an older Holocene event (after 6.4 ka) occurred along this fault, but the primary evidence for this event has been eroded.

Figure 6. Trench 1 South (T1S) west wall. Paleoseismic logging interpretation and photomosiac. The MRE occurred along fault zone B forming the CB colluvial wedge. This event is constrained to between 0.21 and 0.55 ka by samples TR25, and TR28 (Table 2 and Figure 5). The CB colluvial wedge has been significantly modified by erosion.