Holocene earthquakes and late Pleistocene slip rate estimates on the Wassuk Range fault zone, Nevada, USA.

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Electronic supplement: Two tables and figures detailing the inputs and results for radiocarbon and cosmogenic analyses and photos of the rocks sampled for cosmogenic analysis.
Abstract

The Wassuk Range fault zone is an active, 80 km long, east-dipping, high-angle normal fault that flanks the eastern margin of the Wassuk Range in central Nevada. Observations from two alluvial fan systems truncated by the fault provide information on the uplift rate and Holocene earthquake history along the rangefront. At the apex of the Rose Creek alluvial fan, radiocarbon dating of offset stratigraphy exposed in two fault trenches shows that multiple earthquakes resulted in 5.5-7.0 m of vertical offset along the fault since ~9400 cal yr B.P. The southern trench records at least two faulting events resulting in a ~5.5 m scarp since ~9400 cal yr B.P., with the most recent displacement postdating ~2800 cal yr B.P. The northern trench records a ~1 m offset after ~600 cal yr B.P., allows an earlier event at ~1450 cal yr B.P., and records one or more prior events. Although large variations in stratigraphy between trench exposures prevent the development of a unique earthquake chronology, these observations result in a Holocene uplift rate of 0.6–0.8 mm/yr. Approximately 30 km north, the range-front fault has truncated and uplifted the Penrod Canyon fan remnant ~40 m since the surface was abandoned after ~113 ka, based on cosmogenic dating of two large boulders. These data permit a best estimate of the late Pleistocene vertical uplift rate between 0.3-0.4 mm/yr along the Wassuk Range fault zone.
Introduction

The Wassuk Range fault zone is an active, east-dipping normal fault that strikes north-northwest for a distance of over 80 km along the eastern margin of the Wassuk Range, forming the western boundary of the Walker Lake basin (Figure 1). Thermochronologic analysis suggests that rapid extensional deformation and uplift of the Wassuk Range occurred between ~15-12 Ma, with renewed uplift along the present-day, high-angle, rangefront fault beginning ~4 Ma (Surpless et al., 2002; Stockli et al., 2002). Reaching elevations of over 3,400 m, the Wassuk Range is a major tectonic feature in the Central Walker Lane: a complex zone of transtensional faulting that separates the extending Basin and Range from the rigid Sierra Nevada block and accommodates up to 10 mm/yr of Pacific-North American relative right-lateral plate motion (e.g. Thatcher et al., 1999; Bennett et al., 2003; Oldow et al., 2001; Hammond and Thatcher, 2007).

Strain in the Central Walker Lane is strongly partitioned into a zone of dextral-dominated deformation to the east of the Walker Lake basin and extension-dominated deformation to the west (e.g., Oldow, 2003; Wesnousky, 2005; Surpless, 2008). Previous geologic studies show no evidence for significant dextral deformation along the Wassuk Range fault zone (e.g., Dilles, 1993; Stockli et al., 2002; Surpless, 2011), making the active, range-bounding fault ideal to investigate vertical slip rates related to extensional deformation. We report observations from two locations along the Wassuk Range that help constrain the earthquake history and uplift rate along the fault in an effort to add information to regional seismic hazard analysis (Figures 1 and 2). At Rose Creek, two trenches excavated across the fault yield information about the size and timing of Holocene earthquakes and an estimate of the Holocene uplift rate. The second site is at Penrod Canyon, where cosmogenic dating of two large boulders on an uplifted, abandoned fan remnant allows an estimate of the late Pleistocene uplift rate.
**Rose Creek alluvial fan**

Rose Creek drains the highest portion of the Wassuk Range and has produced a large fan on the eastern flank of the range front (Figure 2). The Wassuk Range fault zone cuts the apex of the Rose Creek fan at an elevation of ~1525 m, well above the ~1330 m 13 ka late Pleistocene Lake Lahontan highstand (Figure 2; Adams and Wesnousky, 1999). The fault is expressed by scarps with vertical separations of 1-2 m and 5.5-7 m in Holocene alluvial fan deposits Qy2 and Qy1, respectively (Figure 3). We excavated and mapped trench exposures across the small and large scarps to quantify the timing, displacement, and recurrence of slip on the fault.

**Rose Creek North trench**

The Rose Creek North (RCN) trench was excavated across a ~1 m scarp cutting the Qy2 alluvial fan surface to the northwest of Rose Creek (Figure 3). The ~20 m long trench exposed alluvial fan gravels offset across a series of normal fault strands (Figure 4a). At the base of the footwall, unit 1 is composed of a fine-grained, alluvial gravel layer overlain by a coarse debris flow deposit and a younger fine-grained, alluvial gravel layer. Sitting above and in fault contact with unit 1 across fault strand B, unit 2 is scarp-derived colluvium and fissure fill composed of loosely consolidated pebbles, cobbles, and small boulders in a sandy matrix. A coherent block of the coarse debris flow member of unit 1 is entrained in the unit 2 fissure fill. Unit 3 is a coarse debris flow deposit that overlies unit 2. Fault strand B offsets footwall units 1, 2, and 3. Units 2 and 3 are further offset and truncated by fault strand A. In the hanging wall, the beds of unit 4 are similar in composition to footwall units 1, 2, and 3, though correlation of individual beds across the fault zone is ambiguous. A wedge-shaped package (unit 5) of east dipping and upward-fining
scarp-derived colluvium extends eastward from fault strand A to overlie unit 4. A fissure extending downward from the base of the wedge is filled with unit 5 sands and gravels (subunit 5’). Unit 6 is a charcoal-bearing, alluvial deposit that overlies units 4 and 5. It is composed of brownish–tan, sandy matrix-supported fan gravels that become increasingly silt-rich adjacent to the fault. Subunit 6a is a waterlain, reworked-tephra bearing lens that overlies a charcoal-rich burn layer ~0.15 m above the base of unit 6. Tephra samples RCN-T1 and -T2, taken from unit 6a, are regionally correlated with late Holocene Mono Craters volcanism ~600-2000 14C yr B.P. (Wesnousky, 2005; J. Bell, Nevada Bureau of Mines and Geology, Reno, Nevada, personal communication, 2010). The youngest unit in the trench, unit 7, rests on the scarp face of fault strand A and is a wedge-shaped package of scarp-derived colluvium composed of tan, silty/sandy matrix-supported pebble gravels. Subunit 7’ is a small fissure filled with unit 7 gravels along the westernmost fault strand (strand B). The basal contact of unit 7 overlies a weakly developed Av horizon that caps unit 6. Unit 7 contains two distinct burn layers, depicted as dark grey lenses (Figure 4a). Upslope from the fault, the matrix of unit 7 becomes more sand rich, reflecting an influx of fan material from a small alluvial cone at the base of the rangefront adjacent to the trench (Figure 3). The cone alluvium covers the hanging wall fan surface (unit 3) near the trench and obscures the 1 m fault scarp.

The hanging wall stratigraphy in the north trench exposure is interpreted to record at least two surface-rupturing earthquakes. The wedge-shaped unit 7 and fault-bounded subunit 7’ are interpreted to be scarp-derived colluvium and fissure fill resulting from the most recent movement on fault strands A and B (Figure 4a). Displacement for the event estimated by thickness of the colluvial wedge is ~1.0 m, approximately the same height as the surficial scarp near the trench. The radiocarbon analysis of the youngest charcoal sample taken from the upper
portion of unit 6, ~0.3 m below the basal contact of unit 7, is $614 \pm 57$ cal yr B.P. (sample RCN-RC14 in Figure 4a; Table S1). Charcoal samples from the burn layer in unit 7 yield modern ages and thus are of limited utility in further constraining the age of faulting (samples RCN-RC10 and RCN-RC13 in Figure 4a and Table S1). This limits the occurrence of the most recent displacement to be post ~614 cal yr B.P.

The interpretation of a second earthquake recorded in the hanging wall sediments is based on unit 5’s wedged shape, association with a fissure (subunit 5’), and fault bound contact with unit 2. These features indicate unit 5 was formed by colluvium shed off a scarp produced by slip on fault strand A and was subsequently displaced during the most recent event. The radiocarbon age of charcoal sampled from directly above the basal contact of unit 6 is $1461 \pm 68$ cal yr B.P. (sample RCN-RC1 in Figure 4a; supplemental Table S1). This sample constrains the deposition of unit 6 to after ~1461 cal yr B.P. and limits the minimum age of the earthquake that produced colluvial unit 5, hereafter referred to as the pre 1461 cal yr B.P. event. The surficial geology near the trench suggests that the fan alluvium of unit 6 sourced from a small alluvial cone to the west of the trench (Figure 3) and was deposited atop the scarp-derived colluvium of unit 5 as growth stratigraphy against the pre 1461 cal yr B.P. event scarp. This interpretation suggests the combined thickness of units 5 and 6 adjacent to fault strand A reflects a minimum event displacement of ~1.6 m for pre 1461 cal yr B.P. event (Figure 4a). However, the observed increase in the silt content of unit 6 near fault strand A may represent a pulse of sedimentation resulting from an additional scarp forming earthquake that occurred closely in time to ~1461 cal yr B.P. (as suggested by the location of sample RCN-RC1 at the base of unit 6). If units 5 and 6 resulted from separate earthquakes, the minimum event displacement related to the pre 1461 cal yr B.P. and ~1461 cal yr B.P. ruptures is respectively ~1.3 m and ~0.3 m.
In the footwall, the truncation of unit 1 along fault strand B and the wedge-shape of unit 2 record the occurrence of at least one additional earthquake prior to ~1461 cal yr B.P. The absence of dateable materials within units 1 and 2 and correlative hanging wall deposits precludes further characterization of the earthquakes recorded in footwall stratigraphy.

**Rose Creek South Trench**

The Rose Creek South (RCS) trench was excavated across a ~5.5 m scarp cutting the Qy1 alluvial surface to the southeast of Rose Creek (Figure 3). The ~30 m long trench exposes a thick package of coarse debris flow and colluvium deposits (Figure 4b). The oldest unit exposed in the trench (unit 1) is a debris flow deposit capped by a 20-30 cm thick, black, organic-rich, charcoal bearing, peat-like layer at the base of the trench. This unit is overlain by a thick package of matrix-supported, debris flows containing angular, large boulders (unit 2). Slight reddening at the contacts of individual flow deposits (~1.0 m average thickness) reveals a generally tabular fabric in the otherwise massive package. Footwall units 1 and 2 are truncated by an eastward-dipping normal fault. The hanging wall is similar in composition and texture to unit 2 and is labeled unit 3. Slight reddening along contacts between individual sediment packages within unit 3 is evident toward the easternmost portion of the exposure, but evidence of bedding or horizonation is absent in the western portion of the unit, closer to the fault. Where observed, the average bedding thickness in unit 3 (~0.5 m average) is distinctly less than that recorded in unit 2. Fissures filled with loose, reddish-brown sands and vertically aligned clasts (unit 4) cut units 2 and 3. Unit 5 is a slope-wash deposit that overlies the eastern end of unit 3 and is buried by a fluviial, reworked tephra-bearing deposit (unit 6). Modern slope-wash and aeolian deposits (unit 7) cap the entire exposure.
The coarse and massive deposits exposed in the trench prevent from the extraction of a
detailed earthquake chronology from the exposure. Deposition of the Qy1 surficial fan deposits,
in which the trench was excavated, postdates the deposition of the peat-like layer that caps unit 1,
 radiocarbon dated at 9400±97 cal yr B.P. (RCS-RC1 in Figure 4b; Table S1). Accordingly, the
5.5-7 m scarp that truncates the Qy1 fan surface must result from displacements occurring after
9400±95 cal yr B.P. The massive nature of unit 3 near the contact with the footwall is consistent
with an interpretation that unit 3 is fault-derived colluvium resulting from at least one
earthquake. The eastward gradation of unit 3 into a number of distinct layers capped by incipient
soil development allows a speculative interpretation that each layer represents aggradation at the
distal end of a colluvial wedge subsequent to individual earthquake offsets; however, this
interpretation is complicated by the observation that the deposits appear to be emplaced by
energetic debris flow processes associated with flash floods rather than colluvial deposition.
Withstanding this uncertainty, fissures (filled by unit 4) that cut units 2 and 3 are capped by
modern deposits and record at least one earthquake subsequent to 2806±50 cal yr B.P, the
radiocarbon age of a charcoal sample found within a displaced soil block in the fissure fill
(Sample RCS-RC10 in Figure 4b and Table S1). There is a possible small colluvial deposit (unit
4?) associated with the fissure-producing earthquake along the upward continuation of the main
fault strand, but this relationship is obscured by disturbed stratigraphy due to the presence of a
large boulder in the trench wall. A reworked tephra deposit in the hanging wall (unit 6, samples
RCS-T1 and RCS-T2) is correlated with Mono Craters volcanism between ~600-2000 14C yr
B.P. Deposition of the tephra in the trench wall postdates faulting associated with the
development of unit 3. However, the age relationship between the tephra bearing gravels
(subunit 6a within unit 6) and the event or events that produced the fissures (unit 4) is ambiguous.

*Holocene Uplift Rate*

The fault scarp on the Qy1 surface adjacent to the south trench shows a vertical separation of 5.5-7 m (Figure 3). The radiocarbon date obtained from the base of the hanging wall in the southern trench (sample RCS-RC1 in Figure 5b and Table S1) constrains the age of the fan surface to be less than ~9400±95 cal yr B.P. The stratigraphy in both the north and south trenches indicate that the vertical separation of the Qy1 surface results from multiple earthquakes. Dividing 5.5-7 m by 9400±95 yr yields an estimate of Holocene vertical uplift rate at 0.6-0.8 mm/yr.

**Penrod Canyon alluvial fan**

At the mouth of Penrod Canyon, Quaternary uplift is recorded by a fault scarp that truncates an abandoned alluvial fan surface (Figure 5). The escarpment displays eroded wave-cut benches created by late Pleistocene pluvial lake high-stands (Figure 5) and strikes approximately N30°E at a right step in the NNW-striking range front fault system (Figure 2). The large escarpment cuts middle to late Pleistocene fan and lacustrine platform veneer deposits (House and Adams, 2009) and is paralleled by 3-7 m fault scarps that offset the adjacent Holocene fan deposits (Figure 5). The proximal location and parallel orientation of the young fault scarps relative to the wave-modified scarp indicate the predominantly tectonic origin of the large escarpment and abandoned fan surface (Wesnousky, 2005). Detailed topographic profiles across the larger scarp reveal approximate offsets of 30 m, 40 m, 41 m, and 39 m (Figure 5). Cross
section A-A’ is based on a profile from the highest elevation of the abandoned alluvial fan
surface southeast across the escarpment to the active alluvial fan. At this location, ~40 m of
vertical uplift is evident between the abandoned and active alluvial surfaces (Figure 5).

We sampled two large granitic boulders on the abandoned fan remnant (Figure 5) to
determine the length of time these rocks have been exposed to cosmogenic radiation on the fan
surface (Gosse and Phillips, 2001). The samples were prepared and the amounts of $^{10}$Be and $^{26}$Al
in the rocks were measured at the PRIME Lab of Purdue University (Sharma et al., 2000). BeO
and Al$_2$O$_3$ were purified from the quartz portion of the samples, following procedures developed
by Kohl and Nishiizumi (2000). The $^{10}$Be and $^{26}$Al exposure ages were determined using the
CRONUS-Earth online exposure age calculator, version 2.2 (hess.ess.washington.edu/math/)
(Balco et al., 2008). We calculated $^{10}$Be and $^{26}$Al exposure ages assuming no erosion for each of
the three samples taken from the two boulders, resulting in a total of six ages. The individual
$^{10}$Be and $^{26}$Al concentrations, model ages, and sample information are detailed in Table S2,
available with field photos of the boulders in the electronic supplement to this paper. Four of the
age estimates result from one boulder (samples C2 and CWL1). This boulder yields $^{10}$Be ages of
84.5±1.7 ka and 111.9±2.7 ka and $^{26}$Al ages of 108.8±4.8 ka and 118.1±6.4 ka for samples C2
and CWL1, respectively. Three of these four exposure ages agree to within the 1σ analytical
uncertainties, but the C2 $^{10}$Be age falls outside the 1σ range. It is unusual for sample replicates
from the same boulder to vary this much, especially given the concordance of the $^{26}$Al results;
however there were no obvious problems with the chemistry or the measurements. We sum the
individual probability density functions to determine the mean age for the boulder and calculate
the reduced $\chi^2$ statistic to determine the significance of the age groupings (Balco et al., 2009 &
2011; Schaefer et al., 2009; Rood et al., 2011a). Using all four C2 and CWL1 samples results in
a mean age for the boulder with a 1σ uncertainty of 105.8±13.5 ka and reduced $\chi^2$ value of 26.5.

If the C2 $^{10}$Be age is excluded from the calculations, the resulting mean age of the three-sample set is 112.9±6.25 ka with a reduced $\chi^2$ value of 0.785 (summary probability density function diagrams and statistics available in the electronic supplement). The low reduced $\chi^2$ value of the three-sample estimate gives us confidence in three-sample grouping, and we use the age of 112.9±6.25 ka for the boulder. The $^{10}$Be and $^{26}$Al age for boulder C1 are 75.7±1.7 ka and 89.6±4.6 ka. These estimates do not agree to within 1σ uncertainties. Because the $^{26}$Al dataset is concordant for the C2/CWL1 samples and the C1 and C2 sample $^{26}$Al/$^{10}$Be ratios are higher than the accepted production ratio of 6.75 (Nishiizumi et al., 2007), we use the $^{26}$Al age of 89.6±4.6 ka as the exposure age of the C2 boulder. Although the ages of the two boulders are not in tight agreement it is not unusual to see spread in boulder age estimates for depositional features of this age (e.g. Heyman et al., 2011; Rood et al., 2011a). Surface exposure ages may be affected by a number of geological processes. Weathering, exhumation, and shielding of surfaces by sediment or snow will lead to exposure ages that are less than the true age of the landform (e.g. Heyman et al., 2011; Owen et al., 2011). In contrast, surface exposure of rocks prior to deposition on a fan surface will result in an overestimation of the landform. Recognizing these uncertainties and the small sample size (n=2 boulders), we simply assume the age of the fan surface is best represented by our age estimate for the older boulder (sample C2/CWL1) of 112.9±12.5 ka (2σ).

**Late Pleistocene Uplift Rate**

The vertical offset and exposure age data permit an estimate of a time-averaged late Pleistocene uplift rate along the Wassuk Range fault zone. Dividing the scarp height (~40 m) by the fan surface age estimate of 112.9±12.5 ka results in an initial estimate of Late Pleistocene
range-front uplift equal to about 0.3-0.4 mm/yr. Because our cosmogenic exposure ages assume zero erosion on the sampled boulder, the ages are minimum estimates. In light of this uncertainty, the actual uplift rate may be lower than 0.3-0.4 mm/yr if the fan surface is older than 112.9±12.5 ka.

Discussion and Conclusions

Observations from the Rose Creek trenches provide information on the frequency, size, and timing of surface rupturing earthquakes on the Wassuk Range fault zone. Both trench exposures display records of multiple Holocene earthquakes, although the correlation of individual events between the two trenches is problematic. The most recent event recorded in the northern trench occurred after 614±57 cal yr B.P. with ~1 m of displacement. Prior fault displacement may be explained by either the occurrence of a single >1.6 m displacement prior to 1461±68 cal yr B.P. or two events of >0.3 m and >1.3 m at and before about 1461±68 cal yr B.P, respectively. The footwall stratigraphy shows evidence for at least one additional earlier earthquake; however, the lack of datable materials within the footwall prevents further development of an earthquake history for the fault. The ~1 m surface scarp at the northern trench location represents slip from only the most recent event. The southern trench shows that multiple surface rupturing earthquakes have resulted in a ~5.5-7 m scarp on the Qy1 fan surface since 9400±95 cal yr B.P., with the most recent displacement post-dating 2806±50 cal yr B.P. The height of the scarp and the thickness of the hanging wall debris flow deposits (unit 3, Figure 4b) suggest the likelihood of additional faulting events between 9400±95 cal yr B.P. and the fissure-producing event, but the lack of distinct colluvial stratigraphy and age constraints in the exposure prevents further characterization of individual displacements during this time. The limited
interpretation of the southern exposure is consistent with the earthquake history in the northern
trench. Our results support the interpretation of the geomorphology and soils by Demsey (1987)
suggesting that the Rose Creek fan head scarps record multiple earthquakes on Holocene age
alluvial surfaces.

Two lines of evidence point to a late Pleistocene-Holocene vertical uplift rate along the
Wassuk Range fault zone between 0.3 and 0.8 mm/yr. The multiple event scarp in the Qy1
surface at Rose Creek records 5.5-7 m of vertical separation since 9400±95 cal yr B.P., providing
the basis to estimate a Holocene uplift rate of 0.6-0.8 mm/yr. At Penrod Canyon, cosmogenic
exposure dating suggests that the age of the abandoned fan’s upper surface is 112.9±12.5 ka, and
scarp profiles indicate that was fan was tectonically uplifted 40 m above the correlative lower
surface now buried by alluvium. Dividing the offset by the cosmogenic exposure age results in
an estimated uplift rate of 0.3-0.4 mm/yr. It is likely because of the short time period over which
the Rose Creek rate is determined and the small number of boulders sampled (n=2) at Penrod
Canyon that the formal uncertainties attached to the rate estimates are less than the actual
uncertainties. Thus, we hesitate to conclude that the rates are significantly different. In this
regard, the observations presented in this paper suggest a late Pleistocene-Holocene uplift rate of
~0.3-0.8 mm/yr. This rate is very similar to the estimated post-Pliocene time-averaged uplift rate
of 0.5 – 0.75 mm/yr for the Wassuk Range fault system (Stockli et al., 2002) and is consistent
with a previous Holocene uplift rate estimate of 0.4-0.5 mm/yr based on fault zone
geomorphology (Demsey, 1987).

dePolo and Anderson (2000) find that normal faults with the fastest vertical uplift rates in
Nevada are generally located within the Walker Lane. In the Walker Lane, late Pleistocene
uplift rates for the normal fault-bounded basins range from 0.2-3 mm/yr, with the fastest rates on
the Sierra Nevada frontal fault system (Ramelli et al., 1999; Brothers et al., 2009; Dingler et al., 2009; Rood et al., 2011b; Wesnousky and Caffee, 2011; Sarmeinto et al., 2011). In contrast, uplift rates in the interior portion of the Great Basin are an order of magnitude lower than in the Walker Lane, generally between 0.01-0.4 mm/yr (dePolo and Anderson, 2000). The Wassuk Range Holocene-late Pleistocene vertical uplift rate of 0.3-0.8 mm/yr is similar to previously reported uplift rates for normal faults in the Walker Lane and is significantly higher than uplift rates on faults in the interior Great Basin. Thus, with evidence for at least two Holocene surface rupturing earthquakes and relatively high long-term vertical slip rates, the Wassuk Range fault zone is a significant source of seismic hazard in the Central Walker Lane.

**Data and Resources**

All data used in this paper was collected during the duration of this study or came from published sources listed in the references.
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Figure Captions

Figure 1. The Wassuk Range fault zone in relation to faults within the Walker Lane. Box in inset map shows area of detail and major faults in Nevada and California. Dashed lines mark the boundaries of the Walker Lane. Strike slip faults of the Central Walker Lane are black, normal faults are white. Lake Tahoe (LT), Walker Lake (WL), and Mono Lake (ML) are shown for geographic reference. Faults are modified from the USGS (2006).

Figure 2. Map of the Wassuk Range fault zone. Faults are shown in relation to Quaternary surficial deposits. Location of the Rose Creek and Penrod Canyon study sites are outlined with black boxes and labeled.

Figure 3. Rose Creek alluvial fan paleoseismic and slip rate site. See Figure 2 for site location. (a) Aerial photograph showing the location of the north (RCN) and south (RCS) trenches along the fault scarp in relationship to Rose Creek. (b) Map showing the relationship of the fault to Quaternary surficial deposits at the mouth of Rose Canyon. Mapping is based on field observations and low sun angle air photos, modifying the work of Demsey (1987). The fault is marked as a black line with ticks on the down-thrown side. Trench locations are indicated with thick lines and are labeled RCN (north trench) and RCS (south trench). Numerical annotations indicate vertical separation across surveyed fault scarp profiles (small circles). 1m topographic basemap constructed from a lidar derived DEM of Walker Lake (USGS, 2008).
Figure 4. Sketch logs of the (a) northern and (b) southern trench exposures across the Wassuk Range fault zone at the Rose Creek fan. Trench locations are shown in Figure 3. Unit label numbers correspond to descriptions in text. Tephra (gray stars) and radiocarbon (black circles) sample locations are shown. In the northern trench (a), the major fault strands are labeled (A-B). See text for discussion.

Figure 5. Penrod Canyon alluvial fan slip rate site. See Figure 2 for location. (upper) Abandoned fan surface truncated by the Wassuk Range fault zone at the mouth of Penrod Canyon. Location of the boulders sampled for cosmogenic nuclide analysis is marked with a white star. Numerical annotations indicate vertical separation across surveyed scarp profiles (dashed black lines). Location of illustrated scarp profile marked A-A’. Photograph modified from Wesnousky (2005). (lower) Elevation profile across the ~40 m large wave modified fault scarp. Approximate location of the Holocene (H) and late Quaternary (Q) fault traces marked with red dashed lines.
White Mountain
Schurz
Penrod Canyon
Walker Lake
Copper Canyon
Rose Creek
Mt. Grant 3425m
Hawthorne
North Canyon
Whiskey Flat
Reese River Canyon

Intermediate age alluvial deposits and pediment surfaces
Oldest alluvial fan deposits and pediment surfaces
Undifferentiated, generally bedrock.
Youngest alluvial deposits and surfaces
Historical lake deposits
Pleistocene lake deposits and surfaces
Intermediate age alluvial deposits and pediment surfaces
Oldest alluvial fan deposits and pediment surfaces
Undifferentiated, generally bedrock.
Faults and wave-modified fault scarps

modified from Wesnousky, 2005
Figure 3

- Active wash and fan deposits
- Young fan deposits
- Holocene fan deposits, \(<\sim9,400 \text{ cal yrs BP}\)
- Oldest fan deposits and pediment surfaces
  Undifferentiated, generally bedrock

90 m

(a) South trench
(b) North trench

Rose Creek

Rose Creek

(c) South trench
(d) North trench

Figure 3
(a) Rose Creek North Trench Log

RCN-T1 & T2
Samples from a reworked tephra deposit regionally correlated with Mono Craters volcanism 600-2000 $^{14}$C yr BP.

RCN-RC1
1461 +/- 68 cal yr BP

RCN-RC10
144 +/- 111 cal yr BP

RCN-RC13
139 +/- 111 cal yr BP

RCN-RC15
799 +/- 104 cal yr BP

Region obscured by large boulder. Inset area is benched back about 1m.

(b) Rose Creek South Trench Log

RCS-T1 & T2
Samples from a reworked tephra deposit that are regionally correlated with Mono Craters volcanism 600-2000 $^{14}$C yr BP.

RCS-RC1
9400 +/- 95 cal yr BP

RCS-RC10
2806 +/- 50 cal yr BP

Possible MRE colluvium

Spoils

Figure 4