First Round Comments From Reviewer #1:

Dear Editor,

Thank you for the opportunity to review the manuscript entitled “Plaeoseismology of the Buffalo Valley, Buena Vista, and Southern Shoshone faults, central Basin and Range, Nevada USA” by Rich Koehler, Mark Stirling, and Brad Sion.

The authors present the first examples of geologically derived slip rate data for the Buffalo Valley, Buena Vista, and southern Shoshone faults in the central Basin and Range of Nevada. They employ detailed fault mapping (both remote and field based), soil development characterization, cosmogenic nuclide exposure depth profile data, and boulder exposure ages.

They deliver a cogent and broad slip rate range using the available data and reasonably compare their chronology, soil development, and surficial mapping to other studies in the region.

This information in this study is directly relevant for future National Seismic Hazard Models and is well written and illustrated. For these reasons I am in support of the publication within Seismica

With the consideration of the following suggestions, I would be pleased to see this manuscript published soon!

Sincerely,

<redacted>

Minor Suggestions

Suggested addition of text is shown in red.

Line 28: suggest replacing “abandonment” with “stabilization”

Line 54: …, while the Buena Vista and Shoshone faults are both west-dipping faults with lengths of ~65 km that bound the eastern Buena Vista Valley and the western Shoshone Range, respectively.

Line 79: change “and not direct geologic observations” to “due to lack of geologic observations”

Line 84: For example, the intersection of the…

Line 137: However, field inspection of…

Line 138: Suggest changing “lake” to “basin” change “they” to “these scarps” so it reads, …western margin of the basin revealed that these scarps have rounded…

Line 146: $CaCO_3$ (the 3 is currently a superscript)

Line 147: Bulk sediment samples were collected at 25 cm intervals…. *What depth did you start collecting? Maybe mention that (e.g., "beginning at 10 cm depth")

Line 148: Change "absolute" to "numeric"

Line 157: The textural B horizons in both pits are overlain by silt loam to sandy loam A and Bw horizons with weak structure (22 cm thick in BVSP-1 and 13 cm thick in BVSP-2). This relation suggests Holocene erosion**, deposition**, and subsequent soil development on an older late Pleistocene surface, a phenomenon…

> **doesn't it imply that there had to be stripping of the original A portion of the late Pleistocene soil, then deposition of new material to develop the Holocene soil within? Or is it just addition of material and further development of the lower B horizons? In any case, does this make the 2Bt (and lower horizons) a Btb1 since it is buried (assuming you are using Birkeland, 1999)?

Line 156-159: suggest adding citations for other late Pleistocene soil studies in the Great Basin

Line 168: ^{36}Cl depth profile exposure ages place…

Line 170: "the two samples in the upper 50 cm"

> This reads like there are two samples above 50 cm in each profile. There is only one sample above 50 cm for each profile, right? It looks like just one above 50 in both figures 5 and 6. If so, changing the language to reflect that you are not including the samples taken from within the Av and AB/Bw in pit 1 and Av/Bw in pit 2 would make the point more streamline that you are using soils data to exclude samples within the second iteration of the cosmo model runs.

Line 179: and implies a reasonably broad age range

Line 180: …, thus we apply a range of 52-220 ka for the Qfi fans.

Line 305: remove "relative"

Line 306: are there errors that should be reported with these ages?

Line 329: replace "absolute" with "numeric"

Line 355-357: Suggest rewording second sentence of this paragraph. What about something like this:

Geomorphic characteristic and numeric chronologies of fans from the Walker Lane to the west (e.g. Bormann et al., 2013; Angster et al., 2019) and Pleasant Valley (e.g. Figueiredo et al. 2023; 2024) are similar to the Qfi fans in Buffalo Valley, implying a reasonable relation of Qfi fans across this part of the Basin and Range.

Line 358: (2012)

Line 369-371: The alluvial fans studies by Figueiredo et al. (2023; 2024) have similar geomorphic expression and soil development to the fans we studied in Buffalo Valley, as well as the same bedrock parent materials…

Line 376-378: Furthermore, the ages and slip rate determined by Figueiredo et al., (2024) to the west of the Tobin Range and our estimates in Buffalo Valley to the east of the range support the notion of the Tobin Range deforming as a horst block bound by the Pleasant Valley and Buffalo Valley faults.

Line 405: …independent geologic validation of slip rates used (~0.1 mm/yr) in the 2023…

Figures

Figure 1. Consider labeling the Pleasant Valley fault. I know it is labeled with "1915" but directly labeling it could be helpful.

Figure 3. The soil pit locations are a bit hard to see. Can the black stars be highlighted with a white outline? Or maybe lighten the hillshade and map units.

Figure 4. consider adding vertical exaggeration (2x)

Figures 5 and 6. I think adding the soil horizons to ^{36}Cl concentration curve would be a super helpful visual.

First Round Comments From Reviewer #2

Great paper on some new data on faults in Central Nevada. I enjoyed reviewing it and found it well written. The conclusions are consistent with the evidence and arguments presented.

I had a few pretty minor comments about several sections of the text. I'm attaching a marked up PDF with my comments for the authors to look over. The paper is very good as is, but I'm choosing Revisions Required so that the authors can take a quick look at my comments before this manuscript is published.

Paleoseismology of the Buffalo Valley, Buena Vista, and southern Shoshone faults, central Basin and Range, Nevada, USA

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Author contributions:

Conceptualization, project administration: R. Koehler, M. Stirling. Funding acquisition: R. Koehler, M. Stirling. Investigation (field mapping and geochronologic sampling): R. Koehler, M. Stirling. Geochronologic laboratory analyses: B. Sion, M. Stirling. Visualization: R. Koehler, M. Stirling. Writing – original draft: R. Koehler, M. Stirling. Writing – review & editing: all authors.

Abstract We present the results of a study of the Buffalo Valley, Buena Vista, and southern Shoshone faults in central Nevada. The three active normal faults accommodate extension within the slowly deforming Basin and Range Province in central Nevada. For the Buffalo Valley fault, field and lidar observations indicate that deformation is distributed across several parallel strands that progressively displace alluvial fans. Fault trace mapping, vertical displacement estimates, soil pit descriptions from displaced surfaces, and ^{36}Cl exposure age dates from two soil profiles and a single boulder are used to characterise the geomorphology and slip rate of the fault. Cumulative displacement across the oldest surface is ~21 m and late Pleistocene surfaces are displaced 8-8.6 m. Soils developed into late Pleistocene surfaces have stage II+ to III carbonate development suggesting an age for surface abandonment ~60-200 ka. ^{36}Cl soil depth profile analyses refine the age of these surfaces at a minimum of 54 $^{+}4/^{-}2$ ka and possibly up to 118 ±18 ka where the vertical displacement is 8 m, and a minimum of $77^{+5/-1}$ ka and possibly up to 213 +7/-11 ka where the displacement is 8.6 m, which collectively suggest a vertical slip rate of 0.04 - 0.15 mm/yr. The Buena Vista and southern Shoshone faults were mapped at single sites where faulted fan surfaces were observed, and boulders were sampled for ^{10}Be exposure age dating. Slip rates of 0.02 - 0.09 mm/yr and 0.02 - 0.08 mm/yr for the Buena Vista and southern Shoshone faults, respectively, are estimated from scarp heights and correlation of fan surfaces to Buffalo Valley, and consideration of boulder ^{10}Be exposure ages. The results contribute towards the refinement of seismic hazard models and the assessment of geothermal systems in the region.

Key words: Slip rate, tectonic geomorphology, extension, surface faulting, geochronology

Non-technical summary

The Buffalo Valley, Buena Vista, and southern Shoshone faults in central Nevada are active faults that accommodate crustal extension in the Basin and Range Province. Geologic mapping, fault scarp profiles, soil descriptions, and cosmogenic exposure dating are used to place constraints on the slip rate of each fault. The results indicate that all three faults have slip rates <0.15 mm/yr. These data are applicable to seismic hazard assessments and regional geothermal resource modeling.

1 Introduction

The three active faults addressed in this study are located in the central Basin and Range Province, Nevada USA. The Buffalo Valley fault is an east-dipping normal fault that extends for ~38 km along the east side of the Tobin Range (Fig. 1), while the Buena Vista and Shoshone faults are west-dipping faults with lengths of ~65 km. The Tobin Range represents a horst structure bound on its west side by the Pleasant Valley fault zone, the source of the 1915 Ms 7.6 Pleasant Valley earthquake (Wallace, 1984). Although none of these faults have generated a historic earthquake, long-term tectonic activity is evidenced by prominent tectonic geomorphology including abundant fault scarps crossing fan surfaces, well-developed triangular facets, and over-steepened basal slopes along their respective range fronts.

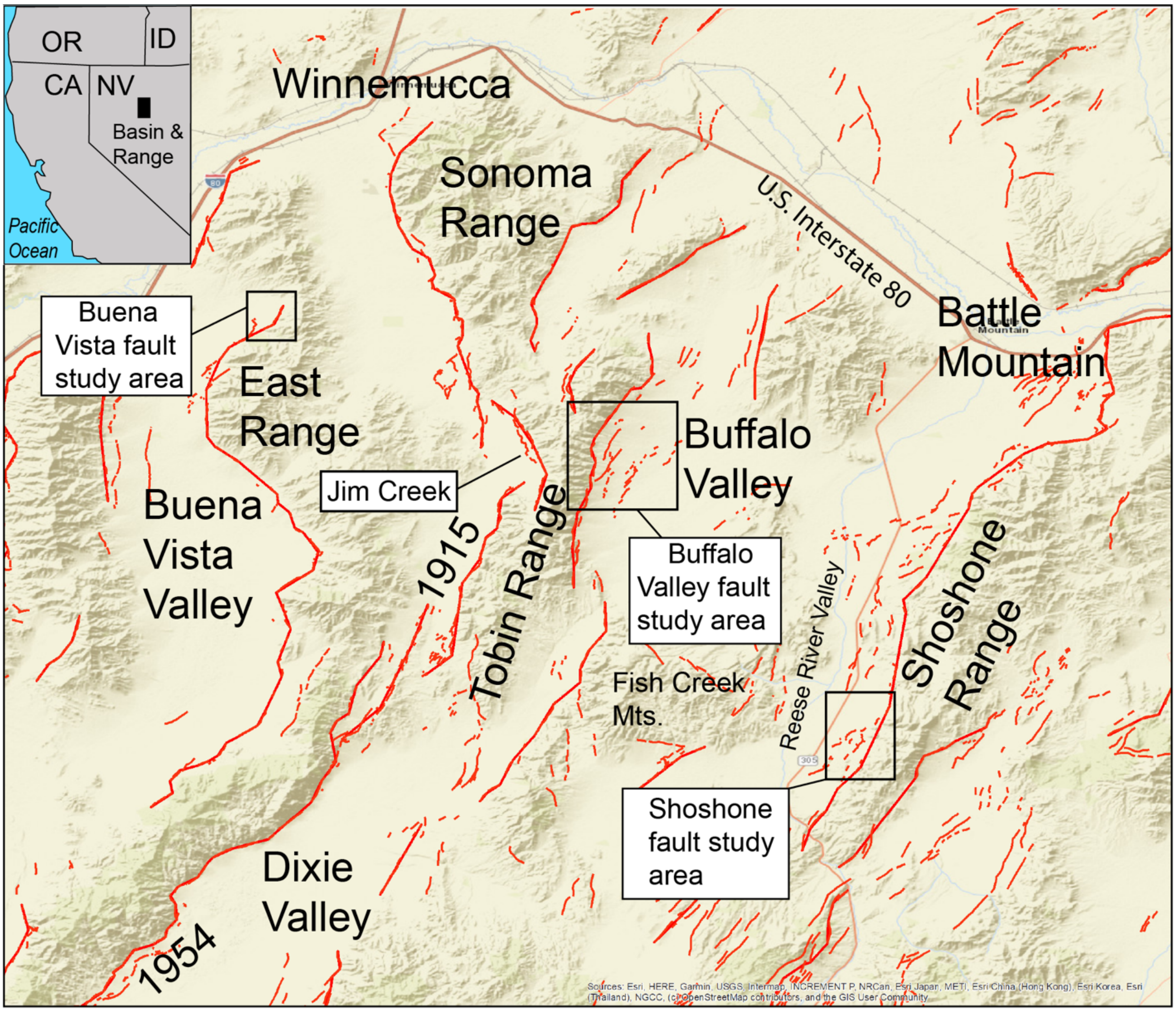

Figure 1. Fault map of central Nevada showing physiographic features and location of the three study areas (labelled). 1954, M6.8 Dixie Valley rupture; 1915, M7.6 Pleasant Valley rupture. Faults from U.S. Geological Survey fault and fold database.

Contemporary extensional strain accumulation measured geodetically across the central Basin and Range is ~1 mm/yr (Hammond et al., 2014). This rate largely agrees with cumulative rates of strain release by active faulting determined in several paleoseismic transects across the region (Personius et al., 2017; Koehler and Wesnousky, 2011; Wesnousky et al., 2005). Although the faults in our study occur within the general area of these transects, they have not previously been the subject of detailed slip rate or paleoseismic studies.

Slip rates are important input parameters for constraining deformation models, such as the 2023 update of the U.S. National Seismic Hazard Model (NSHM; Petersen et al., 2024; Hatem et al., 2022a) and local probabilistic seismic hazards analyses (PSHAs; Valentini et al., 2020). The NSHM assigns a preferred slip rate of 0.1 mm/yr to the three faults, however, this rate was based on evaluation of a suite of uncertainty distributions derived from broad slip rate categories benchmarked by geodetic strain rates (Hatem et al., 2022b), and not direct geologic observations.

Slip rate and recency of faulting are also important modelling input parameters for assessing potential geothermal energy exploration targets. Specifically, these parameters when combined with other geophysical datasets (e.g. Play-fairway analysis) can inform the potential occurrence of blind geothermal systems (Ayling et al., 2022; Faulds et al. 2016). The intersection of the Buffalo Valley fault with the Jersey Valley fault to the south has been characterized as a structural accommodation zone, a favorable structural setting for potential geothermal energy exploration (Burgess & Faulds, 2023; Faulds et al., 2021).

Motivated by a need to refine the geologic slip rates for the three faults for seismic hazard and geothermal energy applications, we conducted office and field based fault trace mapping on lidar hillshade base maps (USGS, 2023), produced topographic profiles across faulted deposits to assess the amount of displacement, and described and sampled soil pits excavated on the footwall of the Buffalo Valley fault to evaluate the relative and absolute ages of displaced surfaces. We also sampled boulders on faulted fan surfaces on the Buena Vista and Shoshone faults to obtain cosmogenic exposure ages.

2 Observations

2.1 Buffalo Valley fault

The Buffalo Valley fault shows prominent fault scarps and triangular facets along the length of the Tobin Range (Fig. 2). Our mapping efforts focused on a ~7-km-long section of the fault between Morning View Canyon and Hoffman Canyon where it projects away from the range front and is expressed by multiple subparallel scarps and grabens that displace alluvial fans of various ages (Fig 3A). Fault traces and Quaternary alluvial fans were mapped based on inspection of lidar hillshades and field reconnaissance. Alluvial fan units were differentiated primarily based on cross cutting and inset relations, relative degree of incision, and drainage patterns. The units include relatively old (Qfo), intermediate (Qfi), and young (Qfy) alluvial fans, following common stratigraphic nomenclature in the Basin and Range (e.g. Koehler and Wesnousky, 2011). The distribution of these surfaces is shown on Fig. 3B. In general, Qfo surfaces are characterized by deep gully dissection and rounded interfluves. Qfi surfaces are characterized by relatively flat surfaces with moderate gully dissection that are inset into Qfo deposits. Qfy deposits are confined to active channels deeply eroded (12-20 m) into Qfo and Qfi deposits in upslope areas and spread out across the piedmont downslope of the fault where they are characterized by anastomosing distributary channels.

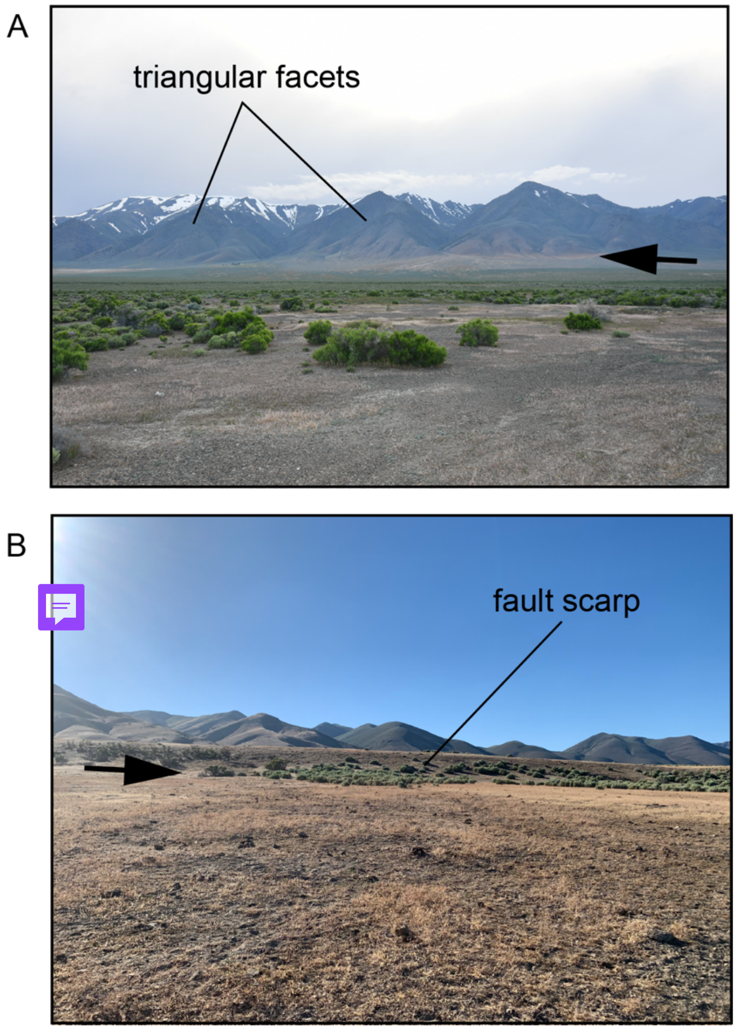

Figure 2. Field photographs showing: (A) prominent tectonic geomorphology along the southern Buffalo Valley fault range front; and (B) a ~5-m-high scarp extending across an alluvial fan at the location of soil pit BVSP-2 (See Fig. 3B for location). Black arrow points to fault in both images.

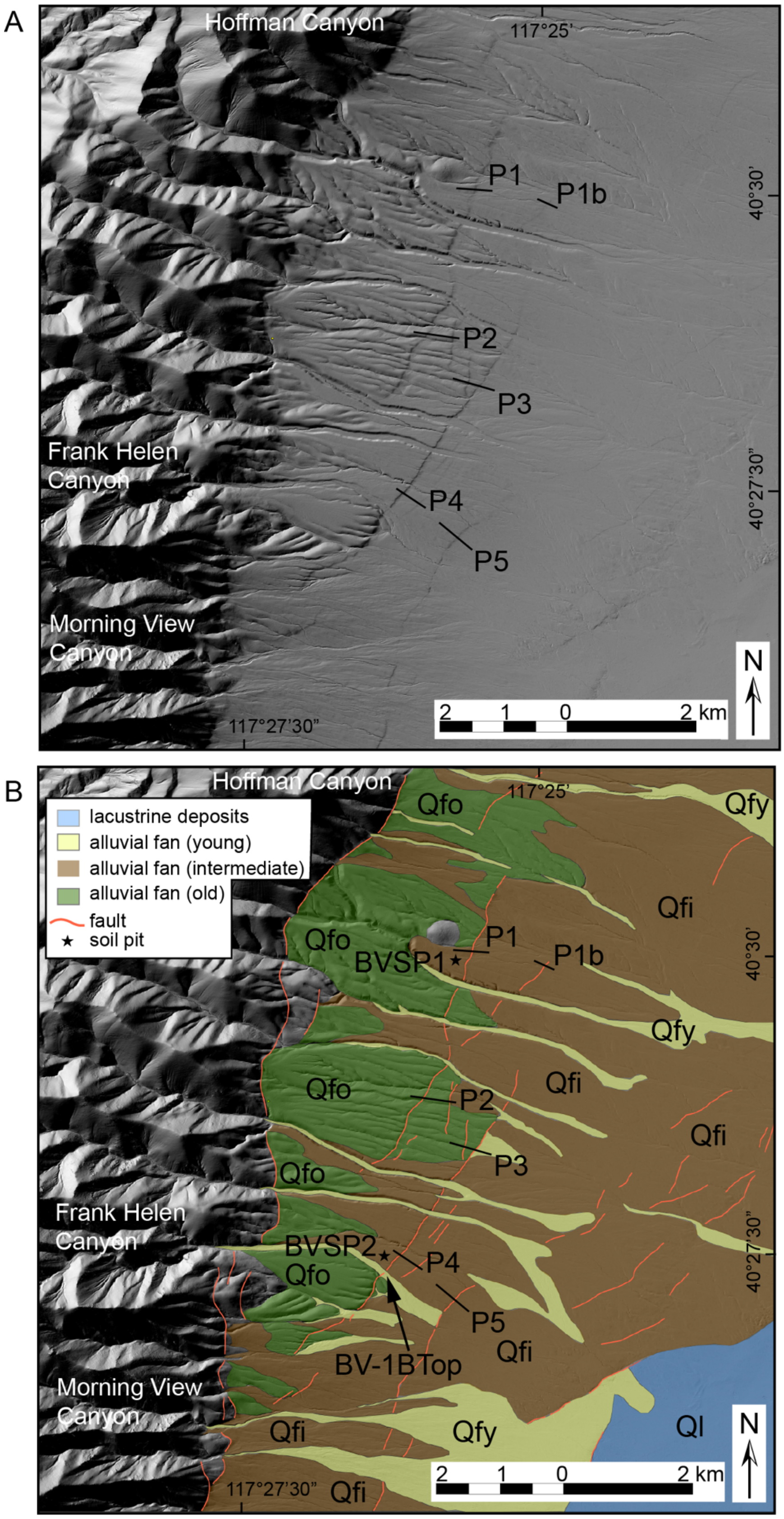

Figure 3. Buffalo Valley study area. (A) uninterpreted lidar hillshade of the Buffalo Valley fault; and (B) Quaternary geologic map of the Buffalo Valley fault. Black stars show locations of soil pits. Black lines

indicate locations of scarp profiles shown in Fig. 4. Lidar hillshade base maps in both panels from US Geological Survey (2023), 1-m resolution.

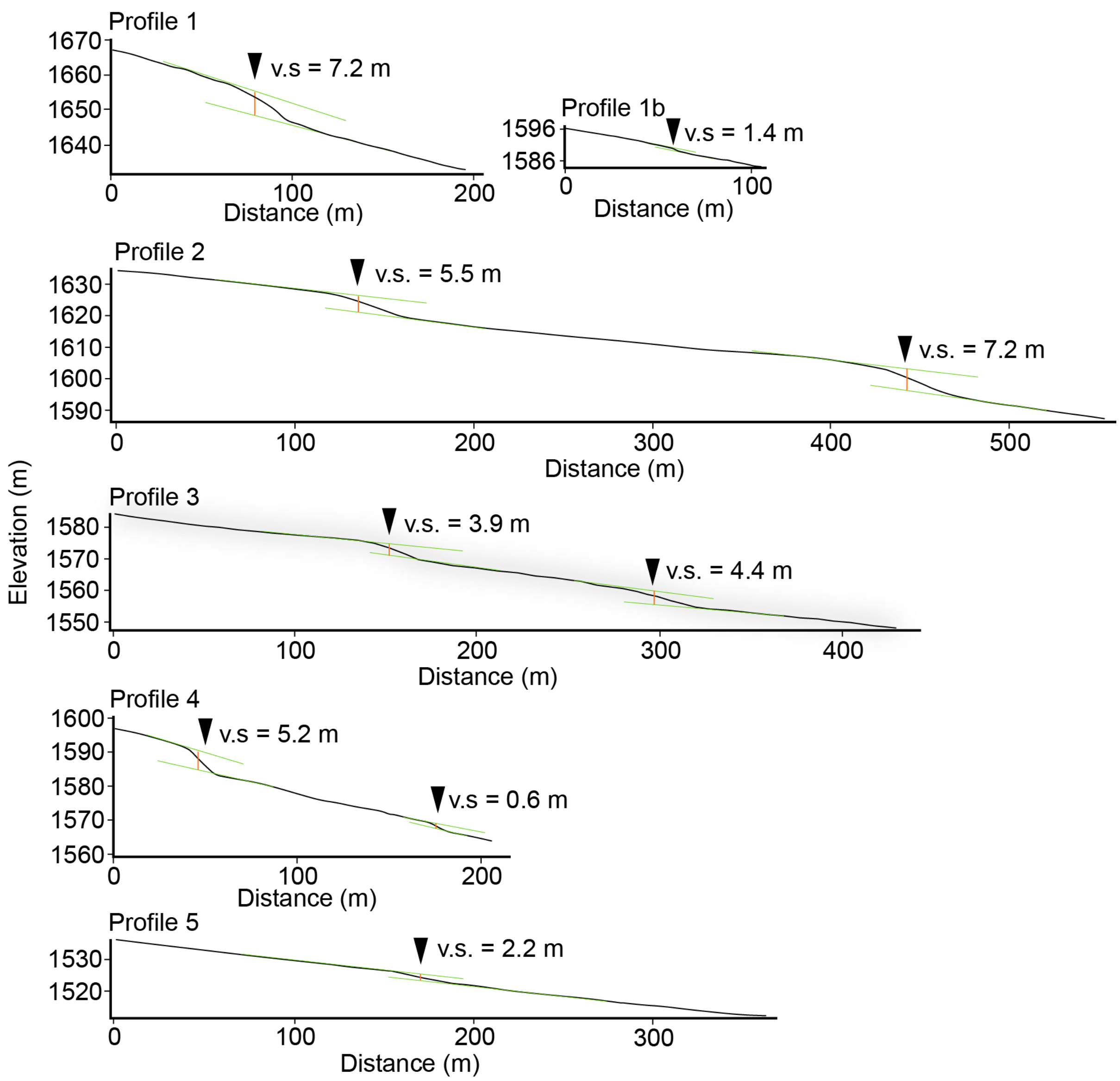

Figure 4. Topographic profiles surveyed across fault scarps that displace middle Pleistocene Qfo fans (Profiles 2 and 3: BVSP-1) and late Pleistocene Qfi fans (Profiles 1, 1b, 4, and 5: BVSP-2) along the Buffalo Valley fault. Light green lines indicate slope projections used to estimate vertical separation. Profile locations are shown on Figure 3B. Along each profile black arrow indicates location of fault interpreted from lidar data.

A pluvial lake existed in Buffalo Valley in the late Pleistocene and reached a maximum elevation of ~1,412-1,416 m based on the sill elevation at the eastern side of the valley. This elevation is lower than the majority of mapped fault scarps providing confidence that they are tectonic in origin, and not shoreline features. Field inspection of subtle scarps near the late Pleistocene highstand elevation along the western margin of the lake revealed that they have rounded crests and curvilinear topographic form consistent with constructional beach berm features. In several cases, mapped faults project into shoreline features (Figure 3B, southeastern corner) indicating that some lower elevation scarps may be lacustrine modified fault scarps.

Soil pits were excavated to a depth of 2 m on the footwall surfaces of two displaced intermediate age (Qfi) alluvial fans (Figs. 3, 5, and 6). Characteristics of individual soil horizons exposed in the pits were described including color, structure, consistence, and texture (Supplemental Section S1). The degree of carbonate accumulation ($CaCO^3$ stage) was assessed to evaluate the relative age of surface abandonment. Samples were collected at 25 cm intervals from each pit for ^{36}Cl depth profile analysis to assess the absolute age of the soil/surface. A complete lab report detailing the geochronologic methods and results is provided in Supplemental Section S2.

The soil exposed in soil pit BVSP-1 (GPS coordinates 40.5006°, -117.4276°) is characterized by a 20-cm-thick sandy clay loam textural Bt horizon and an 80-cm-thick loamy sand Bk horizon with stage II+ to III carbonate development. The soil exposed in soil pit BVSP-2 (GPS coordinates 40.4580°, -117.4381°) near Frank Helen Canyon is characterized by a 20-cm-thick Bt horizon with a silty clay loam texture and a 45-cm-thick silty clay to clay Btk horizon with Stage II+ carbonate development. The textural B horizons in both pits are overlain by silt loam to sandy loam A and Bw horizons with weak structure suggesting Holocene soil development has buried an older late Pleistocene soil, a phenomenon widely observed in the Great Basin in Nevada. Both pits have relatively thick textural Bt and Bk horizons suggesting relative antiquity, however the soil in pit BVSP-2 has slightly less carbonate development. Based on the degree of carbonate development (Stage II+ - III) and comparison to regional datasets (Redwine et al., 2020; Eppes et al., 2003; Machette et al., 1985; Harden et al., 1985) we were initially able to infer that the surfaces were abandoned and soil began to form in the late middle to late Pleistocene about 60-200 ka. This broad age range is consistent with regional patterns of fan aggradation that occurred in climatic transitions between Marine Oxygen Isotope stages 4-3 (~70 ka) and 6-5 (~120 ka; Eppes et al., 2003).

Cosmogenic ^{36}Cl exposure ages place additional constrains on the age of the surfaces. Because of potential soil disturbance and/or burial of the late Pleistocene soil by a Holocene soil as observed in the soil pits, the two samples in the upper 50 cm of each depth profile complicated the age modelling. Thus, age models were evaluated in two separate ways for each pit; first including all depth samples, and second using only samples below 50 cm (Supplemental Section S3). Using all samples from the depth profile, the profile age for soil pit BVSP-1 is 77 +5/-1 ka, and soil pit BVSP-2 shows an age of 54 +4/-2 ka. Excluding samples from the upper 50 cm of the profiles results in a modelled age of 202-220 ka (213 ka mean bayesian solution) for soil pit BVSP-1 and 100-136 ka (118 ka mean bayesian solution) for soil pit BVSP-2. The age difference for the two profiles is considerable, despite both being mapped as Qfi surfaces. The deeper incision of drainage systems at soil pit BVSP-1 is consistent with Qfi being older there than at soil pit BVSP-2 and implies a broad age range represented by Qfi deposits. The modelled ages, however, are generally consistent with the ages inferred from soil carbonate stage development.

We also sampled a single boulder (sample BV-1B Top) on a Qfy surface on the hanging wall of a < 1 m fault scarp immediately south of soil pit BVSP-2 (Fig. 3; Supplementary Section S4) for ^{10}Be exposure age dating. The exposure age of 45 ka (Supplemental Section S5) is reasonable, given that it is the youngest surface above the active channel floodplain, and inset to the Qfi surface at BVSP-2.

Topographic profiles were extracted from lidar point cloud data orthogonal to fault scarps that displace Qfo and Qfi surfaces and used to measure vertical separation across the scarps (Figs. 3 and 4). Profiles 1 and 1b extend across two scarps in the vicinity of soil pit BVSP-1 and indicate a vertical separation of 8.6 m of the Qfi surface. Profiles 2 and 3 extend across multiple sub parallel scarps that displace a Qfo surface and indicate a cumulative vertical separation of 21 m. Profiles 4 and 5 extend across three parallel scarps in a Qfi surface near soil pit BVSP-2 and indicate a cumulative vertical separation of 8 m. The cumulative displacements are considered a minimum because an unknown amount of displacement may be accommodated along the range front, and subtle scarps outside the limits of the profiles may exist.

We calculate a late Pleistocene vertical slip rate for the Buffalo Valley fault by dividing the cumulative displacement of the Qfi surface (three traces) at soil pit BVSP-2 (8 m) by the range of ages obtained from the ^{36}Cl cosmogenic exposure dating of the soil developed into the faulted surface (52-136 ka). The resulting vertical slip rate is 0.06-0.15 mm/yr. Similarly, a slip rate of 0.04-0.11 mm/yr is calculated from the cumulative displacement of Qfi at soil pit BVSP-1 (8.6 m) and the range of cosmogenic exposure ages for the soil profile (76-220 ka). These results collectively give a slip rate range of 0.04-0.15 mm/yr, which we consider to be a minimum estimate for the fault based on the unknown amount of slip at the range front and slip on undetectable scarps to the east of the profiles.

In the above calculations of slip rate, we favor use of the relatively older Qfi surface because of the consistency of soil profile-based exposure age estimates, and its association with multiple-event scarps. We do not use the single cosmogenic ^{10}Be exposure age obtained from the boulder sample on the Qfy surface (Fig. 3). Although the age is reasonable, the small size of the scarp suggests that it is the result of a single event. Additionally, small channels on the surface suggest overtopping of the active channel by floods, which could have modified the position of the boulder. Despite these uncertainties, the boulder age of 45 ka may represent the elapsed time since the most recent earthquake along the Buffalo Valley fault.

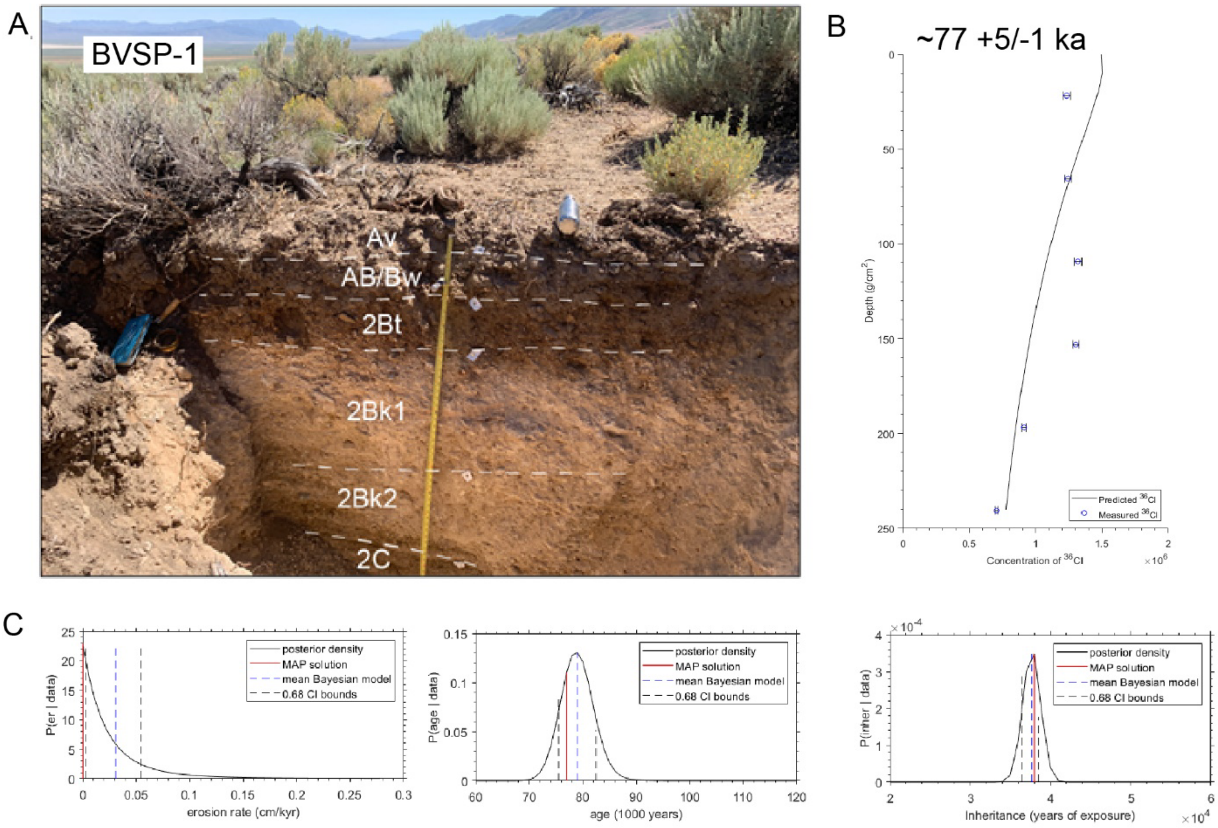

Figure 5. Soil pit BVSP-1. (A) Photograph of soil pit exposure with soil horizons designated, (B) ^{36}Cl concentration versus depth, and (C) from left to right probability distributions of density, age, and inheritance that correspond to model fits to the ^{36}Cl depth profile in B. The best fitting curve shown in B corresponds to an age ~77 +5/-1 ka.

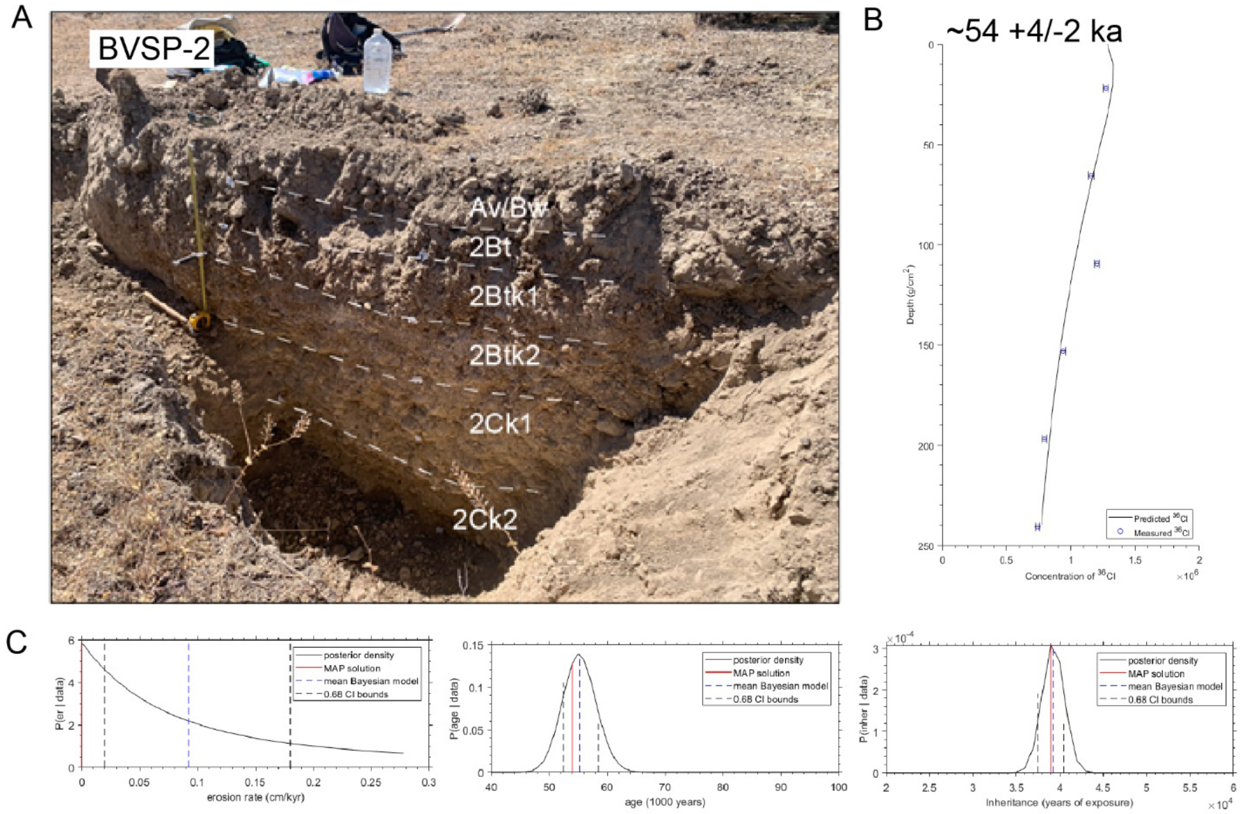

Figure 6. Soil pit BVSP-2. (A) Photograph of soil pit exposure with soil horizons designated, (B) ^{36}Cl concentration versus depth, and (C) from left to right probability distributions of density, age, and inheritance that correspond to model fits to the ^{36}Cl depth profile in B. The best fitting curve shown in B corresponds to an age ~54 +4/-2 ka.

2.2 Buena Vista fault

Our study of the Buena Vista fault focused on the Willow Creek area at the northern end ~~of the fault~~ (Fig. 7). Our mapping of the site uses the same nomenclature as for the Buffalo Valley fault and shows prominent scarps displacing late Pleistocene (Qfi) surfaces, and two late to middle Pleistocene surfaces (Qfo1 and Qfo2). The subdivision of Qfo was necessary because of inset relations and differences in fan geomorphology. Vertical separation across the scarp in Qfi deposits ranges from 1.5 m (Profile 6) adjacent to Willow Creek and 4.9 m (Profile 9) approximately 2 km southwest of Willow Creek (Figs. 7 and 8). Where the fault displaces the Qfo2 surface the hanging wall is buried by Qfo1 and Qfi deposits within a complex graben (Fig.

7). The vertical separation across the Qfo2 surface is 14.5 m (Profiles 7 and 8, Figs. 7 and 8) but may be less given the position of the graben west of the main scarp.

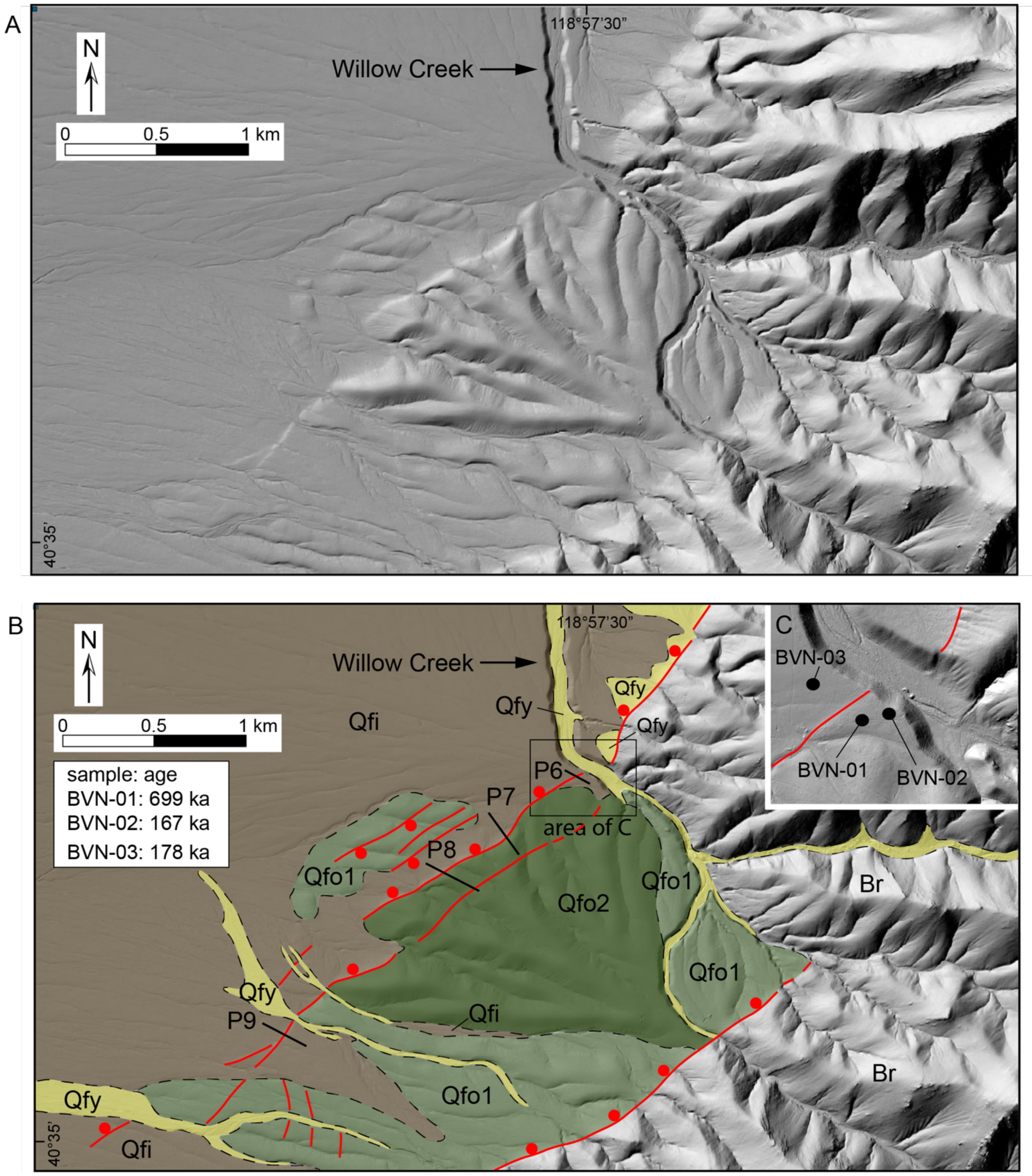

Figure 7. Buena Vista fault study area near Willow Creek (GPS coordinates 40.6051°, -117.9610°. (A) uninterpreted lidar hillshade of the Buena Vista fault site; and (B) Quaternary geologic map of the site. (C) Enlarged image showing displaced Qfi fan and boulder sample locations for ^{10}Be cosmogenic

exposure dating (black circles). Black lines indicate locations of scarp profiles shown in Fig. 8. Lidar hillshade base maps in all panels from US Geological Survey (2023), 1-m resolution.

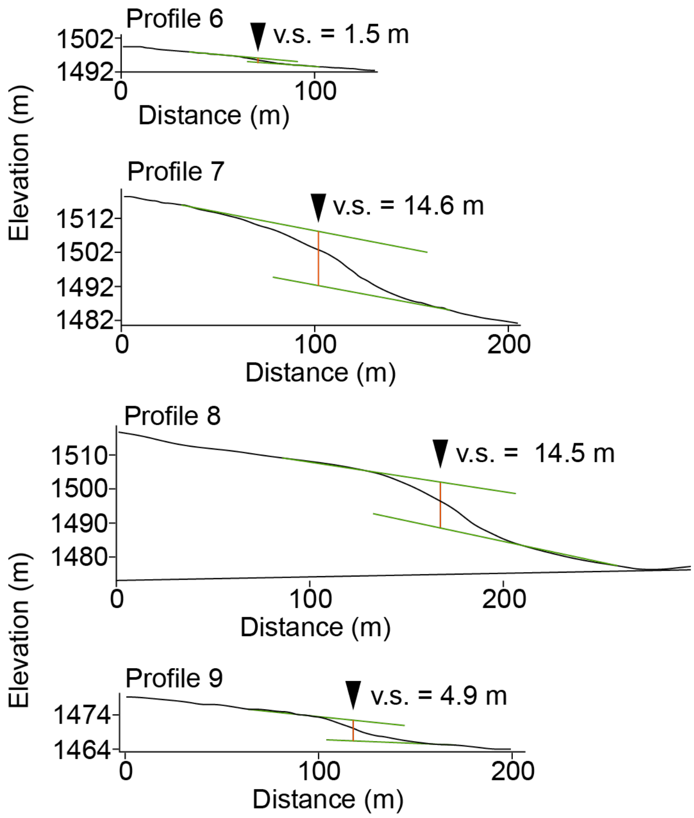

Figure 8. Topographic profiles surveyed across fault scarps that displace middle Pleistocene Qfo fans (Profiles 7 and 8), and late Pleistocene Qfi fans (Profiles 6 and 9) along the Buena Vista fault. Light shaded lines indicate slope projections used to estimate vertical displacement. Note that the scarp heights in Profiles 7 and 8 may under-represent the true throw on Qfo as the hanging wall is mantled with Qfi fan deposits. Along each profile black arrow indicates location of fault interpreted from lidar data. Profile locations are shown on Fig. 7.

The morphology of the Qfi fans along the Buena Vista fault is similar to the Buffalo Valley fans from which we infer that they have a similar relative age (52-220 ka). Cosmogenic ^{10}Be exposure ages for three boulders on the displaced Qfi surface adjacent to Willow Creek are 699 ka, 167 ka, and 178 ka (samples BVN-01, BVN-02, and BVN-03, respectively; Fig. 7 and Supplementary

Sections S4 and S5). While the former is clearly older than our inferred 52-220 ka age based on correlation to the Qfi surfaces in Buffalo Valley, the latter two ages are compatible. At the location where the boulders were sampled, the scarp is 1.5 m high and has a smooth unbevelled profile, suggesting that it is the result of a single event. This implies that only one earthquake has occurred in 167 - 178 ka, a very long time period relative to the typical recurrence intervals of Basin and Range faults. The 699 ka exposure age (sample BVN-01) appears to have been strongly influenced by inheritance, meaning that the boulder may have been derived from a much older surface further up catchment, and has inherited additional ^{36}Cl isotope concentrations while exposed. In consideration of these ambiguities we do not use the scarp height observations and boulder exposure ages adjacent to Willow Creek in the determination of slip rate. We calculate a late Pleistocene vertical slip rate of 0.02 - 0.09 mm/yr for the Buena Vista fault based on the scarp height of the displaced Qfi fan surface 2 km southwest of Willow Creek (4.9 m vertical displacement at Profile 9; Fig. 8), and assuming that the exposure ages for displaced Qfi surfaces along the Buffalo Valley fault (52-220 ka) are a reasonable approximation for the age of the Qfi surfaces along the Buena Vista fault.

2.3 Southern Shoshone fault

Our study of the southern Shoshone fault focused on the mouth of an unnamed drainage within the area shown in Figure 1 in southern Reese River Valley (Valley of the Moon). The site shows prominent scarps displacing a late Pleistocene (Qfi) surface, and two late to middle Pleistocene (Qfo1 and Qfo2) surfaces (Fig. 9). The Qfi surface has similar surficial characteristics to the Qfi fans exposed along the Buffalo Valley and Buena Vista faults from which we infer it has a similar relative age (54-220 ka).

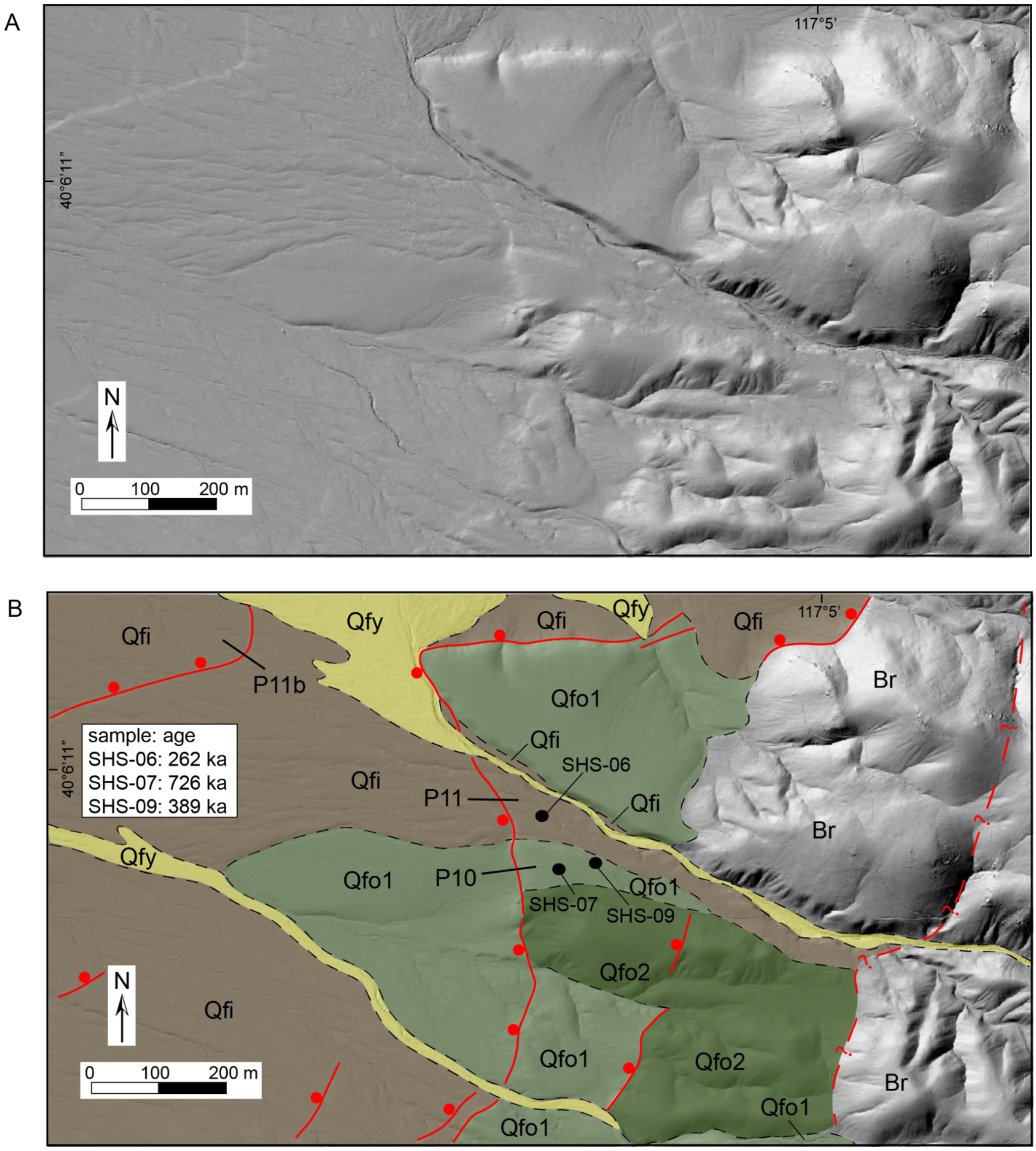

Figure 9. Southern Shoshone fault study area (GPS coordinates 40.1022°, -117.0950°). (A) uninterpreted lidar hillshade of the Southern Shoshone fault site; and (B) Quaternary geologic map of the site. Boulder samples for ^{10}Be cosmogenic exposure dating are shown by black circles. Black lines indicate locations of scarp profiles shown in Fig. 10. Lidar hillshade base maps in both panels from US Geological Survey (2023), 1-m resolution.

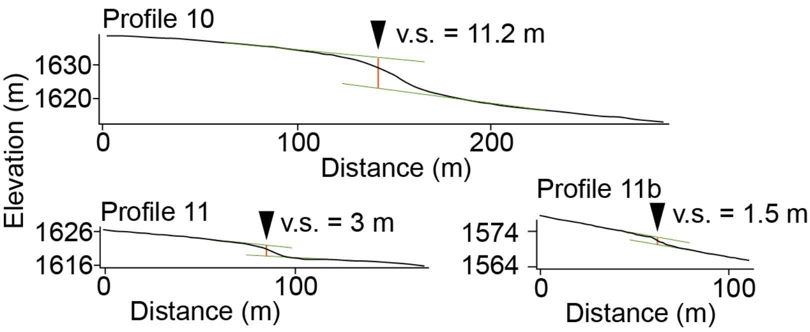

Figure 10. Topographic profiles surveyed across fault scarps that displace a middle Pleistocene Qfo1 fan (Profile 10), and a late Pleistocene Qfi fan (Profiles 11 and 11b) along the southern Shoshone fault. Light-shaded lines indicate slope projections used to estimate vertical displacement. Note that the scarp height in Profile 10 may under-represent the true throw on Qfo1 as the hanging wall is mantled with Qfi fan deposits. Along each profile black arrow indicates location of fault interpreted from lidar data. Profile locations are shown on Figure 9.

We calculate a late Pleistocene vertical slip rate of 0.02 - 0.08 mm/yr for the southern Shoshone fault based on the total displacement of the Qfi surface across two fault strands (combined 4.5 m vertical separation, Profiles 11 and 11b; Figs. 9 and 10), and using the exposure ages for Qfi surfaces in Buffalo Valley (52-220 ka) with the assumption that the similar fan morphology in both valleys indicates a similar relative age. ^{10}Be exposure ages taken from a boulder on the Qfi surface is 262 ka, and ages of 389 ka and 726 ka are obtained from the Qfo1 surface (Supplemental Sections S4 and S5). The Qfi surface exposure age is somewhat older than the 52 - 220 ka we use in the slip rate determination, but the resulting change to the minimum slip rate (0.03 mm/yr) is negligible. The Qfo1 exposure ages are reasonable, given that Qfo surfaces are generally assumed to be middle Pleistocene (Koehler and Wesnousky, 2011). A slip rate of 0.02 – 0.03 mm/yr can be estimated using the Qfo1 exposure ages and the vertical separation of 11.2 m (Profile 10, Fig. 10). This rate overlaps with the lower end of the rate determined from the Qfi surface.

3 Discussion

Our mapping, analysis and interpretations show the three faults on this study have slip rates within the range of slip rates for central Basin and Range faults. Machette et al. (2005) determined a slip rate for the Clan Alpine fault of 0.025-0.08 mm/yr. For the Fairview Peak fault which ruptured in the 1954 M7.1 Fairview Peak earthquake, Bell et al. (2004) determined a vertical slip rate of 0.04-0.21 mm/yr. Based on soil profiles with stage II+ carbonate development, Koehler and Wesnousky (2011) inferred an age for Qfi alluvial fans displaced by faults across U.S. Highway 50 of around 70-130 ka. Their estimate of fan age was based on regional aggradation patterns that occurred during climatic transitions between Marine Oxygen Isotope stages 4-3 (~70 ka) and 6-5 (~130 ka) described by Eppes et al. (2003) and regional studies of carbonate development in soils (e.g. Machette et al., 1985). The vertical displacements and ages of faulted deposits reported by Koehler and Wesnousky (2011) allow the interpretation of vertical slip rates for the Toiyabe Range fault (0.03-0.05 mm/yr) and the Butte Range fault (0.04-0.08 mm/yr). Considering the regional fan aggradation patterns (~70-130 ka; Eppes et al., 2003) which overlap with our inferred soil age determinations and absolute ages in Buffalo Valley we prefer slip rates of 0.06 - 0.12 mm/yr for the Buffalo Valley fault, 0.04-0.07mm/y for the Buena Vista fault, and 0.03 – 0.06 mm/yr for the Shoshone fault.

In the context of recurrence intervals, the slip rates determined in this study for the three faults combined with an assumed vertical displacement of 1-2 m per event would imply earthquake recurrence intervals of 7-50 ka for the Buffalo Valley fault, 11-100 ka for the Buena Vista fault, and 13 - 100 ka for the southern Shoshone fault. These are extreme-bound recurrence intervals, combining maximum displacement with minimum slip rate, and vice versa. While these are long recurrence intervals on an individual fault basis, the combined recurrence interval for ground rupturing earthquakes for the three faults is much shorter (3 – 25 ka).

Estimates of the maximum size of an earthquake that would accompany rupture of the full length of the Buffalo Valley fault can be made using the magnitude- rupture area scaling relations of Stirling et al. (2023). The total rupture length of the fault is supported by geomorphic observations of similar scarp heights along the length of the fault. Using a 38 km fault length, and reasonable estimates of seismogenic thickness and fault dip for the Basin and Range, an estimate of Mw7.0 $\pm$ 0.2 is obtained for the Buffalo Valley fault. An alternative method for estimating Mw takes account of single event displacement (SED; Hanks and Kanamori, 1979). Assuming single event displacements of ~2 m along the Buffalo Valley fault (similar to the 1915 earthquake on the Pleasant Valley fault; Wallace, 1984) yields a maximum estimate of Mw7.1. Maximum magnitude was not calculated for the Buena Vista or Shoshone Range faults because of uncertainties related to rupture length and possible segmentation along these long and geometrically complex faults.

Geochronologic studies are relatively few in the central Basin and Range, however, they are becoming more available as the techniques are refined. Comparison to geochronologic studies from the Walker Lane to the west and Pleasant Valley in which the geomorphic characteristics of fans are similar to the Qfi fans in Buffalo Valley indicates that they have similar ages. Along the Wassuk Range fault, Bormann et al., 2012 report ^{10}Be and ^{26}Al exposure ages on boulders of ~85-125 ka for a Qfi surface displaced 40 m. In a study of the Petrified Springs fault, Angster et al. (2019) applied multiple different dating methods to a Qfi surface with a stage III carbonate soil. The geochronologic results indicate a ^{36}Cl depth profile age of 153 ka and ^{10}Be exposure ages on boulders showed a younger age population (94-165 ka) and an older age population (229-560 ka). Based on the carbonate stage, Angster et al. (2019) preferred the younger population which overlaped with the ^{36}Cl depth profile age. Figueiredo et al. (2023; 2024) conducted geochronologic analyses on alluvial fans along the Pleasant Valley fault along the western flank of the Tobin Range at the latitude of our study. At Jim Creek, they report preliminary ages from four ^{36}Cl depth profiles that range between 56-134 ka (average 90 ka) and calculate a mínimum vertical slip rate of 0.05-0.1 mm/yr based on the combined displacement across two strands of the fault of 8.25 m. The alluvial fans studied by Figueiredo et al. (2023; 2024) have similar characteristics to the fans we studied in Buffalo Valley including surficial geomorphic expresion, slopes, lateral extent from the rangefront, and soils, as well as the same bedrock parent materials (Greenstone, chert, and argillite of the Carboniferous Pumpernickel formation and dominantly chert and quartzite of the Permian Havallah formation; Muller et al. (1951)). Soil exposures in the Jim Creek fan observed during our reconnaissance have an ~20 cm A-Bw horizon that buries relatively thick Bt and Btk horizons, virtually identical in horizonation and thickness to the fans we studied in Buffalo Valley. Furthermore, the ages and slip rate determined by Figueiredo et al. (2024) are compatible to our estimates in Buffalo Valley providing creedence to the notion of the Tobin Range deforming as a horst block.

The Buffalo Valley fault shows considerable variation in morphology and complexity along its strike. The central section of the fault is the only section where multiple traces are observed to the east of the Tobin Range front, whereas the fault is confined to the range front to the north and south. The range front facets are also much more developed to the north and south, and the Tobin Range is much higher in these areas. The correlation of the lowest central part of the Tobin Range with the distributed scarps along the Buffalo Valley fault is perhaps a manifestation of the overall development of the range. The range may have commenced development as two separate ranges, but eventually coalesced to form a range with a topographic low in the center. The complex distributed central section of the Buffalo Valley fault may therefore be the least developed section of the fault and may eventually evolve to a more simple range front fault with ongoing cumulative slip.

4 Conclusions

We have developed slip rate estimates for the Buffalo Valley, Buena Vista, and southern Shoshone faults in central Nevada. Fault trace mapping, vertical displacement estimates, soil pit descriptions from displaced surfaces, ^{36}Cl exposure age dates from two soil profiles, and ^{10}Be exposure ages from alluvial surface boulders were used to characterise the geomorphology and slip rate of the three faults. For the Buffalo Valley fault, ^{36}Cl soil depth profile analyses at two sites on intermediate (Qfi) fan surfaces give exposure age estimates of 52-136 ka where the vertical displacement on the fault is 8 m, and 76-220 ka where the displacement is 8.6 m. These data suggest a vertical slip rate of 0.04-0.15 mm/yr. The Buena Vista and southern Shoshone faults were mapped at single sites where faulted fan surfaces were observed. Slip rates of 0.02 - 0.09 mm/yr and 0.02 - 0.08 mm/yr for the Buena Vista and southern Shoshone faults, respectively, are estimated from scarp heights and correlation of fan surface morphology to Buffalo Valley, and consideration of boulder ^{10}Be exposure ages. The results provide independent geologic validation of slip rates for all three faults (~0.1 mm/yr) used in the 2023 U.S. National Seismic Hazard Model (Hatem et al., 2022b). This work highlights the importance of utilizing soil observations when considering cosmogenic exposure ages for alluvial surfaces. Additionally, the work reinforces the notion that slip rates on central Basin and Range faults are generally similar and consistent with similarities in alluvial fan geomorphology.

Acknowledgements

This work was partially funded by the U.S. Department of Energy (DOE) Geothermal Technologies Program under grant award DE-EE0009254. We gratefully acknowledge the University of Otago sabbatical leave program for partial support of Stirling during his stay in Reno. The University of Otago and the Nevada Bureau of Mines and Geology supported the cosmogenic dating costs. Finally, we thank the participants of the 2024 Friends of the Pleistocene annual field trip early in this work for fruitful discussions and Jerry Annis of Buffalo Valley for land access, backhoe services, and ranch water.

Data and code availability

All data used in this study are contained in the manuscript and electronic supplement including soil descriptions, ^{36}Cl Depth profile data, ^{10}Be surface exposure data, geochemistry and input data to the CRONUScalc Matlab program, ^{10}Be production rate plots, and photographs of sampled boulders. 36Cl Depth profile model used in our analyses based on Marrero et al. (2015), CRONUScalc program available at https://bitbucket.org/cronusearth/cronus-calc/src/master/. CRONUScalc Matlab program used in 10Be exposure age modeling is available at https://hess.ess.washington.edu.

Competing interests

The authors have no competing interests

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Editor Round One Decision Letter:

Dear Rich Koehler, Mark W. Stirling, Brad Sion:

I hope this email finds you well. I have reached a decision regarding your submission to Seismica, "Paleoseismology of the Buffalo Valley, Buena Vista, and southern Shoshone faults, central Basin and Range, Nevada, USA". Thank you once again for submitting your work to Seismica.

I have now received two reviews for your manuscript. As you will see, the reviewers are very positive about the current state of the manuscript and the science that it presents. The revisions they are requesting are very minor, so I will not add any additional, specific commentary at this time. Please note that both reviewers provided separate review files which I will transmit to you shortly (the OJS portal can sometimes be a bit funny about emails with large attachments). As always, thank you for choosing Seismica for the submission of your work. I look forward to seeing the revised version once available. I do not anticipate sending this back out for additional peer review.

When you are ready to resubmit the revised version of your manuscript, please upload:

- A 'cleaned' version of the revised manuscript, without any markup/changes highlighted.
- A pdf version of the revised manuscript clearly highlighting changes/markup/edits.
- A 'response-to-reviewers' letter that shows your response to each of the reviewers' points, together with a summary of the resulting changes made to the manuscript.

If you deem it appropriate, please check that the revised version of your manuscript recognises the work of the reviewers in the Acknowledgements section.

Please note that Seismica does not have any strict deadlines for submitting revisions, but naturally, it is likely to be in your best interest to submit these fairly promptly, and please let me know of any expected delays.

I wish you the best with working on the revisions. Please don't hesitate to contact me with any questions or comments about your submission, or if you have any feedback about your experience with Seismica.

Kind regards,

Randy Williams

Dear editor.

Please find attached my revised manuscript, supplement, and figure files for manuscript entitled "Paleoseismology of the Buffalo Valley, Buena Vista, and southern Shoshone faults, central Nevada USA". I thank the reviewers for the helpful comments and they have all been acknowledged. All of the text change suggestions have been followed. The most salient comments pertained to 1) symbolization for soil horizons in profiles and text to indicate 'b' for buried horizons. This was fixed throughout. 2) Expansion of the text to provide more details on several topics including modeling methods, age of pluvial lake Buffalo, and inheritance of 10Be in some samples. All of these topics were expanded with appropriate referencing.

The attached files include a track changes pdf, a clean manuscript pdf, and electronic supplement pdf, and reconciliation document (response to reviewers). Updated figure files are also provided in publicagtion ready png format at 300 dpi resolution. Please let me know if you require original word files, illustrator files, etc.

Sincerely,

Rich D. Koehler

REVIEWS AND RESPONSES BELOW. RESPONSES IN BLUE COLOR FONT

Dear Editor,

Thank you for the opportunity to review the manuscript entitled "Plaeoseismology of the Buffalo Valley, Buena Vista, and Southern Shoshone faults, central Basin and Range, Nevada USA" by Rich Koehler, Mark Stirling, and Brad Sion.

The authors present the first examples of geologically derived slip rate data for the Buffalo Valley, Buena Vista, and southern Shoshone faults in the central Basin and Range of Nevada. They employ detailed fault mapping (both remote and field based), soil development characterization, cosmogenic nuclide exposure depth profile data, and boulder exposure ages.

They deliver a cogent and broad slip rate range using the available data and reasonably compare their chronology, soil development, and surficial mapping to other studies in the region.

This information in this study is directly relevant for future National Seismic Hazard Models and is well written and illustrated. For these reasons I am in support of the publication within Seismica

With the consideration of the following suggestions, I would be pleased to see this manuscript published soon!

Sincerely,

Sylvia Nicovich

Thank you for the comprehensive review

Minor Suggestions

Suggested addition of text is shown in red.

Line 28: suggest replacing “abandonment” with “stabilization”

Accepted suggestion

Line 54: …, while the Buena Vista and Shoshone faults are both west-dipping faults with lengths of ~65 km that bound the eastern Buena Vista Valley and the western Shoshone Range, respectively.

Suggestion adopted

Line 79: change “and not direct geologic observations” to “due to lack of geologic observations”

Suggestion adopted

Line 84: For example, the intersection of the…

Suggestion adopted

Line 137: However, field inspection of…

Suggestion adopted

Line 138: Suggest changing “lake” to “basin” change “they” to “these scarps” so it reads, …western margin of the basin revealed that these scarps have rounded…

Suggestions adopted

Line 146: $CaCO_3$ (the 3 is currently a superscript)

fixed

Line 147: Bulk sediment samples were collected at 25 cm intervals…. *What depth did you start collecting? Maybe mention that (e.g., “beginning at 10 cm depth”)

Suggestion adopted. Also added “beginning at 20 cm depth” as suggested.

Line 148: Change “absolute” to “numeric”

Suggestion adopted

Line 157: The textural B horizons in both pits are overlain by silt loam to sandy loam A and Bw horizons with weak structure (22 cm thick in BVSP-1 and 13 cm thick in BVSP-2). This relation suggests Holocene erosion**, deposition**, and subsequent soil development on an older late Pleistocene surface, a phenomenon…

**doesn’t it imply that there had to be stripping of the original A portion of the late Pleistocene soil, then deposition of new material to develop the Holocene soil within? Or is it just addition of material and further development of the lower B horizons? In any case, does this make the 2Bt (and lower horizons) a Btb1 since it is buried (assuming you are using Birkeland, 1999)?

Agree that the use of '2' in front of a soil horizon is not the appropriate symbology to indicate a buried soil. Soil horizon symbology has been updated using a subscript 'b' for all buried horizons in the ESupp soil descriptions, figures, and text.

Line 156-159: suggest adding citations for other late Pleistocene soil studies in the Great Basin

Agree that this statement needs reference support. Added Koehler and Wesnousky, 2011; Machette et al., 2005; Adams and Wesnousky, 1999

Line 168: ^{36}Cl depth profile exposure ages place…

Suggestion adopted

Line 170: "the two samples in the upper 50 cm"

This reads like there are two samples above 50 cm in each profile. There is only one sample above 50 cm for each profile, right? It looks like just one above 50 in both figures 5 and 6. If so, changing the language to reflect that you are not including the samples taken from within the Av and AB/Bw in pit 1 and Av/Bw in pit 2 would make the point more streamline that you are using soils data to exclude samples within the second iteration of the cosmo model runs.

Agree that this is a bit misleading. The sentence was modified to indicate which samples were from soil horizons susceptible to bioturbation and younger soil development which complicated the modelling. Now reads "Because of potential soil disturbance and/or burial of the late Pleistocene soil by a Holocene soil as observed in the soil pits, the samples from the AB/Bw horizon in BVSP-1 and the Av/Bw horizon and the top of the 2Bt horizon in BVSP-2 complicated the age modelling.

Line 179: and implies a reasonably broad age range

Suggestion adopted

Line 180: …, thus we apply a range of 52-220 ka for the Qfi fans.

Suggestion adopted

Line 305: remove "relative"

removed

Line 306: are there errors that should be reported with these ages?

Ages now reported as 262 +/- 24 ka, 389 +/- 39 ka, and 726 +/- 90 ka which is based on the Stone production rate models in the CRONUS calculator and are the external error incorporating uncertainties in the production rate scaling in addition to measurement uncertainties.

Also on Line 259 and 260, we added the uncertainties to the ages there as well. The reviewers did not catch that but is the idea as the comment for line 306. Ages are now reported as 699 +/- 85 ka, 167 +/- 15 ka, and 178 +/- 16 ka

Line 329: replace “absolute” with “numeric”

replaced

Line 355-357: Suggest rewording second sentence of this paragraph. What about something like this:

Geomorphic characteristic and numeric chronologies of fans from the Walker Lane to the west (e.g. Bormann et al., 2013; Angster et al., 2019) and Pleasant Valley (e.g. Figueiredo et al. 2023; 2024) are similar to the Qfi fans in Buffalo Valley, implying a reasonable relation of Qfi fans across this part of the Basin and Range.

Suggestion adopted

Line 358: (2012)

fixed

Line 369-371: The alluvial fans studies by Figueiredo et al. (2023; 2024) have similar geomorphic expression and soil development to the fans we studied in Buffalo Valley, as well as the same bedrock parent materials...

Suggestion adopted

Line 376-378: Furthermore, the ages and slip rate determined by Figueiredo et al., (2024) to the west of the Tobin Range and our estimates in Buffalo Valley to the east of the range support the notion of the Tobin Range deforming as a horst block bound by the Pleasant Valley and Buffalo Valley faults.

Suggestion adopted

Line 405: ...independent geologic validation of slip rates used (~0.1 mm/yr) in the 2023...

Suggestion adopted

Figures

Figure 1. Consider labeling the Pleasant Valley fault. I know it is labeled with “1915” but directly labeling it could be helpful.

Agreed. Labeled Pleasant Valley fault as ‘PVF’ on figure and added ‘PVF, Pleasant Valley fault’ to caption.

Figure 3. The soil pit locations are a bit hard to see. Can the black stars be highlighted with a white outline? Or maybe lighten the hillshade and map units.

Agreed. The black stars now have a white outline. Also increased the size of the stars for greater visibility.

Figure 4. consider adding vertical exaggeration (2x).

Added this comment to the caption for figure 4.

Figures 5 and 6. I think adding the soil horizons to ^{36}Cl concentration curve would be a super helpful visual.

Good idea. Soil horizons now added to 36Cl depth profile. Caption updated to reflect this addition

Response to Reviewer 2 (pdf)

Comment line 65: Not from Nevada database or new mapping from this study?

The USGS database is preferred because it is the database with downloadable shapefiles. The USGS database is essentially the same as the Nevada database. This is a regional figure and the new mapping from this study is shown on subsequent figures. It is not used in this regional figure because it does not encompass the full length of the fault (site specific).

Line 90-91: consider “lidar-derived hillshade maps”

Suggestion adopted

Line 103: delete - could just say "multiple subparallel grabens" - implies scarps are present

Elected to leave the text as is “multiple subparallel scarps and grabens”. This is because not all of the scarps are associated with grabens.

Line 104-105: "using lidar-derived hillshades"

Suggestion adopted

Line 109: Add word ‘alluvial’ before surface. Change this to all references to surfaces throughout.

Agree that this is a good idea. Change made throughout manuscript.

Figure 2: could trace out line along base of scarp on this photo to make it more apparent?

A dashed line was added to figure to make base of scarp more apparent.

Line 134: any age dates for highstand of this lake cycle? might be worth adding here

The highstand of Lake Buffalo is not dated. However, its age has been inferred to be equivalent to pluvial Lake Lahontan. Thus, the following sentences were added to clarify its relative age.

“A pluvial lake existed in Buffalo Valley in the late Pleistocene (Reheis, 1999; Mifflin and Wheat, 1979). Although undated, Mifflin and Wheat (1979) inferred that the lake existed during the time of pluvial Lake Lahontan which dessicated after ~15.5 cal. YBP (Adams and Wesnousky, 1999; Adams et al., 2008)”.

Line 141: are these faults older than the lake? I'm assuming thats what you mean by "modified" here - the scarps came first then the lake shorelines modified them

Yes, that is what was meant. Modified the sentence to clarify. Now reads “In several cases, mapped faults project into shoreline features (Figure 3B, southeastern corner) indicating that some lower elevation scarps are tectonic in origin but have been modified by lacustrine processes.

Line 158: citation/reference?

Also pointed out by reviewer 1. Citations were added.

Line 175: consider defining? maybe not needed for the target audience, but I'd like to see a bit of discussion on how you modeled these ages and came up with these solutions.

Agree that this is a topic a little more detailed than the target audience. We added a statement to clarify the method used with a reference. Added sentence reads “The Bayesian solution is the method used to solve the best fitting depth profile (Marrero et al., 2016)”.

Additionaly we added some more explanation on the modeling in the ESupp (Section S3) that now states “The modelling was performed without information from the upper samples and assumes that any erosion was comparable to the subsequent deposition of new material (in terms of overall thickness), and that erosion and deposition occurred as instantaneous events relative to the production rate of 36Cl. Thus, the attenuation length and production rate I the sampled intervals is unchanged during erosional/depositional processes. The modelling was performed without information from the upper samples and assumes that any erosion was comparable to the subsequent deposition of new material (in terms of overall thickness), and that erosion and deposition occurred as instantaneous events relative to the production rate of 36Cl. Thus, the attenuation length and production rate I the sampled intervals is unchanged during erosional/depositional processes”.

Line 230: delete text.

Suggestion adopted

Line 261: bit confusing about which Be10 boulder sample you are discussing here - suggest specifying BVN-01 here to make it more clear.

Suggestion adopted. Sample names were added to the sentence for clarification. Now reads “While sample BVN-01 is clearly older than our inferred 52-220 ka age based on correlation to the Qfi alluvial surfaces in Buffalo Valley, the latter two ages (BVN-02 and BVN-03) are compatible”.

Line 266: add relevant citation/reference?

Agreed. Added a reference here.

Line 267-268: Could you expand on why this appears to have an inherited age? Whats the evidence to suggest the boulder was transported from the older surface? Expand

Although we do not have direct evidence to suggest the boulder was transported, it is a reasonable assumption because it has a much older age than the other two samples on the same surface. We added two qualifying statements to clarify. Now reads “The 699 ka exposure age (sample BVN-01) appears to have been influenced by inheritance because the age is much older than the other two samples from the same surface. We suspect that the boulder may have been derived from a much older surface further up catchment or eroded off the adjacent Qfo surface, and has inherited additional ^{36}Cl isotope concentrations while exposed.

Line 388: could this distributed central section of the Buffalo Valley fault be linked to potential blind geothermal systems? Worth adding some discussion about that here?

Yes it is. A sentence was added to reiterate this point. Now reads “The central section of the fault is also associated with a left step and several traces obliquely oriented to the main fault. These complexities may represent a breached step over or relay ramp, a favorable setting for blind geothermal resources (e.g. Faulds et al., 2021).

Line 417: Yay! Great field trip

Thanks for the complement. I’m glad you enjoyed it.