JOURNAL OF QUATERNARY SCIENCE (2024) 1–13 ISSN 0267-8179. DOI: 10.1002/jqs.3626

JQS Journal of Quaternary Science QRA Quaternary Research Association

Lake Wellington and West Walker River in Great Basin of western United States: History and genesis

STEVEN G. WESNOUSKY[1]* and BRAD SION[2]
[1]Center for Neotectonic Studies and Nevada Seismological Laboratory, University of Nevada, Reno, Reno, NV, USA
[2]Division of Earth and Ecosystem Sciences, Desert Research Institute, Reno, NV, USA

Received 20 October 2023; Revised 15 May 2024; Accepted 15 May 2024

ABSTRACT: Closed basins within the Great Basin of the western United States were home to numerous lakes during the Pleistocene. One of these paleolakes along the western edge of the Great Basin, Lake Wellington, once filled a 10 × 25-km expanse of Smith Valley to depths approaching 90 m. This and other lakes that existed during the Pleistocene are generally considered to be *pluvial*, indicating contemporaneity with either or all a period of cooler climate, increased rainfall and snowmelt, and relatively reduced rates of evaporation as compared to today. Here we combine the results of ^{36}Cl terrestrial cosmogenic nuclide surface exposure dating with soils and geomorphic observations to suggest Lake Wellington was not a pluvial lake but instead the result of a large landslide prior to ~43 ± 15 ka along the West Walker River where it exited Smith Valley. The observations collected also reveal an ancestral course of the West Walker River ~85 m above the current river grade. Attributing the elevation difference to incision caused by active 0.05 ± 0.01 mm a^{-1} uplift of the underlying Singatse and assuming the ancestral course followed the same path as today places the age of the paleoriver course at ~1.7 Ma. © 2024 John Wiley & Sons, Ltd.

KEYWORDS: Great Basin; landslides; paleorivers; pluvial lakes; shorelines

Introduction

Investigators have long used the preservation of lacustrine landforms to map the extent of late Pleistocene lakes within the intermontane valleys of the arid Great Basin Province (e.g. Fig. 1 and Russell, 1885; Gilbert, 1890; Feth, 1961; Snyder et al., 1964; Mifflin and Wheat, 1979; Reheis, 1999a; Reheis et al., 2014). Preserved glacial landforms have likewise been used to identify regions of alpine glaciation in and around the Great Basin that existed during the late Pleistocene (e.g. Fig. 1 and Blackwelder, 1931; Osborn and Bevis, 2001; Gillespie and Zehfuss, 2004). Latest Pleistocene glaciation and lakes reached maximum extents during the last 15 000–25 000 years, within Stage 2 of the marine oxygen isotope record (e.g. Martinson et al., 1987; Reheis, 1999a; Osborn and Bevis, 2001). The approximate contemporaneity of the lakes and ice extent have provided reason (e.g. Jamieson, 1863; Russell, 1889; Gilbert, 1890) to interpret that now dessicated late Pleistocene lakes are generally *pluvial* in origin, the result of either or all a cooler climate, increased rainfall and snowmelt, and lesser rates of evaporation.

Paleolake Wellington was situated along the western margin of the Great Basin (Fig. 1). Existence of the lake is recorded by a large lacustrine bar preserved at the north end of Smith Valley (Fig. 2), herein referred to as the *North Bar*. Lake Wellington is generally included in maps and reports concerning late Pleistocene pluvial lakes in the Great Basin (Snyder et al., 1964; Mifflin and Wheat, 1979; Reheis et al., 2002; Stauffer, 2003). The purposes of this note are to (i) present the results of terrestrial cosmogenic nuclide (TCN) exposure dating of sediments composing the North Bar, (ii) put forth observations to suggest that Lake Wellington was not pluvial in origin but rather was the result of a landslide blocking a river and (iii) document an ancestral course of the West Walker River in Smith Valley.

Prior studies and observations for context

Lake Wellington first appears on the regional map of Pleistocene lakes constructed by Snyder et al. (1964). Mifflin and Wheat (1979) provided the first discussion of Lake Wellington within their seminal report entitled *Pluvial Lakes and Estimated Pluvial Climates of Nevada*. The existence and expanse of the lake is documented within by a large-scale airphoto of Smith Valley that encompasses the North Bar. Adjacent to Lake Wellington is Lake Lahontan, the largest of the pluvia lakes in the western Great Basin (Fig. 1). Dating of organic matter in shoreline features places the most recent highstand of Lake Lahontan at ~15 000 calendar years (e.g. Adams and Wesnousky, 1998; Briggs et al., 2005). Mifflin and Wheat (1979) interpret on the basis of anecdotal soil observations that the highstand and desiccation of Lake Wellington was significantly earlier than Lake Lahontan, and that a yet earlier and higher stage of Lake Wellington overflowed westward across the Singatse Range into Mason Valley (Fig. 3). They suggest this history was the result of stream capture of a headwater portion of the East Walker River near Sonora Junction by the West Walker River due to ice damming, although it is not clear to them or us exactly how or if this could have occurred (Fig. 3).

The history and genesis of Lake Wellington is again addressed in Stauffer's (2003) thesis entitled *Timing of the Last Highstand of Pluvial Lake Wellington, Smith Valley, Nevada*. Soils are formally described on North Bar and a lacustrine surface near Nordyke Pass (Fig. 4). The presence of argillic horizons and stage II+ carbonate development are the basis to conclude similarly to Mifflin and Wheat (1979) that desiccation of Lake Wellington occurred before the desiccation of Lake Lahontan at between ~20 000 and 100 000 years. The existence of the lake

*Correspondence: Steven G. Wesnousky, as above.
E-mail: wesnousky@unr.edu

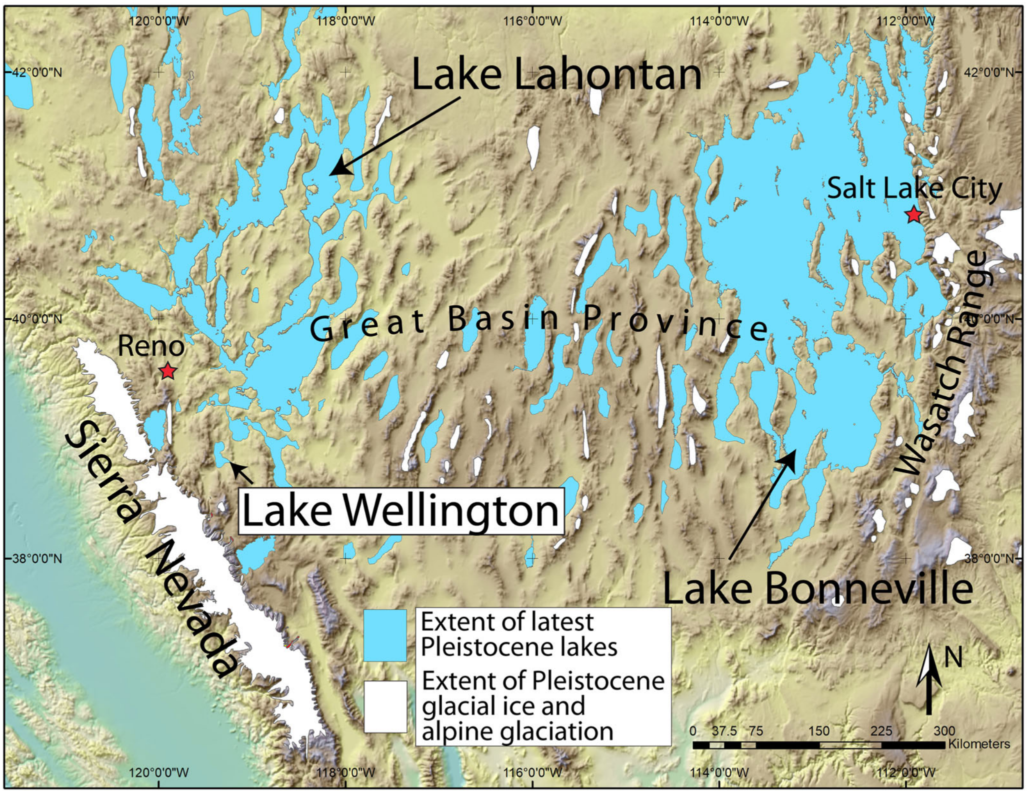

Figure 1. Location of Lake Wellington in Great Basin Province of the western United States. Extent of latest Pleistocene lakes drawn from maps of Reheis (1999b) and Utah Geospatial Information Center (2023). Extent of glacial ice and alpine glaciation compiled from Maley (1987), Osborn and Bevis (2001), and Gillespie and Clark (2011). [Color figure can be viewed at wileyonlinelibrary.com]

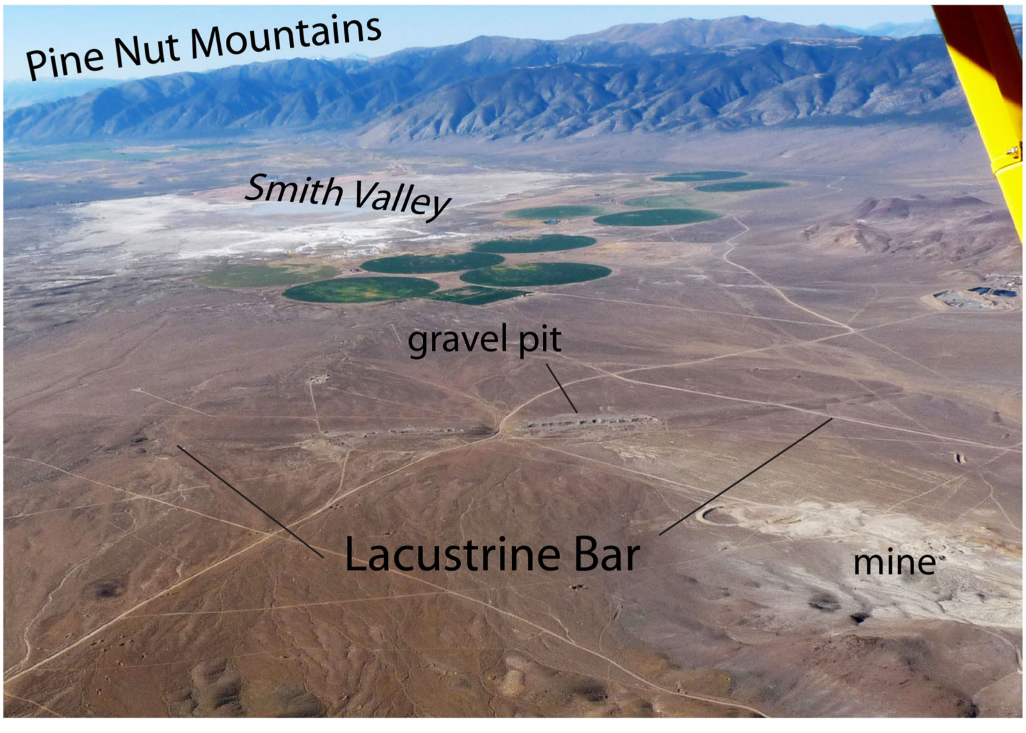

Figure 2. Prominent lacustrine bar (North Bar) at the north end of Smith Valley records past presence of Lake Wellington. View is to the southwest over the valley and toward Pine Nut Mountains. [Color figure can be viewed at wileyonlinelibrary.com]

during the period of 80 000 to 60 000 years ago is supported with collection of a tephra (99AL617-154) in lacustrine sediments ~5 m below the Nordyke Pass soil profile that chemically correlates (0.97 similarity coefficient) to a uniquely dated tephra with a Proto-Mono Craters source (sample WLC-85-2; Stauffer, 2003). The chemistry of a tephra sampled in lacustrine sediments on the west side of Smith Valley (AL98-51A) was not similar to any uniquely dated tephras. For separate purposes, Wesnousky and Caffee (2011) later collected a tephra sample (SGW-SV1-2008) in the same lacustrine sediments on the west side of Smith Valley. Analytical results show that this sample closely matches (~0.96 similarity coefficient) a

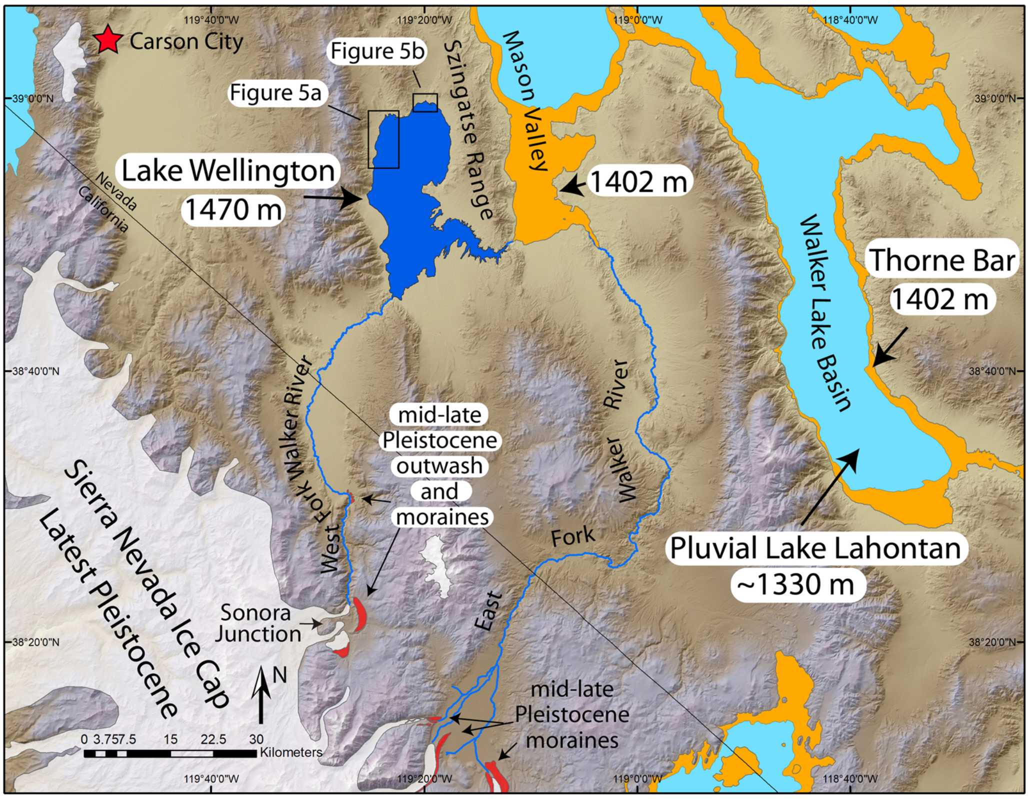

Figure 3. Regional map showing highstand elevations and extents of Lake Wellington (1470 m, dark blue), latest Pleistocene Lake Lahontan (~1330 m, light blue) and mid- to late Pleistocene lake level extrapolated from observations at Thorne Bar (1402 m, orange) in context of physiography, the Sierra Nevada ice cap in latest Pleistocene (white), older mid- to late Pleistocene moraines and outwash deposits at the margins of the ice cap (red), and the east and west forks of the Walker River. Figure pools observations of Reheis (1999b), Gillespie and Clark (2011), and Rood et al. (2011). [Color figure can be viewed at wileyonlinelibrary.com]

Pleistocene tephra (~75–80 ka, correlated age range) recovered from Owens Lake in southeast California, consistent with the results of Stauffer (2003).

In sum, past studies assume the lake is pluvial in origin and it reached its highest stand and then desiccated well before Lake Lahontan about 15 000 calendar years ago. The lake history has not garnered attention since.

Landforms and lake level revisited

High-resolution digital elevation models (DEMs) constructed from Lidar provide a resource unavailable to prior investigators who studied Lake Wellington (United States Geological Survey, 2023). Remnant lacustrine landforms produced by Lake Wellington are most prevalent and well-expressed at the north end of the lake (Fig. 5). Wavecut cliffs, embankments and beach ridges define a distinct curvilinear alignment that defines the shoreline or edge of Lake Wellington (Fig. 5a). The North Bar is likewise distinct in the Lidar imagery (Fig. 5b). The elevation of a lacustrine bar provides a stable measure of lake level at the time of formation (e.g. Adams and Wesnousky, 1999) and places the highstand elevation of Lake Wellington at 1470 m.

Soil development on North Bar revisited

Earlier studies clearly conclude that the development of soil on the North Bar is greater than observed on the ~15 000-year-old lacustrine bars of Lake Lahontan (Adams and Wesnousky, 1999). The photos and a textural profile from a soil pit excavated for this study enhance and confirm the interpretation (Fig. 6). Soil development in arid regions is in part the result of oxidation, production of clays that accompanies weathering and translocation of clays downward through the soil column (Birkeland, 1999). This development in arid regions is further governed by eolian introduction of silt into soil profiles that, with time, also weather to clay (e.g. Adams and Wesnousky, 1999). The relative amount of clay present in a soil column increases with time. The relative age of soils developed on like parent material is thus disclosed by the relative amount of clay in a soil column (e.g. Birkeland, 1999). Horizons of oxidation and clay introduced and formed during soil development are generally deemed the B horizon. In outcrop they are evident by distinct reddening as compared to the underlying parent material on which they develop (Fig. 6). The actual amount of clay in a soil is quantitatively revealed by a textural profile that plots the weight percent of clay, silt and sand with depth. The texture profile for North Bar shows an increase in clay content upwards to 40% as compared to the parent material below on which it is developed. Here the horizon of increased clay content is labeled Bt and confined from about 6–15 cm depth. Plotted in red are the clay weight percent profiles measured in soil pits excavated on similar lacustrine bar deposits preserved on the edge of Lake Lahontan. All show systematically less clay percentages than on North Bar. The plots provide a visualization of the relatively older age of Lake Wellington as compared to latest Pleistocene Lake Lahontan.

TCN surface exposure age of North Bar

North Bar is constructed primarily of siliceous volcanic sediment, reflecting the composition of the surrounding ranges. Sediment sourced from volcanic rocks are amenable to TCN surface exposure dating using the ^{36}Cl isotope (Gosse

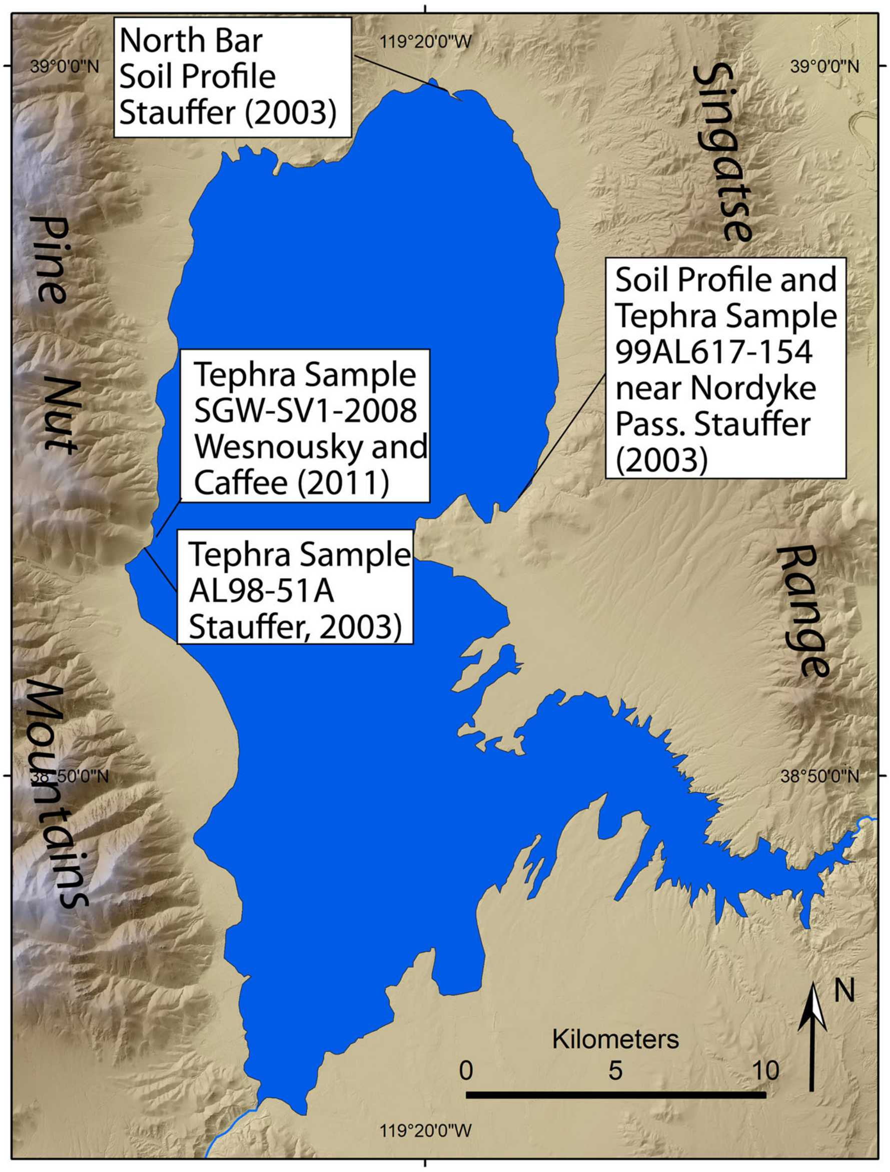

Figure 4. Observations bearing on the history of Lake Wellington from prior studies. [Color figure can be viewed at wileyonlinelibrary.com]

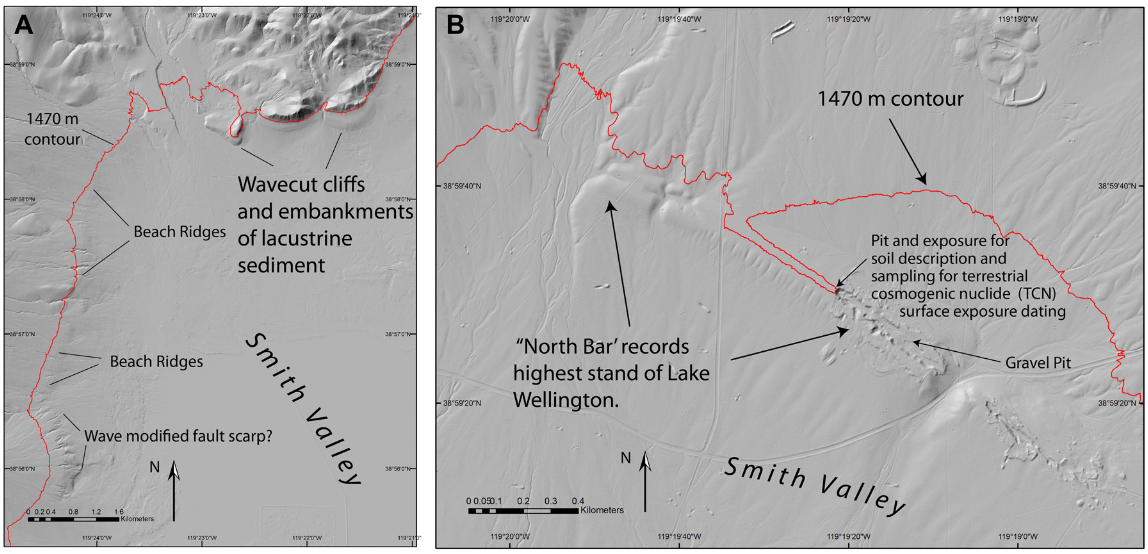

Figure 5. Lacustrine bars, beach ridges, wavecut cliffs and embankments remnant from Lake Wellington are best preserved at the north end of Smith Valley. The highest elevation of *North Bar* is marked by the 1470-m contour (red line). Locations of adjacent pit and gravel pit exposure for soil description and sampling for terrestrial cosmogenic nuclide (TCN) surface exposure dating are indicated by arrows. Location of each image outlined in Fig. 3. [Color figure can be viewed at wileyonlinelibrary.com]

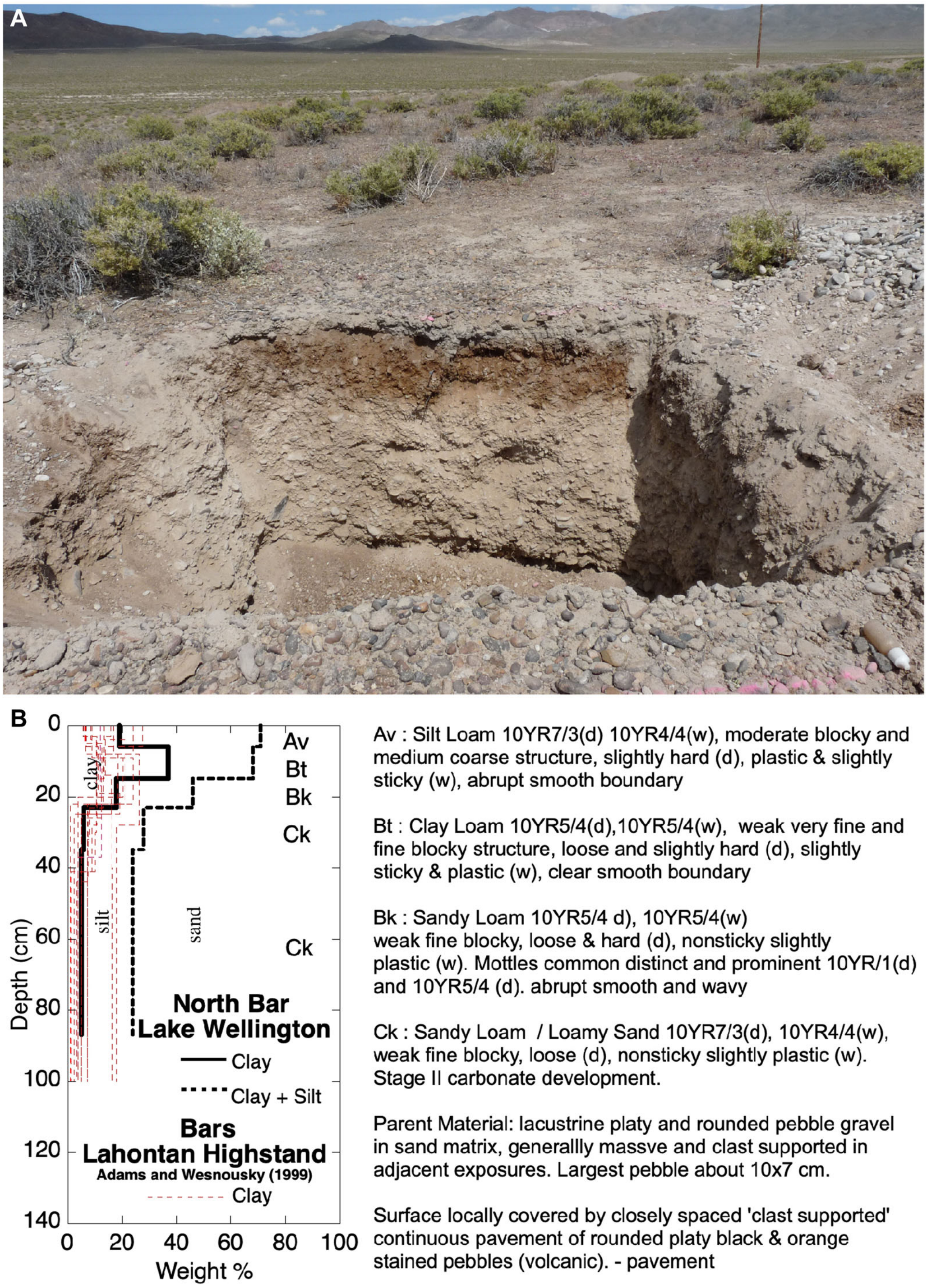

Figure 6. (A) Pit excavated for soil description on North Bar. (B) Visual description of North Bar soil and plot showing depth profile of weight percent clay, silt and sand fractions. Dashed red lines are weight percent clay reported by Adams and Wesnousky (1999) on lacustrine bars of the latest Pleistocene highstand of Lake Lahontan. The relatively older age of North Bar as compared to Lake Lahontan bars is indicated by the relatively greater weight percent of clay in the North Bar profile. Soil description follows conventions described in Birkeland (1999). [Color figure can be viewed at wileyonlinelibrary.com]

and Phillips, 2001). Six bulk samples taken at progressively increasing depths in a gravel pit exposure (Fig. 7a) provide the means to estimate the time since the North Bar surface has been exposed to the atmosphere. Separation of the 250–500-μm fraction and preparation of each sample for accelerator mass spectrometry (AMS) measurement of ^{36}Cl concentration were conducted at the DRI Soil Characterization and Quaternary Pedology Lab of the Desert Research Institute, Nevada, and the PRIME lab of Purdue University, respectively. The PRIME AMS measurements, measured ^{36}Cl concentration and additional inputs for subsequent analysis of the data with the CRONUScalc application (Marrero et al., 2016) are shown in Table 1a and 1b. The observed ^{36}Cl concentrations are generally a decreasing function of depth (Fig. 7b). The decrease in ^{36}Cl with depth is a result of the progressively greater shielding from overburden such that cosmogenic radiation generally reaches no more than ~2 m depth. The concentration at any depth is additionally a function of production rate of ^{36}Cl, any ^{36}Cl inherited from initial deposition, the decay rate of ^{36}Cl, latitude, elevation and density of material subject to cosmogenic radiation. The distributions of age, inheritance and posterior density that yield acceptable curve fits to the ^{36}Cl measurements with the CRONUScalc application (Marrero et al., 2016) are summar-

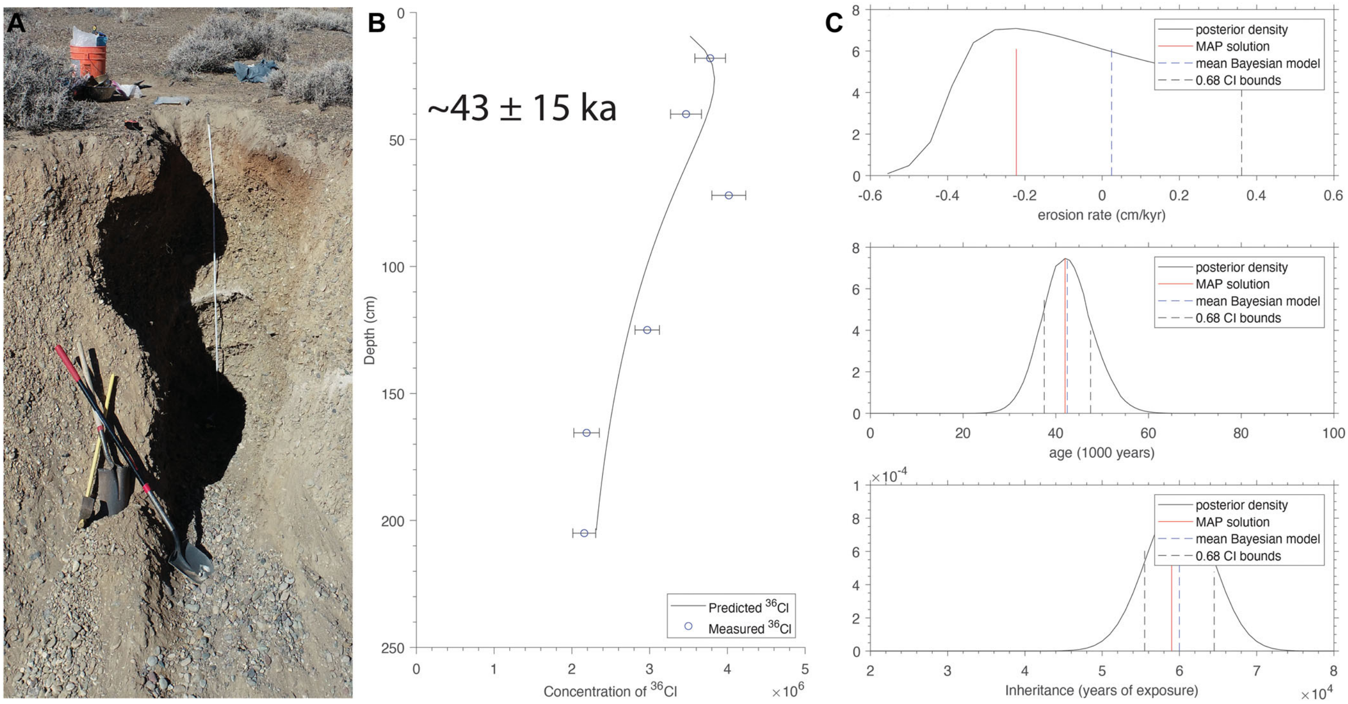

Figure 7. Images and plots documenting (A) exposure from which six samples were extracted for measurement of terrestrial cosmogenic nuclide ^{36}Cl, (B) ^{36}Cl concentration versus depth, and (C) from top to bottom probability distributions of density, age and inheritance that provide acceptable model fits to the ^{36}Cl profile in B. The best fitting curve fit is drawn in B and corresponds to an age ~40 ± 15 ka. [Color figure can be viewed at wileyonlinelibrary.com]

Table 1a. Soil sample Cl and ^{36}Cl concentrations used for computation of depth profile ages in CRONUScalc (Marrero et al., 2016).

Sample ID[a]	Depth (cm)	Sample mass (g)	Carrier solution mass (g)[b]	HF (mL)	^{35}Cl/^{37}Cl	^{36}Cl/Cl ($\times10^{-15}$)	Cl concentration in rock sample (ppm)	^{36}Cl inventory (10^5 at g^{-1})
SV-01	13-23	10.0270	3.1448	35	7.47 ± 0.04	378.7 ± 7.2	178.6 ± 3.8	3.78 ± 0.20
SV-02	35-45	10.0410	3.0930	35	7.46 ± 0.18	353.8 ± 8.4	176.0 ± 6.8	3.47 ± 0.20
SV-03	67-77	10.2520	3.0920	35	6.85 ± 0.13	387.6 ± 6.6	217.2 ± 7.2	4.02 ± 0.22
SV-04	120-130	15.2890	3.1002	48	6.38 ± 0.06	396.6 ± 7.4	177.0 ± 4.2	2.97 ± 0.16
SV-05	163-168	15.1130	3.1347	48	6.55 ± 0.32	293.6 ± 7.9	168.6 ± 11.6	2.19 ± 0.16
SV-06	200-210	15.4310	3.0805	48	6.18 ± 0.20	282.2 ± 8.4	190.0 ± 8.6	2.16 ± 0.15
Blank	–	–	3.0785	35	14.1 ± 0.29	4.3 ± 0.6	–	0.10 ± 0.01

[a] All samples were modeled using a bulk density of 1.80 ± 0.20 g cm^{-3}, covering the range of values typically encountered in alluvial and/or gravel-rich deposits in semi-arid environments.
[b] Carrier solution prepared with concentration of 1.289 ± 0.062 mg Cl g^{-1} and ^{35}Cl/^{37}Cl ratio of 14.9737.

ized in Fig. 7c. The best-fit curve shown in Fig. 7b corresponds to an age of ~43 ka and when viewed in context of the probability distribution plots in Fig. 7c indicates the exposure age of North Bar and correspondingly the time Lake Wellington reached its maximum level was ~40 ± 15 ka.

Origin as a landslide

The elevation of North Bar shows Lake Wellington reached a maximum level of 1470 m (Fig. 8). Latest Pleistocene Lake Lahontan ~15 ka filled to only about 1330 m, some 150 m lower than Lake Wellington (Fig. 8). The two lakes thus never simultaneously formed a single lake. The soils and cosmogenic analysis at North Bar indicate as well that Lake Wellington reached its highest level at ~43 ka, well before the ~15-ka highstand of Lake Lahontan (Adams and Wesnousky, 1998; Briggs et al., 2005). It may be conjectured that Lake Wellington connected to an older and higher stage of Lake Lahontan. The oldest and highest constructional shoreline features preserved along the perimeter of Lake Lahontan basin are documented at Thorne Bar (Fig. 3) in the adjacent Walker Lake basin (Reheis, 1999a, 1999b; Reheis et al., 2002). The ages of the Thorne Bar shoreline features are dated with uranium-series and ^{36}Cl cosmogenic nuclide analyses (Kurth et al., 2011). Thorne Bar shorelines similar in age to Lake Wellington occur at elevations no greater than ~1330 m, some 140 m below the highstand shoreline of Lake Wellington. Yet higher shorelines assessed to be >100 ka are also preserved at Thorne Bar and found at elevations up to 1402 m, still 70 m below the highstand of Lake Wellington (Fig. 8). These observations preclude that Lake Wellington and Pleistocene lakes in the Lake Lahontan basin simultaneously shared the same lake level. Adding to these observations is that Lake Wellington did not exist in a closed basin but rather a basin with an outlet through Wilson Canyon, so it is problematic to simply attribute the genesis of Lake Wellington to pluvial climatic conditions in the Pleistocene.

An alternative interpretation is that Lake Wellington was the result of a major landslide in the narrows of Wilson Canyon (Fig. 8). The outline of Lake Wellington defined by the 1470-m contour of North Bar narrows as it enters eastward into Wilson

Table 1b. Geochemical parameters for ^{36}Cl analyses used in the CRONUScalc program (Marrero et al., 2016).

Sample ID	Depth (cm)	SiO_2 (%)	TiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	CO_2 (%)	Cl (ppm)	B (ppm)	Sm (ppm)	Gd (ppm)	U (ppm)	Th (ppm)	Cr (ppm)	Li (ppm)
SV-01	13–23	70.00	0.59	13.70	4.12	0.03	0.66	1.57	3.33	3.25	0.06	2.27	178.55	5.0	3.4	1.97	3.39	8.9	16	10
SV-02	35–45	70.10	0.65	13.40	4.88	0.05	1.08	1.54	3.07	3.05	0.08	2.97	176.00	5.0	3.4	2.17	3.67	9.0	18	20
SV-03	67–77	74.70	0.38	13.65	2.43	0.02	0.62	1.40	3.22	3.74	0.06	1.50	217.17	5.0	2.8	2.00	3.20	8.8	10	10
SV-04	120–130	75.10	0.43	13.00	2.79	0.03	0.55	1.19	2.92	3.63	0.05	1.55	176.96	5.0	3.4	2.07	3.29	9.6	10	20
SV-05	163–168	76.60	0.43	12.00	2.78	0.03	0.52	1.12	2.69	3.31	0.06	1.94	168.56	5.0	3.0	1.82	2.92	8.8	9	10
SV-06	200–210	65.60	1.02	11.60	12.00	0.23	0.57	2.25	2.31	2.85	0.12	3.08	190.03	5.0	5.5	3.16	4.07	10.3	18	10

Canyon. The cliffs on both sides are steep and unstable at the east end of the canyon. Potential failure planes dipping toward the river are clearly expressed on the northern edge of the canyon (Fig. 9). The instability of the cliffs is underscored with occurrence of a landslide sufficient to close the adjacent State Route 208 for 2 months in January 2023. Another candidate for a major landslip that possibly dammed the Walker River and produced Lake Wellington is suggested in the morphology of the east-facing cliffs near the eastern limit of Wilson Canyon (Fig. 10). Here the steep east-facing cliffs are interrupted by a broad embayment below which there is a lobate mass of rock that protrudes to the southeast. The lobate mass of rock also shown in Fig. 9 gives the appearance of a landslide emanating from the embayment above. The rock mass consisting primarily of quartz monzonite is of sufficient height to have blocked the West Walker to an elevation of 1470 m were it to have crossed the entire canyon (Fig. 9). Stewart and Dohrenwend (1984a) place the northwestward limit of the rock mass along a fault separating Jurassic quartz monzonite from Tertiary volcanics. In sum, it is not difficult to envision a large landslide blocked the entire river to temporarily cause the filling of Lake Wellington.

Accepting the hypothesis that Lake Wellington was the result of a landslide in Wilson Canyon, the North Bar exposure age of ~40 ± 15 ka may be viewed to place a minimum age on the timing of the landslide. The age of the two tephra samples 99AL617-54 and SGW-SV1-2008 extracted from lacustrine sediments along the edges of the lake basin (Fig. 4) reportedly fall between 60 and 80 ka (see preceding Prior Studies section). These observations most simply imply a landslide damming of the lake between 60 and 80 ka and a subsequent breaching of the landslide and abandonment of North Bar at ~40 ± 15 ka.

Ancestral Walker River

Traces of Lake Wellington are not recognized along Wellington Canyon and, if at all present, are limited and subdued compared to those observed to the north (e.g. Figs. 3 and 5). The absence is reasonably attributed to active erosion of the steep cliffs bounding the canyon. Examination of the cliffs does reveal a distinct relatively continuous layer of rounded cobble gravel (Fig. 11). The cobble gravel is extremely carbonate cemented resting unconformably on Tertiary rocks (Stewart and Dohrenwend, 1984a), with a base of about 1485 m, 15 m higher than the 1470-m highstand of Lake Wellington. Particular locations on the map of Fig. 11 are annotated by letters A–E. The expression of the boulder gravel layer in outcrop is captured in part with the view eastward in Fig. 12 from location A to locations B and C. Rounded cobbles perched on small bedrock terraces at the same elevation are also present within the narrows of Wilson Canyon at locations D and E (Fig. 13). The distinctly greater carbonate cementation and higher elevation as compared to observations on North Bar indicate the rounded boulder gravel is significantly older than the highstand of Lake Wellington. It is reasonable to infer they mark an ancestral course of the West Walker River.

The West Walker River is today 85 m below the boulder gravel at location E (1485 m). The east flank of the Singatse Range is bounded by an active normal fault (Fig. 8). Abandonment and subsequent incision of the proposed ancestral course of the West Walker River is most simply attributed to uplift attendant to displacement on the range-bounding normal fault. The average vertical component of slip across the range-bounding fault is reportedly 0.05 ± 0.01 mm a^{-1} over the last ~170 ka (Pierce et al., 2021). An approximate age of the

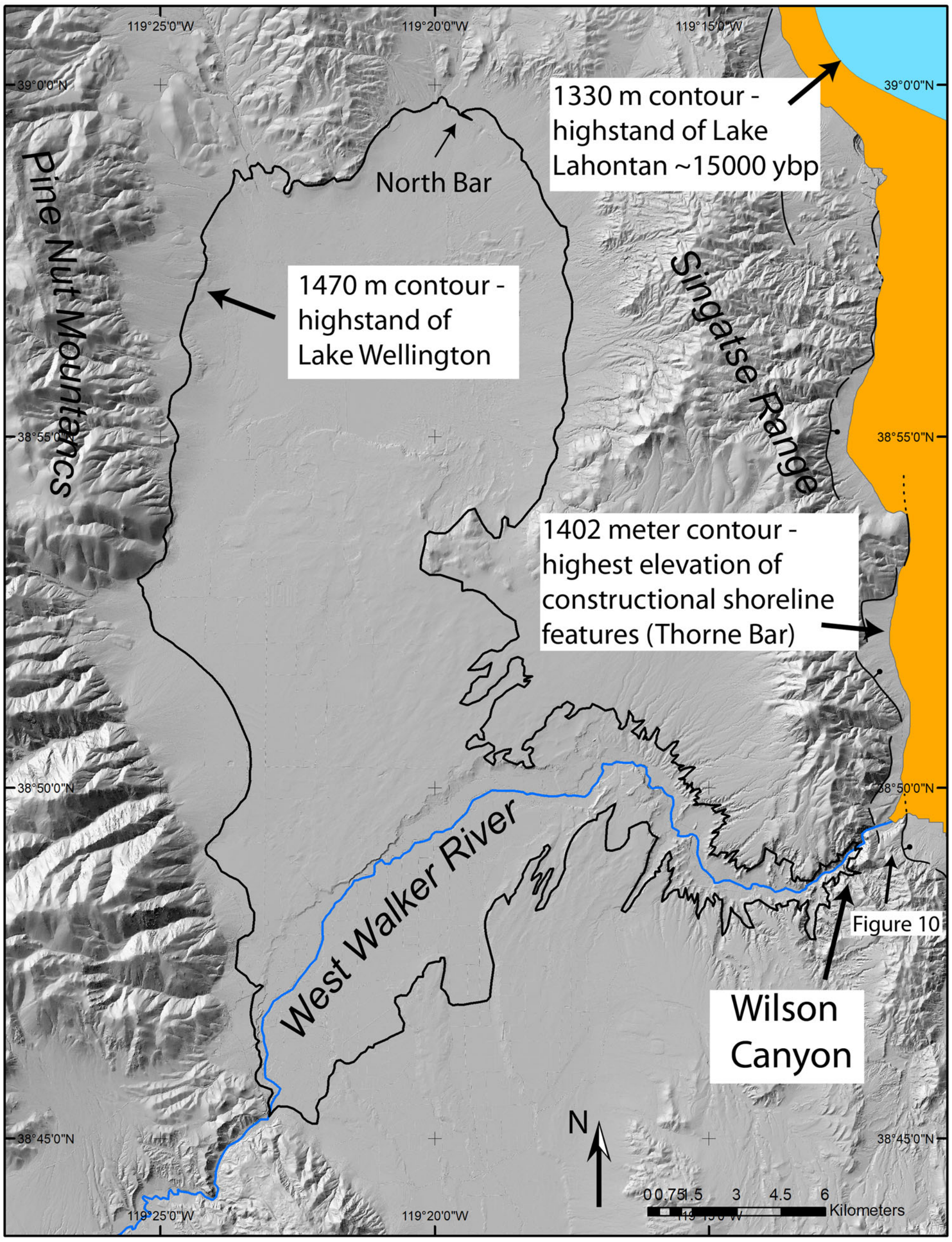

Figure 8. Highstand elevation of Lake Wellington compared to location and highstand extent of latest Pleistocene (blue) and older Pleistocene highstand (orange) of Lake Lahontan. [Color figure can be viewed at wileyonlinelibrary.com]

ancestral West Walker River equal to about 1.7 million years is gained by dividing 85 m by .05 mm a^{-1}. The highest peaks in the Singatse Range are about 2000 m, about 500 meters higher than the boulder gravel of the ancestral course. By the same logic, albeit tenuous, dividing 585 m by .05 mm a^{-1} would indicate inception of the Singatse Range at about 11.7 ka.

The course of the West Walker River today drops about 25 m in elevation (1421–1395 m) along the section of river cliffs that expose higher cobble gravels of the ancestral West Walker River. A similar drop is not observed in the elevations of the rounded cobble gravels that mark the proposed ancestral river. One may surmise that the original gradient of the ancestral river was much less or has been removed by backtilting of the footwall that commonly accompanies displacement on normal faults.

Alluvial fan and pediment surfaces are anomalously large and elevated at the exit of the Walker River into Mason Valley, compared to alluvial fans elsewhere along the east flank of the Singatse range (Figs. 8 and 10). Mapped as Pleistocene in age by Stewart and Dohrenwhend (1984a) their anomalous elevation appears at least in part to be due to uplift on a strand of the Singatse Range bounding fault that splays outboard of the rangefront (Figs. 8 and 10). A strath of cobble gravel is preserved on the surface of the southern of the two fans and exibits carbonate development similar to that observed on those cobbles in Wilson Canyon attributed to an ancestral Walker River (Fig. 14). On this basis it is suggested that these elevated fan surfaces may correlate in time to the older ancestral course of the West Walker River.

An alternative hypothesis

The preceding interpretation assumes the course of the ancestral river flowed eastward from the crest of the Sierra Nevada mountains (Fig. 1) as does the Walker River today. Streams on the western side of the Sierran crest today flow in the opposite direction to the west, and have done so since Tertiary time. It is now often accepted that an extensive paleoriver system existed in the Eocene–Early Miocene and drained westward over much of what is now the Great Basin

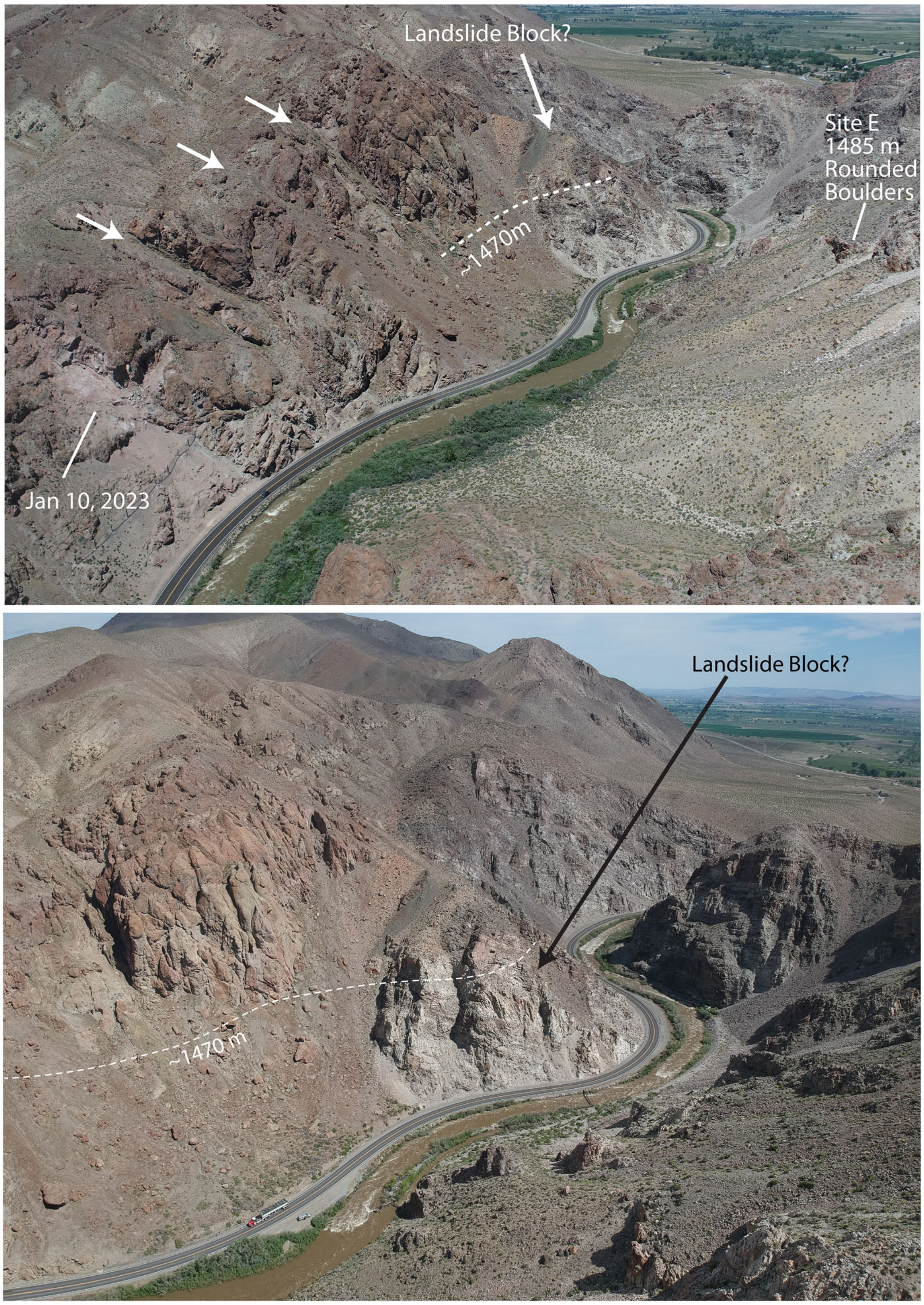

Figure 9. Steep cliffs and potential landslide failure planes (white arrows) conducive to large landslides and a possible landslide block that may have once dammed the Walker River are present on the northern edge of the canyon in these eastward views through the eastern end of Wilson Canyon. Instability of the cliffs is underscored in foreground of upper figure by scar of landslide that in January 2023 closed the adjacent highway for 2 months. [Color figure can be viewed at wileyonlinelibrary.com]

and Sierra Nevada into the Pacific (Yeend, 1974; Garside et al., 2005; Henry, 2009; Lindgren, 1911; Henry et al., 2012). At these times the Sierra Nevada was the western flank of a high plateau, the Nevadaplano of Decelles (2004), over which drainages flowed to the west toward the Pacific. The possibility that the ancestral river deposits described here were deposited by one of these Tertiary streams that flowed westward, opposite to the flow of the Walker River today, warrants consideration.

Flow direction in preserved fluvial deposits may be recorded in the systematics of clast imbrication in the remnant bedload (e.g. Prothero and Schwab, 2013). Likewise, stream flow direction may be indicated with the presence of clasts of unique composition that might only be derived from what was the upstream direction. Inferences made from clast imbrication observed at the few localities affording convenient natural exposure are insufficiently clear to the authors to uniquely establish a paleoflow direction. Likewise, no clasts appeared so visually distinctive to invite ready association to units defined on maps of the area (e.g. Carlson et al., 1978; John et al., 1981; Proffett and Dilles, 1984; Stewart and Dohrenwend, 1984a; 1984b; Stewart et al., 1989) or in brief reconnaissance inspection of the adjacent mountain ranges.

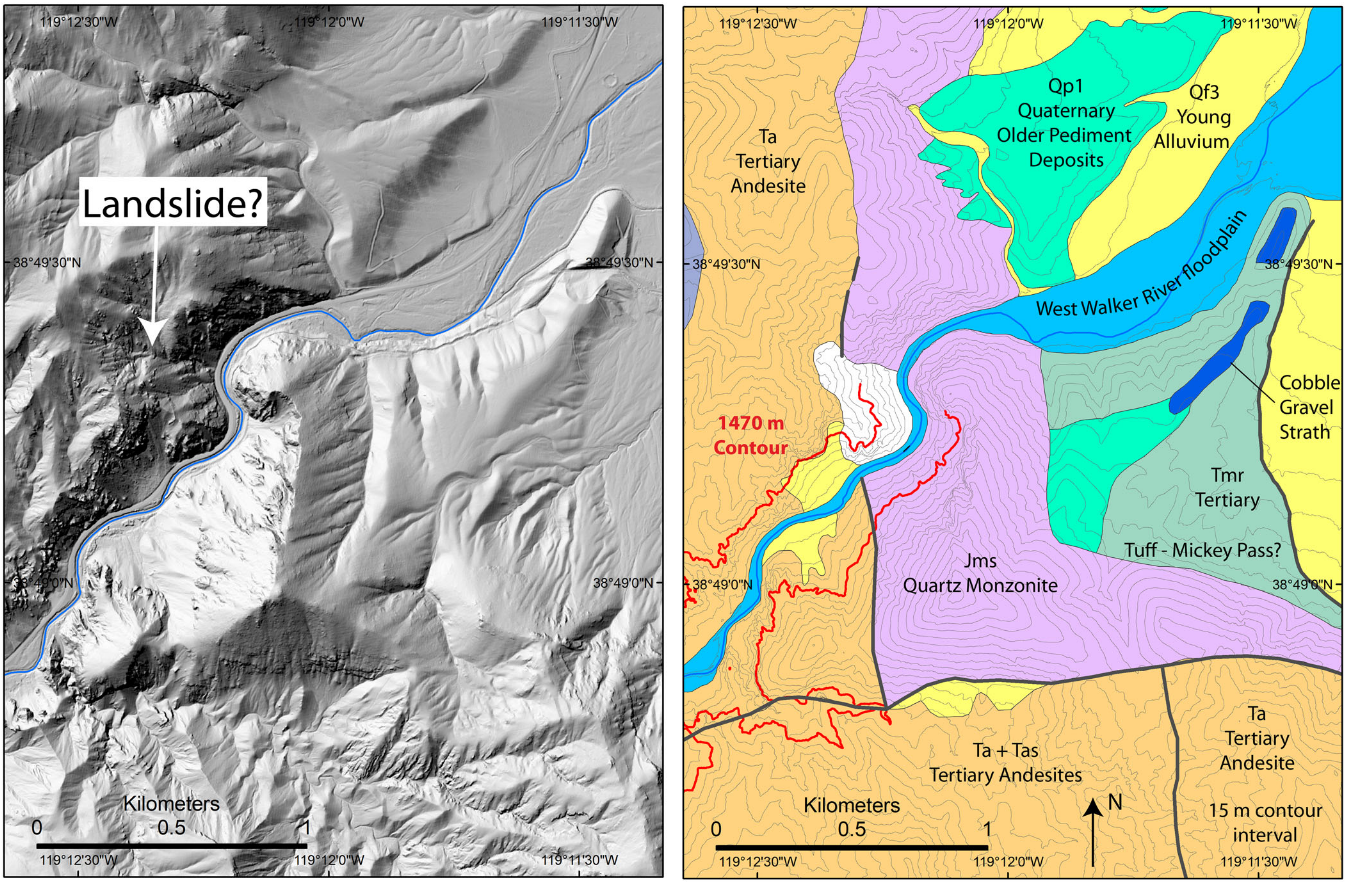

Figure 10. (left) Location of possible landslide that blocked Wilson Canyon to create Lake Wellington. (right) Geologic map at same scale simplified and modified from Stewart and Dohrenwend (1984b). Location shown in Fig. 8. [Color figure can be viewed at wileyonlinelibrary.com]

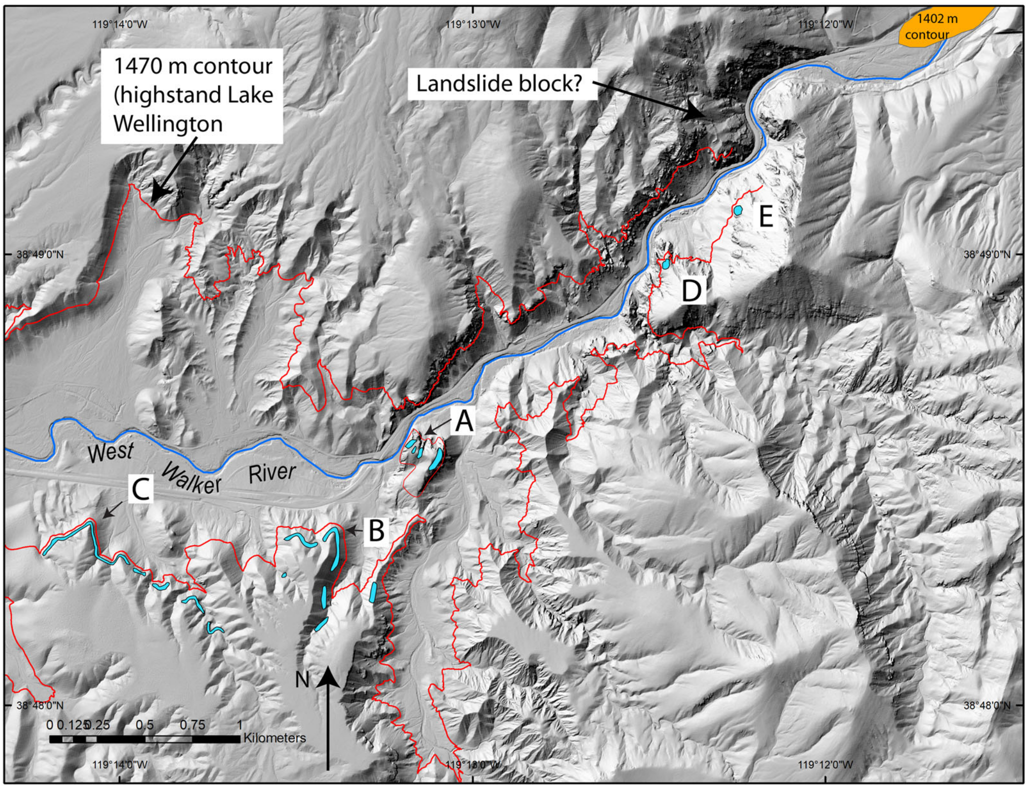

Figure 11. Shaded relief image of Wilson Canyon showing 1470-m highstand contour (red) of Lake Wellington. Remnants of a layer of rounded cobble gravel (blue) in cliffs at an elevation of about 1485 m record an ancestral course of the West Walker River. A possible landslide block that obstructed the West Walker River to form Lake Welllington is also labeled. Letters with arrows are points of reference for images in Figs. 12 and 13 and discussed in the text. [Color figure can be viewed at wileyonlinelibrary.com]

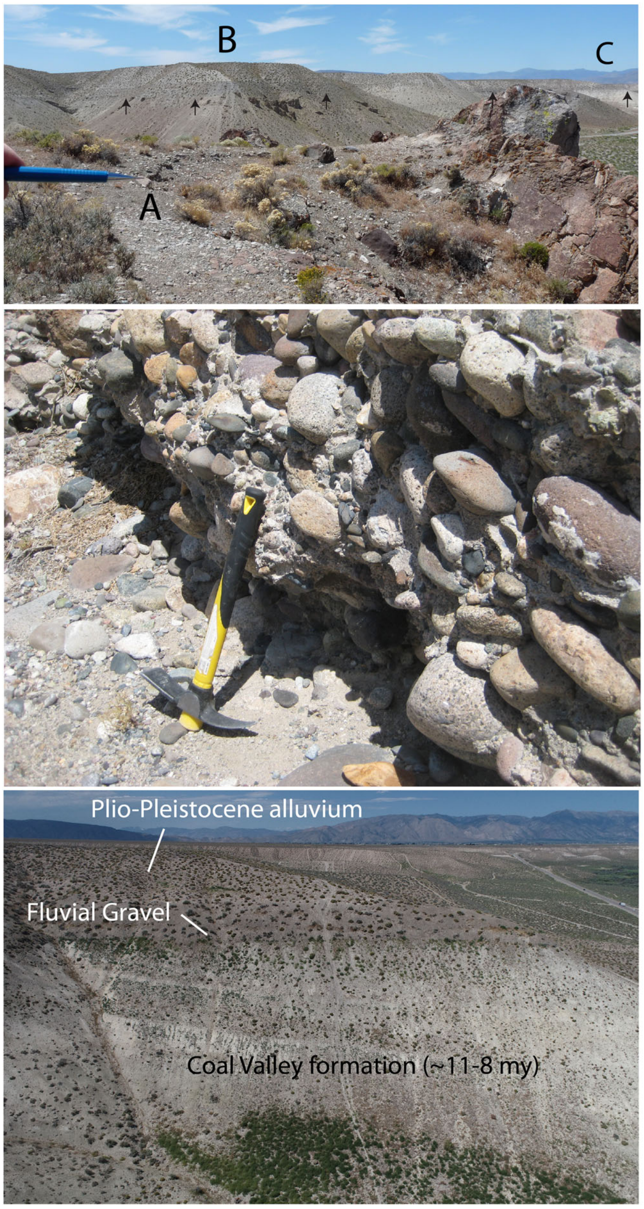

Figure 12. (upper) View westward from point A to points B and C (shown on map in Fig. 11). Upward directed arrows point to base of approximately horizontal layer of rounded cobble gravel that rests unconformably on underlying Tertiary rocks. The base of the layer is ~15 m higher than the maximum level of Lake Wellington. Pencil points to same cobble gravel resting unconformably on small mesa that is point A. (middle) Representative image of extreme carbonate cementation that is characteristic of the cobble gravel layer. (lower) Closer view of exposure at C shows fluvial gravel layer in angular unconformity with underlying Miocene beds of Coal Valley Formation and overlain by Plio-Pleistocene alluvium. [Color figure can be viewed at wileyonlinelibrary.com]

A unique measure of paleoflow direction from these type of measures might ultimately arise with a more rigorous assessment of exposures and geochemical study of the clasts within the deposits, tasks beyond the scope of this study. There are other observations that have bearing on the hypothesis that the ancestral Walker River flowed in direction opposite to what it does today.

Vestiges of the Tertiary paleodrainages that flowed westward are recorded by rounded gravels interbedded with Eocene–Miocene ash-flow tuffs that flowed down and filled broad valleys on the Nevadaplano (Garside et al., 2005; Henry et al., 2012). The gravels of the ancestral Walker River reported here are not interbedded in Miocene stratigraphy but rather sit in angular unconformity on deposits of the Coal Valley Formation (Fig. 12).

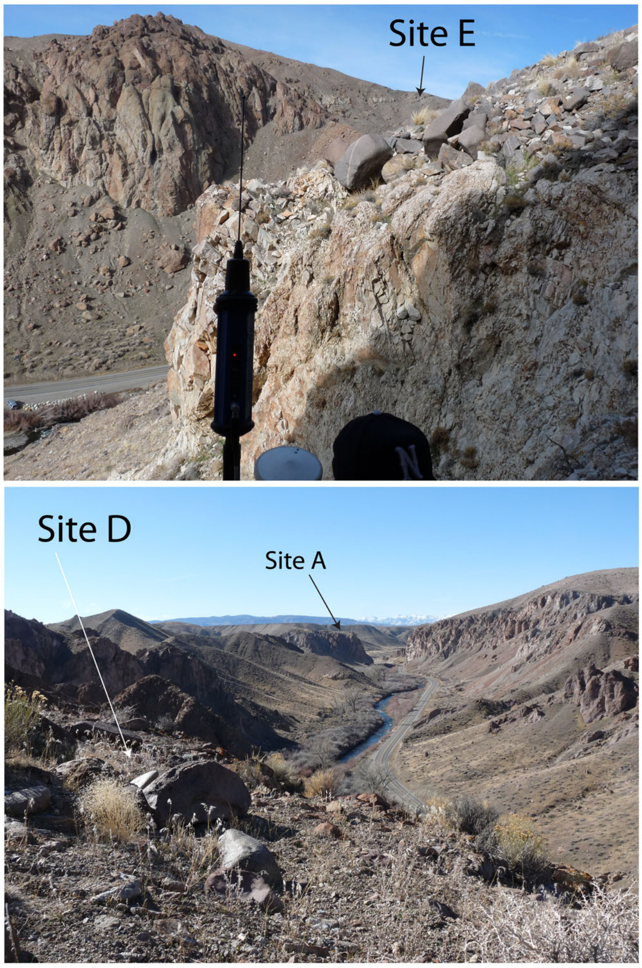

Figure 13. Rounded cobbles and boulders perched on small bedrock terraces at sites E and D at same elevation as cobble gravel layer observed at sites A, B and C in Fig. 12 (see Fig. 11 for map location of all sites). View is to the west in lower image. [Color figure can be viewed at wileyonlinelibrary.com]

The Coal Valley formation consists of interbedded tuffs and lacustrine sediments that filled broad paleovalleys on the Nevadaplano 1–8 Ma (Axelrod, 1956; Stewart, 1980; Stewart and Dohrenwend, 1984a). Subsequent extension associated with Basin and Range normal faulting and development of the eastern Sierran Nevada range front has disrupted and tilted sediments that filled the paleovalleys, and in turn interrupted any westward flow of associated rivers across the Sierra Nevada. If then the gravels of the proposed ancestral course of the Walker River flowed westward, the angular unconformity on which they sit requires that westward flow continued well after the development of Basin and Range topography initiated and the age of previously identified westward-flowing Tertiary paleodrainages.

If the ancestral course of the Walker River flowed westward through Wilson Canyon it would have been accompanied by a westward-directed downstream gradient. The Singatse Range is a normal fault-bounded block that is actively tilting to the west. As such, the preserved gravel of the now abandoned river course should be even greater than when originally deposited. Yet, the preserved gravels exhibit virtually no gradient and so are difficult to reconcile with the hypothesis of westward flow.

Summary

A major lacustrine bar deposit at an elevation of 1470 m preserved on the desert landscape records the presence of Paleolake

Figure 14. Carbonate-cemented cobble and boulder gravel above strath on underlying Tertiary rocks where the West Walker River leaves the Singatse Range and enters Mason Valley. [Color figure can be viewed at wileyonlinelibrary.com]

Wellington at the north end of Smith Valley, Nevada. TCN surface exposure dating of the bar places the age of the lake highstand at before ~40 ± 15 ka. Pleistocene lakes in the closed Lake Lahontan basin are generally considered pluvial. Interpretations that Lake Wellington is of pluvial origin are problematic because Smith Valley is not a closed basin. Observations presented here lead to the suggestion that Lake Wellington resulted from a large landslide near the outlet of the West Walker River in Wilson Canyon where it flows out of Smith Valley. Exposures also reveal an ancestral course of the West Walker River at an elevation of ~85 m above the current grade of the West Walker River that is estimated at ~1.7 Ma.

Data and Resources

Remaining data are from published sources listed in the references.

Acknowledgements. Most appreciated are early reviews of the manuscript provided by Ken Adams and Marith Reheis, and insights concerning Tertiary river systems of the Great Basin offered by Chris Henry. The submitted manuscript benefitted yet further with the additional constructive comments from Marith and an anonymous reviewer. Alexandra Sarmiento and Roberto Civico long ago graciously helped in excavating the soil pit. Research was supported by National Science Foundation Grant EAR 1920514. This is Center for Neotectonic Studies Contribution no. 87.

Data availability statement

Data (rock samples) destroyed in analysis. All measurements provided in manuscript.

References

Adams, K.D. & Wesnousky, S.G. (1998) Shoreline processes and the age of the Lake Lahontan highstand in the Jessup embayment, Nevada. *Geological Society of America Bulletin*, 110, 1318–1332.

Adams, K.D. & Wesnousky, S.G. (1999) The Lake Lahontan highstand: age, surficial characteristics, soil development, and regional shoreline correlation. *Geomorphology*, 30, 357–392.

Axelrod, D.I. (1956) Mio-Pliocene floras from west-central Nevada. *University of California Publications in Geological Sciences*, 33, 321.

Birkeland, P. (1999) *Soils and Geomorphology*. Oxford University Press.

Blackwelder, E. (1931) Pleistocene glaciation in the Sierra Nevada and Basin Ranges. *Geological Society of America Bulletin*, 42, 865–922.

Briggs, R.W., Wesnousky, S.G. & Adams, K.D. (2005) Late Pleistocene and late Holocene lake highstands in the Pyramid Lake subbasin of Lake Lahontan, Nevada, USA. *Quaternary Research*, 64, 257–263.

Carlson, J.E., Stewart, J.H., Johannesen, D. & Kleinhampl, F.J. (1978). Preliminary geologic map of the Walker Lake 1 degree by 2 degree quadrangle, U.S. Geological Survey Monograph Open-File Report OF-78-523 (1:250,000).

DeCelles, P.G. (2004) Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western USA. *American Journal of Science*, 304, 105–168.

Feth, J.H. (1961). A new map of western conterminous United States showing the mzximum known or inferred extent of Pleistocene lakes, United States Geological Survey Professional Paper 424-B, Art., 47 B110-B112.

Garside, L.J., Henry, C.D., Faultds, J.E. & Hinz, N.H. (2005) The upper reaches of the Sierra Nevada auriferous gold channels, California and Nevada. In: Rhoden, H.N., Steininger, R.C. & Vikre, P.G. (Eds.) *Geological Society of Nevada Symposium: Window to the World, Reno*. Geological Society of Nevada, Nevada, 209–235.

Gilbert, G.K. (1890) Lake Bonneville, U.S. Geological Survey Monograph **1** pp. 438.

Gillespie, A.R. & Clark, D.H. (2011) Glaciations of the Sierra Nevada, California, USA. In: Ehlers, J., Gibbard, P.L. & Hughes, P.D., (Eds.) *Quaternary Glaciations - Extent and Chronology*. Elsevier Ltd. pp. 447–462.

Gillespie, A.R. & Zehfuss, P.H. (2004) Glaciations of the Sierrra Nevada, California, USA, in *Quaternary Glaciations* J. Ehlers and P. L. Gibbard (Editors), 51-62.

Gosse, J.C. & Phillips, F.M. (2001) Terrestrial in situ cosmogenic nuclides: theory and application. *Quaternary Science Reviews*, 20, 1475–1560.

Henry, C.D. (2009) Uplift of the Sierra Nevada, California. *Geology*, 37, 575–576.

Henry, C.D., Hinz, N.H., Faulds, J.E., Colgan, J.P., John, D.A., Brooks, E.R. et al. (2012) Eocene-Early Miocene paleotopography of the Sierra Nevada-Great Basin-Nevadaplano based on widespread ash-flow tuffs and paleovalleys. *Geosphere*, 8, 1–27.

Jamieson, T.F. (1863) On the parallel roads of Glen Roy, and their place in the history of the glacial period. *Quarterly Journal of the Geological Society*, 19, 235–259.

John, D.A., Giusso, J., Moore, W.J. & Armin, R.A. (1981). Reconnaissance geologic map of the Topaz Lake 15 minute Quadrangle, California and Nevada, U.S. Geological Survey Open-file report (1:62,500).

Kurth, G., Phillips, F.M., Reheis, M.C., Redwine, J.L. & Paces, J.B. (2011) Cosmogenic nuclide and uranium-series dating of old, high shorelines in the western Great Basin, USA. *Geological Society of America bulletin*, 123, 744–768.

Lindgren, W. (1911). The Tertiary gravels of the Sierra Nevada of California, USGS Professional Paper 73 pp. 226.

Maley, T. (1987). Glaciation in Idaho, in *Exploring Idaho geology. ID: Mineral Land Publications*, https://digitalatlas.cose.isu.edu/geo/glaciers/glaciers.htm (accessed June 5, 2023), Idaho State University.

Marrero, S.M., Phillips, F.M., Caffee, M.W. & Gosse, J.C. (2016) CRONUS-Earth cosmogenic 36Cl calibration. *Quaternary Geochronology*, 31, 199–219.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C. & Shackleton, N.J. (1987) Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000 year chronostratigraphy. *Quaternary Research*, 27, 1–29.

Mifflin, M.D. & Wheat, M.M. (1979) Pluvial lakes and estimated pluvial climates of Nevada. *Nevada Bureau of Mines and Geology, Bulletin*, no. 75, 45pp.

Osborn, G. (2001) Glaciation in the Great Basin of the Western United States. *Quaternary Science Reviews*, 20, 1377–1410.

Pierce, I.K.D., Wesnousky, S.G., Owen, L.A., Bormann, J.M., Li, X.N. & Caffee, M. (2021). Accommodation of plate motion in an incipient strike-slip system: the central Walker Lane, Tectonics 40.

Proffett, J.M. & Dilles, J.H. (1984). Geologic Map of the Yerington District, Nevada, Nevada Bureau of Mines and Geology Map 77 (1:24,000).

Prothero, D.R. & Schwab, R. (2013). Sedimentary Geology W. H. Freeman Press 3rd edition pp. 500.

Reheis, M.C. (1999a) Highest pluvial-lake shorelilnes and Pleistocene climate of the western Great Basin. *Quaternary Research*, 52, 196–205.

Reheis, M.C. (1999b). Extent of Pleistocene Lakes in the Western Great Basin, USGS Miscellaneous Field Studies Map MF-2323 scale 1:800,000.

Reheis, M.C., Adams, K.D., Oviatt, C.G. & Bacon, S.N. (2014) Pluvial lakes in the Great Basin of the western United States—a view from the outcrop. *Quaternary Science Reviews*, 97, 33–57.

Reheis, M.C., Sarna-Wojcicki, A.M., Reynolds, R.L., Repenning, C.A. & Mifflin, M.D. (2002) Pliocene to middle Pleistocene lakes in the western Great Basin: Ages and connections. *Great Basin Aquatic Systems History: Smithsonian Contributions To Earth Sciences*, 33, 53–108.

Rood, D.H., Burbank, D.W. & Finkel, R.C. (2011) Chronology of glaciations in the Sierra Nevada, California, from 10Be surface exposure dating. *Quaternary Science Reviews*, 30, 646–661.

Russell, I.C. (1885). Geological history of Lake Lahontan, a Quaternary lake of northwestern Nevada, in *Monograph XI of the Geological Survey*, Washington, DC, 288.

Russell, I.C. (1889). Qaternary history of Mono Valley, California, U. S. Geological Survey Eighth Annual Report, 1886-1887 261–394.

Snyder, C.T., Hardman, G. & Zdenek, F.F. (1964). Pleistocene lakes in the Great Basin, United States Geological Survey Miscellaneous Geologic Investigations Map I-416 Scale: 1,000,000.

Stauffer, H.L. (2003). Timng of the last highstand of fluvial Lake Wellington, Smith Valley, Nevada, in *Department of Geology*, San Jose State University, 107.

Stewart, J.H. (1980). Westward streamflow in Miocene of west-central Nevada, IN Geological Survey Research 1980: U.S. Geological Survey Professional Paper, 1175, p. 89., Geological Survey Research 1980: U.S. Geological Survey Professional Paper 1175 page 89.

Stewart, J.H., Brem, G.F. & Dohrenwend, J.C. (1989). Geologic Map of Desert Creek Peak quadrangle, Lyon and Douglas Counties, Nevada, and Mono County, California, U. S. Geological Survey Miscelleneous Field Studies.

Stewart, J.H. & Dohrenwend, J.C. (1984a). Geologic map of the Yerington 15-minute quadrangle, Nevada, United States Geological Survey Open-File Report 84-212.

Stewart, J.H. & Dohrenwend, J.C. (1984b). Geologic map of the Wellington Quadrangle, Nevada, United States Geological Survey Open-file report 84-211 (scale 1:62,500).

United States Geological Survey (2023). 3D Elevation Program 1-Meter Resolution Digital Elevation Model, https://apps.nationalmap.gov/viewer/ (accessed Jan 2023).

Utah_Geospatial_Data_Center (2023). Historic Lake Bonneville, GIS Data Layer https://gis.utah.gov/data/water/historic-lake-bonneville/ Accessd June 6, 2023.

Wesnousky, S.G. & Caffee, M. (2011) Range-bounding normal fault of smith valley, nevada: limits on age of last surface-rupture earthquake and late Pleistocene rate of displacement. *Bulletin of the Seismological Society of America*, 101, 1431–1437.

Yeend, W.E. (1974). Gold-bearing gravel of the ancestral Yuba River, Sierra Nevada, California, U. S. Geological Survey Professional Paper 772 44 p.

