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Terrestrial cosmogenic surface exposure dating of glacial and associated landforms in the Ruby Mountains-East Humboldt Range of central Nevada and along the northeastern flank of the Sierra Nevada

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ABSTRACT

Deposits near Lamoille in the Ruby Mountains-East Humboldt Range of central Nevada and at Woodfords on the eastern edge of the Sierra Nevada each record two distinct glacial advances. We compare independent assessments of terrestrial cosmogenic nuclide (TCN) surface exposure ages for glacial deposits that we have determined to those obtained by others at the two sites. At each site, TCN ages of boulders on moraines of the younger advance are between 15 and 30 ka and may be associated with marine oxygen isotope stage (MIS) 2. At Woodfords, TCN ages of boulders on the moraine of the older advance are younger than ~60 ka and possibly formed during MIS 4, whereas boulders on the correlative outwash surface show ages approaching 140 ka (~MIS 6). The TCN ages of boulders on older glacial moraine at Woodfords thus appear to severely underestimate the true age of the glacial advance responsible for the deposit. The same is possibly true at Lamoille where clasts sampled from the moraine of the oldest advance have ages ranging between 20 and 40 ka with a single outlier age of ~80 ka. The underestimations are attributed to the degradation and denudation of older moraine crests. Noting that boulder ages on the older advances at each site overlap significantly with MIS 2. We speculate that erosion of the older moraines has been episodic, with a pulse of denudation accompanying the inception of MIS 2 glaciation.

1. Introduction

Terrestrial cosmogenic nuclide (TCN) surface exposure dating of boulders is now frequently employed to estimate the age of glacial deposits and interpret the timing of late Pleistocene glacial advances and recessions (e.g., Owen et al., 2005; Gillespie and Clark, 2011; Jimenez-Sanchez et al., 2013). Application of the method remains challenging though because early stabilization and denudation of glacial landforms, as well as weathering, exhumation, prior exposure, and shielding of the surface that is being dated by snow and/or sediment reduces the concentration of TCNs, resulting in an underestimate of the true age of the landform (Hallet and Putkonen, 1994; Owen and Dortch, 2014). Alternatively, prior exposure of the boulder before deposition may result in an overestimation of the landform's age. Problems associated with the application of TCN methods to date moraines have been discussed in depth in numerous studies (Hallet and Putkonen, 1994; Benn and Owen, 2002; Putkonen and Swanson, 2003; Putkonen and O'Neal, 2006; Seong et al., 2007, 2009; Putkonen et al., 2008; Applegate et al., 2010; Chevalier et al., 2011; Owen and Dortch, 2014).

A number of investigators have used conventional and TCN studies to quantify rates of bare-rock weathering (Summerfield and Hulton, 1994; Brown et al., 1995; Bierman and Steig, 1996; Gosse et al., 1997; Fleming et al., 1999), and these rates are commonly cited and assumed when calculating surface exposure ages (e.g., Balco et al., 2008). Simultaneous measurement of multiple TCNs on boulders also affords a method to assess the exposure and erosion history of a clast (e.g., Klein et al., 1986; Lal, 1991; Nishiizumi et al., 1991). Similarly, models of surface degradation have been invoked to correct for the

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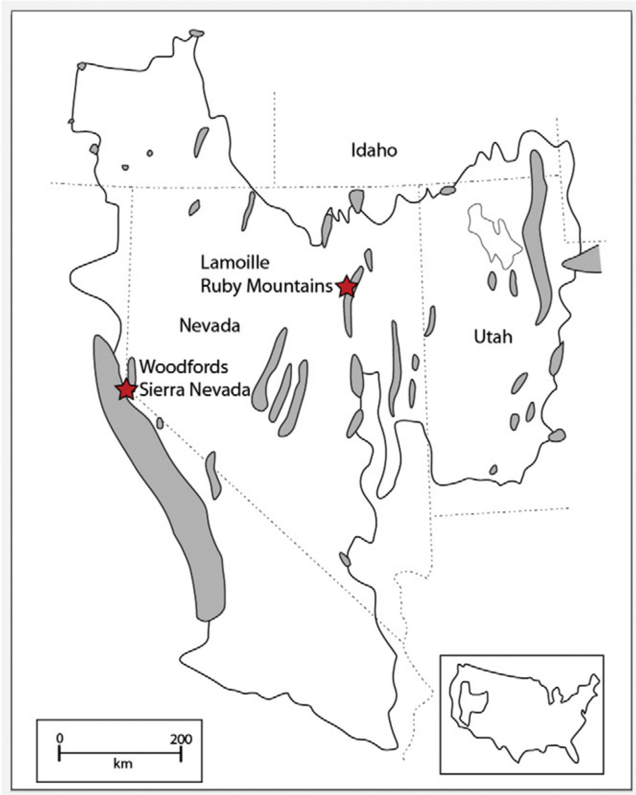

Fig. 1. Location of study areas on schematic map of glaciated ranges (shaded) draining into the Great Basin of the western United States (adapted from Osborn and Bevis (2001).

effect of denudation on TCN ages computed for samples on sloping unconsolidated deposits or, more specifically, glacial moraines (e.g., Putkonen and Swanson, 2003).

Assessing the uncertainties caused by weathering that are attendant to cosmogenic surface exposure age calculations nonetheless remains problematic, particularly for surfaces formed prior to the time period over which radiocarbon dating techniques may be employed to independently corroborate calculations (~40 ka). In this brief note we compare TCN dating of glacial deposits at two locations by different laboratories and investigators. The two locations are located between 38.5°and 40.5°N, along the east flank of the Sierra Nevada near the town of Woodfords in California and the western flank of the Ruby Mountains-East Humboldt Range adjacent to the town of Lamoille in central Nevada (Fig. 1). The results illustrate the significant impediment imposed by weathering processes to the use of TCN in confidently dating older glacial moraines at these two sites.

2. Glacial deposits and sample distributions at Woodfords and Lamoille

2.1. Woodfords, California, Sierra Nevada

Pleistocene moraines and outwash deposits are preserved at the eastern end of Hope Valley along the Carson River as it flows eastward from the Carson Range of the Sierra Nevada (Fig. 2). Similar moraines and associated outwash surfaces have long been recognized and studied along the eastern flank of the Sierra Nevada (Blackwelder, 1931; Birman, 1964; Burke and Birkeland, 1979; Gillespie and Clark, 2011). Other than appearing on the map of Armin and John (1983), a generalized sketch in Ramelli et al. (1999), and interpreted by Clark et al. (1984) in their estimation of California fault slip rates, little attention

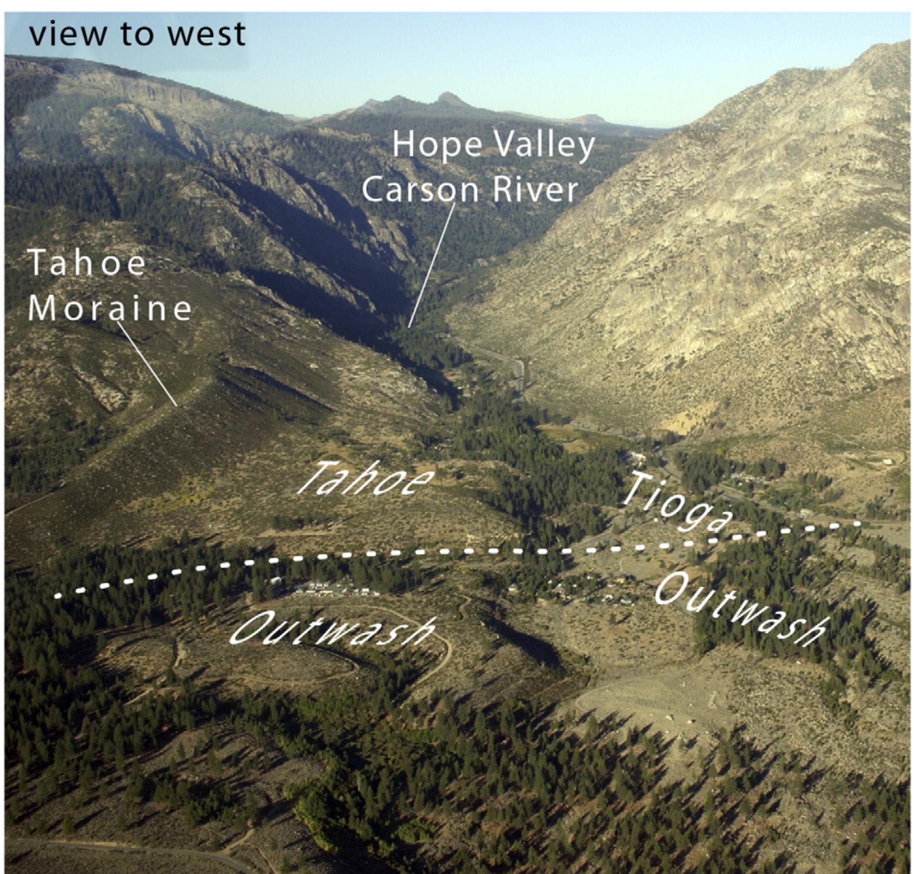

Fig. 2. Pleistocene glacial landforms and deposits preserved along the course of the east-flowing Carson River. Trace of Genoa fault is dashed line.

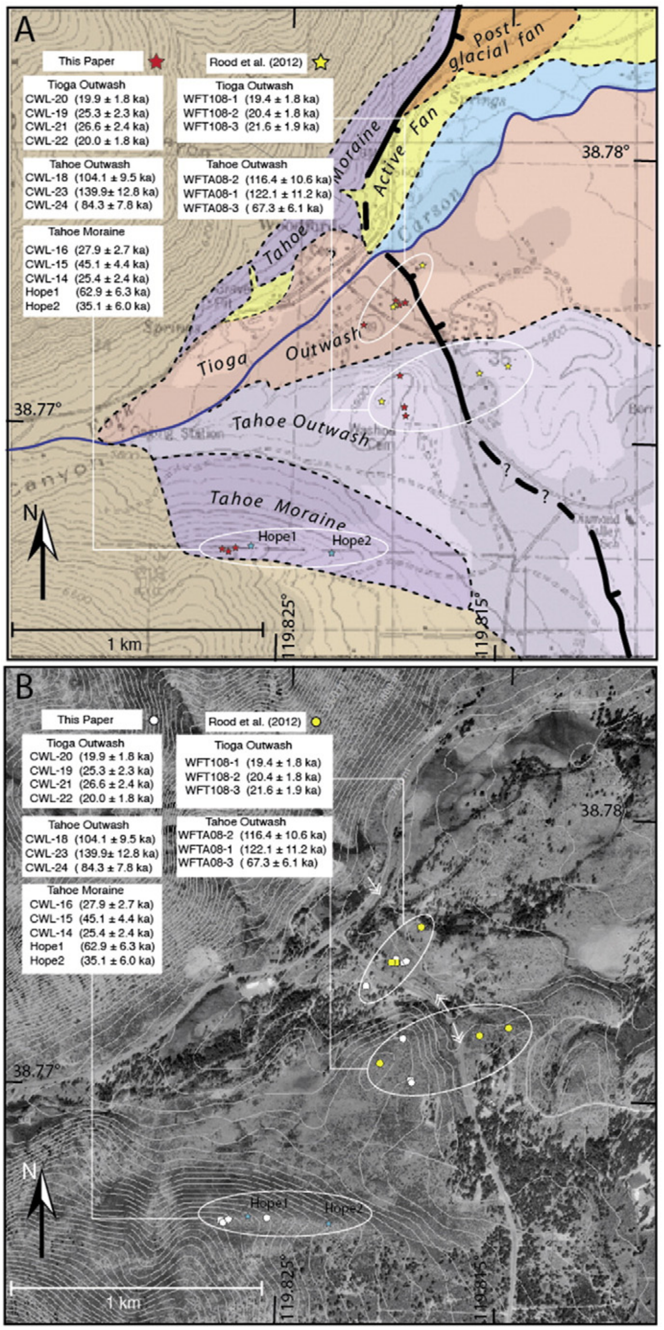

Fig. 3. Surficial geologic map (A) and orthophotoquad (B) showing locations of boulders sampled for ^{10}Be surface exposure dating by Rood et al. (2011a; yellow symbols) and this paper (white symbols).

has been paid to the deposits at Woodfords until the recent work of Rood et al. (2011a, b). They used ^{10}Be TCN surface exposure dating to determine the ages of a half-dozen boulders preserved on the glacial outwash surfaces. The distribution of their sample sites is shown on a surficial geologic map and orthophotoquad in Fig. 3. The labeling of map units follows that of Rood et al. (2011a) which in turn follows the tradition of Blackwelder's (1931) interpretation of glacial stages on the east side of the Sierra Nevada. Deposits of the most recent and penultimate major glacial advances were labeled by Blackwelder (1931) as the Tioga and Tahoe stages, respectively. Outwash deposits of the Tioga and Tahoe stages and a Tahoe moraine are present at Woodfords (Figs. 2 and 3). Samples of Rood et al. (2011a) were collected from the Tioga and Tahoe outwash surfaces. Concurrently, we collected samples for ^{10}Be surface exposure dating from boulders from the same two outwash surfaces sampled by Rood et al. (2011a) and also the correlative (Tahoe) moraine. The sample locations are also shown in Fig. 3.

2.2. Lamoille, Nevada, Ruby Mountains-East Humboldt Range

Evidence of glaciation was first recognized in the Ruby Mountains-East Humboldt Range by Hague and Emmons (1877) during the U.S. Geological Exploration of the Fortieth Parallel survey led by Clarence King. Blackwelder (1931) here interpreted, as he did in the Sierra Nevada, that glacial deposits record two major late Pleistocene glacial advances, which he correlated with the Tioga and Tahoe stages of glaciation in the Sierra Nevada. He named the two stages Angel Lake and Lamoille, respectively. Sharp (1938) shortly after conducted a detailed description of glacial deposits throughout the Ruby-East Humboldt Range and followed Blackwell (1931) in recognizing evidence of the two distinct Angel Lake and Lamoille late Pleistocene glacial advances. He too correlated the advances to the Tioga and Tahoe stages of glaciation in the Sierra Nevada. Fig. 4 provides a similar vantage point as the view displayed by Sharp (1938; his Fig. 6) to show the moraines he correlated to the Angel Lake and Lamoille stage glacial advances. The photo encompasses Seitz and Hennen canyons on the western flank of the range near the town of Lamoille, Nevada. Laabs et al. (2013) has recently reported ^{10}Be surface exposure ages for more than two dozen boulders distributed along the crests of the terminal and recessional moraines of the Angel Lake advance in Seitz Canyon. In an earlier unreported study, we collected boulders for ^{10}Be analysis from Angel Lake and from Lamoille age moraines in neighboring Hennen Canyon (Fig. 5). The sample locations of both studies are shown in Fig. 5.

3. Sampling and laboratory analysis

3.1. Prior studies

Rood et al. (2011a) and Laabs et al. (2013) provided detailed descriptions of their sampling methodologies at Woodfords and Lamoille, respectively. We followed the same approach. Samples were preferably taken from the outer 1 to 5 cm of the upper, preferably flat and least-weathered surfaces of the largest boulders located along and near the crests of moraines and, at Woodfords, an outwash surface. This particular constraint is relaxed with the (older) Lamoille moraine because large intact boulders are more infrequent than on the associated Angel Lake moraine (Sharp, 1938; Wayne, 1984) and so the bulk of collected samples were obtained from cobbles and small boulders. Glacial deposits at Woodfords contain primarily granite clasts, whereas at Lamoille the clasts include granites, gneisses, and quartzites. All samples were chemically isolated and prepared for $^{10}Be/^{9}Be$ measurements following or modified from the approaches of Kohl and Nishiizumi (1992); Ditchburn and Whitehead (1994); Bierman et al. (2002), and Munroe et al. (2006). Measurements of $^{10}Be/^{9}Be$ were made by accelerator mass spectrometry (AMS). Samples from Woodfords collected by Rood et al. (2011a) were prepared and analyzed at the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Lab, whereas in this study we conducted sample preparation and AMS measurements at the Purdue University Rare Isotope Measurement (PRIME) Laboratory. Samples collected at Lamoille by Laabs et al. (2013) were prepared at SUNY Genesco and the AMS analyses conducted at PRIME Laboratory. The samples we collected at Lamoille were prepared and measured with AMS at CAMS.

Exposure-age calculations by Laabs et al. (2013) and Rood et al. (Rood et al., 2011a,b) were made with the CRONUS-Earth online exposure age calculator, vers. 2.2 (hess.ess.washington.edu/math/; Balco

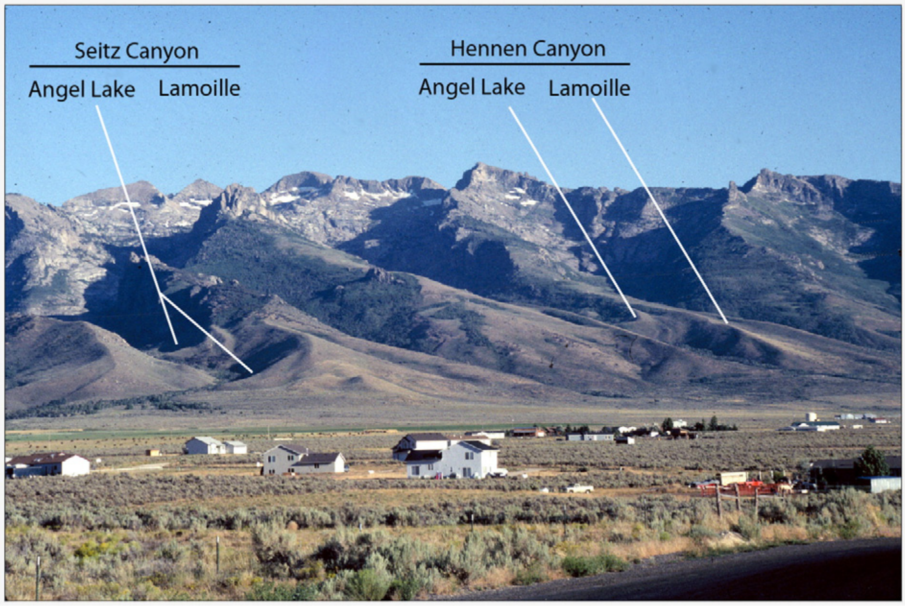

Fig. 4. View eastward showing Angel Lake and Lamoille stage moraines of Seitz and Hennen canyons in the Ruby-East Humboldt Range. Assignment of stages follows Sharp (1938).

et al., 2008) and include corrections for finite sampling depth, shielding (according to Lal, 1991), and boulder erosion. In this paper, we use the same CRONUS vers. 2.2 age calculator for samples we have collected and processed to determine exposure ages. Zero erosion is assumed for all samples. In this regard, we have recalculated exposure ages of a subset of Laabs et al.'s (2013) samples for which they assumed an erosion rate. The resulting difference in ages from those published in Laabs et al. (2013) is generally <1 ka, a difference that is not significant to the aims of this study. The inputs to the CRONUS calculator and the resulting exposure age estimates and uncertainties are summarized for all samples in Table 1.

4. Geomorphology

4.1. Woodfords

The Tioga outwash surface is inset to the Tahoe outwash surface and is thus younger (Figs. 2 and 3). A similar relationship requires that the Tahoe outwash surface is younger than the Tahoe moraine: it sits below and is inset into the Tahoe moraine. The geomorphology thus preserves three surfaces or deposits of relatively increasing age: the youngest Tioga outwash, the intermediate Tahoe outwash surface, and the oldest Tahoe moraine.

4.2. Lamoille, Ruby Mountains-East Humboldt Range

Geomorphic relationships are straightforward at Seitz and Hennen canyons (Figs. 4 and 5). Moraines identified as Angel Lake stage are clearly inset into those interpreted to be of older Lamoille stage. Both we and Laabs et al. (2013) collected samples on Angel Lake stage moraines, albeit in separate though directly adjacent canyons. Similar to the Woodfords site, geomorphic relations in Hennen and Seitz canyons require that Angel Lake moraines and outwash be younger than the mapped Lamoille moraines.

5. Comparison of results

The ages of all samples are summarized in Fig. 6 and Table 1. The vertical axis of the plot is exposure age. Individual samples are ordered from left to right in Fig. 6 according to the sample numbers in Table 1 and grouped according to their location. The uncertainty bars represent the 1σ external uncertainties output by CRONUS. The values on the left side of the plot are for samples collected from the Tioga and Tahoe outwash and Tahoe moraine surfaces at Woodfords. Values to the right are from the samples collected from Angel Lake and Lamoille moraines in Seitz and Hennen canyons near Lamoille. The blue and red symbols denote samples collected by Rood et al. (2011a) and Laabs et al. (2013), respectively, whereas those that are black are from this study.

5.1. Woodfords

The morphostratigraphic relationships of the surfaces we sampled are not reflected in the progression of TCN ages. The Tahoe moraine exhibits younger exposure ages than the Tahoe outwash surface, sufficiently young that some also overlap with the ages obtained for the Tioga outwash surface; thus violating the stratigraphic relationships observed at the site. Both we and Rood et al. (2011a) collected and processed samples on the Tioga and Tahoe outwash surfaces. Exposure ages from the studies are respectively similar for the two surfaces. The ages for the Tioga outwash surfaces are generally quite tightly clustered and fall between 20 and 25 ka (Fig. 6). Both studies also show a general agreement of ages on the Tahoe outwash surface, displaying a broad range of ages ranging between about 80 and 160 ka (Fig. 6). Ages on the Tahoe moraine are limited to those collected in our study: Rood et al. (2011a) did not report ages on the Tahoe moraine. The similarity in ages obtained from sample preparation and AMS measurement from different laboratories for the Tioga and Tahoe outwash surfaces provides confidence in our sampling and laboratory methods. Following this logic, the young ages obtained on the Tahoe moraine that violate geomorphic relations are most reasonably explained by a geologic process that has limited the time that boulders on the surface of the moraine have been exposed to cosmogenic radiation since deposition: either boulder weathering or denudation.

5.2. Lamoille, Ruby Mountains-East Humboldt Range

Surface exposure age determinations for Angel Lake moraines from the Laabs et al. (2013) and our study agree well and range between

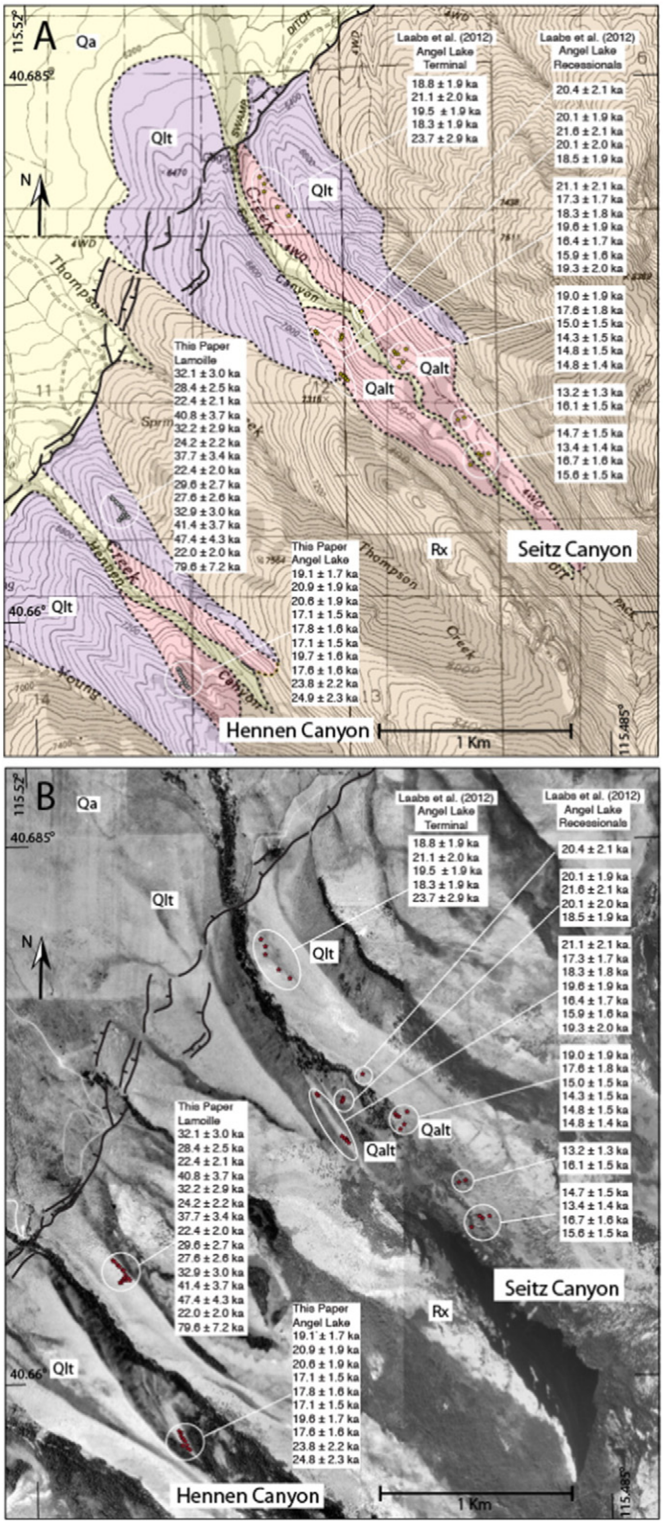

Fig. 5. Surficial geologic map (A) and orthophotoquad (B) showing locations of boulders sampled for ^{10}Be surface exposure dating by Laabs et al. (2013; along Hennen Canyon) and this paper (along Seitz Canyon).

~15 and 25 ka (Fig. 6). The younger ages are generally obtained from recessional moraines located relatively higher in Seitz Canyon (Figs. 4 and 5; Laabs et al., 2013). The agreement between the surface exposure ages determined from the separate laboratories, as at Woodfords, gives further assurance that resulting ages from each study are not biased by any collection, processing, or analytic errors. Surface exposure ages for the older Lamoille moraine are limited to our study in Hennen Canyon and were obtained from transects along the moraine crest and flank (Figs. 4 and 5). The surface exposure ages show a broader range of values than found on the younger Angel Lake surfaces, ranging from about 20 to 40 ka for the samples on the crest and flank of the moraine, with the exception of a singular outlier of ~80 ka for a sample on its flank.

6. Discussion

Periodic changes in the oxygen isotope composition of benthic and planktonic foraminifera recorded in deep-sea cores are ascribed to global changes in the temperature and isotopic composition of the oceans that accompany the extraction of large amounts of water from the oceans during glacial periods (Olausson, 1963; Shackleton, 1967). A portion of the marine oxygen isotope record is shown in Fig. 7 (Hays et al., 1976; Martinson et al., 1987b). Following the system introduced by Arrhenius (1952), periods of warm and cold are referred to as stages, with stage 1 designating the present warm period and preceding stages labeled with increasing positive integers, with odd values indicating warm stages and even cold. Moraines mark periods of glacial advances. It has been common practice to compare ages determined for glacial moraines to the marine oxygen isotope record and the results of similar nearby studies. For convenience of discussion, we do the same here (Fig. 7).

6.1. Woodfords

The Tioga outwash deposits are the youngest glacial deposits preserved at Woodfords (Figs. 2 and 6). The range of boulder exposure ages on the outwash surface correlate to marine oxygen isotope stage (MIS) 2, and like the youngest moraine and outwash deposits recorded elsewhere along the Sierran front to the south, they are attributed to the global last glacial maximum (LGM; Gillespie and Clark, 2011; Rood et al., 2011a). The older boulder ages (80–160 ka) on the Tahoe outwash are consistent with geomorphic relations but difficult to readily interpret in the context of the marine oxygen isotope record. The exposure ages span nearly the entirety of MIS 5 and 6. Rood et al. (2011a) correlated the outwash deposits to the last advance of MIS 6 glaciation on the basis of surface exposure ages determined for boulders on similarly situated glacial moraine and outwash deposits elsewhere to the south along the eastern flank of the Sierra Nevada. In contrast, the younger ages (~25 to 67 ka) of boulders on the Tahoe moraine are not consistent with geomorphology. On the basis of geomorphic position, they should be equal to or older than the 80–150 ka year span of ages on the Tahoe outwash, yet instead they in fact display an overlap with range of boulder exposure ages for the Tioga outwash surface.

Accepting the absence of any error in collection and processing of samples, the young ages found for the Tahoe moraine are most readily interpreted to be the result of erosion or denudation. Hein et al. (2009) have documented moraine boulders in Patagonia that are significantly younger (~100 ka) than adjacent outwash, concluding that flat outwash surfaces are more stable for TCN dating than steep-sided moraines where degradation leads to exhumation of moraine boulders. This may explain the young ages observed on the Tahoe moraine crest at Woodfords. The geomorphic expression of the Tahoe moraine remains quite sharp with numerous large boulders along the crest (Figs. 2 and 8), and while weathering of the boulder clasts is evident on the moraine crest, it is no more so than observed on boulders dating to >100 ka on the broader low-lying Tahoe outwash surface (Fig. 8e). Clearly, if we sampled boulders only from the moraine, the age of the Tahoe glacial advance here would likely be significantly underestimated. The result at this site is at odds with the common assumption, derived largely from numerical landscape denudation models, that moraine crest lowering rates diminish quickly with time and that relatively few TCN ages from older moraine crests are required

Table 1
Data table.

Sample name	Latitude	Longitude	Elevation	Thickness	Shielding (horizon)	Measured 10Be/g quartz	±	Plotting number	Lal (1991)/Stone (2000) Const. prod. Model	σ (ka) external	Lal (1991)/Stone (2000) Time-Dependent Model	σ (ka) external
	(DD)	(DD)	(m)	(cm)	correction	[Be-10] atoms g^{-1}	atoms g^{-1}		Age (ka)		Age (ka)	
Woodfords (this paper)[a]												
Tioga outwash												
CWL19	38.7747	119.8210	1711	3	0.9933	4.04E + 05	1.09E + 04	1	25.3	2.3	24.7	2.2
CWL20	38.7737	119.8224	172	3	0.9922	3.21E + 05	8.69E + 03	2	19.9	1.8	19.7	1.8
CWL21	38.7746	119.8206	1715	4	0.9940	4.22E + 05	1.08E + 04	3	26.6	2.4	25.9	2.3
CWL22	38.7747	119.8206	1716	4.5	0.9940	3.17E + 05	6.91E + 03	4	20.0	1.8	19.8	1.7
Tahoe outwash												
CWL18	38.7719	119.8206	1816	2.5	0.9964	1.77E + 06	3.27E + 04	14	104.1	9.5	97.0	8.6
CWL23	38.7705	119.8202	1770	3	0.9953	2.27E + 06	3.65E + 04	15	139.9	12.8	128.0	11.3
CWL24	38.7704	119.8201	1772	3	0.9970	1.39E + 06	3.77E + 04	16	84.3	7.8	78.8	7.1
Tahoe Moraine										0.0	0.0	0.0
CWL14	38.7653	119.8286	1919	2	0.9961	4.75E + 05	1.69E + 04	26	25.4	2.4	24.8	2.3
CWL15	38.7652	119.8285	1922	4	0.9958	8.28E + 05	3.59E + 04	27	45.1	4.4	42.0	4.0
CWL16	38.7653	119.8282	1920	2	0.9958	5.22E + 05	2.33E + 04	28	27.9	2.7	27.1	2.6
HOPE1	38.7655	−119.8264	1905	2	1.0000	1.13E + 06	5.26E + 04	29	62.9	6.3	58.9	5.8
HOPE2	38.7654	−119.8224	1853	2	1.0000	6.12E + 05	8.87E + 04	30	35.1	6.0	33.3	5.6
Ruby Mountains, Hennon Canyon (this paper)[b]												
Angel Lake Moraine												
A-01	40.6577	115.5113	2264	7.0	0.94	4.25E + 05	1.10E + 04	74	19.1	1.7	19.0	1.7
A-02	40.6577	115.5112	2266	4.0	0.96	4.87E + 05	1.25E + 04	75	20.9	1.9	20.7	1.8
A-03	40.6576	115.5112	2268	5.0	0.95	4.71E + 05	1.21E + 04	76	20.6	1.9	20.4	1.8
A-04	40.6575	115.5112	2270	7.0	0.94	3.82E + 05	9.99E + 03	77	17.1	1.6	17.1	1.5
A-05	40.6574	115.5111	2273	6.0	0.94	4.02E + 05	1.04E + 04	78	17.8	1.6	17.8	1.6
A-06	40.6573	115.5110	2275	6.0	0.94	3.85E + 05	1.01E + 04	79	17.1	1.6	17.0	1.5
A-07	40.6571	115.5109	2279	3.5	0.97	4.68E + 05	1.26E + 04	80	19.7	1.8	19.5	1.7
A-08	40.6571	115.5109	2278	3.5	0.97	4.20E + 05	1.06E + 04	81	17.6	1.6	17.6	1.6
A-09	40.6570	115.5108	2282	2.5	0.97	5.73E + 05	1.40E + 04	82	23.8	2.2	23.4	2.1
A-10	40.6569	115.5107	2281	2.0	0.98	6.06E + 05	1.77E + 04	83	24.9	2.3	24.4	2.2
Lamoille Moraine												
L-01	40.6658	115.5152	2100	3	0.97	6.78E + 05	2.16E + 04	87	32.1	3.0	31.0	2.8
L-02	40.6657	115.5151	2103	4.5	0.96	5.87E + 05	1.10E + 04	88	28.4	2.5	27.6	2.4
L-03	40.6657	115.5151	2103	5.5	0.95	4.55E + 05	1.28E + 04	89	22.4	2.1	22.1	2.0
L-04	40.6656	115.5149	2109	5.0	0.95	8.33E + 05	1.98E + 04	90	40.8	3.7	38.7	3.4
L-05	40.6655	115.5148	2110	5.0	0.95	6.60E + 05	1.58E + 04	91	32.2	2.9	31.1	2.7
L-06	40.6653	115.5146	2119	6.0	0.94	4.91E + 05	1.21E + 04	92	24.2	2.2	23.8	2.1
L-07	40.6653	115.5145	2120	5.5	0.95	7.74E + 05	1.84E + 04	93	37.7	3.4	36.0	3.2
L-08	40.6651	115.5144	2123	3.5	0.97	4.79E + 05	1.18E + 04	94	22.4	2.0	22.1	1.9
L-09	40.6649	115.5142	2127	5.0	0.95	6.13E + 05	1.49E + 04	95	29.6	2.7	28.7	2.5
L-10	40.6648	115.5141	2131	5	0.95	5.75E + 05	2.09E + 04	96	27.6	2.6	27.0	2.5
L-11	40.6649	115.5144	2124	7.0	0.93	6.55E + 05	1.65E + 04	101	32.9	3.0	31.7	2.8
L-12	40.6649	115.5146	2121	4.5	0.95	8.55E + 05	2.04E + 04	102	41.4	3.8	39.2	3.5
L-13	40.6647	115.5147	2110	4.5	0.95	9.72E + 05	2.08E + 04	103	47.4	4.3	44.5	3.9
L-14	40.6647	115.5146	2115	10	0.9	4.13E + 05	1.04E + 04	104	22.0	2.0	21.7	1.9
L-15	40.6649	115.5145	2097	5.0	0.94	1.58E + 06	2.70E + 04	105	79.6	7.2	75.0	6.6
Woodfords (Rood et al. (2011a,b))												
Tioga Outwash												
WFTI08–1	38.7759	−119.8199	1691	3	0.994	2.99E + 05	7.20E + 03	8	19.4	1.8	19.0	1.7
WFTI08–2	38.7746	−119.821	1712	2	0.993	3.22E + 05	7.90E + 03	9	20.4	1.9	20.0	1.8
WFTI08–3	38.7746	−119.8212	1713	5	0.993	3.32E + 05	7.90E + 03	10	21.6	2.0	21.1	1.9
Tahoe Outwash										0.0	0.0	0.0
WFTA08–1	38.7721	−119.8171	1663.	4	0.985	1.77E + 06	3.17E + 04	20	122.1	11.2	112.6	10.0
WFTA08–2	38.7724	−119.8158	1725	3	0.991	1.79E + 06	2.66E + 04	21	116.4	10.6	107.5	9.5
WFTA08–3	38.771	−119.8216	1789	3	0.995	1.10E + 06	2.11E + 04	22	67.3	6.1	63.1	5.5
Ruby Mountains, Seitz Canyon (Laabs et al. (2013))												
Angel Lake Terminal Moraine												
SC-17	40.6805	−115.5059	1991	3	0.99545	3.70E + 05	1.90E + 04	65	18.8	1.9	18.6	1.8
SC-18	40.6802	−115.5056	1998	4	0.99479	4.13E + 05	1.70E + 04	66	21.1	2.0	20.8	2.0
SC-19	40.6798	−115.5056	2007	6	0.99441	3.77E + 05	1.60E + 04	67	19.5	1.9	19.2	1.8
SC-20	40.6791	−115.5048	2028	5.5	0.99645	3.62E + 05	2.10E + 04	68	18.3	1.9	18.1	1.9
SC-21	40.6787	−115.5041	2040	4	0.99414	4.76E + 05	4.00E + 04	69	23.7	2.9	23.1	2.8
Angel Lake Recessional Moraines												
SC-1	40.671	−115.5007	2173	5	0.992	4.60E + 05	2.00E + 04	38	21.1	2.1	20.7	2.0
SC-2	40.6711	−115.5008	2170	5.5	0.992	3.75E + 05	1.60E + 04	39	17.3	1.7	17.1	1.6
SC-3	40.6712	−115.5009	2169	7	0.995	3.92E + 05	2.10E + 04	40	18.3	1.9	18.0	1.8
SC-4	40.6712	−115.501	2169	3	0.995	4.33E + 05	1.70E + 04	41	19.6	1.9	19.2	1.8

(continued on next page)

Table 1 (*continued*)

Sample name	Latitude (DD)	Longitude (DD)	Elevation (m)	Thickness (cm)	Shielding (horizon) correction	Measured 10Be/g quartz [Be-10] atoms g^{-1}	± atoms g^{-1}	Plotting number	Lal (1991)/Stone (2000) Const. prod. Model Age (ka)	σ (ka) external	Lal (1991)/Stone (2000) Time-Dependent Model Age (ka)	σ (ka) external
SC-5	40.6713	−115.5011	2168	5	0.995	3.56E + 05	2.10E + 04	42	16.4	1.7	16.2	1.7
SC-6	40.6732	−115.5025	2125	3	0.995	3.42E + 05	1.60E + 04	43	15.9	1.6	15.8	1.5
SC-7	40.6733	−115.5026	2119	4	0.995	4.09E + 05	2.30E + 04	44	19.3	2.0	19.0	1.9
SC-22	40.6729	−115.5011	2116	6	0.989	4.17E + 05	1.70E + 04	45	20.1	1.9	19.8	1.9
SC-23	40.673	−115.501	2113	5	0.989	4.49E + 05	1.80E + 04	46	21.6	2.1	21.1	2.0
SC-24	40.6729	−115.5011	2115	4	0.989	4.23E + 05	1.80E + 04	47	20.1	2.0	19.8	1.9
SC-25	40.6731	−115.501	2112	5	0.989	3.85E + 05	2.10E + 04	48	18.5	1.9	18.2	1.8
SC-26	40.6742	−115.4998	2104	5.	0.989	4.22E + 05	2.10E + 04	49	20.4	2.1	20.0	2.0
SC-30	40.6724	−115.4971	2123	5	0.981	3.96E + 05	2.00E + 04	50	19.0	1.9	18.7	1.8
SC-32	40.6722	−115.4977	2110	2	0.981	3.72E + 05	1.90E + 04	51	17.6	1.8	17.3	1.7
SC-33	40.6722	−115.4976	2112	3	0.981	3.16E + 05	1.50E + 04	52	15.0	1.5	14.9	1.4
SC-34	40.6723	−115.4978	2110	3	0.981	3.00E + 05	1.80E + 04	53	14.3	1.5	14.2	1.5
SC-28	40.6716	−115.4975	2110	5	0.985	3.07E + 05	1.60E + 04	54	14.8	1.5	14.7	1.5
SC-29	40.6718	−115.4973	2114	0	0.986	3.22E + 05	1.40E + 04	55	14.8	1.4	14.7	1.4
SC-38	40.6692	−115.4936	2140	2	0.963	2.81E + 05	1.20E + 04	56	13.2	1.3	13.2	1.2
SC-39	40.6691	−115.494	2145	6	0.951	3.27E + 05	1.30E + 04	57	16.1	1.5	15.9	1.5
SC-41	40.6675	−115.4922	2148	5	0.95	3.02E + 05	1.60E + 04	58	14.7	1.5	14.6	1.5
SC-42	40.6674	−115.4926	2144	7	0.945	2.69E + 05	1.50E + 04	59	13.4	1.4	13.3	1.4
SC-43	40.6675	−115.4928	2144	5.5	0.953	3.42E + 05	1.40E + 04	60	16.7	1.6	16.5	1.6
SC-44	40.667	−115.4933	2145	9	0.944	3.07E + 05	1.30E + 04	61	15.6	1.5	15.4	1.5

[a] Samples collected and analyzed in 2008 to 2010.
[b] Samples collected and analyzed in 2003/4. All sample ages computed from listed variables using Vers. 2.2 of Cronus age calculator (hess.ess.washington.edu/math/: Balco et al., 2008) and sample densities of 2.7 g/cm^3, the production rate standard 07KNSTD and standard (std) elevation flag of the CRONUS calculator, and zero boulder erosion rate.

to approximate timing of emplacement (e.g., Putkonen and Swanson, 2003). The possibility of course remains that sampling a yet greater number of boulders would yield samples with ages in concert with geomorphic relationships.

6.2. Lamoille, Nevada, Ruby Mountains-East Humboldt Range

The observations at Woodfords provide context to interpret the results obtained for the moraine deposits at Lamoille. The ages of boulders collected from younger Angel Lake moraine deposits are consistent with an MIS 2 last glacial maximum of about 20 ka (Figs. 6 and 7). As at Woodfords, exposure ages from the older (in this case Lamoille) moraine overlap with the ages found for boulders on the Angel Lake moraine. The Lamoille ages average ~30 ka and exhibit an outlier of 80 ka. The outlier may be the result of inheritance, though the likelihood appears small in light of studies that report only a few percent of dated moraine boulders have had prior exposure (Putkonen and Swanson, 2003; Heyman et al., 2011; Murari et al., 2014). Taking the TCN ages at face value, the observations would place the Lamoille advance not soon before that of Angel Lake, and thus both possibly of MIS 2 age.

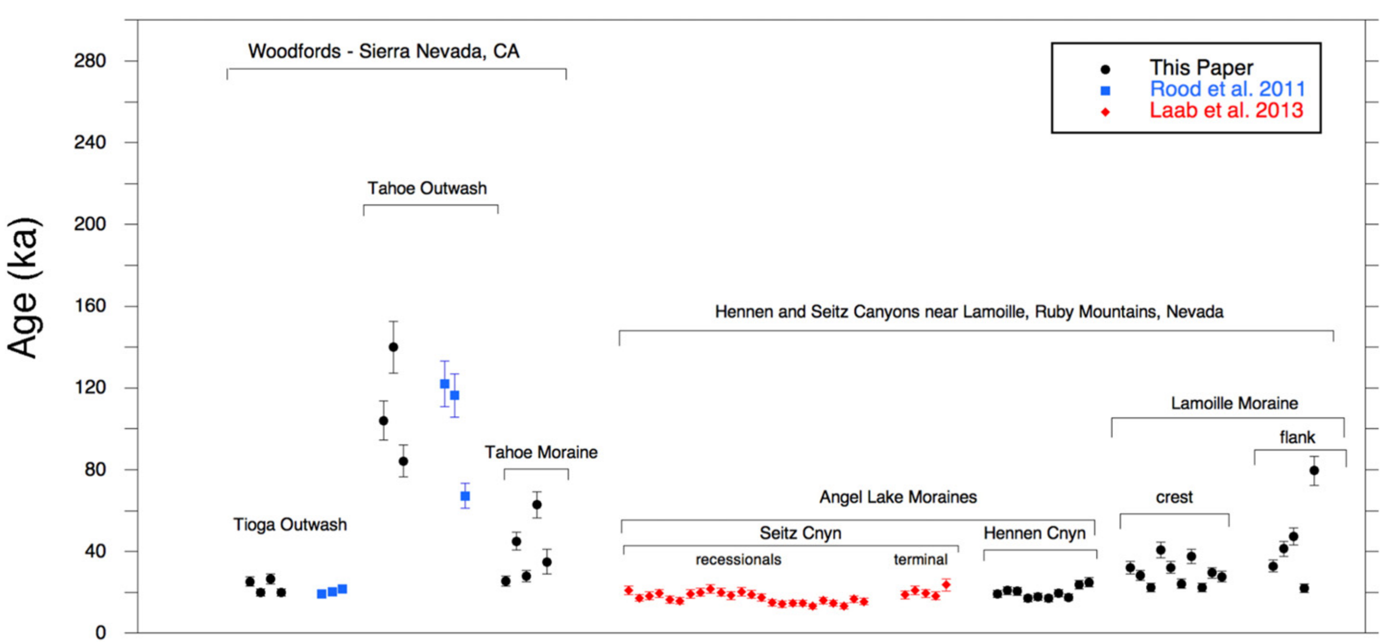

Fig. 6. Comparison of TCN exposure ages determined from different investigators on glacial moraines and outwash surfaces near Woodfords, California (Figs. 2 and 3) along the east flank of the northern Sierra Nevada and near the town of Lamoille along the west flank of the Ruby Mountains, Nevada (Figs. 4 and 5). Red and blue symbols are ages for samples previously collected and analyzed by Rood et al. (2011a) and Laabs et al. (2013), and black symbols are those from this study. The samples are ordered from left to right according to sample number in Table 1 and grouped according to the respective sites and glacial deposits.

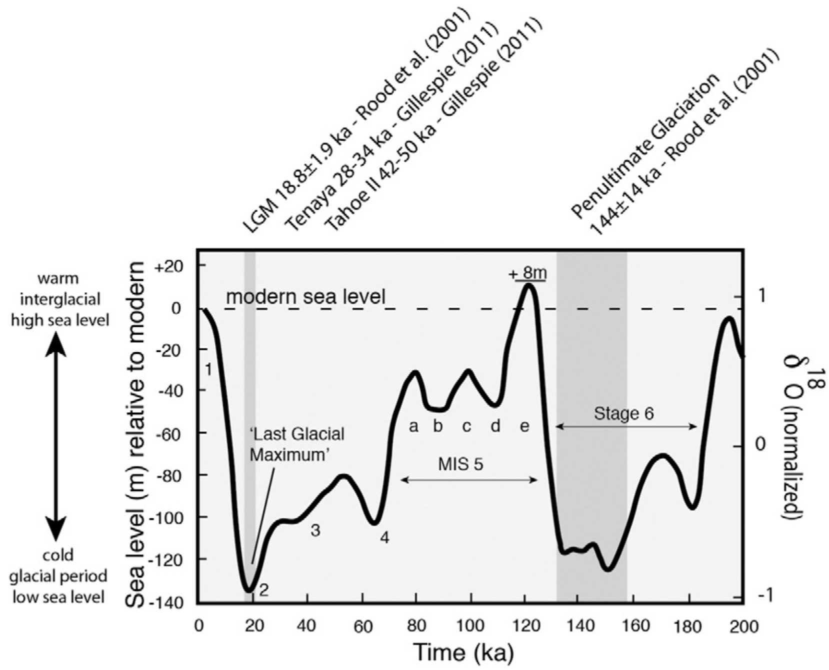

Fig. 7. Marine oxygen isotope record and approximate global sea level curve adapted from Martinson et al. (1987a). Ages of last glacial maximum and penultimate glaciation interpreted by Rood et al. (2011a) are shaded and correlate with stages 2 and 6 of the marine oxygen isotope record. Deposits of previously recognized glaciations summarized in Gillespie and Clark (2011) and referred to as Tenaya and Tahoe II were not unequivocally recognized by Rood et al. (2011a).

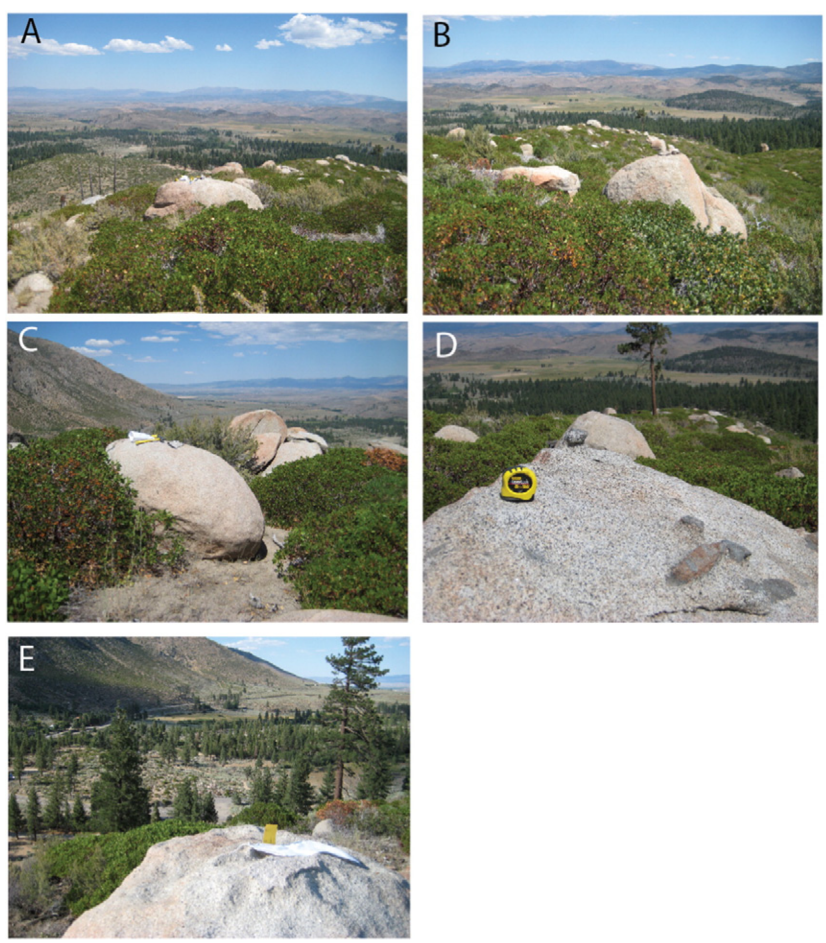

Fig. 8. (A) View eastward of numerous large boulders along Tahoe moraine crest at Woodfords. Boulder in foreground is CWL-14 (TCN age 25.4 ka). (B) Boulder in foreground is CWL-15 (TCN age 46,755 ka). (C) Boulder CWL-16 (TCN age 27.9 ka) (D) Characteristic of boulder erosion observed on unsampled boulder observed along Tahoe moraine crest at Woodfords. (E) Characteristics of boulder erosion observed on this (Sample CWL-18 TCN age 104.1 ka) on Tahoe outwash surface are not discernibly different than observed for boulders on moraine crest.

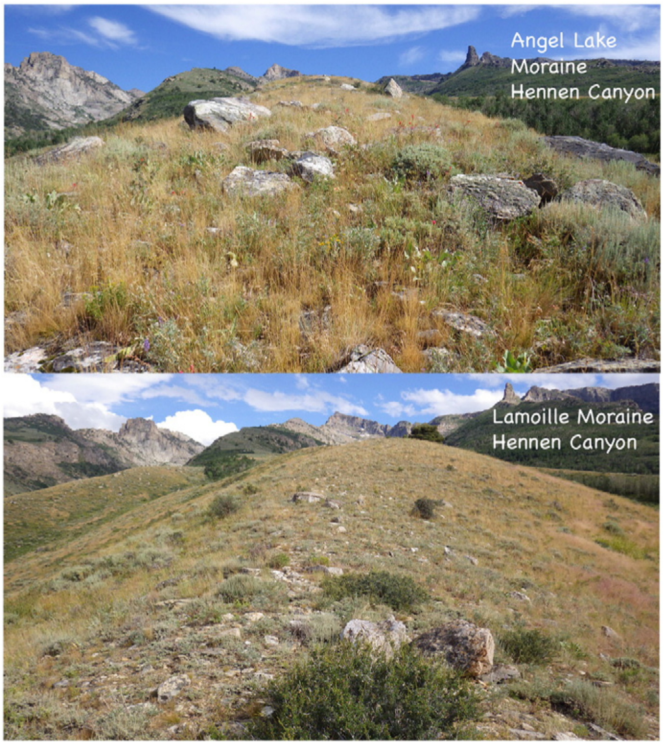

Fig. 9. Northward views along crests of Angel Lake and Lamoille moraines at Hennen Canyon illustrates greater abundance of large boulders on younger Angel Lake moraine.

Ignoring the possibility of inheritance and accepting boulder erosion, the oldest 80 ka value may be interpreted as a minimum age of the Lamoille moraine, and possibly correlate with MIS 4 (Fig. 7). Major glacial advances of MIS 2 and 6 are recorded at similar sites in the continental interior near Yellowstone and the Wind River Range, but not MIS 4 (Phillips et al., 1997; Licciardi and Pierce, 2008). In this context and in light of observations at Woodfords, and the relative lack of boulders on the older Lamoille moraine as compared to the younger Angel Lake moraine (Fig. 9), we cannot rule out that the older Lamoille moraine is yet much older than the oldest 80 ka sample, perhaps even as old as MIS 6 (penultimate glacial).

7. Conclusion

Moraines and outwash deposits near Lamoille in the Ruby Mountains-East Humboldt Range of central Nevada and at Woodfords on the eastern edge of the Sierra Nevada each record two distinct glacial advances. We have compared independent assessments of TCN surface exposure ages of glacial deposits that we have determined to those reported by others at the two sites. At each site, TCN ages of boulders on moraines of the younger advance are generally between 15 and 30 ka and probably formed during the latter part of MIS 2. At Woodfords, TCN ages of boulders on the moraine of the older advance are between 25 ka and 65 ka (MIS 4), whereas boulders on the correlative outwash surface have ages approaching ~150 ka (MIS 6). The TCN ages of boulders on older glacial moraine at Woodfords thus appear to severely underestimate the true age of the glacial advance responsible for the landforms and deposits. The same is possibly true at Lamoille where boulders sampled from the moraine of the oldest advance have ages ranging from 20 to 40 ka with a single outlier age of ~80 ka. The underestimations are attributed to the greater degradation and denudation of older moraine crests at the two sites. Finally, noting that boulder ages on the older advances at each site overlap significantly with MIS 2, one may speculate that erosion of the older moraines has been episodic, with a pulse of denudation accompanying the inception of MIS 2 glaciation.

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References

Applegate, P.J., Urban, N.M., Laabs, B.J.C., Keller, K., Alley, R.B., 2010. Modeling the statistical distributions of cosmogenic exposure dates from moraines. Geosci. Model Dev. 3 (1), 293–307.
Armin, R.A., John, D.A., 1983. Geologic Map of the Freel Peak 15-minute Quadrangle, California and Nevada. U. S. Geological Survey Miscellaneous Investigations Series, Map pp. 1–1424.
Arrhenius, G., 1952. Sediment cores from the east Pacific. Swedish Deep-Sea Expedition, 1947–1948, Repts., 5, p. 227.
Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J., 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from (10)Be and (26)Al measurements. Quat. Geochronol. 3 (3), 174–195.
Benn, D.I., Owen, L.A., 2002. Himalayan glacial sedimentary environments: a framework for reconstructing and dating the former extent of glaciers in high mountains. Quat. Int. 97-8, 3–25.
Bierman, P., Steig, E.J., 1996. Estimating rates of denudation using cosmogenic isotope abundances in sediment. Earth Surf. Process. Landf. 21 (2), 125–139.
Bierman, P.R., Davis, M.W., Marsella, K., Pavich, M., Colgan, P., Mickelson, D., Larsen, J., 2002. In: Grew, E.S. (Ed.), Mineralogy, Petrology and Geochemistry Review Mineral Geochemica, pp. 147–205.
Birman, J.H., 1964. Glacial geology across the crest of the Sierra Nevada, California. Geol. Soc. Am. Spec. Pap. 75, 78.
Blackwelder, E.B., 1931. Pleistocene glaciation in the Sierra Nevada and Basin Ranges. Geol. Soc. Am. Bull. 42, 865–922.
Brown, E.T., Stallard, R.F., Larsen, M.C., Raisbeck, G.M., Yiou, F., 1995. Denudation rates determined from the accumulation of in situ-produced BE-10 in the Luquillo Experimental Forest, Puerto Rico. Earth Planet. Sci. Lett. 129 (1–4), 193–202.
Burke, R.M., Birkeland, P.W., 1979. Re-evaluation of multi-parameter relative dating techniques and their application to the glacial sequence along the eastern Escarpment of the Sierra-Nevada, California. Quat. Res. 11 (1), 21–51.
Chevalier, M.-L., Hilley, G., Tapponnier, P., Van Der Woerd, J., Jing, L.-Z., Finkel, R.C., Ryerson, F.J., Li, H., Liu, X., 2011. Constraints on the late Quaternary glaciations in Tibet from cosmogenic exposure ages of moraine surfaces. Quat. Sci. Rev. 30 (5–6), 528–554.
Clark, M.M., K.H.K., Lienkaemper, J.J., Harwood, D.S., Lajoie, K.R., Matti, J.C., Perkins, J.A., Rymer, M.J., Sarna-Wojcicki, A.M., Sharp, R.V., Sims, J.D., Tinsley, J.C., Ziony, J.I., 1984. Preliminary slip-rate table and map of late-Quaternary faults of California. U. S. Geological Survey open-file report, 84–106, pp. 12 with 16 plates.
Ditchburn, R.G., Whitehead, N.E., 1994. The separation of ^{10}Be from silicates. 3d Workshop of the South Pacific Environmental Radioactivity Association, pp. 4–7.
Fleming, A., Summerfield, M.A., Stone, J.O., Fifield, L.K., Cresswell, R.G., 1999. Denudation rates for the southern Drakensberg escarpment, SE Africa, derived from in-situ-produced cosmogenic Cl-36: initial results. J. Geol. Soc. 156, 209–212.
Gillespie, A.R., Clark, D.H., 2011. Glaciations of the Sierra Nevada, California, USA. In: Eheler, J., Gibard, P.L., Hughes, P.D. (Eds.), Quaternary Glaciations - Extent and Chronology. Elsevier Ltd., 2011, pp. 447–462.
Gosse, J.C., Dort, W., Sorenson, C., Steeples, D., Grimes, J., Hecht, G., 1997. Insights on the depositional age and rate of denudation of the pre-Illinoian till in Kansas from terrestrial cosmogenic nuclides. Geological Socity of America Abstracts with Programs, North Central Section. Vol. 29(4), p. A17.
Hague, A., Emmons, S.F., 1877. Descriptive Geology, United States Geological Exploration of the Fortieth Parallel (Clarence King: Geologist in Charge). Government Printing Office, Washington, p. 537.
Hallet, B., Putkonen, J., 1994. Surface dating of dynamic landforms - young boulders on aging moraines. Science 265 (5174), 937–940.
Hays, J.D., Imbrie, J., Shackelton, N.J., 1976. Variations in the earth's orbit: pacemaker of the ice ages. Science 194, 1121–1132.
Hein, A.S., Hulton, N.R.J., Dunai, T.J., Schnabel, C., Kaplan, M.R., Naylor, M., Xu, S., 2009. Middle Pleistocene glaciation in Patagonia dated by cosmogenic-nuclide measurements on outwash gravels. Earth Planet. Sci. Lett. 286 (1–2), 184j–1197.
Heyman, J., Stroeven, A.P., Harbor, J.M., Caffee, M.W., 2011. Too young or too old: evaluating cosmogenic exposure dating based on an analysis of compiled boulder exposure ages. Earth Planet. Sci. Lett. 302 (1–2), 71–80.
Jimenez-Sanchez, M., Rodriguez-Rodriguez, L., Garcia-Ruiz, J.M., Dominguez-Cuesta, M.J., Farias, P., Valero-Garces, B., Moreno, A., Rico, M., Valcarcel, M., 2013. A review of glacial geomorphology and chronology in northern Spain: timing and regional variability during the last glacial cycle. Geomorphology 196, 50–64.

Klein, J., Giegengack, R., Middleton, R., Sharma, P., Underwood, J.R., Weeks, R.A., 1986. Revealing hisories of exposure using insitu produced Al-26 and Be-10 in Libyan Desert glass. Radiocarbon 28 (2 A), 547–555.
Kohl, C.P., Nishiizumi, K., 1992. Chemical isolation of quartz for measurement of in situ produced cosmogenic nuclides. Geochim. Cosmochim. Acta 56, 3583–3587.
Laabs, B.J.C., Munroe, J.S., Best, L.C., Caffee, M.W., 2013. Timing of the last glaciation and subsequent deglaciation in the Ruby Mountains, Great Basin, USA. Earth Planet. Sci. Lett. 361, 16–25.
Lal, D., 1991. Cosmic-ray labeling of erosion surfaces - insitu nuclide production-rates and erosion models. Earth Planet. Sci. Lett. 104 (2–4), 424–439.
Licciardi, J.M., Pierce, K.L., 2008. Cosmogenic exposure-age chronologies of Pinedale and Bull Lake glaciations in greater Yellowstone and the Teton Range, USA. Quat. Sci. Rev. 27 (7–8), 814–831.
Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C., Shakleton, N.J., 1987b. Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000 year chronostratigraphy. Quat. Res. 27, 1–29.
Martinson, M.D., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C., Shackelton, N.J., 1987a. Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000 year chronostratigraphy. Quat. Res. 27, 1–29.
Munroe, J.S., Laabs, B.J.C., Shakun, J.D., Singer, B.S., Mickelson, D.M., Refsnider, K.A., Caffee, M.W., 2006. Latest Pleistocene advance of alpine glaciers in the southwestern Uinta Mountains, Utah, USA. Evidence for the influence of local moisture sources. Geology 34, 841–844.
Murari, M.K., Owen, L.A., Dortch, J.M., Caffee, M.W., Dietsch, C., Fuchs, M., Haneberg, W.C., Sharma, M.C., Townsend-Small, A., 2014. Timing and climatic drivers for glaciation across monsoon-influenced regions of the Himalayan-Tibetan orogen. Quat. Sci. Rev. 88, 159–182.
Nishiizumi, K., Kohl, C.P., Arnold, J.R., Klein, J., Fink, D., Middleton, R., 1991. Cosmic-ray produced ^{10}Be and ^{26}Al in antarctic rocks - exposure and erosion history. Earth Planet. Sci. Lett. 104 (2–4), 440–454.
Olausson, E., 1963. Evidence of climatic changes in North Atlantic dee-sea cores, with remarks on isotopic paleotemperature analysis. Prog. Oceanogr. 3, 221–252.
Osborn, G., Bevis, K., 2001. Glaciation in the Great Basin of the western United States. Quat. Sci. Rev. 20 (13), 1377–1410.
Owen, L.A., Dortch, J.M., 2014. Nature and timing of Quaternary glaciation in the Himalayan-Tibetan orogen. Quat. Sci. Rev. 88, 14–54.
Owen, L.A., Finkel, R.C., Barnard, P.L., Ma, H.Z., Asahi, K., Caffee, M.W., Derbyshire, E., 2005. Climatic and topographic controls on the style and timing of Late Quaternary glaciation throughout Tibet and the Himalaya defined by Be-10 cosmogenic radionuclide surface exposure dating. Quat. Sci. Rev. 24 (12 − 13), 1391–1411.
Phillips, F.M., Zreda, M.G., Evenson, E.B., Hall, R.D., Chadwick, O.A., Sharma, P., 1997. Cosmogenic Cl-36 and Be-10 ages of Quaternary glacial and fluvial deposits of the Wind River Range, Wyoming. Geol. Soc. Am. Bull. 109 (11), 1453–1463.
Putkonen, J., Connolly, J., Orloff, T., 2008. Landscape evolution degrades the geologic signature of past glaciations. Geomorphology 97 (1–2), 208–217.
Putkonen, J., O'Neal, M., 2006. Degradation of unconsolildated Quaternary landforms in the western North America. Geomorphology 75, 408–419.
Putkonen, J., Swanson, T., 2003. Accuracy of cosmogenic ages for moraines. Quat. Res. 59 (2), 255–261.
Ramelli, A.R., Bell, J.W., dePolo, C.M., Yount, J.C., 1999. Large-magnitude, Late Holocene earthquakes on the Genoa fault, west-central Nevada and eastern California. Bull. Seismol. Soc. Am. 89 (6), 1458–1472.
Rood, D.H., Burbank, D.W., Finkel, R.C., 2011a. Chronology of glaciations in the Sierra Nevada, California, from Be-10 surface exposure dating. Quat. Sci. Rev. 30 (5–6), 646–661.
Rood, D.H., Burbank, D.W., Finkel, R.C., 2011b. Spatiotemporal patterns of fault slip rates across the Central Sierra Nevada frontal fault zone. Earth Planet. Sci. Lett. 301 (3–4), 457–468.
Seong, Y.B., Owen, L.A., Bishop, M.P., Bush, A., Clendon, P., Copland, L., Finkel, R., Kamp, U., Shroder Jr., J.F., 2007. Quaternary glacial history of the central karakoram. Quat. Sci. Rev. 26 (25–28), 3384–3405.
Seong, Y.B., Owen, L.A., Caffee, M.W., Kamp, U., Bishop, M.P., Bush, A., Copland, L., Shroder, J.F., 2009. Rates of basin-wide rockwall retreat in the K2 region of the Central Karakoram defined by terrestrial cosmogenic nuclide Be-10. Geomorphology 107 (3–4), 254–262.
Shackleton, N.J., 1967. Oxygen isotope analyses and Pleistocene temperatures re-assessed. Nature 215 (5096), 15–17.
Sharp, R.P., 1938. Pleistocene glaciation in the Ruby-East Humboldt range, northeastern Nevada. J. Geomorphol. 1, 296–323.
Stone, J.O., 2000. Air pressure and cosmogenic isotope production. J. Geophys. Res. Solid Earth 105 (B10), 23753–23759.
Summerfield, M.A., Hulton, N.J., 1994. Natural controls of fluvial denudation rates in major world drainage basins. J. Geophys. Res. Solid Earth 99 (B7), 13871–13883.
Wayne, W.J., 1984. Glacial chronology of the Ruby Mountains - East Humboldt Range, Nevada. Quat. Res. 21, 286–303.