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.

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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 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; Nishizumi et al., 1991). Similarly, models of surface degradation have been invoked to correct for the...
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. 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).](image)

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

Fig. 5. Surficial geologic map (A) and orthophotoquad (B) showing locations of boulders sampled for 10Be surface exposure dating by Laabs et al. (2013; along Hennen Canyon) and this paper (along Seitz Canyon).
### Table 1
Data table.

|-------------|---------------|----------------|---------------|---------------|---------------------|--------------------------------------|-------------------|----------------|-----------------------------|-----------------------------|---------------|---------------|
| Woodfords (this paper)  

#### Tioga outwash

|-------------|---------------|----------------|---------------|---------------|---------------------|--------------------------------------|-------------------|----------------|-----------------------------|-----------------------------|---------------|---------------|

#### Tahoe Moraine

|-------------|---------------|----------------|---------------|---------------|---------------------|--------------------------------------|-------------------|----------------|-----------------------------|-----------------------------|---------------|---------------|

#### Ruby Mountains, Hennon Canyon (this paper)

|-------------|---------------|----------------|---------------|---------------|---------------------|--------------------------------------|-------------------|----------------|-----------------------------|-----------------------------|---------------|---------------|

#### Woodfords (Rood et al. (2011a,b))

|-------------|---------------|----------------|---------------|---------------|---------------------|--------------------------------------|-------------------|----------------|-----------------------------|-----------------------------|---------------|---------------|

(continued on next page)
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.

![Image of Table 1](image)

Table 1 (continued)

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<td>3.07E+05</td>
<td>1.30E+04</td>
<td>61</td>
<td>15.6</td>
<td>1.5</td>
<td>15.4</td>
<td>1.5</td>
<td></td>
</tr>
</tbody>
</table>

* 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/cm³, the production rate standard 07KNSTD and standard (std) elevation flag of the CRONUS calculator, and zero boulder erosion rate.

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.
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. 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.
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 older 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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