1 **Cosmogenic Nuclide Data Sets from the Sierra Nevada, California, for Assessment**
2 **of Nuclide Production Models: II. Sample Sites and Evaluation**

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15 **Abstract**
16

17 The Cosmic-Ray Produced Nuclide Systematics on Earth Project (CRONUS-Earth
18 Project) has reused a limited number of ‘legacy’ ¹⁰Be, ²⁶Al, and ³⁶Cl samples of latest
19 Pleistocene age for the assessment of cosmogenic nuclide production rates independently
20 derived by the CRONUS-Earth Project. The studies re-evaluated here include ones from
21 the Sierra Nevada, California, originally measured by Nishiizumi et al. (1986), Evans et
22 al. (1997), and Phillips et al. (2009). We have also analyzed a limited number of new
23 samples from the same area. We have reevaluated the geological context of the legacy

samples, their chronological controls, and the consistency of the data. The locations and settings of the 1986 samples for ^{10}Be and ^{26}Al calibration can be verified to within reasonable degree of precision using comparison of published locations and field photos with Google Earth imagery. Two cosmogenic sites, Greenstone Lake and Baboon Lakes, were also the localities where key ^{14}C samples for glacial chronology were collected, giving confidence in the application of the ^{14}C constraints to the cosmogenic nuclide samples. A considerable amount of more distant radiocarbon dating work supports an age of $15,750 \pm 500$ years for the exposure of the cosmogenic calibration samples associated with the Tioga 4 glacial retreat. These samples do all appear to be on surfaces that were exposed by final Tioga glacier retreat ($15,750 \pm 500$ years), but below the limits of the Recess Peak advance (13,550-13,050 years). The ^{36}Cl samples reported by Phillips et al. (2009) and Evans et al. (1997) were from the terminal moraine of the last Tioga glacier advance ($16,100 \pm 500$ years), the final Tioga glacier retreat ($15,750 \pm 500$ years), and the Recess Peak glacial episode ($13,300 \pm 250$ years). When ages are calculated for these samples using the final CRONUS-Earth Project production rates and scaling models, they are in good agreement with the independent radiocarbon age control, with the exception of the ^{36}Cl ages from the Recess Peak episode, which average about 15% young. The most likely reasons for this discrepancy are either inadequate understanding of snow shielding or error in the assignment of the age of the Recess Peak glacial advance.

Keywords

Sierra Nevada, glacial chronology, cosmogenic nuclide production rate, beryllium-10,
aluminum-26, chlorine-36

1. Introduction

1.1 The CRONUS-Earth Project

The Cosmic-Ray Produced Nuclide Systematics on Earth Project (CRONUS-Earth Project) was funded by the U.S. National Science Foundation in 2005. The purpose of the CRONUS-Earth Project is to resolve inconsistencies in the theoretical and empirical basis for application of terrestrial cosmogenic nuclides in the earth sciences. As part of these activities, new calibrations of ^{10}Be , ^{26}Al , and ^{36}Cl production have been performed. CRONUS-Earth Project geological samples must meet rigorous requirements with regard to sample characteristics and sampling methodology (CRONUS-Earth Project, 2005). Only sites sampled during the course of the project that had very secure independent chronologies, clear-cut exposure histories, and minimal complications from site-specific issues such as snow or soil cover or erosion were used for the production-rate calibrations. These were termed ‘primary calibration sites’ (see Phillips et al., 2015, for more detail). The results of the production-rate calibrations are available in Borchers et al. (2015) and Marrero et al. (2015b).

Additional sites were needed for assessing the calibrations and quantifying their uncertainties. For this purpose, most of the sites were ‘legacy’ studies (i.e., independent of, and prior to, the CRONUS Project) performed prior to 2011. In addition a limited

number of 'new' sites were sampled for the CRONUS Project that did not have all the qualities needed for primary sites. Both of these were required to have similar qualities as the primary sites, but to a less rigorous degree. These were termed 'secondary sites'. Note that these secondary sites were used only to assess the nuclide production rates obtained using the primary sites and to quantify the uncertainty associated with the nuclide production rates. They were not used as calibration samples. A set of previously published studies from the Sierra Nevada, California, were included in this secondary category.

1.2 Review of Cosmogenic Nuclide Studies in the Sierra Nevada

The first attempts at measurement and application of terrestrial cosmogenic nuclides were made in the 1950's and 1960's (see Cerling and Craig, 1994, for a history of this period). However, lack of adequate analytical methods prevented practical use of terrestrial cosmogenic nuclides until the late 1980's. The first strong demonstrations of utility and calibrations of cosmogenic nuclide production rates were published in 1986. Among these papers was Nishiizumi et al. (1986). Although this publication demonstrated the feasibility of measuring ^{10}Be and ^{26}Al in terrestrial surficial rocks, actual calibration of the production rates was first published three years later by Nishiizumi et al. (1989). In this paper the authors reported on ^{10}Be and ^{26}Al measurements from glacially modified rock surfaces in the Sierra Nevada, California, and used these results to calibrate the production rates of these nuclides. The measurements were based on rock samples collected during the summer of 1986.

The Nishiizumi et al. (1989) calibration was used directly for many years. Subsequent developments in theoretical understanding of cosmogenic nuclide systematics, such as scaling theory, and the accumulation of additional calibration data have rendered the original calibration obsolete, but the data set still forms a foundation for current production models (e.g., Balco et al., 2008).

Shortly following Nishiizumi et al. (1989), cosmogenic ^{36}Cl was applied to the chronology of Sierra Nevada glaciation prior to the latest Pleistocene deglaciation (the time of exposure of the Nishiizumi samples) (Phillips et al., 1990). Subsequently, there have been numerous additional works on cosmogenic nuclide chronology of Sierra Nevada glacial features (e.g., Phillips et al., 1996; James et al., 2002; Phillips et al., 2009; Rood et al., 2011). Chlorine-36 was applied to many samples from these studies, as well as additional ^{10}Be .

In addition to studies employing cosmogenic nuclides to further the understanding of Sierra Nevada glacial chronology, there was an additional use of samples from this setting for further calibration work. Evans et al. (1997) reported the results from boulders that were sampled in 1994 at several localities in the vicinity of the Nishiizumi 1986 sites. They separated K-feldspars from these samples for constraining the production of ^{36}Cl by spallation of K. In addition, Cl was leached from K-feldspars containing high Cl concentrations and used to test the formulation for calculating ^{36}Cl production from low-energy neutron absorption by Cl.

The documentation of the 1986 and 1994 Sierra Nevada sample sites was fairly minimal, which was the typical practice at that time. Additionally, the analytical standardization for ^{10}Be analysis has been revised (Nishiizumi et al., 2007; Chmeleff et

al., 2010; Korschinek et al., 2010), and numerous additional constraints on the glacial chronology of the Sierra Nevada have been published since 1989. These factors have prompted a re-evaluation of the sample characteristics in order to assess the utility of the Nishiizumi et al. (1989) data set for inclusion in the CRONUS-Earth Project ^{10}Be and ^{26}Al secondary data set. Furthermore, due to the large amount of ^{36}Cl data collected from settings similar to the 1986 ^{10}Be sample set, some of these historical samples can be used as secondary data, supplemental to that collected in the CRONUS-Earth Project, in order to evaluate the uncertainty associated with the production rates for ^{36}Cl .

The main objective of this paper is to document the locations, nature, and chronological context of these Sierra Nevada legacy samples using a consistent and up-to-date methodology. Based on this documentation, we assign independent ages to the samples (i.e., independent of the cosmogenic exposure ages) for comparison with the exposure ages calculated using the CRONUS-Earth calibration. Our secondary objective is to understand the sources of any bias or excess scatter observed in the comparison of the independent and cosmogenic ages. The principal possible sources that we focus on are error in the calibrated nuclide production rates, inadequacies in the snow-cover corrections, and error in the assigned independent ages. This paper does not cover the use of the Sierra Nevada samples for a systematic evaluation of the accuracy and uncertainty of the CRONUS-Earth cosmogenic-nuclide production models. That evaluation is published in Phillips et al. (2015).

1.3 Late Pleistocene Sierra Nevada Glacial Chronology

The chronology of the samples collected by previous investigators can be established by reference to their position within the sequence of late Pleistocene glacial advances in the Sierra Nevada. The generally accepted terminology and conceptual framework for the glacial sequence of the Sierra Nevada was established by Blackwelder in 1931 (Blackwelder, 1931). He named the McGee, Sherwin, Tahoe, and Tioga glacial stages, although without numerical chronology, since the means for such were lacking in his time. Of these, we need be concerned here with only the Tioga, inasmuch as only samples from the Tioga-age features were collected for use in any of the calibration exercises. The Tioga glaciation has subsequently been subdivided into four advances, numbered 1 through 4 (Phillips et al., 1996; Phillips et al., 2009). Investigations by Clark and Gillespie (1997) demonstrated that there have been only two post-Tioga glacial advances in the range: the Recess Peak and the Matthes. The Recess Peak glaciers advanced only a few thousand years after the Tioga retreat and are therefore very latest Pleistocene rather than Holocene. The Matthes advance was during the late Holocene and culminated during the Little Ice Age (Konrad and Clark, 1998). It was much less extensive than the Recess Peak glaciation. No Matthes samples were used in the Sierra Nevada secondary data set.

In the first paper in this series (Phillips, 2015) the data available for radiocarbon age constraints on the retreat of late Pleistocene glaciers in the Sierra Nevada were compiled and evaluated. These were compared with supplementary paleoenvironmental data (mostly from lacustrine and marine cores) to arrive at non-cosmogenic age estimates for the chronology of events related to the exposure history of the Sierra Nevada samples included in the CRONUS-Earth secondary data sets. Based on this evaluation, Phillips

(2015) proposed the following chronology for the terminal Pleistocene deglaciation of the Sierra Nevada: Tioga 3 maximum at 18.5 ± 0.5 ka, Tioga 4 maximum at 16.2 ± 0.5 ka, midpoint of Tioga 4 retreat at 15.75 ± 0.5 ka, and Recess Peak maximum at 13.25 ± 0.25 ka.

This paper builds on the first paper in the series by examining the Sierra sites (Figure 1) individually and assessing where they fit in the glacial sequence. We discuss separately the classic 1986 sampling for ^{10}Be and ^{26}Al by Nishiizumi et al., the ‘legacy’ ^{36}Cl samples of Evans et al. (1997) and Phillips et al. (2009), and a ‘new’ sampling for both ^{10}Be and ^{36}Cl undertaken at the Baboon Lakes (Figure 1) as part of this study. The cosmogenic ages for these samples are then compared with the independent chronology and the potential causes of any discrepancies are evaluated.

2. Description of the CRONUS-Earth Secondary Sample Sites in the Sierra Nevada

2.1 Legacy ^{10}Be - ^{26}Al Sites (WG86- series)

In order to be used in the CRONUS-Earth secondary data set, the sites sampled in 1986 must be well documented and capable of being relocated. Using copies of the original field notes accompanying the sample collection, together with historical

Figure 1. Map of a portion of California containing the southern and central Sierra Nevada, showing localities mentioned in the text. The ^{10}Be sample localities are indicated by yellow stars and the ^{36}Cl localities by blue stars. TL = Twin Lakes, GL=Greenstone Lake, EL=Ellery Lake, MS=Mount Starr, RL=Ruby Lake, MP=Morgan Pass, ML=Morgan Lake, HB=Humphreys Basin, BC=Bishop Creek, BL=Baboon Lakes. The shading on the map corresponds to elevation, with white indicating greater than 3,000 m and brown less than 1,000 m.

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photographs taken at the time of sampling and field maps, the locations and settings of the 1986 samples were reevaluated by Phillips (2011).

The original sampling was performed before Global Positioning System (GPS) navigation was generally available and sample locations were visually located on topographic maps. Some of the sample sites were later revisited by K. Nishiizumi and GPS locations were recorded, but the precision of GPS at that time was still significantly less than current precision. Based on a combination of actual field photos, field notes, maps, and GPS measurements, evaluated in the context of Google Earth imagery and digital elevation model, the locations of the samples were reassessed. Although in some cases (particularly the Twin Lakes samples) there were some ambiguities, the horizontal positions of the samples could be resolved to within uncertainties ranging from ± 50 m to ± 100 m and the elevation resolved to uncertainties ranging from ± 10 m to ± 15 m, with the exception of sample W86-4, assigned an uncertainty of ± 20 m. The location information and other parameters related to production-rate scaling are given in Table 1.

Table 1. Field data, ^{10}Be and ^{26}Al concentrations, and LSDn ages for samples from Nishiizumi et al. (1986).

Map Number Field Number	Units	51 W86-1	51 W87-3	52 W86-4	53 W86-5	53 W86-6	53 W86-8	54 W86-10	55 W86-11	55 W86-12	56 W86-13
Concentration ^{10}Be	10^6 atoms $^{10}\text{Be}/\text{g quartz}$	0.420	0.562	0.459	0.511	0.518	0.509	0.341	0.316	0.349	0.299
$\pm$ ^{10}Be concentration	10^6 atoms $^{10}\text{Be}/\text{g quartz}$	0.052	0.106	0.049	0.060	0.066	0.078	0.056	0.037	0.095	0.030
^{10}Be age (LSDn scaling)	ka	16.1	20.2	16.7	16.4	16.6	16.3	19.3	16.4	18.0	20.7
$\pm$ ^{10}Be age	ka	1.9	3.1	1.7	1.8	2.0	2.4	2.7	1.8	4.5	1.8
Concentration ^{26}Al	10^6 atoms $^{26}\text{Al}/\text{g quartz}$	2.81	-	2.68	3.45	3.27	3.22	2.41	2.26	2.26	2.23
$\pm$ ^{26}Al concentration	10^6 atoms $^{26}\text{Al}/\text{g quartz}$	0.16	-	0.17	0.16	0.15	0.17	0.14	0.12	0.12	0.14
^{26}Al age (LSDn scaling)	ka	15.5	18.2	14.3	16.0	15.2	15.0	19.4	16.7	16.7	21.7
$\pm$ ^{26}Al age	ka	0.8	1.0	0.9	0.7	0.7	0.7	1.0	0.9	0.9	1.2
Assumed erosion	mm/kyr	0	0	0	0	0	0	0	0	0	0
Bulk density	g/cm^3	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65
Sample thickness	cm	1	1	1	1	1	1	1	1	1	1
Latitude	decimal degrees	37.9823	37.9823	37.4211	37.4197	37.4197	37.4197	38.8708	38.8717	38.8717	38.8553
Longitude	decimal degrees	119.2986	119.2986	118.7656	118.7688	118.7688	118.7688	120.1964	120.1973	120.1973	120.2219
Elevation	m	3175	3175	3530	3565	3565	3565	2440	2450	2450	2145
Pressure	hPa	693.4	693.4	663.7	660.8	660.8	660.8	758.9	757.9	757.7	786.8
Site Snow Shielding	unitless	0.80	0.80	0.83	0.83	0.83	0.83	0.78	0.78	0.78	0.78
Sample Snow Shielding	unitless	0.98	0.80	1.00	1.00	1.00	1.00	0.78	0.93	0.93	0.78
Topographic Shielding	unitless	0.76	0.96	0.65	0.72	0.72	0.72	1.00	0.92	0.92	1.00
Total Shielding	unitless	0.74	0.77	0.65	0.72	0.72	0.72	0.78	0.86	0.86	0.78
Effective Atten Length	g/cm^2	106	156	91	94	94	94	148	118	118	144
Surface Dip	degrees	58	5	75	70	70	70	7	45	45	15
Direction of Dip	degrees	160	160(?)	130	135	135	135	200	145	145	?

(Excel version of Table 1 is included in Appendix A.)

The locations of the sample sites relative to the Recess Peak glacial limit are of concern; if the samples are from within the Recess Peak limit, the exposure age will presumably reflect the Recess Peak retreat, which was about 2,500 years later than the Tioga retreat. In one case, the local Recess Peak limit has been mapped and published: Greenstone Lake by Clarke et al. (2003) (see Fig. 2 in Phillips, 2015). For the other two sites, the locations of the Recess Peak moraines were ascertained by mapping using Google Earth imagery and checked by communication with D.H. Clark (Western Washington Univ.), who has independently examined or mapped Recess Peak deposits in these areas. All of the ^{10}Be sample sites were verified as being below the Recess Peak limits.

2.1.1 Saddlebag Lake (Greenstone Lake) Locality

Calibration samples W86-1, 2 and 3 were collected in the Lee Vining Creek drainage, near Tioga Pass. Only W86-1 and 3 were reported in Nishiizumi et al. (1986). They named the site as ‘Saddlebag Lake’. We have generally referred to it as

‘Greenstone Lake’, to emphasize its proximity to the critical Greenstone Lake core and radiocarbon dates, and because it is considerably closer to Greenstone Lake than Saddlebag Lake. Figure 2 in Phillips (2015) shows the locations of the samples relative to the Recess Peak limit. Sample W86-1 was collected from approximately 2 m up the face of a granite step dipping at 58°. Sample W86-3 was from the tread of a step nearby and was nearly horizontal.

2.1.2 Mt. Starr Locality

Mount Starr is a peak on the boundary of the Rock Creek and Mono Creek drainages. Samples W86-4, 5, 6, and 8 were collected from steeply inclined, glacially modified surfaces on the lower southeastern flanks of the Mount Starr cliffs, above and to the west of the Mono Pass trail. All samples were from bedrock outcrops that dipped ~70°. Figure 2 shows the locations, along with the Recess Peak glacial limit, estimated using Google Earth imagery.

Figure 2. Locations of 'Mt. Starr' ^{10}Be and ^{26}Al calibration samples as reported in Nishiizumi et al. (1986) and as relocated in this study, indicated using filled yellow circles. 'ms' and 'rl' ^{36}Cl calibration samples from Evans et al. (1997) are also shown, using filled blue circles. Sample sites are identified by the map numbers in Tables 1 and

A.1. The limit of the Recess Peak glaciation (“Rp) is illustrated in red. Refer to Figure 1 for location map.

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2.1.3 Twin Lakes Locality

There are numerous “Twin Lakes” in the Sierra Nevada. The Twin Lakes close to which the $^{10}\text{Be}/^{26}\text{Al}$ samples reported by Nishiizumi et al. (1986) were collected are in the Desolation Wilderness west of Lake Tahoe, on the Fallen Leaf Lake 7.5 minute quadrangle. Samples W86-10 through 12 were collected from north of Twin Lake, on sloping bedrock surfaces. W86-9 and 10 dipped 7° while W86-11 and 12 dipped 45° . Sample W86-13 was above Wright’s Lake, about 2.8 km southwest of the previous three samples. It was also from a relatively flat surface, dipping 15° . The locations of these samples are shown in Figure 3.

Figure 3. Locations of the Twin Lakes samples ^{10}Be and ^{26}Al calibration samples as reported in Nishiizumi et al. (1986) and as relocated in this study, indicated by yellow circles. Sample sites are identified by the map numbers in Table 1. No Recess Peak moraines have been mapped in this area. Refer to Figure 1 for location map.

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2.2 Legacy Chlorine-36 Sample Sites

Only a very limited number of samples from the Sierra Nevada were analyzed by the CRONUS-Earth Project for evaluation of ^{36}Cl production parameters, but, just as is the case for ^{10}Be and ^{26}Al , there are numerous ‘legacy’ samples that are suitable for providing constraints on ^{36}Cl production. These include whole-rock samples from the

Tioga 4 terminal moraine, the final Tioga deglaciation, and the Recess Peak advance in the Bishop Creek and Paiute Creek drainages published by Phillips et al. (2009) and potassium-feldspar mineral separates and Cl leachates published by Evans et al. (1997). In addition, a small number of whole-rock samples and potassium-feldspar separates from a Recess Peak-age site, which have not previously been published, were analyzed in the course of the CRONUS-Earth Project.

The drainages from which the Phillips et al. (2009) ^{36}Cl samples were collected are only 20 to 25 km south of the Rock Creek drainage that was the source of the W86-4 through 8 ^{10}Be samples. Additionally, primary radiocarbon control for the chronology of the Recess Peak glaciation has come from the Baboon Lakes in the Bishop Creek drainage (Clark and Gillespie, 1997). In selecting samples out of the Phillips et al. (2009) data set for inclusion in this study as secondary calibration samples, we sought localities that had four qualities: a clear-cut geological context that would unambiguously relate them to the Sierra Nevada deglacial chronology developed in this paper, that contained a wide range of Cl concentrations, that were from situations with minimal snow cover, and that produced internally consistent analytical results. The sample numbering system (“map numbers”) of Phillips et al. (2009) has been preserved for samples from that paper.

In addition to the samples from Phillips et al. (2009), Evans et al. (1997) have also reported analysis of ^{36}Cl from Sierra Nevada samples. Some of these samples were collected from sites very close to the locations that Nishiizumi et al. (1986) obtained their ^{10}Be samples and should thus be directly comparable to them. Potassium-feldspar mineral separates were analyzed from these samples. Some of the feldspars contained high concentrations of Cl. These samples were finely crushed and leached to release the

Cl. The leachates can be used as a check on the ^{36}Cl production rates for high-Cl samples.

The samples from Phillips et al. (2009) and Evans et al. (1997) that were used for the ^{36}Cl uncertainty-evaluation exercise are listed in Table A.1. Their locations are given in Figures 2, 4, 5, 6, and 7. Further background on the setting of these samples can be found in Phillips et al. (2009). The samples were collected between 1994 and 1997 with locations determined using Global Positioning System technology that was less accurate than today and thus their locations were reevaluated in the same fashion as the ^{10}Be locations described above. Their locations may therefore differ slightly from those in the original references. The samples from Phillips et al. (2009) are drawn from three sources: erratic boulders high in Humphreys Basin, boulders from the Tioga 4 terminal moraine on the Middle Fork of Bishop Creek, and erratic boulders and bedrock related to the retreat of the Recess Peak glacier in the Bishop Creek drainage. Those from Evans et al. (1997) are from near Ellery Lake on Tioga Creek, from the Mt. Starr site described above, and from near Morgan Pass in the Rock Creek drainage.

Most of the ^{36}Cl samples used in this study were noted in the field to have fresh, relatively unweathered surfaces, but glacial striations or smoothing was generally not found. We assigned these samples a uniform assumed surface erosion rate of 1 mm/kyr (see discussion in Phillips et al., 2009, for justification of this assignment). However, samples 130-136 (from the Rock Creek area) were noted in the field to have striated surfaces and these were assigned surface erosion rates of 0 mm/kyr.

2.2.1 Bishop Creek “Forks” Locality

322

323 This locality is informally named for the U.S. Forest Service ‘Forks Campground’
324 just inside of the Tioga 4 terminal moraine, which is located at the confluence of the
325 Middle and South Forks of Bishop Creek (Figure 4). Samples 98-101 were collected by
326 Phillips et al. (2009) from four boulders on the crest of the Tioga 4 terminal moraine or
327 just below it. This moraine was deposited during the peak of the Tioga 4 readvance. The
328 samples were all taken from the tops of boulders ranging from 3.5 to 1.8 m, thus
329 minimizing snow cover. This site receives much less snow than does Humphreys Basin
330 (<13 cm average June-to-July water equivalent compared to >30 cm in Humphreys Basin
331 (California Department of Water Resources, 2012)).

332 This advance preceded the final recession of the Tioga glaciers and thus must
333 have a slightly older age than the Humphreys Basin samples. As evaluated by Phillips
334 (2015), the beginning of the Tioga 4 retreat can be dated to about 16,000 years. Evidence
335 presented by Clark (1976) and by Phillips et al. (2009) indicates that the retreat of the
336 Tioga 4 glacier from its terminal position in Bishop Creek was very rapid, and this is
337 consistent with an age of the Tioga 4 terminal moraine about 500 years older than the
338 final disappearance of the Tioga 4 ice (i.e., the Humphreys Basin samples). The ‘Forks’
339 samples have therefore been assigned an age of $16,200 \pm 500$ years.

340

Figure 4. Glacial geology map of the 'Forks' locality and sample locations based on mapping of Phillips et al. (2009). Samples from Phillips et al. (2009) used in this study are blue triangles, samples not used are in green; sample numbers are keyed to Table A.1. The Tioga 4 (Ti4) terminal and lateral moraines are in dark blue, the Tioga 3 (Ti3) in light blue, and pre-Tioga (PTiY) moraines in pink. The blue dashed line is the glacial trimline. Refer to Figure 1 for location map.

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2.2.2 Mt. Starr ³⁶Cl Locality

Evans et al. (1997) reported ^{36}Cl analyses from K-feldspar separates out of samples collected in the vicinity of the Nishiizumi et al. (1989) Mt. Starr locality. The locations of the Evans et al. samples are shown in Figure 2 using blue circles. Samples 131 and 132 were collected closest to the ^{10}Be sample sites. 131 was from bedrock with traces of glacial striation on a whaleback buttress above the base of the Mt. Starr cliff. The sample position on the edge of a small cliff precluded snow accumulation. 132 was from a lightly weathered but not polished surface on a steeply dipping bedrock buttress at the base of the Mt. Starr Cliff. Sample 133 was from a steeply dipping slab with a striated surface downstream of Ruby Lake. Snow accumulation was deemed minimal at all three sites.

2.2.3 Humphreys Basin Locality

Erratic boulders collected by Phillips et al. (2009) from Humphreys Basin (113 through 117) are from a setting completely analogous to the ^{10}Be calibration samples of Nishiizumi et al. (1986): a high basin exposed by the melting of the last remnants of the Tioga 4 glacier, and therefore have been assigned the same age of $15,750 \pm 500$ years. Samples 113, 114, and 115 were collected from the tops of large boulders situated on or near the crest of a low, broad moraine that projects out of the southwest corner of Desolation Lake (see Figure 5). The moraine was deposited by glacial ice that flowed from the highlands in the northeast corner of Desolation Basin into the deep trough presently occupied by Desolation Lake. It is the highest-elevation constructional feature in the basin and thus probably represents the last minor pause of the Tioga glacier prior to

Figure 5. Location of Humphreys Basin ^{36}Cl samples from Phillips et al. (2009). Sample sites are indicated by yellow circles; sample numbers are keyed to Table A.1. Tioga 4 (Ti4) moraines are indicated in blue, Neoglacial (Ng) (Matthes) in brown, and Pliocene-Early Pleistocene (P-Pl) diamicton in green. Red arrows are ice-flow directions indicated by striations and red dotted line is the east-west ice-flow divide. Mapping is from Phillips et al. (2009). Refer to Figure 1 for location map.

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2.2.4 Ellery Lake Locality

Evans et al. (1997) collected two samples at one locality (el-2 and el-3; not illustrated on a map), on the top of the ridge that overlooks Ellery Lake (along the Tioga Pass road) on the northeast. Both had excellently preserved glacial polish and both dipped steeply to the west. Due to the aspect and steepness, snow cover was considered negligible. Erosion was also considered negligible. This site is the same drainage basin as the Nishiizumi et al. (1989) Greenstone Lake site (Tioga Creek) and is located 7.4 km downstream, and thus also well below the Recess Peak glacial limit.

2.2.5 Morgan Pass/Lake Locality

Evans et al. (1997) sampled additional granodiorite bedrock in the vicinity of Morgan Lake, 4 km southeast of the Mt. Starr locality, shown in Figure 6. Morgan Pass separates the Rock Creek drainage (within which the Mt. Starr samples were taken) from

the Pine Creek drainage. Samples 134 and 135 were taken from the crest of Morgan Pass. Sample 134 was from “beautifully polished” bedrock on the crest of a roche moutonnée standing 2-3 m above the general surface. The position was noted as windswept and unlikely to retain snow for long. Sample 135 was from 10 above the base of a steep granite face with “beautifully striated surfaces” and was deemed too steep to retain snow. Sample 136 was a polished but lightly eroded surface 8 m up the face of a buttress on the north side of the Morgan Lakes valley, below Upper Morgan Lake. Due to the steep dip of the face and position 8 m above the valley floor, snow accumulation was thought to be highly unlikely.

Figure 6. Location of Morgan Pass and Morgan Lake ^{36}Cl samples collected by Evans (1997). Sample numbers are keyed to Table A.1. Recess Peak (Rp) moraines are indicated in red. Refer to Figure 1 for location map.

2.2.6 Bishop Creek Recess Peak Age Localities

Samples were collected by Phillips et al. (2009) from three sites in the Bishop Creek drainage (Figure 7). The first was a Recess Peak terminal moraine in the Treasure Lakes drainage (South Fork of Bishop Creek). The second was erratics on the Recess Peak terminal moraine in the Baboon Lakes drainage (Middle Fork of Bishop Creek), and the third was two erratics in the glacial valley above the Baboon Lakes, paired with two bedrock samples at the same locations. Locations of the Baboon Lakes samples 121, 122, and 125-127 are illustrated in Figure 7. The boulder in the Treasure Lakes drainage (119) was from a 5 m-high boulder on the outermost ridge of the prominent Recess Peak terminal moraine between the upper and lower Treasure Lakes. Likelihood of snow cover was deemed very low due to the boulder height and exposed position.

Figure 7. Locations for Recess Peak age samples in the Baboon Lakes drainage based on mapping of Phillips et al. (2009). Sample locations are keyed to Table A.1. Samples from this study and from Phillips et al. (2009) that were employed in this study are shown as blue triangles, samples not used as green triangles (note that 126 and 127 are at same location as 125). Neoglacial (Ng) (Matthes) deposits are in brown, Recess Peak (Rp) moraines, based on Clark and Gillespie (1997), are in pink, and Tioga 4 (Ti4) in blue. Blue dotted lines are glacial trimlines. Refer to Figure 1 for location map.

{This figure to be given color on web version and black-and-white in print}

The remaining three samples were collected from the valley floor between the Baboon Lakes and Sunset Lake, within the Recess Peak glacial limit. Samples BPCR96-

06 and -07 (map number 122) were a bedrock/boulder pair at the outlet of Sunset Lake. Although from a broad “whaleback” bedrock outcrop about 2 m high, 06 undoubtedly is subject to a moderate level of snow cover. The bedrock retained traces of glacial polish and thus has not been eroded. Sample 07 was from a 0.3 m erratic boulder perched on the same outcrop. Sample 121 was polished bedrock from the edge of a ~10 m high step in the granitic bedrock above the upper Baboon Lakes. Retention of snow for any length of time is unlikely.

The dating of the Recess Peak readvance has been evaluated by Phillips et al. (2015), and based on this evaluation an age of $13,300 \pm 250$ yr has been used for all of these samples. This is consistent with the post-Recess Peak $13,090 \pm 70$ yr calibrated radiocarbon age from bulk organics overlying Recess Peak outwash in a core augered in the Baboon Lakes (Clark and Gillespie, 1997).

2.3 New ^{10}Be - ^{36}Cl Site at Baboon Lakes

The Baboon Lakes locality has been described in detail by Clark and Gillespie (1997) and is the source of one of the important primary radiocarbon constraints on the timing of the Recess Peak glaciation. Samples from the Recess Peak terminal moraine between the lower Baboon Lake and the upper lakes were dated using ^{36}Cl by Phillips et al. (2009), but yielded inconsistent results, for unknown reasons, but possibly related to snow cover. The moraine was therefore resampled in 2007 (samples 125-127) high on the right lateral where snow would be likely to be blown off rather than accumulating, as was the case for the 1997 sample locality. Unlike the 1996 collection, for which only

whole-rock samples were analyzed, K-feldspar and biotite mineral separates were analyzed as well. The boulders ranged between 1.8 and 2.0 m high. Of the three boulders sampled, only 126 was directly on the crest and therefore likely to remain snow-free due to wind erosion; the other two were from the lee (east) side of the crest and likely to have had at least some snow cover.

3. Sample Processing, Analysis, and Interpretation

Most of the samples employed in this study are legacy samples that are reinterpreted from previous studies. The methods used for sample processing and analysis are documented in those source publications.

3.1 Legacy ^{10}Be - ^{26}Al Samples

Purified quartz was separated from the rock samples by grinding to $<700\ \mu\text{m}$, followed by physical separation and then repeated dissolution in dilute HF, as described in Nishiizumi et al. (1989) and later in more detail by Kohl and Nishiizumi (1992). The ^{10}Be concentrations of the Nishiizumi et al. (1989) samples had to be recalculated to be consistent with the current isotope-ratio value of the analytical standard used (Nishiizumi et al., 2007).

3.2 New ^{10}Be Samples (Baboon Lakes site)

496 The ^{10}Be analyses of the Baboon Lakes samples were also performed under the
 497 CRONUS-Earth Project by John O. Stone at the University of Washington. He isolated
 498 quartz from the granodiorite samples by flotation in heavy liquids and selectively
 499 dissolved the grain surfaces in dilute HF (Kohl and Nishiizumi, 1992). Aluminum and
 500 beryllium were then separated and purified using well-established methods
 501 (<http://depts.washington.edu/cosmolab/chem/>). Isotopic analyses were performed at the
 502 Lawrence Livermore Center for Accelerator Mass Spectrometry (LLNL-CAMS). Be
 503 isotope ratios were normalized to a value of $^{10}\text{Be}/^9\text{Be} = 2.851 \times 10^{-12}$ for the 01-5-4
 504 standard described by Nishiizumi et al. (2007) as per the 07KNSTD normalization of the
 505 CRONUS online calculator (Balco et al., 2008). Results are shown in Table 2.
 506
 507 Table 2. Sample data and ages, calculated using the LSDn scaling (Lifton et al, 2014), for
 508 Baboon Lakes ^{10}Be samples.

Map Number Field Number	Units	125 BL07-01	126 BL07-02	127 BL07-03
Concentration ^{10}Be	10^5 atoms $^{10}\text{Be}/\text{g}$ sample	5.08	4.79	4.62
$\pm$ ^{10}Be concentration	10^5 atoms $^{10}\text{Be}/\text{g}$ sample	0.06	0.06	0.06
Calculated Age	ka	11.96	13.47	12.77
$\pm$ Calculated Age	ka	0.15	0.18	0.17
Assumed erosion	mm/kyr	1	1	1
Bulk density	g/cm^3	2.75	2.75	2.75
Sample thickness	cm	4	5.5	4.5
Latitude	decimal degrees	37.1683	37.1682	37.1680
Longitude	decimal degrees	241.3799	241.3796	241.3799
Elevation	m	3380	3387	3387
Pressure	hPa	676	676	676
Site Snow Shielding	unitless	0.94	0.94	0.94
Sample Snow Shielding	unitless	0.99	0.99	0.99
Topographic Shielding	unitless	0.99	0.99	1.00
Total Shielding	unitless	0.98	0.98	0.99
Lambda Effective	g/cm^2	145	145	145

3.3 Legacy ^{36}Cl Samples

The processing of the legacy ^{36}Cl samples from Bishop Creek and Humphreys Basin has been discussed by Phillips et al. (2009). All of these were whole-rock samples of granite and utilized isotope-dilution mass spectrometry (Desilets et al., 2006) for the determination of ^{36}Cl and Cl concentrations. Samples were ground, leached in dilute nitric acid and sodium hydroxide, and dissolved in a mixture of hydrofluoric and nitric acids to which was added an isotopically enriched ^{35}Cl spike. The natural and spike chlorine was then precipitated by addition of silver nitrate. The resultant silver chloride was purified of sulfur (an interfering isobar in the accelerator mass spectrometric analysis of ^{36}Cl) and analyzed by accelerator mass spectrometry at PRIME Lab, Purdue University. The procedure is described in more detail in Kurth et al. (2011) and laboratory procedures are given in Kurth (2003).

The samples from the remaining legacy ^{36}Cl sites (Mt. Starr, Ellery Lake, Morgan Pass/Lake) were processed by separation of feldspar grains from the granite. The feldspar was separated by heavy-liquid flotation, followed by a hot nitric acid leach. For the samples intended for measurement of ^{36}Cl from K spallation (those in Table A.4 from these sites that are without “(Cl)” following the sample name), the feldspars were dissolved in a hot hydrofluoric/nitric acid mixture. An unenriched stable chloride carrier was added and silver chloride precipitated by addition of silver nitrate. The $^{36}\text{Cl}/\text{Cl}$ ratio was determined by accelerator mass spectrometry on the Australia National University 14UD Pelletron. Chloride concentration was measured by ion chromatography after

pyrohydrolysis. The procedure is described in Evans et al. (1997) and given in detail in Stone et al. (1996).

Four of the samples from these sites (those in Table A.4 with “(Cl)” following the sample name) were intended for measurement of ^{36}Cl from low-energy neutron absorption by ^{35}Cl . These were processed by crushing under deionized water in a corundum mortar. The rock powder was separated by centrifugation and the silver chloride precipitated by addition of silver nitrate. The samples were then processed in a manner similar to the other samples, as summarized above. This procedure is described in more detail in Evans et al. (1997).

3.4 New ^{36}Cl Samples (Baboon Lakes site)

The ^{36}Cl samples from the Baboon Lakes site were processed and analyzed as part of the CRONUS-Earth Project. In brief, for ^{36}Cl whole-rock samples, after grinding to fine sand grain size, the sample was divided using a sample splitter to obtain the sample for ^{36}Cl processing as well as material for elemental analyses. For mineral separates, fractions were separated using magnetic separation followed by heavy-liquid separation. If additional separation was necessary, froth flotation was used. The samples were leached overnight in nitric acid and dried in the oven prior to dissolution with nitric and hydrofluoric acids. The samples were precipitated as AgCl , purified through dissolution/reprecipitation, sulfur was removed using BaNO_3 and a syringe filter, and then dried. The samples were sent to PRIME Lab, Purdue University, for AMS analysis. Target elements were determined via X-ray fluorescence (XRF) on an aliquot separated

from the sample prior to dissolution. XRF major-element analysis was performed at Michigan State University and trace-element analysis was performed by SGS Mineral Services in Canada. Details of the sample preparation methodology can be found in Marrero (2012).

Sampling data for the ^{36}Cl and ^{10}Be samples are given in Appendix A, Table A.1, the complete ^{36}Cl data are given in Table A.2, and the results of the ^{10}Be analyses in Table 2.

4. Calculation of surface-exposure ages for testing of CRONUS production rates

The objective of this study was to document and evaluate a data set that was independent of the “primary” CRONUS-Earth calibration data set, for the purpose of testing the accuracy of the CRONUS-Earth calibration and of assigning empirical uncertainties to the production parameters obtained through the calibration. The use of the Sierra Nevada secondary samples, among a large number of other similar samples, for this purpose is detailed in Borchers et al. (2015), Marrero et al. (2015b), and Phillips et al. (2015). The calibrations were performed for all of the seven published methods for global scaling of cosmogenic-nuclide scaling. The accuracy and precision of these scaling methods, as assessed from the statistics of the calibrations, varied widely. We reiterate that the Sierra Nevada data set described in this paper was not used to calibrate production rates; it was only used to evaluate accuracy and to help quantify production-rate uncertainties.

An additional objective of this study was to evaluate the Sierra Nevada samples with regard to trends in accuracy and precision. The explanations of such trends may help to elucidate the causes of error or scatter in the global primary and secondary data sets. They may also point to problems or shortcomings in the collection and/or interpretation of cosmogenic nuclide data that could be addressed in order to improve methods or models. In order to generate a data set of Sierra Nevada ages for this purpose, we used one of the best-performing global scaling models from the CRONUS calibration, as detailed below.

All data, both legacy and original, were converted into surface-exposure ages using the CRONUS-Earth calculator (“CRONUScalc”) (Marrero et al., 2015a). The complete ^{10}Be and ^{36}Cl data in CRONUScalc format are given in Tables A.3 and A.4, respectively. Accelerator mass spectrometry analytical data are listed in Table A.5. Chlorine-36 ages are reported in Table A.2 and ^{10}Be ages in Table 4. CRONUScalc was calibrated using the CRONUS-Earth primary calibration data set (Borchers et al., 2015). CRONUScalc calculates ages using production rates calibrated to seven commonly used global scaling methods (Marrero et al., 2015a). The Sierra Nevada samples described in this paper, along with many other groups of samples, were used in the evaluation of these methods. The outcome of this evaluation was that the “Lifton-Sato-Dunai nuclide-dependent (commonly abbreviated “LSDn” or “Sa”)” scaling (Lifton et al., 2014) was recommended because its accuracy was similar to other high-performing scaling methods and it has a stronger basis in atomic physics. In this paper only the ages calculated using this method are reported; the results are listed in Tables 2 and A.2. Ages calculated using alternative scaling methods are available in Marrero et al. (2015b) and Phillips et al.

(2015). The CRONUS-calibrated production rates associated with the LSDn scaling are as follows (all in units of atoms $\text{g}^{-1} \text{yr}^{-1}$): ^{10}Be in quartz 3.92 ± 0.31 , ^{26}Al in quartz 28.5 ± 3.1 , ^{36}Cl from Ca 56.0 ± 4.3 , ^{36}Cl from K 155 ± 11 . The $P_f(0)$ production parameter for production of ^{36}Cl by low-energy neutron absorption by ^{35}Cl (see Marrero et al., 2015a, for further information) is 759 ± 180 neutrons $(\text{g air})^{-1} \text{yr}^{-1}$.

5. Snow shielding and scaling of cosmogenic-nuclide concentrations

The Sierra Nevada is subject to heavy winter snowfall, with snow depths exceeding 3 m in some areas. Snow-shielding corrections are thus potentially quite significant (e.g., site snow shielding of 0.78 at the Twin Lakes site). Traditionally, shielding due to a layer of snow on a sample surface has been quantified by estimating the mass coverage (i.e., g cm^{-2}) due to snow and then calculating the resultant reduction in the cosmic-ray flux using the standard spallation attenuation length, as described by Gosse and Phillips (2001). However, recent publications have suggested that the actual effects on snow cover on cosmogenic-nuclide production are more complicated than this simple model. Modeling by Zweck et al. (2013) has indicated that the reduction in the high-energy neutron flux is greater than the standard model would indicate, but that the flux of the lowest energy neutrons (“thermal neutrons”) is enhanced. These effects are in large part due to the strong energy-moderating properties of the hydrogen in snow.

Two recent studies have addressed these phenomena. Delunel et al. (2014) used a network of cosmic-ray snow gauges in the Massif Central of France to empirically evaluate the reduction of cosmic-ray intensity under varying depths of snow. Their

results showed an even stronger reduction of the cosmic-ray counts than that predicted by Zweck et al. (2013) (e.g., 20% reduction for the standard model, 30% reduction by the Zweck et al, 2013, calculations, and 50% reduction based on their observations). They attributed this to preferential sensitivity of their detectors to the fast neutron portion of the spectrum (0.1 to 10 MeV), compared to the simulations of Zweck et al. (2013) that emphasized high-energy neutrons (>10 MeV), which are less sensitive to energy moderation. Most cosmogenic nuclides are predominantly produced by the high-energy neutrons, but the cross-section for ^{36}Cl production by spallation of K peaks at about 7 MeV (Reedy, 2013) and should thus be subject to the enhanced attenuation observed by Delunel et al. (2014). At the low end of the energy spectrum, Dunai et al. (2014) monitored thermal neutrons within granite blocks under varying thickness of water and other hydrogen-rich materials. They observed marked increases in the thermal-neutron flux, as predicted by Zweck et al. (2013). For commonly encountered depths of snow, these corresponded to 200 to 300% increases in the thermal-neutron flux. Their calculations indicated that for rock compositions for which 30% of the production of ^{36}Cl was from absorption of thermal neutrons by ^{35}Cl (a common proportion), the over-all production rate of ^{36}Cl would be enhanced by ~50%. The large magnitude of the snow effects seen by Delunel et al. (2014) and Dunai et al. (2014) suggests that snow cover could cause ages calculated from ^{36}Cl concentrations to show very large discrepancies compared to those from nuclides produced predominantly by high-energy neutrons.

In this paper we have calculated snow shielding corrections using the standard methodology described in Gosse and Phillips (2001). This is partly because the studies described above are new and relatively untested and partly because the methodology for

employing these new approaches is not entirely clear. The most important reason is because part of the objective of the study is to provide data to quantify the uncertainty associated with applying the CRONUS-Earth models and production parameters to suites of ages calculated using standard, current methods. However, our data do contain at least a limited number of samples that were analyzed for both a nuclide produced by high-energy neutrons (^{10}Be) and one produced by fast and thermal neutrons (^{36}Cl) and this offers the opportunity to evaluate the magnitude of age discrepancies due to snow cover.

We note that in many cases samples were collected from settings intended to minimize snow cover (e.g., steeply dipping surfaces or tall boulders on ridge crests where wind is likely to blow away snow). Estimated snow-cover corrections for these samples are therefore typically less than ‘site’ corrections calculated assuming a flat, ground-level surface.

5.1 Snow Shielding

5.1.1 Snow and Topographic Shielding for the Legacy $^{10}\text{Be}/^{26}\text{Al}$ Samples

The “Site Snow Shielding” values shown in Table 1 for the Nishiizumi et al. (1989) samples were calculated by Candace Kohl using snow survey data from the California Department of Water Resources. Data collected over many years were averaged on a monthly basis. The resultant attenuation, calculated using the standard methodology described in Gosse and Phillips (2001), was calculated for each month and then summed over the year to give an average annual snow attenuation. The snow

correction must be applied on a sample-by-sample basis. For samples from boulders with tops above ground level, the boulder height was subtracted from each monthly snow depth and the average annual snow attenuation calculated using only the residual snow in excess of the boulder height. Samples from steeply dipping rock surfaces will retain little or no snow. In Table 1 the full correction was applied to samples with less than 20° dip and no correction to samples with 70° or greater dip. For samples with 45° dip we applied 30% of the full snow correction and to the sample with 58° dip we applied only 10% of the full correction.

5.1.2 Snow and Topographic Shielding for the Legacy Bishop Creek/Humphreys Basin ³⁶Cl Samples

The snow shielding corrections for the Bishop Creek/Humphreys Basin samples were calculated in the same fashion as for the legacy ¹⁰Be – ²⁶Al samples described above. There are five snow-course measurement sites reported for the area, providing an unusually comprehensive data set. The individual data were regressed as a function of elevation, allowing the correction to be interpolated for nuclide-sampling sites at elevations different than the snow-measurement sites. As described above, many samples were collected from the tops of high boulders or other settings that minimized snow depth, and adjustments were accordingly made to the level-ground snow-shielding estimates.

692 5.1.3 Snow and Topographic Shielding for the Legacy Mt. Starr, Morgan, and Ellery ^{36}Cl
693 Samples

694
695 The Mt. Starr, Morgan, and Ellery samples were all collected from sites that were
696 selected on the basis of little to no likelihood of significant snow accumulation, according
697 to the sampling field notes. They therefore were assigned no snow-shielding corrections.

698
699 **6. Results from the ^{36}Cl and $^{10}\text{Be}/^{26}\text{Al}$ Age Comparisons**

700
701 The ^{10}Be and ^{36}Cl ages of the Sierra Nevada samples, calculated using the
702 CRONUS-Earth calibration, are plotted grouped by sampling location in Figure 8 and the

Figure 8. Summary of ^{36}Cl and ^{10}Be ages from the Sierra Nevada secondary sites. Sources of data are cited at the top of the figure, but ages have been recalculated using the LSDn scaling (Lifton et al., 2013) and CRONUS-Earth production rates (Borchers et al., 2014 and Marrero et al., 2014). Values are reported in Tables 1 and A.2. Samples represented by empty symbols were excluded from averages as outliers (Table 3). Blue horizontal lines illustrate the independent age constraints adopted for each site. The two sets of data to the right that are identified as “This study” are ‘new’ samples; the rest are ‘legacy’ samples.

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site statistics are summarized in Table 3. The “age uncertainties” that are shown in both these sources are derived from the nuclide and geochemical uncertainties associated with the respective analyses, as well as propagation of uncertainties related to the sampling parameters. The estimated uncertainties associated with the production parameters (Phillips et al., 2015) are also propagated through into the final age uncertainties.

Table 3. Statistics on cosmogenic nuclide ages from Sierra Nevada sites.

Feature Dated	Nuclide	Independent Age (ka)	Mean Calculated			Percent Age Unc. Rel to Indep Age (%)
			Age (ka)	Age without Outliers (ka)	Percent Deviation (%)	
Tioga maximum, Middle Fk Bishop Cr	³⁶ Cl	16.1±0.5	16.5±0.2	16.5±0.2	2.3	10.3
Tioga 4 retreat, Nishiizumi 1989	¹⁰ Be	15.75±0.5	17.7±1.7	16.7±0.2	5.8	15.6
Tioga 4 retreat, Nishiizumi 1990	²⁶ Al	15.75±0.6	16.9±2.3	15.6±0.9	-0.8	5.0
Tioga 4 retreat, Humphreys Basin	³⁶ Cl	15.75±0.5	15.1±0.5	15.1±0.5	-3.9	7.2
Tioga 4 retreat, Evans	³⁶ Cl	15.75±0.5	13.5±4.6	15.2±1.7	-3.3	13.4
Recess Peak, upper Bishop Cr	³⁶ Cl	13.3±0.25	11.5±1.1	11.5±1.1	-10.5	8.9
Recess Peak, Baboon Lakes	¹⁰ Be	13.3±0.25	12.7±0.6	12.7±0.6	-4.3	1.3
Recess Peak, Baboon Lakes	³⁶ Cl	13.3±0.25	10.4±2.6	11.3±1.0	-14.9	8.9

The uncertainty associated with the mean calculated ages is the standard deviation of the individual ages, not the average age uncertainty. The outliers excluded for the “Tioga 4 retreat, Nishiizumi 1989” samples were numbers W86-3, W86-10, and W86-13. As discussed below in Section 7.4.1, these samples were heavily snow shielded, and application of the snow shielding correction produced anomalously old ages. The outliers excluded for the “Tioga 4 retreat, Evans” samples were ms-2(leachate) and mp-2(leachate). These yielded anomalously young ages, probably for analytical reasons. The outliers excluded for the “Recess Peak, Baboon Lakes, ³⁶Cl” samples were FBL07-01, FBL07-03, and F2BL07-03, which also yielded anomalously young ages, also

probably for analytical reasons. The “Percent Age Uncertainty Relative to Independent Age” column reports the average age uncertainty as a percentage of the independent age.

In general, the mean calculated ages without outliers are in fair-to-good agreement with the independent ages. These are generally well within the average age uncertainties (i.e., comparing the last two columns of Table 3). However, the various data sets do appear to exhibit some evidence of bias, and in some data sets there are deviations of individual samples that are large compared to the age uncertainties. In particular, we note that on average the Tioga 4 maximum or retreat samples are in good agreement with the independent ages, but that the samples from the various sites tend to cluster slightly above or below the expected age. This is not true of the the Recess Peak ^{36}Cl samples from upper Bishop Creek and Baboon Lakes, which differ by -10.5 and -14.9 percent, respectively.

7. Discussion and Evaluation of Systematic Errors

The ages given above are only for the LSDn scaling method and are intended to illustrate. Ages for the Sierra Nevada secondary samples calculated using all seven scaling methods are given in Borchers et al. (2015) and Marrero et al. (2015b) as part of the evaluation of the CRONUS-Earth cosmogenic nuclide production-rate calibration using the entire, much more comprehensive, secondary data sets. These samples, again as part of the larger secondary data sets, are used by Phillips et al. (2015) to quantify the uncertainty associated with the production parameters.

In this paper the emphasis is on evaluating any anomalies in the Sierra Nevada data set with regard to biases of the mean ages relative to the independent ages, or with regard to unusually large variability within individual data sets. Most of the discussion focuses on factors affecting ^{36}Cl because the anomalously young Recess Peak ^{36}Cl ages are the only really significant bias. The sources of variability can be divided into systematic factors and local factors. The most important systematic factors are production rates, spatial scaling, and temporal scaling. The most important local factors are snow shielding, analytical issues, and possible error in the assigned independent ages. These will be discussed in Section 7.4.

7.1 Production Rates (for ^{36}Cl Samples Only)

One possible source of bias in the age distributions between sample sites is miscalibrated production rates. Here we discuss the possible effects only for the ^{36}Cl samples. If one site, for example, had production of ^{36}C predominantly from spallation of K, while at another it was predominantly from absorption of low-energy neutrons by Cl, and the production constants were not in proper proportions, the ages would exhibit bias from site to site. We note, in particular, that the Tioga 4 ^{36}Cl ages are in reasonably good agreement with the independent ages but the Recess Peak ages are not; this mechanism could explain the discrepancy if the sites were compositionally different and one of the production rates were significantly in error.

We defer discussion of ^{10}Be and ^{26}Al because there is only one significant production reaction each for ^{10}Be and ^{26}Al , and thus the effects of production-rate

calibration cannot be separated from those of scaling. For ^{36}Cl , in contrast, with three significant production reactions, between-site bias could be produced if the production rates for the various reactions are not in their correct relative proportions. We discuss possible effects of combined production rates and scaling on ^{10}Be and ^{26}Al in Section 7.2.

To test the possibility of internally inconsistent production rates for different target elements, using the entire ^{36}Cl data set, we have plotted normalized age (defined here as calculated ^{36}Cl age for each sample divided by the site mean age) against the percentage of production from various reactions. In Figure 9 normalized age is plotted against the percentage of spallation production from K. (Production from spallation of Fe and Ti is small and was neglected in the percentage calculation, hence the remainder of the spallation production can be attributed to Ca). Only samples with greater than 70% of their production from spallation were used in this figure. Were the CRONUS-Earth calibrated values for the spallation production rates not in the proper proportion, the data should exhibit covariation between the proportion of production from K and the normalized age. This is not observed, thus there is no evidence that error in specifying the relative proportions of production from K and Ca is responsible for any bias observed in Figure 8.

Figure 9. Normalized age, defined as the age calculated for each sample using the LSDn scaling (Lifton et al., 2013) and CRONUS-Earth production rates (Borchers et al., 2014 and Marrero et al., 2014), divided by the site mean age, plotted against the proportion of spallation production from K as opposed to Ca (i.e., 60% from K corresponds to 40% from Ca). Only samples with >70% production from potassium and calcium spallation, combined, were used in this figure. “Rock Creek” refers to the Morgan and Mt. Starr localities of Evans et al. (1997).

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802 In Figure 10 we examine the possibility of an analogous incorrect specification of
803 the ratio of spallation (of K and Ca) to low-energy neutron absorption by Cl. Normalized
804 age is plotted against percent production from Cl (with the remainder attributed to
805 spallation). An incorrect value for the $P_f(0)$ parameter (describing the low-energy
806 neutron flux) relative to the spallation production rates would produce covariation
807 between the normalized age and the percent production from Cl; this is not observed. We
808 conclude that incorrect specification of the relative values of the production parameters
809 are not likely to explain any biases observed in Figure 8.

810 Information on relative accuracy of production rates may also be obtained from a
811 comparison of nuclides. The ^{26}Al and ^{36}Cl ages are in very good agreement. The ^{10}Be
812 and ^{36}Cl ages in this data set are in agreement within the propagated age uncertainties.
813 However, Figure 8 indicates that there is a slight tendency for the ^{10}Be ages to be older
814 than the ^{36}Cl ages for both the Tioga 4 and the Recess Peak samples. Specifically, the
815 average normalized ^{10}Be ages of Nishiizumi samples without large snow-cover
816 corrections are 1.04 ± 0.01 compared to 0.99 ± 0.03 for the comparable Humphreys Basin
817 ^{36}Cl average, and the normalized ^{10}Be age of 0.97 ± 0.05 for the Baboon Lakes samples
818 can be compared to 0.84 ± 0.07 for the ^{36}Cl ages from the same boulders. This may
819 possibly indicate a small discrepancy in the relative production rates of these two
820 nuclides, although it is noteworthy that the oldest ^{36}Cl ages from both sites are very
821 similar to the ^{10}Be ages.

Figure 10. Normalized age, defined in Figure 9, plotted against percent production from low-energy neutron absorption by Cl, with the remainder being K and Ca spallation production. “Rock Creek” refers to the Morgan and Mt. Starr localities of Evans et al. (1997).

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7.2 Spatial Scaling

In the evaluation conducted here, the scaling method of Lifton et al. (2014) has been employed. Spatial inaccuracies in this scaling (for ^{10}Be and ^{26}Al , which are produced by a single predominant reaction, inaccuracies in either scaling or the calibrated production rate) could produce biases between the calculated and independent ages. However, Table 3 shows that the Tioga 4-age samples for all the nuclides are generally grouped closely around the specified independent ages (average deviation less than the average age uncertainties) and thus do not indicate any significant error in either scaling or production rate. In contrast, the Recess Peak ^{36}Cl samples show significant bias toward young ages (average deviations greater than the average age uncertainties). We have already concluded that this bias is probably not due to discrepancies in the production rates from the various target elements. With regard to the spatial scaling, the Recess Peak ages are intermediate in elevation between the Tioga 4 maximum samples ('Forks site', Bishop Creek) and the Humphreys Basin samples, both of which are in good agreement with the independent ages. Inaccuracy in spatial scaling would not produce this inconsistency, and thus some other cause is probably responsible for the bias in the Recess Peak samples.

7.3 Temporal Scaling

The scaling method of Lifton et al. (2014) employs a detailed geomagnetic-field history, together with an evaluation of geomagnetic-field modulation of the cosmic-ray flux based on numerical modeling to provide temporal scaling of the cosmogenic production rates. Unaccounted-for factors in this temporal scaling (e.g., an unaccounted

negative anomaly in the non-dipole geomagnetic field over the Sierra Nevada between 15.75 and 13.3 ka, followed by a compensating positive anomaly subsequent to 13.3 ka) could in principle explain a negative bias in the Recess Peak ages while maintaining little bias in the Tioga 4 ages. However, the magnitude of these fluctuations in the period between the glacial advances (amounting to 2.45 ka) would have to be extremely large to have such an obvious effect when subsequently integrated over 13.3 ka of simultaneous exposure. Furthermore, the signs and durations of the anomalies would have to be quite fortuitous to produce the observed result. Finally, we would expect that the ^{36}Cl ages from the Baboon Lakes site would be affected the same as the ^{10}Be and ^{26}Al ages, but this is not the case (the ^{10}Be ages are close to the independent age whereas the ^{36}Cl ages show a bias toward being too young). Thus, although this explanation is possible, we do not consider it to be likely.

7.4 Evaluation of Local Factors

None of the systematic factors examined above provide a plausible explanation for the observed negative bias of the calculated ages from Recess Peak deposits, but not from Tioga 4 deposits. This points to local factors as a possible explanation. The most plausible local factors are incorrect snow shielding, analytical problems, and incorrect assignment of the independent ages. (We note that, due to the relatively young ages of these samples and the resistant nature of the granitic samples collected, difference in surface erosion are unlikely to produce any significant deviations in the calculated ages.)

7.4.1 Snow Shielding

The Sierra Nevada is subject to heavy winter snowfall, with snow depths exceeding 3 m in some areas. Snow-shielding corrections are thus potentially quite significant (e.g., site snow shielding of 0.78 at the Twin Lakes site). As described above, snow-shielding corrections were calculated using snow-course data and using the standard methodology described in Gosse and Phillips (2001). However, in many cases samples were collected from settings intended to minimize snow cover (e.g., steeply dipping surfaces or tall boulders on ridge crests where wind is likely to blow away snow). Estimated snow-cover corrections are therefore typically less than the ‘site’ corrections calculated assuming a flat, ground-level surface.

The ages of the ^{10}Be and ^{26}Al samples from the Nishiizumi et al. (1989) study exhibit a bimodal distribution, and inspection indicates that this is almost certainly related to the snow-shielding correction. For the purposes of the comparisons below, the old Lal (1991) scaling was used. Topographic shielding was computed using the equations in Gosse and Phillips (2001), as implemented by CHLOE (Phillips and Plummer, 1996). It includes both effects from the blocking of cosmic radiation by topography and from the dip of the rock surface. The “Site Snow Shielding” values shown in Table 1 were calculated as described in Section 5.1.1.

The nuclide concentrations and scaling factors in Table 1 were used to evaluate the influence of spatial, geometric, and snow-cover scaling on the consistency of these data. Values for the scaled ^{10}Be and ^{26}Al concentrations are given in Tables 4 and 5. The

scaling corrections in these tables were applied cumulatively; in other words, each column contains all of the scaling corrections shown to the left.

Table 4. ^{10}Be data rescaled to account for variations in elevation, topographic shielding, and snow cover.

	Renormalized ^{10}Be Conc.		Elev/Lat Scaled ^{10}Be		Topo Scaled ^{10}Be		Topo + Snow Scaled ^{10}Be	
	10^6 atoms/g	$\pm$	10^6 atoms/g	$\pm$	10^6 atoms/g	$\pm$	10^6 atoms/g	$\pm$
W86-1	0.420	0.052	0.0455	0.0057	0.0599	0.0075	0.0611	0.0076
W86-3	0.562	0.106	0.0610	0.0115	0.0633	0.0119	0.0788	0.0148
W86-4	0.459	0.049	0.0412	0.0044	0.0637	0.0068	0.0637	0.0068
W86-5	0.511	0.060	0.0450	0.0053	0.0625	0.0073	0.0625	0.0073
W86-6	0.518	0.066	0.0456	0.0058	0.0633	0.0081	0.0633	0.0081
W86-8	0.509	0.078	0.0448	0.0068	0.0622	0.0095	0.0622	0.0095
W86-10	0.341	0.056	0.0569	0.0094	0.0569	0.0094	0.0731	0.0120
W86-11	0.316	0.037	0.0524	0.0062	0.0570	0.0067	0.0613	0.0072
W86-12	0.349	0.095	0.0579	0.0158	0.0631	0.0172	0.0678	0.0185
W86-13	0.299	0.030	0.0608	0.0061	0.0610	0.0061	0.0783	0.0078
Mean	0.428	0.063	0.0511	0.0077	0.0613	0.0090	0.067	0.010
St Dev	0.091		0.0071		0.0024		0.007	
Coeff Var (%)	21.4		14.0		4.0		9.8	

Table 5. ^{26}Al data rescaled to account for variations in elevation, topographic shielding, and snow cover.

	Published ^{26}Al Conc.		Elev/Lat Scaled ^{26}Al		Topo Scaled ^{26}Al		Topo + Snow Scaled ^{26}Al	
	10^6 atoms/g	$\pm$	10^6 atoms/g	$\pm$	10^6 atoms/g	$\pm$	10^6 atoms/g	$\pm$
W86-1	2.81	0.16	0.305	0.017	0.401	0.018	0.409	0.305
W86-3	3.48	0.21	0.377	0.023	0.392	0.028	0.488	0.242
W86-4	2.68	0.17	0.241	0.015	0.372	0.015	0.372	0.283
W86-5	3.45	0.16	0.304	0.014	0.422	0.014	0.422	0.213
W86-6	3.27	0.15	0.288	0.013	0.400	0.013	0.400	0.181
W86-8	3.22	0.17	0.283	0.015	0.394	0.015	0.394	0.174
W86-10	2.41	0.14	0.402	0.023	0.402	0.030	0.517	0.484
W86-11	2.26	0.12	0.375	0.020	0.408	0.021	0.439	0.522
W86-12	2.39	0.12	0.397	0.020	0.432	0.021	0.464	0.204
W86-13	2.23	0.14	0.453	0.028	0.454	0.037	0.583	1.106
Mean	2.820	0.154	0.3424	0.0189	0.4077	0.0213	0.449	0.371
St Dev	0.498		0.067		0.023		0.065	
Coeff Var (%)	17.6		19.7		5.7		14.5	

As expected, for the unscaled concentrations there is considerable variability, dominated by site-to-site variation caused principally by differences in production rate arising from differences in elevation and to a lesser extent differences in geomagnetic

latitude. Application of the elevation/latitude scaling provides a considerable reduction in the variation of the ^{10}Be concentration. The coefficient of variation of the entire data set is reduced from 21 to 14%. The remaining variability is presumably produced by differences in topographic and snow shielding. Dividing by the topographic shielding coefficient results in a further very substantial reduction in the coefficient of variation, from 14 to 4%. This is actually smaller than the average reported analytical coefficient of variation of the samples (Table 4). Presumably, the remaining variation should be even further reduced by application of the snow-shielding scaling coefficient. Unfortunately this is not the case. The coefficient of variation of the corrected concentrations is increased from 4% to 10% by the snow correction. In effect, the snow coefficient ‘overcorrects’ the samples. Before application of the snow correction, the samples from the flat exposures had ^{10}Be concentrations very similar to those from non-snow-covered sites. Aluminum-26 shows very similar patterns (Table 5).

The reason for this discrepancy is not obvious. One possible reason is that snow depth has been grossly overestimated. This seems unlikely; snow depths in midwinter in the Sierra Nevada are normally many meters and there are no data to indicate that these sites experience anomalously low snow cover of the magnitude required to explain the discrepancy. The sites needing correction for snow shielding are in valley bottoms where windblown snow tends to collect, rather than on wind-deflated ridge tops. Another possible reason is that calculations for topographic shielding have significantly underestimated the shielding correction for the sloping surfaces (i.e., that the shielding coefficients should be smaller). However, for the samples without snow-cover issues, the topographic shielding correction greatly reduces the coefficient of variation of the sample

concentrations and this seems quite unlikely if it is seriously in error. Furthermore, the topographic shielding calculation has a strong physical basis (Nishiizumi et al., 1989; Gosse and Phillips, 2001). The discrepancy may point to a smaller effect from snow shielding than is calculated from the standard mass shielding calculation, such as that given in Gosse and Phillips (2001). However, the recent numerical simulations by Zweck et al. (2013) and the cosmic-ray flux data under snow by Delunel et al. (2014), both discussed in Section 5, point in the opposite direction: shielding by snow is about 40% *more* effective than by silicate rock (i.e., an effective attenuation coefficient of 109 g cm⁻², or more, for snow compared to 153 g cm⁻² for quartz). In summary, we have no ready explanation and this puzzling discrepancy points to a need for further investigation of snow-cover effects.

The ³⁶Cl samples associated with the Tioga 4 advance show small site-to-site biases (+2 to -4 percent, compared to average individual sample age uncertainties of 7 to 13 percent). These could easily be explained by small errors in the estimation of the snow-cover correction that vary systematically from site to site.

The ³⁶Cl samples from the Recess Peak advance, in contrast, show site age biases of -10 and -15 percent that are significantly larger than the average age uncertainties of 9 percent. Whether this can plausibly be attributed to error in the snow correction is equivocal. Four of the seven total Recess Peak samples were assigned small snow shielding values (0.96 to 0.99) because they were from tall boulders that were in positions where snow was thought to be rapidly blown off their tops. This may have resulted in underestimation of the snow-shielding coefficient. (Note in this regard that only three boulders were sampled at the Baboon Lakes site; the large number of ³⁶Cl analyses

reported were performed on different mineralogical fractions of these three boulders.) One piece of evidence possibly favoring this hypothesis is that if the oldest age from each of the three sample groups (upper Bishop Creek ^{36}Cl , Baboon Lakes ^{10}Be , Baboon Lakes ^{36}Cl) is averaged, the mean is 13.5 ± 0.2 ka, in very good agreement with the independent age of 13.3 ± 0.25 ka. However, arguing against this hypothesis, the “old” ^{10}Be and ^{36}Cl ages at the Baboon Lakes come from different boulders, and the old age is not replicated on the other mineralogical fractions.

Another argument against snow as the entire explanation for the underestimation of the Recess Peak ages is that the magnitude of the postulated snow cover seems to be too large to be reasonable. Snow normally persists from January through June (California Department of Water Resources, 2012). Averaging the significant snow cover over six months and assuming a standard production attenuation coefficient of 150 g cm^{-2} and an annual average reduction of the production rate by 14.9% would require approximately 50 g cm^{-2} snow cover during the six snow months, or about 2 m of snow. This is about double the average monthly snow accumulation on flat surfaces in this area during this part of the year (California Department of Water Resources, 2012). Given that the boulders are in general 1 to 2 m tall and are from areas exposed to removal of snow cover by wind, this degree of snow cover does not seem feasible. Even assuming the boulders carried as much snow as flat surfaces, a reduction of age by only about 7% would be justified under the traditional approach.

However, the results of Delunel et al. (2014) render this inference less certain. Application of their snow-shielding algorithm implies that an average winter snow depth

of 10 g cm^{-2} , equivalent to about 40 cm depth of snow, would reduce the annual production rate by about 15%. This much winter snow cover cannot be ruled out.

In summary, errors in, or inadequate models for, snow-cover estimation clearly played a role in the spread of the legacy ^{10}Be data, and are a plausible explanation for the site-to-site biases of the Tioga 4 ^{36}Cl ages distributions. Whether snow-cover effects explain the mean age discrepancy of the Recess Peak ages is equivocal. Application of the Delunel et al. (2014) results indicates that a reduction of the average annual production rate by $\sim 15\%$ may be consistent with realistic snow accumulations. Under the traditional approach, the snow depths are inadequate to explain the production-rate reduction. Furthermore, even assuming that the Delunel et al. (2014) results are applicable, this still leaves open the question of why the traditional approach apparently successfully corrected the Tioga 4 samples, which are from very similar boulders as the Recess Peak one, but did not do so for the Recess Peak samples. This suggests that snow cover is not the entire explanation for the systematic underestimation of the Recess Peak ages.

7.4.2 Target-Element Dependence of Snow Shielding

Evidence from the Sierra Nevada data set for and against the applicability of the Delunel et al. (2014) and Dunai et al. (2014) snow-shielding results is equivocal. In order to more thoroughly investigate this issue, we have examined the relation between calculated ^{36}Cl ages and the principal target element for ^{36}Cl production. As described above (Section 5), the results of Delunel et al. (2014) indicate that under snow cover

1003 there is a significant reduction in the flux of neutrons in the 0.1 to 10 MeV range; the
1004 peak of the cross section for production of ^{36}Cl from spallation of K is at about 7 MeV.
1005 Conversely, the results of Dunai et al. (2014) show a strongly enhanced thermal-neutron
1006 flux under the snow blanket; production of ^{36}Cl from ^{35}Cl is predominantly in the thermal
1007 energy range. These observations indicate that snow-covered samples for which
1008 production is largely from spallation of K should yield anomalously young ages and
1009 those for which production is largely from Cl should yield anomalously old ages.

1010 The Baboon Lakes data are well suited to investigating this prediction. Chlorine-
1011 ^{36}Cl concentrations were measured in whole-rock samples and in a range of mineral
1012 separates, some of which were K-rich and others Cl-rich. A maximum of ~15% of the
1013 production was from spallation of Ca, thus production is very largely dominated by K
1014 and Cl, the elements that are apparently sensitive to snow cover. In Figure 11 we have
1015 plotted the calculated ^{36}Cl age as a function of the percentage of production from K. Due
1016 to the low Ca concentrations, samples with low production from K are dominated by
1017 production from Cl.

Figure 11. Apparent ^{36}Cl age for Baboon Lakes, Recess Peak age, boulder samples, as a function of the percentage of ^{36}Cl production from spallation of K. Calcium concentrations are low, therefore low percentage ^{36}Cl production from spallation of K corresponds to high percent production from thermal neutron absorption by Cl.

The samples in Figure 11 are identified by boulder number because of likely differences in the amount of snow cover. Boulder 2 was on the moraine crest and was deemed likely to be blown free of snow most of the time. The ^{10}Be age from this boulder was 13.4 ka, which is close to the maximum possible age for the Recess Peak moraines, supporting this inference. Boulders 1 and 3 were a short distance on the lee side of the crest, suggesting the possibility of some snow retention. The ^{10}Be ages of boulders 1 and

3 were 12.0 and 12.8 ka, respectively. Assuming that these differences from boulder 2 can be ascribed to snow cover, and that the attenuation follows the standard model (which is likely because the average neutron energy for spallation of ^{10}Be is very high), then average winter snow cover (6 months) can be calculated to be about 40 g cm^{-2} for boulder 1 and 20 g cm^{-2} for boulder 2. These average winter snow covers then correspond to snow shielding corrections of 0.75 and 0.80 for production from K (0.1 to 10 MeV neutrons), according to Delunel et al. (2014). According to Figure 6 of Dunai et al. (2014), these snow covers should produce thermal neutron fluxes of 150 to 200 % of those on snow-free surfaces. Pro-rated over the entire year, production rates from thermal neutron absorption by Cl should be enhanced by 75 to 100 %.

Based on these calculations, boulder 2 should show little variation in apparent ^{36}Cl age as a function of percentage of production from K. This is indeed what is observed in Figure 11. Boulders 1 and 3 should exhibit a variation in apparent age of about 100 % over the full range of production from K (i.e., from +75 % for the low-K samples to -25% for the high K samples). This is not observed in Figure 11. Boulder 3 shows no apparent variation in age with percent production from K. Boulder 1 appears to show a weak correlation of increasing apparent age with decreasing production percentage from K, as predicted. However, the total magnitude of the difference is only about 40% rather than the 100% predicted.

Keeping in mind that we have not demonstrated that boulders 1 and 3 undergo significant snow cover, but rather only inferred it, the data in Figure 11 provide at best weak support for the postulated effects of snow cover on K-rich and Cl-rich samples.

Boulder 3 shows no apparent trend of age with composition and although boulder 1 does show the expected covariation, the magnitude is less than half of the expected value.

7.4.3 Analytical Problems

Irregularities during sample processing and analysis are always a potential cause of a systematic discrepancy. There is no direct evidence that anything went wrong during the processing or analysis of the Recess Peak ^{36}Cl samples. Possible support for this cause is offered by the observation that two of 24 ^{36}Cl samples gave ages in the expected range (13.55 to 12.95 ka) and that the average of the three ^{10}Be samples, 12.7 ± 0.6 ka, is closer to the expected range than is the average of all the Recess Peak ^{36}Cl samples, 11.4 ± 1.0 ka. Arguing against an analytical artifact is the observation that samples analyzed in the late 1990's (numbers 119-122) gave ages nearly identical to those analyzed in 2011 (numbers 125-127). Other groups of samples (98-101 and 113-117) analyzed during the same interval in the same laboratory gave ages close to the expected ranges. We cannot rule out an analytical artifact particular to the Recess Peak samples, but there is no positive evidence to support it.

7.4.4 Error in Independent Age Assignment

Both the ^{10}Be and the ^{36}Cl age distributions associated with the Tioga 4 advance show a generally acceptable agreement with the independent age assignment of 15.75 ± 0.5 ka, discussed above. Although small biases from site to site are apparent, these are

within the expected uncertainty bounds and probably reflect minor mis-estimation of local parameters such as snow cover. In contrast, the underestimation of the age of the Recess Peak moraine by the majority of samples is outside of the expected bounds and is not well explained by any of the factors discussed so far. One possibility is that the exposure age of the materials sampled is actually closer to that of the majority of cosmogenic ages than it is to the assigned age.

The evidence regarding the chronology of the Recess Peak advance has been summarized above and discussed in detail by Phillips (2015). Direct evidence, based on radiocarbon dating of lacustrine sediment layers above and below barren silt layers attributed to Recess Peak glacier outwash, appears to be strong and internally consistent between several sites and cores. This pre-Younger Dryas age appears to be supported by the ^{10}Be results from Baboon Lake. However, a survey of hemispheric, regional, and local paleoclimate records offers only weak support for a strong cooling during the 13.5 – 13.1 ka interval and instead more generally indicates strong cooling at the time of the Younger Dryas. Thus we cannot rule out the possibility that the age of the Recess Peak materials should actually be in the range of 12.9 to 11.6 ka. The mean of all the ^{36}Cl ages (less outliers) of 11.4 ± 1.0 ka is in good agreement with the ending of the Younger Dryas.

8. Conclusions

Our detailed review of the chronological controls on the exposure of samples comprising the Sierra Nevada deglacial ^{10}Be production-rate calibration data set, and the

1098 subsequent ^{36}Cl samples collected in the same area, shows that the chronological control
1099 is much stronger than it was in 1986, that the exposure age of the samples is older by
1100 ~50% than was believed in 1986, and that the control is adequate to use the samples for
1101 purposes of assessment of the utility of the CRONUS-Earth cosmogenic production
1102 model (note that they were not used in the calibration data set).

1103 In addition, we have evaluated the settings from which legacy ^{36}Cl data in the
1104 Sierra Nevada were collected and included them in the secondary CRONUS-Earth data
1105 set. The best-documented constraints on deglacial-period chronology are from two of the
1106 drainages from which secondary sample sets (both ^{10}Be and ^{36}Cl) were taken (Saddlebag
1107 Lake/Greenstone Lake and Bishop Creek). Phillips (2015) has presented a large amount
1108 of evidence to support final Tioga deglaciation at $15,750 \pm 500$ years and apparently
1109 strong, although not unequivocal, evidence for a maximal extent of the Recess Peak at
1110 $13,300 \pm 250$ years before 1950. The three ^{10}Be sample sets from different localities do
1111 not show systematic variations that would indicate the timing of deglaciation varied from
1112 site to site.

1113 Reevaluation of the field documentation for the 1986 ^{10}Be sample collection
1114 demonstrates that sample locations and characteristics can be specified with sufficient
1115 accuracy to use them for the evaluation of the new production rates. The principal source
1116 of scatter within the distribution of ^{10}Be ages can be attributed to the snow-shielding
1117 correction, which if calculated using standard procedures, are as large as 20 to 30%. The
1118 shielding factor seems to drastically overcorrect the ages of samples from this data set
1119 that are from flat surfaces with large winter snow accumulations, for reasons that cannot
1120 be identified with certainty. If the samples that are not subject to significant snow

shielding are averaged, they yield means of 16.7 ± 0.2 ka (for ^{10}Be) and 15.6 ± 0.9 ka (for ^{26}Al) using the new CRONUS-Earth production model, in reasonable agreement with the new independent age assignment for Tioga 4 retreat of 15.75 ± 0.5 ka. The new ^{10}Be ages for the Recess Peak advance, averaging 12.7 ± 0.6 ka, are also in agreement with the independent age of 13.3 ± 0.25 ka. These samples form part of a much larger secondary data set used by Phillips et al. (2015) to assess the uncertainty associated with the CRONUS-Earth ^{10}Be production model.

The average of the normalized ages for the ^{36}Cl samples associated with the Tioga 4 glacial cycle (normalized age is necessary because the Tioga 4 maximum and retreat samples have slightly different ages) is 0.99 ± 0.07 , showing excellent agreement with the independent age. However, the samples associated with the Recess Peak advance average 11.4 ± 1.0 ka, about 15% younger than the assigned independent age. It is difficult to attribute this discrepancy to systematic, global factors. Possible explanations include a mis-assignment of the independent age, an undetected analytical artifact, or some other unidentified problem. In any case, we do not find a basis for excluding these samples from the CRONUS-Earth secondary data set and they have been used, along with numerous other secondary samples, by Marrero et al. (2015b) to assess the uncertainty of the CRONUS-Earth ^{36}Cl production model.

We have used the new ^{36}Cl samples from the Recess Peak moraine at Baboon Lakes to test the nuclide-specific snow-shielding predictions of Delunel et al. (2014) and Dunai et al. (2014). The results were equivocal, with one boulder apparently exhibiting the expected decrease in apparent ^{36}Cl age as production shifted from Cl-dominance to K-dominance, but the magnitude of the decrease was significantly less than expected.

We recommend that additional field studies be conducted to provide better tests of these snow-shielding predictions.

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