SUPPLEMENTAL DATA

S1. Methods

S1.1 Field sampling

Deposits were sampled for geochronology using a combination of surface boulder samples and a depth profile. For both moraines and outwash surfaces, samples were collected from areas with minimal indications of surface modification, e.g., well-preserved moraine crests and terrace treads. Landforms were assigned relative ages based on characteristics such as morphology, dissection, soil development, grain size distribution, and boulder weathering. Younger (Tioga) deposits were identified as having sharp moraine crests or undissected terrace treads, less well-developed soils, poorly-sorted bouldery grain size distribution, and boulders with little surface relief. Older (Tahoe) deposits were characterized by broad moraine crests or highly dissected terrace treads, well developed soils, grain size distributions dominated by only the largest boulders, and abundant boulders with case-hardening and/or deeply eroded surfaces. The largest suitable boulders were chosen (generally >1 m above the ground surface) to reduce the influence of exhumation, snow cover, or rotation. In order to reduce the uncertainties in erosion processes, boulders with well-preserved surfaces were favored, e.g., glacial striations, polish, case-hardened exteriors, low surface relief, while boulder surfaces with obvious evidence of spalling, e.g., Bierman and Gillespie (1991), pitting, or granular erosion were avoided. Horizontal surfaces near the center of large boulders were favored to reduce errors introduced by corrections for surface geometry. Sample latitude, longitude, and elevation were measured using a handheld GPS unit with a calibrated barometric altimeter. Topographic shielding was measured with a clinometer and compass. Boulder dimensions and sample thicknesses (1-5 cm) were measured for each of the 3-12 samples collected from each moraine or outwash terrace. For the Sonora Junction depth profile, a ~3-m deep trench was excavated with a backhoe in a well-preserved part of the terrace tread. The trench wall was cleaned, and level lines were marked every 20 cm from 20-280 cm below the surface. Samples of bulk sediment (i.e. all grain sizes, cobbles to sand) were taken at each interval over a depth range of ~5 cm (i.e. 2.5 cm on each side of the level line), collected from bottom to top in order to avoid sample contamination.

S1.2. Analytical methods, data reduction, and exposure age calculations

Quartz purification and ^{10}Be extraction was completed at Lawrence Livermore National Laboratory (LLNL). Rock samples were crushed and sieved to 250-500 µm size fractions. Bulk sediment samples were generally sieved to 250-500 µm size fractions, but the 500 µm-1 mm size fractions were included when necessary to increase sample yield. Quartz was separated and meteoric ^{10}Be removed using methods described by Kohl and Nishiizumi (1992). The Be carriers used at LLNL are low-background carriers prepared from beryl with $5 \pm 3 \times 10^{-16}$ ^{10}Be/^{9}Be ratios. After adding Be carrier, quartz was dissolved in a $HF/HN0_3$ solution. The solution was dried down to volatilize silicon fluorides, and fumed several times with $HClO_4$ to evaporate residual fluoride. Be was separated using ion exchange chromatography as described in Stone (2004) with anion exchange using HCl and cation exchange using dilute H_2SO_4 and HCl (Ditchburn and Whitehead, 1994). Be was then precipitated as beryllium hydroxide, ignited to beryllium oxide, mixed with niobium powder, and loaded into stainless steel cathodes prior to measurement.

^{10}Be/^{9}Be isotope ratios were measured at the Center for Accelerator Mass Spectrometry (CAMS) using the high-intensity LLNL modified Middleton cesium sputter source in combination with the CAMS FN mass spectrometer (Rood et al., 2010). $^9Be^{3+}$ ion beam currents were ~15-35 μA and boron corrections were generally <1%. 1σ analytical uncertainties for ^{10}Be/^{9}Be ratios were 1.5–5.6%. Process blanks were ~49,000 ± 26,000 ^{10}Be atoms, ~0.1–5.7% of the total number of ^{10}Be atoms in the samples. Be isotope ratios were calibrated to the 07KNSTD3110 standard described in Nishiizumi et al. (2007); samples normalized to 07KNSTD3110 use the revised nominal isotope ratio and revised ^{10}Be decay constant.

Exposure-age calculations were made with the CRONUS-Earth online exposure age calculator, Version 2.2, as described in Balco et al. (2008) using a constant production rate model and the scaling scheme for spallation of Lal (1991) / Stone (2000). This version of the CRONUS calculator (constants: 2.2-dev) uses a reference spallogenic ^{10}Be production rate of 4.49 ± 0.39 atoms g^{-1} yr^{-1} (± 1σ, SLHL) and muonogenic production after Heisinger et al. (2002a, 2002b). Corrections for topographic shielding and surface geometry are all <3%, calculated using the CRONUS-Earth online geometric shielding calculator, Version 1.1. Sample thickness corrections are all <4%.

S2. Results

S2.1 Bridgeport Basin

The elevation of the basin floor is ~1,970 m, significantly (~600 m) higher than valleys in a comparable position to the north and south (Clark et al., 2003). Due to the low slope and high elevation of the valley, Pleistocene glaciers with snowlines similar to those of other Sierra Nevada glaciers (Kessler et al., 2006) flowed far into the basin. Sharp (1972) mapped the distribution of glacial deposits of at least five different ages (including Tioga, Tenaya, Tahoe, Mono Basin, and Sherwin), which are some of the most well-preserved glacial deposits in the eastern Sierra Nevada. Boulders on moraine crests and terrace treads are mostly granitoid rock types (e.g. Cathedral Peak granite), except at Virginia Creek where boulders are composed of metamorphic lithologies (mostly metavolcanic, chert, calcsilicate hornfels, and metaconglomerate rocks).

S2.1.1 Buckeye Creek (Figure S1)

Nine boulders from a Tahoe outwash terrace (BCTA06-, Table 1) yield ages between 106 and 167 ka, of which the oldest and four youngest ages are outliers. The remaining samples define a peak in the cumulative PDF (Figure S2) with an average ^{10}Be age of 148 ± 2 ka (n = 4; $\chi_R^2 = 0.5$; P = 0.72).

The Tioga outwash terrace (BCTI07-, Table 1) gives ages ranging from 8 to 21 ka. After the two youngest samples are omitted as outliers, the data (n = 4) show a broad peak with a mean age of 20.0 ± 0.7 ka (Figure S3). The χ_R^2 value (2.8) and $P = 0.04$ indicates scatter slightly beyond analytical uncertainty. However, the oldest age (21.0 ± 0.4 ka) and mean overlap within 1σ errors, so the mean and standard deviation (20.0 ± 0.7 ka) is taken to approximate the depositional age.

S2.1.2 Robinson Creek (Figure S1)

Nine boulder ages from the right-lateral Tahoe moraine at Robinson Creek (RCTA05-, Table 1) scatter between 53 to 153 ka. Mean ages for a group of samples (Figure S4) are 121 ± 8 ka ($n = 5$, $\chi_R^2 = 4.9$, and $P < 0.01$). This χ_R^2 value is not acceptable at the 5% confidence limit, so the oldest age of 153 ± 3 ka is used to estimate the depositional age.

S2.1.3 Green Creek (Figure S5)

Samples from the left-lateral Tahoe moraine (GCTA07-, Table 1) give highly-scattered ages ranging from 21 to 190 ka. The distribution has no clear peak (Figure S6) and an extremely high χ_R^2 value (3850) and $P < 0.01$. The oldest age (190 ± 4 ka) is taken as the best approximation of the depositional age, although this age is tentative.

S2.1.4 Virginia Creek (Figure S7)

Samples from the right-lateral Tahoe moraine at Virginia Creek give scattered exposure ages between 23 and 150 ka ($n = 8$; $\chi_R^2 = 2750$; $P < 0.01$). The data shows evidence for a compound moraine with two pulses of deposition. A young peak in the age distribution ($n = 3$) gives an average age of 23.5 ± 0.3 ka (Figure S8). The remaining data are scattered toward older ages, indicating samples (1) with inheritance or (2) from an older glaciation. Inheritance is observed to be minimal in moraine deposits in adjacent catchments, so these older ages may indicate a second previous period of glacial deposition. The oldest sample in the distribution (150 ± 3 ka) is taken as the age of the older glacial advance.

S2.2 Mono Basin

The Mono Basin was a site of glaciation, volcanism, and faulting throughout the Quaternary. The canyons draining the Sierra Nevada were extensively glaciated in the Pleistocene, but unlike the valleys to the north, the geomorphology of the Mono Basin is influenced by lacustrine and volcanic deposits. Glacial moraines of at least five different ages were mapped by Bursik (1989), including Tioga, Tenaya, Tahoe, Mono Basin, and Sherwin. Dated boulders were generally composed of Mono Dome granodiorite.

S2.2.1 Lundy Canyon (Figure S9)

Boulder ages from the right-lateral Sherwin moraine (LCSH07-, Table 1) scatter between 42 and 101 ka with no peak (Figure S10) and an extremely high χ_R^2 value (369) and $P < 0.01$. The oldest age of 101 ± 2 ka is taken as a minimum depositional age.

Results for the Mono Basin right-lateral moraine give scattered ages between 22 to 46 ka (LCMB07-, Table 1). After the two youngest boulders are omitted as outliers (Figure S11), the samples give a mean age of 41.1 ± 4.1 ka ($n = 4$; $\chi_R^2 = 15$; $P < 0.01$). The oldest age (45.8 ± 1.1 ka) and the mean overlap within error, so the mean is chosen as the best approximation of the depositional age, although this may be a minimum. This result may indicate deposition during MIS 3, but this interpretation is uncertain.

The right-lateral Tioga moraine gives ages from 14 to 20 ka (LCTI07-, Table 1), of which the youngest sample is omitted as an outlier (Figure S12). The remaining boulders ($n = 5$) give a mean age of 17.9 ± 1.6 ka ($\chi_R^2 = 16$; $P < 0.01$) that overlaps with the oldest age (19.8 ± 0.5 ka). Thus, the mean and standard deviation was chosen to estimate the moraine age. Boulders from the Tioga outwash terrace (SJTIO-07-, Table 1) yield ages ranging from 13 to 18 ka. The youngest age is a clear outlier, but the remaining 5 boulder ages produce a peak (Figure S13) with a mean age of 17.7 ± 1.0 ka ($\chi_R^2 = 1.2$; $P = 0.29$).

S2.3 Woodfords (Figure S14)

Pleistocene glaciers of the eastern slope of the Sierra Nevada occupied Hope Valley (upper West Carson River drainage near Carson Pass) and had outlets near Woodfords (Armin and John, 1983). Subsequent mapping indicates that at least two suites of glacial deposits are present at Woodfords (Ramelli et al., 1999), including moraines and an outwash terrace of the Tahoe glaciation and an outwash terrace of the Tioga glaciation (Figure S14). Large granodiorite boulders were sampled for ^{10}Be surface exposure age dating.

Three boulders from the Tahoe outwash terrace (WFTA08-, Table 1) give exposure ages that scatter between 70 and 131 ka. Due to the extremely high χ_R^2 value (444), $P < 0.01$, and grouping of the two oldest samples (Figure S15), the oldest age of 131 ± 3 ka is used as the best estimate of the depositional age.

Results for the Tioga outwash terrace (WFTI08-, Table 1) show clustered ages ranging from 20 to 22 ka (Figure S16) with a mean age of 20.7 ± 1.1 ka ($n=3$; $\chi_R^2 = 4.8$; $P < 0.01$). The mean age overlaps within error of the oldest sample (21.8 ± 0.5 ka), so the mean is chosen to approximate the depositional age of the terrace.

2.4 Recalculated ages from previous work

2.4.1 ^{10}Be studies

James et al. (2002) dated glacial deposits in the northern Sierra Nevada on the west side of the crest. Boulders on an early Tioga moraine in Bear Valley range in age from 19 to 22 ka. Individual ages agree well within errors (Figure S17) with a mean of 20.5 ± 1.8 ka ($n=2$; $\chi_R^2 = 1.4$; $P < 0.23$).

Benn et al. (2006) produced ages on a Tioga moraine in the southern Sierra Nevada near Whitney Portal. Results show a bimodal distribution (Figure S18) with ages scattering between 18 and 20 ka with a mean age of 18.9 ± 1.1 ka (n=6; $\chi_R^2 = 4.6$; $P < 0.01$). The mean and oldest age (20.2 ± 0.9 ka) overlap within 1σ errors, therefore the mean is used as the best-estimate age.

In Mono Basin, results from the Tioga 3 moraine at Bloody Canyon (Schaefer et al., 2006) give nicely clustered result. Ages in the PDF peak (Figure S19) scatter from 17 to 20 ka. Four boulders give a mean age of 18.4 ± 1.6 ka ($\chi_R^2 = 1.7$; $P < 0.16$), which is taken as the depositional age.

Results from Amos et al. (2010) provide data on the timing of glacial retreat in the southern Sierra Nevada west of the crest. In the Kern Canyon at Soda Springs, a Tioga terminal moraine gives a well defined peak in ages (Figure S20) that vary between 18 and 19 ka. A mean of all six boulders give an age of 18.3 ± 1.0 ka ($\chi_R^2 = 1.3$; $P < 0.26$).

2.4.2 ^{36}Cl results from Bloody Canyon (Phillips et al., 2009)

Twelve boulders from the Tahoe 1 moraine have ages that range from 64 to 168 ka, of which the oldest and four youngest ages are outliers. The remaining samples define a peak in the cumulative PDF (Figure S21) with an average ^{36}Cl age of 144 ± 7 ka ($n = 6$; $\chi_R^2 = 1.9$; $P = 0.09$), which is considered to be the age as deposition. The Tahoe 2 moraine gives ^{36}Cl ages between 67 and 145 ka, but ten boulders define a clear peak in the PDF (Figure S22). After removing the seven youngest samples as outliers, the mean age is 134 ± 6 ka ($n = 10$; $\chi_R^2 = 1.5$; $P = 0.14$). The Tahoe 3 moraine gives ^{36}Cl ages that scatter from 56 to 127 ka. The A group of samples (Figure S23) give a mean age of 100 ± 7 ka ($n = 6$; $\chi_R^2 = 2.7$; $P = 0.02$), which results in an age estimate with only moderate confidence. Boulder ^{36}Cl ages for the Tahoe 4 moraine show a broad range from 48 to 131 ka with no clear peak in the distribution (Figure S24). The mean age for all samples is 92 ± 22 ka ($n = 22$; $\chi_R^2 = 75$; $P < 0.01$). The high χ_R^2 and low P for these results make estimating a depositional age difficult, and the oldest age (131 ± 4 ka) is considered a minimum age. Similarly, the Bishop Creek Tahoe 5 moraine (Figure S25) gives ^{36}Cl ages that are highly scattered ($n = 3$; $\chi_R^2 = 223$; $P < 0.01$) from 53 to 132 ka with the oldest age considered a minimum age for the deposit of 132 ± 5 ka. The Tahoe 6 ^{36}Cl ages (Figure S26) range from 30 to 129 ka with the oldest age (129.3 ± 4.2 ka) giving a lower limit on the depositional age.

The Bishop Creek Tioga 1 moraine boulders give ^{36}Cl ages ranging from 16 to 33 ka. After excluding the two oldest and two youngest boulders as outliers, the remaining samples produce a broad peak in the PDF (Figure S27). This group has a mean age of 22.2 ± 1.7 ka ($n = 6$; $\chi_R^2 = 5$; $P < 0.01$) and an oldest age of 23.8 ka, therefore the mean is taken as a moderately confident estimate of the depositional age. Nine boulders from a Tioga 3 moraine yield ^{36}Cl ages between 7 and 20 ka, of which the youngest two ages are clear outliers. The remaining samples show clustered ages (Figure S28) with an average ^{36}Cl age of 18.5 ± 0.8 ka ($n = 11$; $\chi_R^2 = 1.6$; $P = 0.09$). Samples from the Tioga 4 moraine give scattered ^{36}Cl ages ranging from 11 to 22 ka. The distribution has a broad peak (Figure S29), X_R^2 value of 4.6, and $P < 0.01$. The mean age (15 ± 1 ka) is taken as the best approximation of the depositional age, although the oldest age (17.6 ± 0.5 ka) may be more appropriate. For this reason, the true age of the Tioga 4 moraine is known with relatively low confidence.

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