



1 **Deglaciation of the Sierra Nevada (USA) during Heinrich Event 1**

2

3 Richard A. Becker¹, Aaron M. Barth², Shaun A. Marcott³, Basil Tikoff³, and Marc W. Caffee^{4,5}

4 ¹Department of Earth and Environment, Boston University, 685 Commonwealth Ave, Boston,

5 MA 02215, USA

6 ²Department of Geology, Rowan University, 201 Mullica Hill Rd, Glassboro, NJ 08028, USA

7 ³Department of Geoscience, University of Wisconsin-Madison, 1215 W Dayton St, Madison, WI

8 53706 USA

9 ⁴Department of Physics and Astronomy, Purdue University, 525 Northwestern Ave, West

10 Lafayette, IN 47907, USA

11 ⁵Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium

12 Mall Dr, West Lafayette, IN 47907, USA

13 *Correspondence to:* Richard A. Becker (rabecker@bu.edu)



14 **Abstract** (≤ 250 words)

15 A polar jet stream (PJS) split by the Laurentide Ice Sheet (LIS) is a well-established
16 feature of Ice-Age atmospheric circulation. California's central Sierra Nevada Mountains (37–
17 38° N) lie near the reconstructed position of the PJS's southern branch. Previous studies
18 concluded that rapid deglaciation began here at ca. 16–15 ka after millennia of relatively stability
19 at ~60% LGM length. However, this conclusion is largely based on the behavior of glaciers in a
20 single valley, Bishop Creek Canyon. We report 31 new ^{10}Be samples from two new locations –
21 Lyell Canyon and Mono Creek Canyon – and 26 recalculated ^{36}Cl dates from Bishop Creek
22 Canyon ($n = 57$). These dates indicate rapid deglaciation began at 16.4 ± 0.8 ka and lasted for ca.
23 1.0 kyr. Placing two previously published paleoenvironmental reconstructions (Swamp Lake and
24 McLean's Cave) with centennial-or-better-scale resolution on new age-depth models that provide
25 age-uncertainty estimates, we find evidence for warming in the central Sierra Nevada at $16.4 \pm$
26 0.4 ka and drying at 16.20 ± 0.13 ka. Collectively, we interpret that rapid deglaciation began at
27 16.20 ± 0.13 ka. This timing is indistinguishable from that of Heinrich Event 1 (HE1), which
28 occurred between 16.22 ± 0.04 ka and 16.04 ± 0.04 ka. We hypothesize that the Sierra Nevada's
29 deglaciation was driven by a northward repositioning and focusing of the winter-storm track over
30 western North America in response to PJS reunification, bringing warmer and drier weather to
31 the central Sierra Nevada, and that PJS reunification occurred in response HE1 thinning the LIS.

32

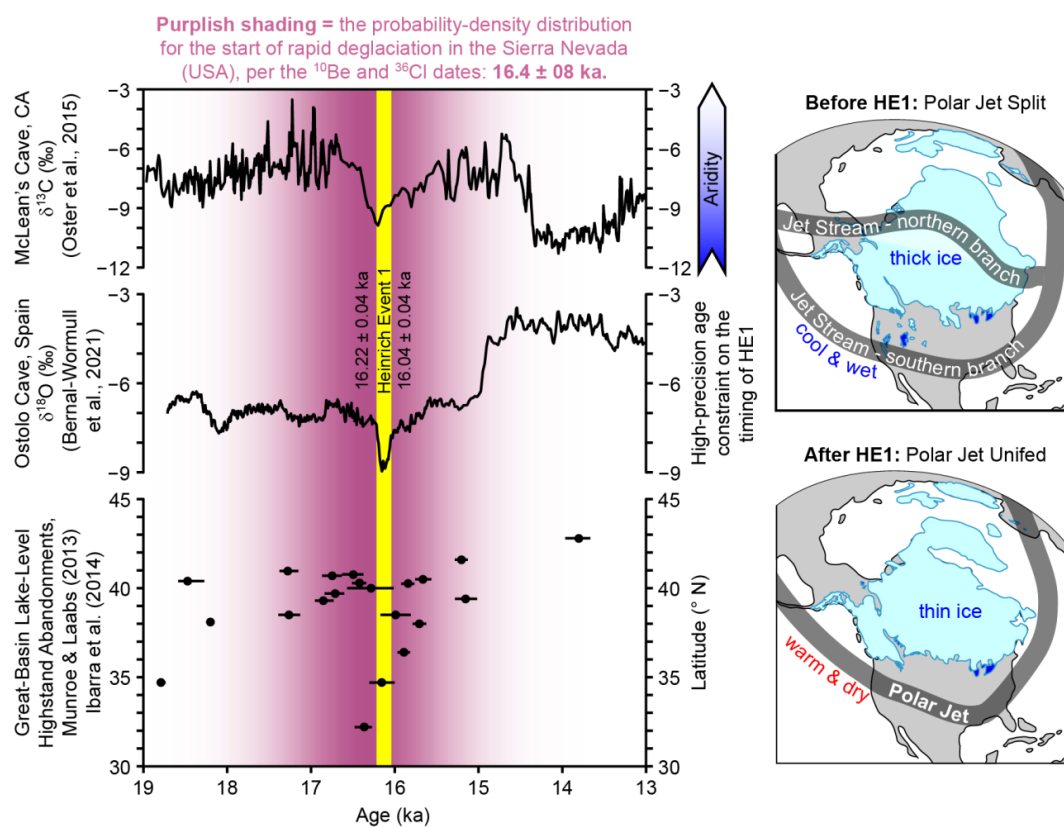
33

34 **Keywords**

35 Polar Jet Stream, Laurentide Ice Sheet, Sierra Nevada Mountains, Yosemite National Park,
36 Heinrich Event 1, Be-10, Cl-36, Atmospheric Reorganization



37 Graphical Abstract



38



39 **Short Summary** (≤ 500 characters including spaces)

40 We report 31 new ^{10}Be and 26 recalculated ^{36}Cl dates from the Sierra Nevada Mountains (USA)
41 and conclude that deglaciation's final and rapid phase began at 16.4 ± 0.8 ka. In comparing this
42 timing with high-resolution regional paleoclimate proxies, we interpret that rapid deglaciation
43 most likely began at 16.20 ± 0.13 ka, which is indistinguishable in timing from Heinrich Event 1.
44 We interpret that the range's deglaciation was likely driven by a reunification of the polar jet
45 stream at this time.



46 1. Introduction

47 Abrupt, millennial- and centennial-scale climate changes are a prominent characteristic of
48 the last deglaciation in contrast to the relative stability of the Holocene (e.g., Mayewski et al.,
49 2004; Denton et al., 2010; Clark et al., 2012; Shakun et al., 2012; Marcott et al., 2013).
50 Numerous climate reversals of varying extents and magnitudes punctuated the latest Pleistocene,
51 including the Younger Dryas (e.g., Mangerud et al., 1974; Mangerud, 2021), the Antarctic Cold
52 Reversal (Jouzel et al., 1995), and the Heinrich and Dansgaard-Oeschger events (Heinrich, 1988;
53 Dansgaard et al., 1993). Understanding these events – including their rate, timing, magnitude,
54 geographical extent, duration, and ultimately their causes and consequences – has been a
55 principal endeavor within Quaternary science (e.g., Alley, 2000; Ganopolski and Rahmstorf,
56 2001; Hemming, 2004; Douglass et al., 2006; Firestone et al., 2007; Ackert et al., 2008; Putnam
57 et al., 2010a; Laabs et al., 2011; Rasmussen et al., 2014; Bahr et al., 2018; Barth et al., 2018;
58 Pedro et al., 2018; Li and Born, 2019).

59 **Field**-based studies in the Sierra Nevada Mountains (USA) – such as geomorphic
60 observations (Clark, 1976; Clark and Clark, 1995) and ^{10}Be , ^{26}Al , and ^{36}Cl surface-exposure
61 dating (James et al., 2002; Phillips et al., 2009) – indicate that the range's glaciers responded
62 strongly to a large and abrupt change in climate **near the end of the last deglaciation**. After Sierra
63 Nevadan glaciers reached their greatest extents, broadly in-phase with the **global Last Glacial**
64 **Maximum** (LGM; Phillips et al., 2009; Rood et al., 2011), they receded for several thousand
65 years – with episodic advances superimposed on this general trend – **before readvancing** to ~60
66 % LGM-length. **Glaciers** in the Sierra Nevada rapidly melted following this readvance (Clark,
67 1976; Clark and Clark, 1995), receding from ~60 % LGM-length to ~~<3 km length~~ (0–23 %
68 LGM-length) in “**500 yr or less, and certainly less than 1000 yr**” (Phillips et al., 2009, p. 1031).



69 This rapid ice recession may have been driven by a sharp reduction in precipitation either
70 contemporaneously with or immediately following Heinrich Event 1 in the North Atlantic
71 (Benson et al., 1996; Phillips et al., 1996).

72 This readvance and subsequent deglaciation suggest two reorganizations in atmospheric
73 circulation over the northeastern Pacific Ocean. An earlier reorganization that brought cooler
74 summers and/or wetter winters to the Sierra Nevada (driving the readvance) and a later, larger
75 magnitude and more permanent reorganization that brought warmer summers and/or drier
76 winters to the range (driving the deglaciation). This inference, derived from the Sierra Nevada's
77 geomorphology, is supported by a regional reconstruction of sea-surface temperatures (SSTs) in
78 the northeast Pacific that records cooling between ca. 18 ka and ca. 17 ka and warming after ca.
79 16.5 ka (Praetorius et al., 2020). Numerical modeling shows these cooler SSTs would have
80 generated a deeper and longer lasting snowpack in the Sierra Nevada, with warmer SSTs having
81 the opposite effect (Peteet et al., 1997).

82 The duration of the Tioga 4 deglaciation provides a maximum constraint on the duration
83 of the second reorganization. However, the cosmogenic surface-exposure ages constraining the
84 duration of this deglaciation to <500–1000 years (Phillips et al., 2009) are all associated with a
85 single former glacier – the Bishop Creek Glacier – thus permitting the possibility that glacial
86 recession was substantially slower (or more rapid) elsewhere in the range.

87 Here, we investigate the timing and duration of the final deglaciation in the Sierra
88 Nevada with thirty-one new ^{10}Be -concentration measurements from two other drainage basins in
89 the central portion of the range: (1) Tuolumne Meadows and Lyell Canyon in Yosemite National
90 Park and (2) Lake Thomas A. Edison (which was Vermillion Valley prior to 1954 C.E.) and
91 Mono Creek Canyon in the Sierra National Forest (Fig. 1). In converting these ^{10}Be



92 concentrations into surface-exposure ages, we consider multiple sources of uncertainty –
93 especially with regards to the snow-shielding correction.

94 Additionally, we further constrain the timing and nature of the climate changes that drove
95 the range's deglaciation – beyond the constraints imposed by the thirty-one new ^{10}Be dates – by
96 reevaluating four legacy datasets. In particular, we (1) recalculate twenty-six ^{36}Cl dates on the
97 timing and duration of the deglaciation within the vicinity of Bishop Creek Canyon (Phillips et
98 al., 2009) using updated ^{36}Cl production rates and scaling schemes (e.g., Marrero, 2012; Lifton et
99 al., 2014; Marrero et al., 2016), (2) recalibrate the age-depth model for the Swamp Lake
100 paleoenvironmental reconstruction (Street et al., 2012) and (3) the radiocarbon dates reported by
101 Munroe and Laabs (2013) and Ibarra et al. (2014) on the highstands of seventeen Great Basin
102 Pleistocene lakes with IntCal 20 (Reimer et al., 2020) and Bchron 4.7.6 (Haslett and Parnell,
103 2008), and (4) recalculate the age-depth model for speleothem ML1 from McLean's Cave (Oster
104 et al., 2015) using Bchron. We find evidence of warming and drying in the Sierra Nevada and
105 adjacent regions ca. 16.2 ka and interpret these changes as resulting from a northward shift and
106 focusing of the winter-storm track over North America in response to Heinrich Event 1, which is
107 indistinguishable in timing from the start of the Tioga 4 deglaciation (Bernal-Wormull et al.,
108 2021; Pérez-Mejías et al., 2021).

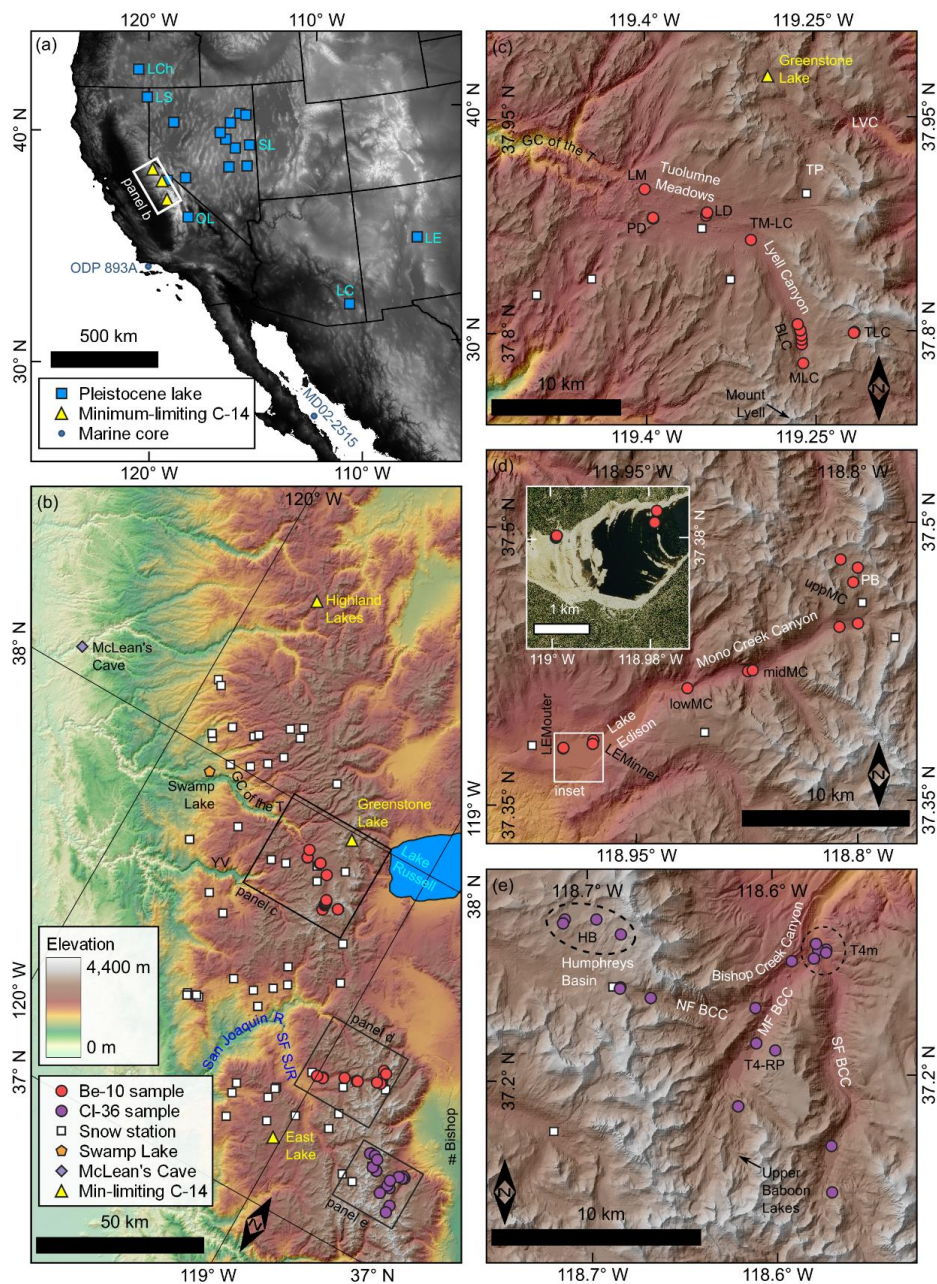


Figure 1. Maps showing the locations of the field areas and relevant data sets. **(a)** Location of the central Sierra Nevada Mountain range (panel b) in the western United States. Pleistocene lakes mentioned in the text are abbreviated as follows (north to south): LCh – Lake Chewaucan; LS – Lake Surprise; SL – Spring Lake; OL – Owens Lake; LE – Lake Estancia; and LC – Lake Cochise. For the names of the unlabeled lakes, please see Munroe and Laabs (2013). **(b)** Location of the field areas within the central Sierra Nevada. Abbreviations (north to south): GC



116 of the T – Grand Canyon of the Tuolumne River; YV – Yosemite Valley; and SF SJR – South
117 Fork of the San Joaquin River. **(c)** Map of the Tuolumne Meadows and Lyell Canyon field area.
118 Sampling-location abbreviations (from distal to proximal): LM – lower Tuolumne Meadows; PD
119 – Pothole Dome; LD – Lembert Dome; TM-LC – unnamed roche moutonnée near the junction of
120 Tuolumne Meadows with Lyell Canyon; BLC – bottom of Lyell Canyon; MLC – a mid-
121 elevation within Lyell Canyon; and TLC – top of Lyell Canyon. Other abbreviations on panel c:
122 LVC – Lee Vining Canyon; TP – Tioga Pass; and GC of the T – Grand Canyon of the Tuolumne
123 River. **(d)** Map of the Lake Edison and Mono Creek Canyon field area. Sampling-location
124 abbreviations (distal to proximal): LEMouter – the outermost moraine beneath Lake Edison
125 (which was created in 1954 C.E. by the damming of Mono Creek and the flooding Vermillion
126 Valley); LEMinner – the innermost moraine beneath Lake Edison; lowMC – lower Mono Creek;
127 midMC – middle Mono Creek; and uppMC – upper Mono Creek. The other abbreviation on
128 panel d: PB – Pioneer Basin. **(e)** 2014 aerial photo of the Lake Edison moraine complex, which
129 was exposed by drought. **(f)** Map of Bishop Creek Canyon and vicinity. Sampling-location
130 abbreviations: T4m – the Tioga 4 moraine; HB – Humphrey’s Basin; and T4-RP – scattered
131 sampling locations between the Tioga 4 moraine and the Recess Peak moraines. Other
132 abbreviations on panel f: NF BCC – the North Fork of Bishop Creek Canyon; MF BCC – the
133 Middle Fork of Bishop Creek Canyon; and SF BCC – the South Fork of Bishop Creek Canyon.



134 **2. Regional setting**

135 2.1. *Physical geography of the Sierra Nevada*

136 The Sierra Nevada is a ~600-km-long mountain range that parallels the western boundary
137 of North America and hosts the highest elevation within the contiguous United States: Mt.
138 Whitney at 4421 m (14,505 ft). The range formed during the Mesozoic as a result of subduction
139 and arc magmatism (Gilluly, 1969; Hamilton, 1969; McPhillips and Brandon, 2010; Gabet,
140 2014). Quartz-bearing lithologies are abundant in the central and southern Sierra Nevada. That
141 portion of the range is primarily granitic plutons with scattered metasedimentary and
142 metavolcanic wall rocks (e.g., Bateman, 1992).

143 The range's length, orientation, and elevation make it **an effective barrier to** maritime air
144 masses originating over the Pacific (e.g., Pandey et al., 1999). Furthermore, the range
145 experiences a Mediterranean climate with dry summers and wet winters characterized by
146 abundant snowfall. In Tuolumne Meadows for example (~2600 m elevation), 82% of its 1985–
147 2017 **precipitation** arrived in the six months between November 1 and April 30 and 50% of that
148 precipitation was snow (<http://cdec.water.ca.gov>). Average April snow depths at the elevation of
149 Tuolumne Meadows were approximately 2 m between 1946 and 2008 (Fig. S1).

150 2.2. *Glacial history of the Sierra Nevada*

151 Within the Sierra Nevada, the last glaciation is termed the Tioga (Blackwelder, 1931) and
152 is divided into five glacial advances: from oldest to youngest these are Tioga 1–4 (Phillips et al.,
153 1996; Phillips et al., 2009) and then the comparatively minor Recess Peak (Birman, 1964; Clark
154 and Gillespie, 1997). **Tioga 1** predates both the local and global LGM (Phillips et al., 1996;
155 Phillips et al., 2009); Tioga 2 marks the local LGM, which was ca. 24–21 ka (e.g., Clark et al.,
156 2003; Phillips et al., 2009; Amos et al., 2010; Rood et al., 2011); Tioga 3 represents a **readvance**



157 to ~90 % the LGM ice extent ca. 23–20 ka (e.g., Schaefer et al., 2006; Phillips et al., 2009; Stock
158 and Uhrhammer, 2010); and Tioga 4 marks a readvance to ~60 % LGM ice extent ca. 16 ka
159 (Phillips et al., 2009; Phillips, 2016).

160 Rapid deglaciation of the Sierra Nevada began immediately after the Tioga 4 readvance
161 (Clark and Gillespie, 1997). During the subsequent Recess Peak readvance, which culminated ca.
162 13.3 ka (Phillips, 2016; Marcott et al., 2019), northward-flowing glaciers deposited moraines
163 ~0–3 km from their cirque headwalls (~1–23 % LGM length; Moore, 1981; Clark and Gillespie,
164 1997; Clark et al., 2003) while southward-facing cirques rarely contain Recess Peak moraines
165 (Clark and Gillespie, 1997). This paper focuses the Tioga 4 readvance and the subsequent
166 deglaciation.

167 2.2.1. *Geomorphic constraints on the magnitude and duration of the Tioga 4 deglaciation*

168 Multiple geomorphic observations suggest Sierra Nevadan glaciers rapidly melted
169 following the Tioga 4 readvance (Birman, 1964; Clark, 1976; Clark and Clark, 1995). First, other
170 than the relatively minor Recess Peak deposits (e.g., Birman, 1964; Clark and Gillespie, 1997;
171 Phillips et al., 2009; Marcott et al., 2019), the innermost end moraines of the Sierra Nevada – the
172 Tioga 4 moraines – are ~60 % the distance (15 and 22 km in Bishop Creek and Mono Creek
173 Canyons, respectively) from the cirques to the Tioga 2 moraines (Clark, 1976; Clark and Clark,
174 1995; Phillips et al., 2009). Distal of ~60 %, end moraines are common and bedrock basins are
175 typically sediment-filled; proximal of ~60 %, bedrock basins are water-filled, bedrock-outcrop
176 exposure is excellent, and glacial sediments are primarily isolated boulders and till patches
177 (Clark, 1976; Clark and Clark, 1995).

178 Second, within the Lake Edison moraine complex – which is an assemblage of
179 approximately eleven end moraines in the Mono Creek drainage at 63–58 % LGM-glacier length



180 (24–22 km; Figs. 1d–e and 2) – till thickness systematically decreases from the outermost to
181 innermost moraine; immediately behind the innermost moraine, till is absent for 4 km (Birman,
182 1964). Although Birman (1964) interpreted the decreased till thickness as a temporal evolution
183 toward lower debris concentrations in the Late Pleistocene glaciers of the Sierra Nevada, it is
184 also consistent with rapid deglaciation. Phillips (2016) correlated the entire Lake Edison moraine
185 complex with the Tioga 4 glacial advance and used the elevation difference between the
186 moraines and various unspecified cirque headwalls in the Mono Creek drainage to reconstruct an
187 equilibrium-line altitude (ELA) of 2800 m for the Tioga 4 advance. Based on Pioneer Basin’s
188 cirque-floor elevation (~3400 m), this reconstruction implies the Tioga 4 deglaciation was driven
189 by a ≥ 600 m ELA rise. This ELA rise is a minimum estimate because the climatological
190 snowline may have risen above the elevation of the cirque floors.

191



192



193

194 **Figure 2.** A 1908 photograph by G. K. Gilbert of one of the moraines within what is now the
195 Lake Edison moraine complex. Photo courtesy of the United States Geological Survey's
196 (USGS's) Denver Library Photographic Collection; item identifier ggk03340.



197 Finally, upvalley from the Tioga 4 end moraines – and presumably within the footprint of
198 the former Tioga 4 accumulation zone – low-relief ridges emanate from tributary-valley
199 junctions and parallel the inferred direction of former ice flow (e.g., Birman, 1964, Plate 1).
200 Clark (1976) observed numerous such ridges in the vicinity of Tuolumne Meadows (at ~30 %
201 LGM-glacier length) and Clark and Clark (1995) observed similar ridges in the upper reaches of
202 Mono Creek Canyon (at ~10 % LGM-glacier length). These low-relief, ice-flow parallel ridges
203 are inferred to be medial moraines (Clark, 1976; Clark and Clark, 1995). Based on the presence
204 of these medial moraines – and the absence of crosscutting end moraines and other ice-marginal
205 landforms – Clark (1976) and Clark and Clark (1995) interpreted that Sierra Nevadan glaciers
206 stagnated and rapidly melted ~~at the end of the last glaciation.~~

207 2.2.2. Radiocarbon constraints on the timing of the Tioga 4 deglaciation

208 Phillips (2016) reviewed radiocarbon constraints on the timing of the Tioga 4
209 deglaciation and placed this event at 15.75 ± 0.5 ka (1 σ). This determination was based on three
210 bulk-sediment radiocarbon dates from **high-altitude** ponds within the Tioga 4 glacial footprint
211 (Fig. 1b). From north to south, and when calibrated with Calib 8.2 (Stuiver and Reimer, 1993)
212 and IntCal20 (Reimer et al., 2020), these dates are 15.95 ± 0.29 ka from the Highland Lakes in
213 the North Fork of the Stanislaus River drainage ($13,270 \pm 200$ ^{14}C -yrs; Clark et al., 1995), 15.69
214 ± 0.09 ka from Greenstone Lake in the Lee Vining Creek drainage ($13,090 \pm 60$ ^{14}C -yrs; Clark et
215 al., 2003), and 16.13 ± 0.10 ka from East Lake in the North Fork of the Kings River drainage
216 ($13,400 \pm 60$ ^{14}C -yrs; Power, 1998; Fig. S2). Although a small dataset, these three dates span
217 ~160 km of the Sierra Nevada and include locations north of, nearly adjacent to, and just south
218 of the new ^{10}Be dates we report. As these radiocarbon dates are from the basal layers of high-
219 elevation ponds – and there is no compelling evidence for the contaminating presence of “dead



220 carbon” (carbon without radiocarbon activity; a topic we discuss further in Sect. 5.2.1.) – these
221 dates suggest widespread deglaciation of the Sierra Nevada by ca. 16 ka, or in Phillips’s (2016)
222 interpretation, at 15.75 ± 0.5 ka.

223 The youngest of these three minimum-limiting radiocarbon ages – the 15.69 ± 0.09 ka
224 date from Greenstone Lake (Clark et al., 2003) – is especially relevant to this manuscript.
225 Greenstone Lake is only 15–25 km north of Tuolumne Meadows and Lyell Canyon (Fig. 1c) and
226 erratic boulders deposited during the Tioga 4 deglaciation indicate that the Tioga 4 ice divide
227 was northeast of the modern hydrologic divide: ice flowed across Tioga Pass (TP on Fig. 1c)
228 from what is now the Lee Vining Creek watershed and contributed to the former Tuolumne
229 Glacier (Huber, 2007; Wahrhaftig et al., 2019). The bedrock geology requires these erratics to
230 have come from ≤ 4 km of Greenstone Lake (Bateman et al., 1983). After crossing Tioga Pass,
231 erratic boulder trains and streamlined landforms demonstrate (Wahrhaftig et al., 2019) these
232 originally-near-Greenstone-Lake parcels of ice passed through Tuolumne Meadows ~ 1 –2 km
233 north of our sampling sites on Lumbert Dome (LD on Fig. 1c) and in lower Tuolumne Meadows
234 (LM on Fig. 1c).

235 As a result of the Greenstone Lake radiocarbon date’s calibrated-age-uncertainty
236 envelope, Greenstone Lake was both deglaciated and accumulating organic carbon by 15.42 ka
237 (Fig. S2; Haslett and Parnell, 2008; R Core Team, 2024). Thus, the Greenstone Lake radiocarbon
238 date (1) constrains the timing of deglaciation in a directly adjacent glacial system (that of Lee
239 Vining Canyon; LVC on Fig. 1c) and (2) suggests that Tuolumne Meadows was almost certainly
240 deglaciated (if not also revegetating) by 15.4 ka. We therefore adopt 15.4 ka as a minimum-
241 limiting constraint on the timing of deglaciation in Tuolumne Meadows and 15.75 ± 0.5 ka



(Phillips, 2016) as the best estimate for the timing of deglaciation in the high-elevation lake basins elsewhere in the Sierra Nevada.

2.2.3 Chlorine-36 constraints on the timing and duration of the Tioga 4 deglaciation

Phillips et al. (2009) tested the geomorphic interpretation of an abrupt end to the last glaciation in the Sierra Nevada by ^{36}Cl -dating boulders and bedrock outcrops in the vicinity of Bishop Creek (Fig. 1f). Applying then-current exposure-age calculation methods (i.e., Phillips et al., 2001), five dates from the Tioga 4 moraine in the Middle Fork of Bishop Creek Canyon (“T4m” on Fig. 1e) yielded a mean age and standard deviation of 15.2 ± 1.0 ka, fifteen samples scattered between the Tioga 4 moraine and the Recess Peak moraines yielded a mean age and standard deviation of 14.7 ± 1.0 ka, and five samples from Humphreys Basin (“HB” on Fig. 1e), a broad collection of cirques west of the modern drainage divide, yielded a mean age and standard deviation of 15.2 ± 0.6 ka. Note that – although Humphreys Basin is west of the Sierra Crest – striations indicate the Tioga ice divide was 0.5–1.0 km west of the modern hydrologic divide in this location (Matthes, 1960; Phillips et al., 2009): Humphreys Basin contributed ice to both the San Joaquin and Bishop Creek Glaciers. Based on these dates, Phillips et al. (2009) concluded that the Tioga 4 deglaciation lasted <500–1000 years.



258 **3. Materials and methods**

259 **3.1. Field areas and sample collection**

260 We sampled thirty-one boulders in two drainages on the western slope of the Sierra
261 Nevada (Figs. 1 and S3–S8; Tables S1–S3): (1) Tuolumne Meadows and Lyell Canyon in
262 Yosemite National Park and (2) Lake Thomas A. Edison and Mono Creek Canyon in the Sierra
263 National Forest.

264 **3.1.1. Tuolumne Meadows and Lyell Canyon**

265 We collected eighteen samples from seven locations along the flowline of the former
266 Tuolumne Glacier in Yosemite National Park (Fig. 1c). From distal to proximal these are: (1) a
267 single sample from a boulder on a bedrock slope above lower Tuolumne Meadows (LM; 24 km
268 from the cirque headwall on Mount Lyell; Fig. S7), (2) three samples from Pothole Dome (PD;
269 22 km; Fig. S7), (3) three samples from Lembert Dome (LD; 18 km; Figs. S7 and S8), (4) a
270 single sample from an unnamed roche moutonnée near the junction of Tuolumne Meadows with
271 Lyell Canyon (TM-LC; 15 km; Fig. S6), (5) six samples from the bottom of Lyell Canyon (BLC;
272 6 km; ~2740 meters above sea level; Figs. S5 and S6), (6) a single sample from a mid-elevation
273 within Lyell Canyon (MLC; 4 km; ~220 m above the bottom of Lyell Canyon; Fig. S5), and (7)
274 three samples from the top of Lyell Canyon (TLC; 2 km; ~670 m above the bottom of Lyell
275 Canyon; Fig. S5). Collectively, these eighteen boulders range from 46 cm to 2.5 m tall and half
276 of the sampled surfaces (9 / 18) had glacial striations or similar evidence for no appreciable post-
277 glacial weathering (Table S1).

278 These samples provide minimum constraints on the timing and duration of the Tioga 4
279 deglaciation in the Tuolumne drainage because the location of the Tuolumne Glacier's Tioga 4
280 terminus is unknown and thus undated. Based on the Tuolumne Glacier's LGM length (94 km;



281 Dühnforth et al., 2010) and other Tioga 4 moraines within the Sierra Nevada being located at
282 ~60 % LGM length (Clark, 1976; Clark and Clark, 1995; Phillips et al., 2009), the Tuolumne
283 Glacier's Tioga 4 terminus was likely in the lower reaches of the Grand Canyon of the Tuolumne
284 (Fig. 1b). If so, ice-marginal landforms recording the position of the Tuolumne Glacier's Tioga 4
285 terminus may not have been preserved, given the Canyon's steep slopes. We note that an
286 analogous situation was documented in Utah's steep-walled Big Cottonwood Canyon (Quirk et
287 al., 2018).

288 3.1.2. *Lake Thomas A. Edison and Mono Creek Canyon*

289 We collected thirteen samples from five locations along the flowline of the former Mono
290 Creek Glacier in the Sierra National Forest (Figs. 1d). From distal to proximal these are: (1) three
291 samples from the outermost end moraine beneath Lake Thomas A. Edison (LEMouter; 24 km
292 from the cirque headwall in Pioneer Basin; Figs. S4 and S5), (2) two samples from the innermost
293 end moraine beneath Lake Edison (LEMiner; 22 km; Fig. S4), (3) a single sample from the
294 lower portion of Mono Creek Canyon (lowMC; 15 km; Fig. S4), (4) two samples from the
295 middle portion of Mono Creek Canyon (midMC; 11 km; Figs. S3 and S4), and (5) five samples
296 from the upper portion of Mono Creek Canyon (uppMC; 1–5 km; Fig. S3). Note that Lake
297 Edison was created in 1954 C.E. with the construction of the Vermillion Valley Dam and that
298 approximately nine additional end moraines lie between the outermost and innermost Lake
299 Edison moraines (Figs. 1d, 2, and S9). Collectively, these thirteen boulders range from 35 cm to
300 2.4 m and 25 % of the sampled surfaces had striations or glacial polish indicating little-to-no
301 post-glacial erosion (Table S1).



302 3.2. *Laboratory preparation*

303 Samples were prepared at the University of Wisconsin-Madison. Collected rocks were
304 crushed to 425–841 μm , processed through a Frantz LB-1 Magnetic Barrier Separator to remove
305 magnetic grains, and etched in solutions of 2 % HF and 2 % HNO_3 while rotating on an APW
306 Wyatt HR-50. Quartz purity was measured by ICP-AES analysis prior to ion exchange
307 chromatography. Samples with ≤ 200 ppm Al were dissolved in concentrated HF and HNO_3 ,
308 spiked with a ^9Be carrier solution (OSU-White; Table S3), and dried. Beryllium fluoride was
309 converted into BeCl_2 by repeatedly dissolving and drying the samples in HClO_4 ($\geq 4\times$) before
310 redissolving them in 8 M HCl. Iron, Ti, and Ca were removed with anion column
311 chromatography (Bio-Rad AG1-X8 100–200 mesh chloride-form resin) and NH_4OH
312 precipitations. The Be fraction was separated using cation chromatography (Bio-Rad AG50W-
313 X8 100–200 mesh hydrogen-form resin) and precipitated in centrifuge tubes at a pH of ~ 8.5 by
314 adding NH_4OH . Finally, the samples were dried in quartz crucibles on a hotplate at incremental
315 heating steps of $\sim 55^\circ\text{C}$, $\sim 70^\circ\text{C}$, and $\sim 180^\circ\text{C}$ before being incinerated at $\sim 900^\circ\text{C}$ to produce
316 BeO , which was mixed with Nb and packed into AMS targets. Isotopic ratios were measured at
317 PRIME Lab, Purdue University, in relation to the 07KNSTD standard (Table S3).

318 3.3. *Selection of legacy data*

319 To complement the new ^{10}Be samples from Yosemite National Park and the Sierra
320 National Forest, we include in our analysis twenty-six ^{36}Cl samples (Tioga 4) reported by
321 Phillips et al. (2009) from the vicinity of Bishop Creek (Fig. 1e): the five boulder samples from
322 the crest of the Tioga 4 moraine, sixteen boulder and bedrock measurements from locations
323 between the Tioga 4 and Recess Peak moraines, and the five boulder samples from Humphreys
324 Basin. Phillips et al. (2009) reported two additional ^{36}Cl measurements on a single sample



(BPCR91-11) from a roche moutonnée 1.2 km behind the Tioga 4 moraine – but both ages were anomalously old (ca. 22 ka) and we preemptively excluded this sample from our reanalysis. We also exclude the twenty-three bedrock ^{10}Be samples reported by Dühnforth et al. (2010) from Tuolumne Meadows and Lyell Canyon because uncertainties regarding the degree of inheritance and snow shielding. These samples were collected from small bedrock protrusions (e.g., roche moutonnées) and the heights of these protrusions were not reported. Additionally, we exclude the one ^{10}Be date and nine ^{26}Al dates reported by James et al. (2002) on the final deglaciation of the northwestern Sierra Nevada because of imprecision in these early cosmogenic dates.

3.4. Snow-shielding correction

Snow-shielding corrections for the thirty-one new ^{10}Be samples from Yosemite National Park and the Sierra National Forest were calculated using the historical relationship (ca. 1946–2008 C.E.) between monthly average snow water equivalent (SWE) and elevation (Fig. S21), the modern relationship between average snowpack density and SWE (Fig. S22c), and equation 3.76 from Gosse and Phillips (2001):

$$S_{\text{snow}} = \frac{1}{12} \sum_i^{12} e^{-\left(\frac{(z_{\text{snow},i} - z_{\text{sample}}) \rho_{\text{snow},i}}{\Lambda_{f,e}} \right)}, \quad (1)$$

where $z_{\text{snow},i}$ is monthly average snow depth, z_{sample} is boulder height, $\rho_{\text{snow},i}$ is monthly average snow density, and $\Lambda_{f,e}$ is the effective attenuation length of the cosmogenic ray flux. The historical relationship between monthly average SWE and elevation (Fig. S21) was derived from all the active California Department of Water Resources (CA DWR) snow-monitoring stations in the drainage basins of the Tuolumne, Merced, and San Joaquin Rivers with at least ten years of observations for a particular month (Fig. 1b; Tables S4–S6). The median number of stations over the six snowiest months (December through May) is forty-five. The relationship between average snowpack density and SWE (Fig. S22c) was derived from 15,971 daily observations of



348 snow depth and SWE within these three drainage basins. We propagated uncertainties in boulder
349 height, snow depth, and snow density into the shielding uncertainties (Table S1). We assume
350 historical snow depths and densities are representative of the post-glacial interval and do not
351 apply a time-evolving snow-shielding correction (e.g., Ye et al., 2023). Additional details about
352 how we calculated the snow-shielding corrections are in the supplement (Sect. S.5.).

353 For the twenty-six legacy ^{36}Cl dates on the Tioga 4 ice advance and subsequent
354 deglaciation from the vicinity of Bishop Creek, we used the snow-shielding correction factors
355 reported by Phillips et al. (2009), which they calculated using Eq. 1 in conjunction with data
356 from CA DWR snow-monitoring stations near Bishop Creek.

357 3.5. *Exposure-age calculations*

358 Surface-exposure ages were calculated using version 3.0.2 of the Balco et al. (2008)
359 calculator with the underlying constants last updated on 3 March 2024 (the “Version 3”
360 calculator), CRONUScalc 2.0 (Marrero et al., 2016), and CREp (Martin et al., 2017). CREp does
361 not report a version number (Dr. Pierre-Henri Blard, personal communication, 16 July 2018);
362 these ages were calculated on 3 March 2024. While employing additional calculators provides
363 little-to-no leverage on the problem of systematic uncertainties within ^{10}Be dating – which are
364 chiefly related to the spatial and temporal scaling of ^{10}Be production rates (e.g., Balco, 2011;
365 Borchers et al., 2016) – we are unaware of any scientific rationale for preferring the results of
366 one calculator over another. Our rationale for providing multiple calculations is to assess the
367 sensitivity of the various calculators on our primary conclusions.

368 Across all three calculators (Balco et al., 2008; Marrero et al., 2016; Martin et al., 2017)
369 we used LSDn scaling (Lifton et al., 2014) and the ERA-40 atmospheric model (Uppala et al.,
370 2005). We preferred the LSDn scaling model over the time independent (St) and dependent (Lm)



versions of Lal-Stone scaling (Nishiizumi et al., 1989; Lal, 1991; Stone, 2000; Balco et al., 2008) because of LSDn's grounding in first principles and its ability to explain ^{10}Be concentrations that appear supersaturated with St scaling (Balco, 2016). With regards to the atmospheric model, the Version 3 calculator and CRONUScalc 2.0 are both hardcoded to use ERA-40; for CREp, we elected to use ERA-40 over the U.S. standard atmosphere (NOAA et al., 1976) because of ERA-40's greater fidelity to observed atmospheric pressures (Balco, 2015). As for geomagnetic field reconstruction, the Version 3 calculator is hardcoded to use Lifton (2016) while CRONUScalc 2.0 is hardcoded to use Lifton et al. (2014); for CREp, we adopted Lifton (2016).

We used each calculator's default production-rate-calibration dataset. For the Version 3 calculator and for CRONUScalc 2.0 this is the CRONUS-Earth primary ^{10}Be calibration dataset (Putnam et al., 2010b; Marrero, 2012; Kelly et al., 2015; Lifton et al., 2015; Phillips et al., 2016). As such, the Version 3 calculator uses a non-dimensional LSDn fitting parameter of 0.838 ± 0.048 ; it does not report a sea-level high-latitude (SLHL) production rate in atoms g^{-1} quartz yr^{-1} . Balco (2018) discusses this reporting decision. CRONUScalc 2.0 uses a SLHL ^{10}Be production rate of $3.92 \pm \sim 0.33$ atoms g^{-1} quartz yr^{-1} (Borchers et al., 2016; Marrero et al., 2016); it does not report an LSDn fitting parameter. CREp's default ^{10}Be -production-rate dataset is every published production-rate-calibration study without a major demonstrated flaw (Martin et al., 2017); on 3 March 2024 CREp used a SLHL production rate of 4.06 ± 0.23 atoms g^{-1} quartz yr^{-1} based on the work of Gosse et al. (1995), Farber et al. (2005), Balco et al. (2009), Putnam et al. (2010a), Fenton et al. (2011), Kaplan et al. (2011), Goehring et al. (2012), Young et al. (2013), Claude et al. (2014), Kelly et al. (2015), Martin et al. (2015), Small and Fabel (2015), Stroeven et al. (2015), and Putnam et al. (2019). CREp also does not report an LSDn scaling factor. While we focus this manuscript's interpretations on the ages inferred from the globally distributed



394 production-rate datasets, we also consider the impact on our interpretations of calculating the
395 exposure ages with ^{10}Be production rates derived from the Promontory Point calibration site
396 (Sect. 5.2.2; Lifton et al., 2015).

397 For the Version 3 calculator and CREp (Martin et al., 2017), the reported internal age
398 uncertainties solely reflect ^{10}Be concentration uncertainty while the external uncertainties reflect
399 ^{10}Be concentration and production-rate uncertainties. For CRONUScalc 2.0 (Marrero et al.,
400 2016), the internal age uncertainties reflect twelve sources of uncertainty (Tables S1–S3): sample
401 latitude, longitude, elevation, thickness, density, topographic shielding, erosion rate, ^{10}Be
402 concentration, attenuation length, boulder height, modern SWE by month as a function of
403 elevation (Fig. S21), and average snowpack density as a function of SWE (Fig. S22c). The
404 external age uncertainties we report for CRONUScalc include these same twelve sources of
405 uncertainty plus the production rate and scaling uncertainties (Borchers et al., 2016).

406 We adjusted all reported surface-exposure ages such that they are relative to 1950 C.E. in
407 order to facilitate comparison with the calibrated radiocarbon dates. (The Version 3 calculator
408 and CREp report exposure durations prior to sampling; CRONUScalc 2.0 reports exposure ages
409 relative to 2010 C.E.) We also rounded all cosmogenic age uncertainties mentioned in the text up
410 to the next highest tenths position [when reported in units of kiloannum (ka)] in order to avoid
411 rounding the uncertainties down to lower values than justifiable (e.g., the 0.434 ka uncertainty
412 for sample TM14-15 in the CRONUScalc column of Table 1 becomes 0.5 ka in the text).

413 3.6. *Outlier identification and group-age and uncertainty calculations*

414 For the locations where we report or recalculate at least three samples, we identify
415 outliers using an approach inspired by Tulenko et al. (2022): we first calculate the arithmetic
416 mean and standard deviation of all the surface-exposure ages from a particular location and then



417 assess – within the CRONUScalc 2.0 ages – whether any samples deviate by more than twice
418 their internal age uncertainty ($>2\sigma$) from their group’s arithmetic mean. If so, we label the most
419 extreme deviator from the arithmetic mean an outlier across all three calculators, recalculate the
420 mean, and assess whether any sample still deviates by more than two standard deviations from
421 this new mean. If so, we iterate the outlier identification and rejection protocol described above
422 until all remaining samples are within twice their internal age uncertainty of their group’s mean
423 age. For the dataset we report here, iterating this approach more than twice was not required and
424 we only reject four samples out of the forty-nine samples (8 %) from locations where we report
425 three or more samples.

426 For the locations where we report two or fewer samples, we identify outliers using
427 geomorphic relative-age relationships with the larger sampling groups.

428 We use the CRONUScalc results to identify outliers for three reasons. First, applying this
429 algorithm across all three calculators might result in some samples being rejected within one
430 calculator’s results and not those of another. Second, using the CRONUScalc results for outlier
431 identification is the most conservative implementation of this outlier-identification protocol
432 because the CRONUScalc results include more sources of uncertainty than the results of the
433 other two calculators. Finally, as of this writing, CRONUScalc is the only calculator of the three
434 that calculates ^{36}Cl surface-exposure ages (although we acknowledge that both the Version 3
435 calculator and CREp have ^{36}Cl -calculation methods in development). Thus, at the time of
436 writing, using the CRONUScalc results to identify outliers provides analytic uniformity across
437 the combined dataset of ^{10}Be and ^{36}Cl ages.



438 To calculate each sampling location's external age uncertainty, we multiplied each
439 group's standard deviation by the average ratio of the external-to-internal age uncertainties in
440 that group.

441 3.7. *Deglaciation duration calculations*

442 We calculated deglaciation's duration within Lyell, Mono Creek, and Bishop Creek
443 Canyons using 1×10^5 trial Monte Carlo simulations. As input, these simulations used each
444 sampling group's mean surface-exposure age and the standard deviation of the ages in that
445 group. We then filtered the results of these Monte Carlo simulations and identified trials with
446 simulated deglaciation ages consistent with the geomorphic relative-age requirements of the
447 sampling sites (see Sect. S.6.).

448 3.8. *Recalibration of previously published datasets*

449 We used IntCal20 (Reimer et al., 2020) and the R package Bchron 4.7.6 (Haslett and
450 Parnell, 2008; R Core Team, 2024) to recalibrate the radiocarbon ages in the ca. 18–10 ka
451 portion of the Swamp Lake paleoenvironmental reconstruction (Street et al., 2012) and the
452 radiocarbon ages that constrain the timing of Great Basin pluvial-lake highstands (Munroe and
453 Laabs, 2013; Ibarra et al., 2014). We also used Bchron to construct a new age-depth model for
454 speleothem ML1 from McLean's Cave (Oster et al., 2015). Our goal with the new age-depth
455 models was to provide age uncertainties for the undated horizons in the Swamp Lake core and in
456 speleothem ML1, as the original age-depth models do not provide age uncertainties at these
457 depth increments.

458



459 4. Results

460 4.1. New ^{10}Be dates from Tuolumne Meadows and Lyell Canyon

461 We report eighteen new ^{10}Be samples from Tuolumne Meadows and Lyell Canyon in
462 Yosemite National Park. After rejecting three outliers (Sect. S.7.), the fifteen remaining samples
463 yield ages ranging 15.5–13.9 ka (Version 3 calculator), 16.4–14.7 ka (CRONUScalc 2.0), and
464 16.3–14.7 ka (CREp; Table 1). Across all three calculators, the location with the oldest surface-
465 exposure age is lower Tuolumne Meadows (the most distal sampling site) and the youngest
466 location is the bottom of Lyell Canyon (an intermediate location, but the site with the **greatest ice**
467 **thickness**). In the Version 3 results, the sample (TM14-15) from lower Tuolumne Meadows has
468 an age of 15.2 ± 0.3 ka (1 σ internal-age uncertainty) and the six samples from the bottom of
469 Lyell Canyon have a mean and standard deviation of 14.4 ± 0.3 ka (Fig. 3b; Table 2). In contrast,
470 CRONUScalc and CREp produce ages and internal uncertainties of 16.0 ± 0.5 ka and 16.0 ± 0.3
471 ka, respectively, for the sample from lower Tuolumne Meadows – and means and standard
472 deviations of 15.1 ± 0.2 ka and 15.1 ± 0.3 ka, respectively, for the six samples from the bottom
473 of Lyell Canyon (Fig. 3c–d; Table 2). Thus, CRONUScalc and CREp are producing surface-
474 exposure ages for these samples that are ca. 0.8 kyr (5 %) older than the ages produced by the
475 Version 3 calculator.

476 However, all three calculators produce nearly identical median estimates for the duration
477 of the Tioga 4 deglaciation in Tuolumne Meadows and Lyell Canyon (i.e., the age difference
478 between the lower Tuolumne Meadows sample and the mean age of the samples from the bottom
479 of Lyell Canyon): 0.8 kyr with a 95 % confidence range of 0.2–1.5 kyr (Version 3 calculator),
480 0.9 kyr with a 95 % confidence range of 0.1–1.9 kyr (CRONUScalc 2.0; Fig. 3i), and 0.9 kyr
481 with a 95 % confidence range of 0.3–1.5 kyr (CREp; Fig. 3j).

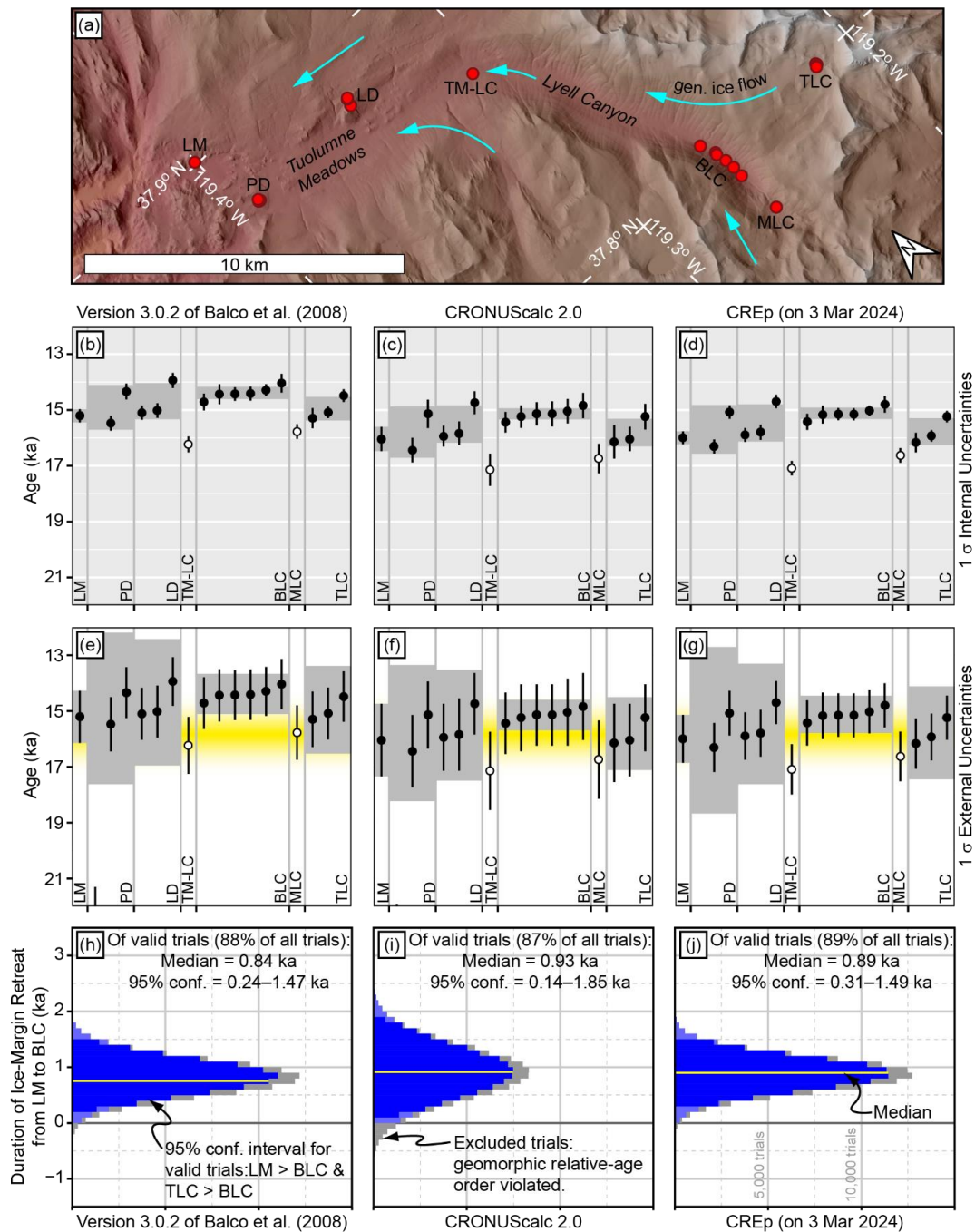


Figure 3. Sampling locations in the Tuolumne Meadows and Lyell Canyon field area, along with the surface-exposure ages and deglaciation durations inferred from those samples. **(a)** Sampling locations in Tuolumne Meadows and Lyell Canyon. Sampling-location abbreviations (from distal to proximal): LM – lower Tuolumne Meadows; PD – Pothole Dome; LM – Lambert



487 Dome; TM-LC – an unnamed roche moutonnée near the junction of Tuolumne Meadows with
488 Lyell Canyon; BLC – the bottom of Lyell Canyon; MLC – a mid-elevation within Lyell Canyon;
489 and TLC – the top of Lyell Canyon. **(b–d)** The ^{10}Be surface-exposure ages and 1σ internal
490 uncertainties. The gray boxes are the mean age of the retained ^{10}Be ages plus/minus one standard
491 deviation. Rejected outliers are depicted with hollow symbols. Note that the extreme outlier (ca.
492 22–25 ka) from Pothole Dome (TM14-13) is outside the age range shown here. **(e–g)** The
493 surface-exposure ages and 1σ external uncertainties. The yellow shading’s intensity represents
494 the relative probability of deglaciation, according to Phillip’s (2016) interpretation of the
495 minimum-limiting radiocarbon dates. **(h–j)** Histograms for the duration of deglaciation. Each
496 histogram is based on a 1×10^5 trial Monte Carlo simulation. We defined “valid” trials as those
497 where the simulated deglaciation age of lower Tuolumne Meadows (LM) and the top of Lyell
498 Canyon (TLC) were both older than the bottom of Lyell Canyon’s (BLC’s) simulated
499 deglaciation age.
500

501 **Table 1.** Individual ^{10}Be and ^{36}Cl sample surface-exposure ages across the three calculators.

Calculator:	Balco et al. (2008)			Marrero et al. (2016)			Martin et al. (2017)		
	v. 3.0.2 (with 3 Mar 2024 constants)			CRONUScalc 2.0			CREp (on 3 Mar 2024)		
Sample name	Age (ka)	Int. Err. (ka)	Ext. Err. (ka)	Age (ka)	Int. Err. (ka)	Ext. Err. (ka)	Age (ka)	Int. Err. (ka)	Ext. Err. (ka)
<u>New Be-10 samples from Tuolumne Meadows and Lyell Canyon</u>									
<u>Top of Lyell Canyon (TLC)</u>									
C2-Boulder1	15.085	0.206	0.932	16.040	0.436	1.300	15.928	0.210	0.840
C2-Boulder2	15.294	0.364	0.991	16.140	0.598	1.400	16.168	0.350	0.900
UpLy-12-10	14.484	0.228	0.902	15.240	0.460	1.200	15.238	0.210	0.790
<u>Mid-elevation within Lyell Canyon (MLC)</u>									
TM14-01	15.773	0.265	0.975	16.740	0.525	1.400	16.626	0.260	0.890
<u>Bottom of Lyell Canyon (BLC)</u>									
LoLy-11-08	14.436	0.357	0.940	15.240	0.402	1.200	15.169	0.320	0.830
TM14-02	14.432	0.244	0.892	15.140	0.418	1.100	15.146	0.220	0.780
TM14-03	14.715	0.301	0.925	15.440	0.367	1.100	15.426	0.290	0.810
TM14-04	14.296	0.215	0.877	15.040	0.438	1.200	15.026	0.180	0.770
TM14-05	14.040	0.335	0.900	14.840	0.454	1.200	14.796	0.300	0.790
TM14-06	14.414	0.252	0.904	15.140	0.449	1.100	15.156	0.220	0.790
<u>An unnamed roche moutonnée between Tuolumne Meadows and Lyell Canyon (TM-LC)</u>									
TM14-07	16.233	0.284	1.019	17.140	0.575	1.400	17.086	0.260	0.900
<u>Pothole Dome in Tuolumne Meadows (PD)</u>									
TM14-11	14.339	0.287	0.910	15.140	0.510	1.200	15.076	0.240	0.800
TM14-12	15.473	0.269	0.970	16.440	0.442	1.300	16.306	0.240	0.880
TM14-13	22.761	0.474	1.460	23.940	0.997	2.000	23.866	0.430	1.250
<u>Lower Tuolumne Meadows (LM)</u>									
TM14-15	15.207	0.239	0.936	16.040	0.434	1.300	15.996	0.230	0.860
<u>Lembert Dome in Tuolumne Meadows (LD)</u>									
TM14-16	13.941	0.271	0.872	14.740	0.413	1.100	14.696	0.240	0.770
TM14-17	15.019	0.264	0.931	15.840	0.430	1.300	15.796	0.270	0.840
TM14-18	15.098	0.249	0.932	15.940	0.370	1.200	15.896	0.250	0.850
<u>New Be-10 samples from Lake Edison and Mono Creek Canyon</u>									
<u>Pioneer Basin and upper Mono Creek Canyon (uppMC)</u>									
MR-14-03	14.963	0.208	0.925	15.840	0.343	1.200	15.796	0.210	0.820
MR-14-04	14.861	0.304	0.945	15.640	0.396	1.200	15.666	0.300	0.820
MR-14-05	14.657	0.226	0.901	15.440	0.385	1.200	15.416	0.210	0.780
MR-14-06	14.863	0.325	0.952	15.740	0.611	1.300	15.656	0.320	0.830
MR-14-07	14.699	0.292	0.932	15.440	0.420	1.200	15.456	0.280	0.810
<u>Mid Mono Creek Canyon (midMC)</u>									
MR-13-02	20.077	0.312	1.234	21.040	0.505	1.400	21.027	0.270	1.000
MR-14-08	17.871	0.252	1.108	18.840	0.536	1.400	18.826	0.230	0.950
<u>Lower Mono Creek Canyon (lowMC)</u>									
MR-13-01	15.136	0.433	1.009	16.040	0.594	1.400	15.997	0.420	0.920
<u>Innermost moraine beneath Lake Edison (LEMinner)</u>									
LEM-14-14	15.534	0.366	1.005	16.440	0.532	1.400	16.406	0.340	0.910
LEM-14-15	15.647	0.365	1.011	16.640	0.574	1.300	16.526	0.350	0.910
<u>Outermost moraine beneath Lake Edison (LEMouter)</u>									
LEM-16-28	18.579	0.377	1.184	19.540	0.552	1.400	19.524	0.340	1.010
LEM-16-29	4.703	0.210	0.351	4.860	0.205	0.350	4.964	0.200	0.310
LEM-16-30	19.421	0.336	1.221	20.340	0.520	1.400	20.374	0.290	1.010
<u>Recalculated Cl-36 samples from Bishop Creek Canyon and vicinity (from Phillips et al., 2009)</u>									
<u>Tioga 4 moraine within the Middle Fork of Bishop Creek Canyon (T4m)</u>									
BpCR97-8	N.A.	N.A.	N.A.	14.740	0.869	1.500	N.A.	N.A.	N.A.
BpCR97-9	N.A.	N.A.	N.A.	16.840	0.977	1.700	N.A.	N.A.	N.A.
BpCR97-13	N.A.	N.A.	N.A.	17.040	0.927	1.800	N.A.	N.A.	N.A.
BpCR97-14	N.A.	N.A.	N.A.	16.340	1.023	1.900	N.A.	N.A.	N.A.
BpCR97-15	N.A.	N.A.	N.A.	16.440	0.996	1.800	N.A.	N.A.	N.A.
<u>Scattered boulders and bedrock outcrops between the Tioga 4 (T4m) and Recess Peak moraines in Bishop Creek Canyon (SB&O)</u>									
BpCr95B-6(99)	N.A.	N.A.	N.A.	14.940	0.815	1.400	N.A.	N.A.	N.A.
BPCR96-1	N.A.	N.A.	N.A.	14.640	0.734	1.500	N.A.	N.A.	N.A.
BpCr96-16	N.A.	N.A.	N.A.	16.640	1.164	1.500	N.A.	N.A.	N.A.
BpCr96-17	N.A.	N.A.	N.A.	14.740	0.718	1.400	N.A.	N.A.	N.A.



BpCr95-3(99)	N.A.	N.A.	N.A.	15.340	0.818	1.400	N.A.	N.A.	N.A.
BPCR96-10	N.A.	N.A.	N.A.	15.940	0.998	2.000	N.A.	N.A.	N.A.
BPCR96-11	N.A.	N.A.	N.A.	14.040	0.715	1.400	N.A.	N.A.	N.A.
BpCr95B-1(99)	N.A.	N.A.	N.A.	16.240	0.877	1.400	N.A.	N.A.	N.A.
<i>BpCR97-3</i>	<i>N.A.</i>	<i>N.A.</i>	<i>N.A.</i>	<i>17.640</i>	<i>0.973</i>	<i>1.400</i>	<i>N.A.</i>	<i>N.A.</i>	<i>N.A.</i>
BpCR97-4	N.A.	N.A.	N.A.	17.540	0.964	1.700	N.A.	N.A.	N.A.
<i>BpCR97-2</i>	<i>N.A.</i>	<i>N.A.</i>	<i>N.A.</i>	<i>11.940</i>	<i>0.757</i>	<i>1.000</i>	<i>N.A.</i>	<i>N.A.</i>	<i>N.A.</i>
BpCR97-1a	N.A.	N.A.	N.A.	16.440	0.906	1.300	N.A.	N.A.	N.A.
BpCR97-1b	N.A.	N.A.	N.A.	16.540	0.876	1.300	N.A.	N.A.	N.A.
BpCr96-21	N.A.	N.A.	N.A.	14.940	0.765	1.100	N.A.	N.A.	N.A.
BpCr96-22	N.A.	N.A.	N.A.	15.840	1.612	1.800	N.A.	N.A.	N.A.
BpCr95-2(99)	N.A.	N.A.	N.A.	15.540	0.784	1.200	N.A.	N.A.	N.A.
<i>Humphreys Basin (HB)</i>									
HB97-1	N.A.	N.A.	N.A.	15.940	0.868	1.200	N.A.	N.A.	N.A.
HB97-2	N.A.	N.A.	N.A.	17.340	0.849	1.300	N.A.	N.A.	N.A.
HB97-3	N.A.	N.A.	N.A.	16.040	0.685	1.100	N.A.	N.A.	N.A.
HB97-4	N.A.	N.A.	N.A.	15.340	0.727	1.400	N.A.	N.A.	N.A.
HB97-5	N.A.	N.A.	N.A.	16.440	0.814	1.300	N.A.	N.A.	N.A.

502



Table 2. Mean surface-exposure age and standard deviation for each sampling location. Location abbreviations: TLC – Top of Lyell Canyon; MLC – Middle elevation within Lyell Canyon; BLC – Bottom of Lyell Canyon; TM-LC – an unnamed roche moutonnée near the junction of Lyell Canyon with Tuolumne Meadows; PD – Pothole Dome; LM – lower Tuolumne Meadows; LD – Lember Dome; uppMC – Pioneer Basin and the upper reaches of Mono Creek Canyon; midMC – mid-valley location within Mono Creek Canyon; lowMC – the lower reaches of Mono Creek Canyon; LEMinner – the innermost moraine beneath Lake Edison; LEMouter – the outermost moraine beneath Lake Edison; T4m – the Tioga 4 moraine in the Middle Fork of Bishop Creek Canyon; SB&O – scattered boulders and outcrops between the Tioga 4 moraine and the Recess Peak moraines; and HB – Humphrey’s Basin.

512 Peak moraines, and HD – Humphrey's Basin.											
Balco et al. (2008)						Marrero et al. (2016)			Martin et al. (2017)		
v. 3.0.2 (with 3 Mar 2024 constants)						CRONUScalc 2.0			CREp (on 3 Mar 2024)		
Sampling location	n _i	n _f	Age (ka)	1 σ internal (ka)	1 σ external (ka)	Age (ka)	1 σ internal (ka)	1 σ external (ka)	Age (ka)	1 σ internal (ka)	1 σ external (ka)
Tuolumne Meadows and Lyell Canyon											
TLC	3	3	14.954	0.421	1.572	15.807	0.493	1.303	15.778	0.483	1.663
MLC	1	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
BLC	6	6	14.389	0.220	0.723	15.140	0.200	0.548	15.120	0.206	0.667
TM-LC	1	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
PD	3	2	14.906	0.802	2.717	15.790	0.919	2.438	15.691	0.870	2.981
LM	1	1	15.207	0.239	0.936	16.040	0.434	1.300	15.996	0.230	0.860
LD	3	3	14.686	0.646	2.261	15.507	0.666	1.983	15.463	0.666	2.158
Lake Edison and Mono Creek Canyon											
uppMC	5	5	14.809	0.127	0.448	15.620	0.179	0.521	15.598	0.158	0.498
midMC	2	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
lowMC	1	1	15.137	0.434	1.009	16.040	0.570	1.400	15.997	0.420	0.920
LEMinner	2	2	15.591	0.081	0.223	16.540	0.141	0.344	16.466	0.085	0.222
LEMouter	3	2	19.003	0.593	2.008	19.940	0.566	1.513	19.949	0.601	1.920
Bishop Creek Canyon and vicinity											
T4m	5	5	NA	NA	NA	16.280	0.907	1.646	NA	NA	NA
SB&O	16	14	NA	NA	NA	15.926	0.973	1.565	NA	NA	NA
HB	5	5	NA	NA	NA	16.220	0.740	1.190	NA	NA	NA

513



514 4.2. *New ^{10}Be dates from Lake Thomas A. Edison and Mono Creek Canyon*

515 We report thirteen new ^{10}Be samples from Lake Edison and Mono Creek Canyon. After
516 rejecting three outliers (Sect. S.7.), the ten remaining samples yield ages ranging 19.4–14.7 ka
517 (Version 3 calculator), 20.3–15.4 ka (CRONUScalc 2.0), and 20.4–15.4 ka (CREp; Table 1).

518 The mean age of the outermost Lake Edison moraine varies by 0.9 kyr (5 %) across the
519 three calculators (Table 2): the Version 3 calculator dates stabilization of the outermost moraine
520 to 19.0 ± 0.6 ka (mean and standard deviation; $n = 2$; Fig. 4c) while CRONUScalc dates it to
521 19.9 ± 0.6 ka (Fig. 4d) and CREp dates it to 19.9 ± 0.7 ka (Fig. 4e).

522 Likewise, the innermost Lake Edison moraine's age also varies by ca. 1 kyr across the
523 calculators (Table 2): the Version 3 calculator suggests stabilization at 15.6 ± 0.1 ka (mean and
524 standard deviation; $n = 2$; Fig. 4c) while CRONUScalc and CREp place it at 16.5 ± 0.2 ka (Fig.
525 4d) and 16.5 ± 0.1 ka (Fig. 4e), respectively. Thus, despite calculator-based differences of 0.9
526 kyr (6 %) in the timing of this event, all three calculators indicate that the outermost Lake Edison
527 moraine predates the onset of rapid deglaciation in the Mono Creek drainage basin by ca. 3.4
528 kyr, with the Version 3 calculator producing a median estimate of 3.4 kyr (and with a 95 %
529 confidence range of 2.2–4.6 kyr), CRONUScalc producing a median estimate of 3.4 kyr (2.2–4.5
530 kyr), and CREp producing a median estimate of 3.5 kyr (2.3–4.7 kyr).

531 Following abandonment of the innermost Lake Edison moraine (i.e., the start of the Tioga
532 4 deglaciation), the ice-margin retreated up Mono Creek Canyon. A single sample from lower
533 Mono Creek Canyon (lowMC), 7 km behind the innermost Lake Edison moraine and 15 km
534 from the cirque headwall in Pioneer Basin, yields exposure ages of 15.1 ± 0.5 ka (1 σ internal;
535 Version 3; Fig. 4c), 16.0 ± 0.6 ka (CRONUScalc; Fig. 4d), and 16.0 ± 0.5 ka (CREp; Fig. 4e;
536 Table 2). The five samples from upper Mono Creek Canyon (1–5 km from the cirque headwall)



537 produce mean ages and standard deviations of 14.8 ± 0.2 ka (the Version 3 calculator; Fig. 4c),
538 15.6 ± 0.2 ka (CRONUScalc; Fig. 4d), and 15.6 ± 0.2 ka (CREp; Fig. 4e; Table 2). All three
539 calculators produce similar median estimates for the duration of the Tioga 4 deglaciation in
540 Mono Creek Canyon (Fig. 4i–k): 0.8 kyr (with a 95 % confidence interval of 0.5–1.1 kyr; the
541 Version 3 calculator), 1.0 kyr (0.5–1.4 kyr; CRONUScalc 2.0), and 0.9 kyr (0.6–1.2 kyr; CREp).

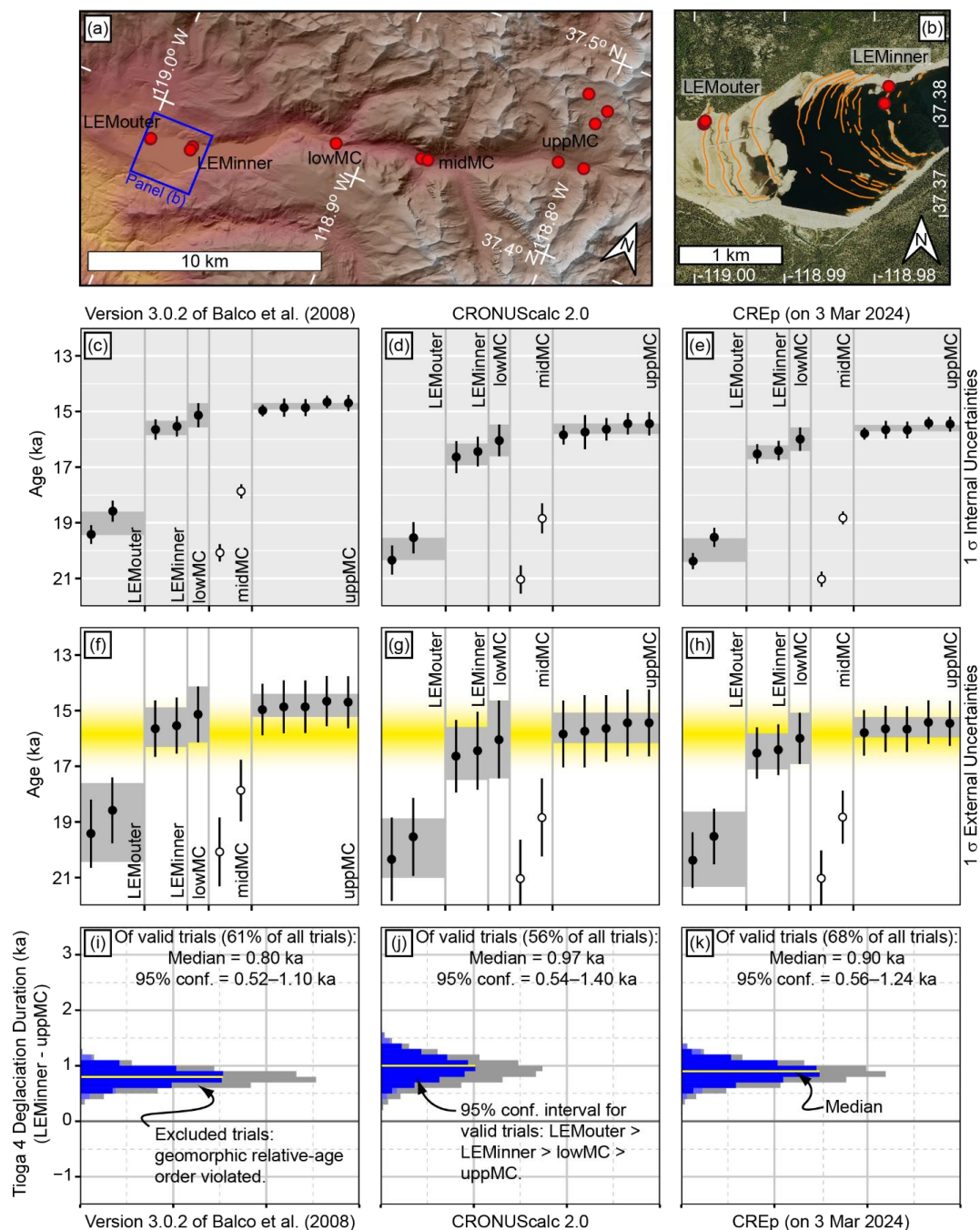


Figure 4. (a) Sampling locations in the Lake Edison and Mono Creek Canyon field area. Sampling-location abbreviations (from distal to proximal): LEMouter – the outermost moraine of the Lake Edison moraine complex; LEMinner – the innermost Lake Edison moraine; lowMC –



546 lower Mono Creek Canyon; midMC – middle Mono Creek Canyon; and uppMC – upper Mono
547 Creek Canyon. **(b)** 2014 aerial photo of Lake Edison at a low-water stage with moraine crests
548 traced in orange. **(c–e)** Beryllium-10 ages and 1σ internal uncertainties from the Version 3
549 Calculator **(c)**, CRONUScalc 2.0 **(d)**, and CREp **(e)**. Gray boxes enclose each sample group's
550 mean age plus/minus one standard deviation. Rejected outliers shown with hollow symbols. Note
551 the extreme outlier (ca. 5 ka) from the outermost Lake Edison moraine (LEM-14-29) is outside
552 the displayed age range. **(f–h)** Beryllium-10 ages and 1σ external uncertainties. The yellow
553 shading's intensity is proportional to the relative probability of deglaciation, per Phillip's (2016)
554 interpretation of basal radiocarbon dates. **(i–k)** Results of a 1×10^5 trial Monte Carlo simulation
555 of deglaciation's duration in this drainage basin. We defined "valid" trials as those where the
556 simulated deglaciation ages run from oldest to youngest in the following order: the outermost
557 Lake Edison moraine, the innermost Lake Edison moraine, lower Mono Creek Canyon, and
558 upper Mono Creek Canyon.



559 4.3. *Recalculated ^{36}Cl dates from the vicinity of Bishop Creek Canyon*

560 We report twenty-six recalculated ^{36}Cl ages from the vicinity of Bishop Creek Canyon.

561 The five boulders from the Tioga 4 moraine within the Middle Fork of Bishop Creek Canyon
562 produce a mean age of 16.3 ± 1.7 ka (1σ external uncertainty), fourteen samples (we reject two
563 samples as outliers; Sect. S.7.) from boulders and bedrock outcrops scattered between the Tioga
564 4 and Recess Peak moraines (which we will henceforth refer to as the “valley-bottom samples”
565 for brevity) produce a mean age and standard deviation of 15.9 ± 1.6 ka, and the five boulders
566 from Humphreys Basin produce a weighted-mean age of 16.2 ± 1.2 ka (Fig. 5c; Table 2).

567 Using these mean ages and their associated 1σ internal uncertainties as input into a
568 Monte Carlo model that requires Tioga 4 moraine abandonment (and stabilization) to precede
569 deglaciation of Humphreys Basin and the valley-bottom locations results in 61 % of the Monte
570 Carlo trials being retained and produces a median estimate for the duration of the Tioga 4
571 deglaciation within Bishop Creek Canyon of 1.3 kyr with a 95 % confidence range of 0.1–3.3
572 kyr (Fig. 5d).

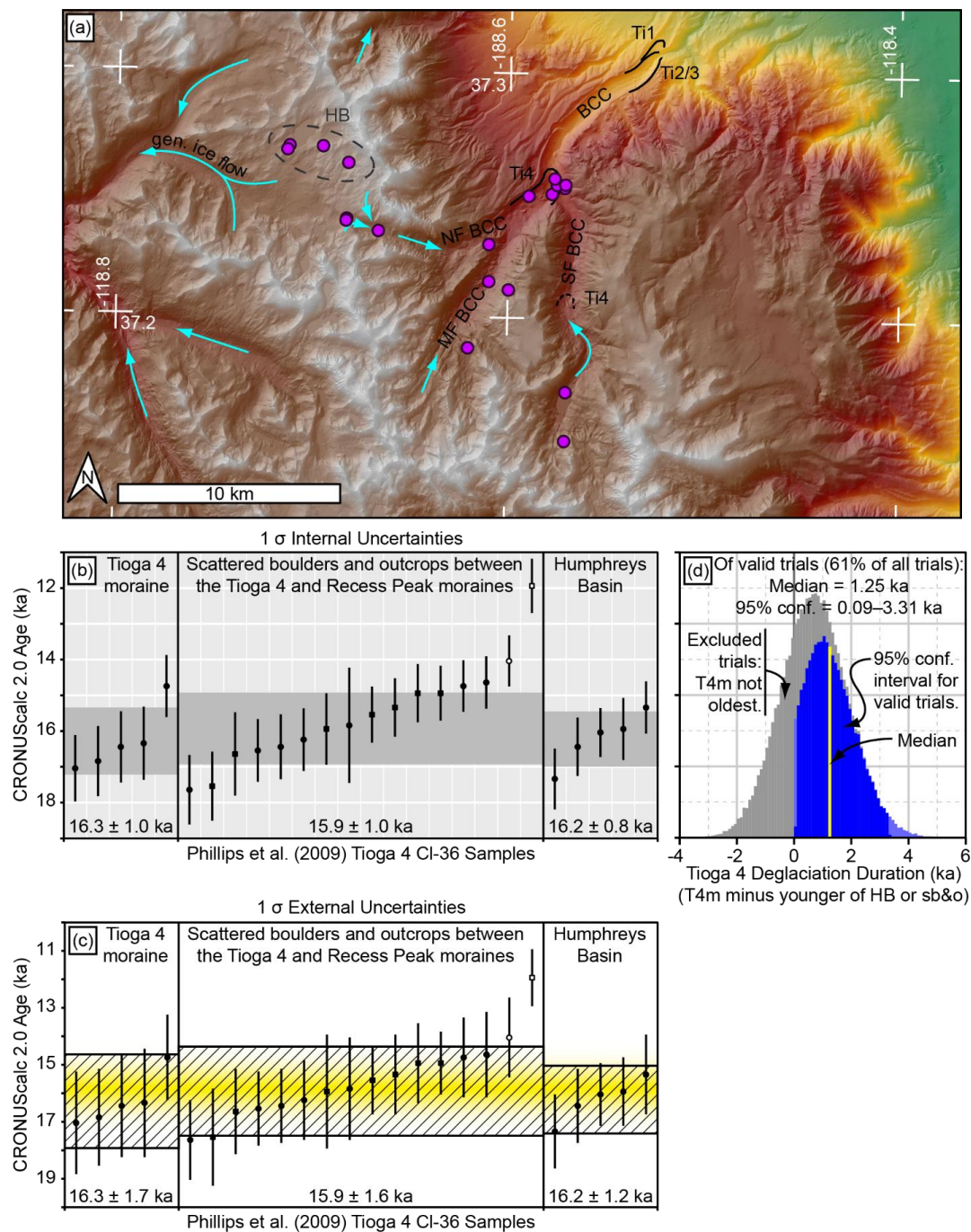


Figure 5. Phillips et al. (2009) Tioga 4 sampling locations in Bishop Creek Canyon and its vicinity, along with the recalculated surface-exposure ages and inferred deglaciation durations.



576 **(a)** Phillips et al. (2009) Tioga-4 sampling locations (purple circles). Abbreviations: Ti1 – the
577 Tioga 1 moraine; Ti2/3 – the Tioga 2/3 moraine; Ti4 – the Tioga 4 moraine; HB – Humphrey’s
578 Basin; BCC – Bishop Creek Canyon; NF BCC – the North Fork of Bishop Creek Canyon; MF
579 BCC – the Middle Fork of Bishop Creek Canyon; SF BCC – the South Fork of Bishop Creek
580 Canyon. Solid black lines are moraines; the dashed black line is a likely (Tioga 4) ice-marginal
581 position (Phillips et al., 2009). **(b)** Chlorine-36 surface-exposure ages and 1 σ internal age
582 uncertainties. Circles are boulder samples; squares are bedrock samples. Solid symbols are
583 retained samples; hollow symbols are rejected outliers. The gray boxes are the mean age of the
584 retained ^{36}Cl ages plus/minus one standard deviation. **(c)** Chlorine-36 ages and 1 σ external age
585 uncertainties. The hatched boxes enclose the mean age of each sampling group, plus/minus one
586 standard deviation. The yellow shading’s intensity is proportional to deglaciation’s relative
587 probability, according to Phillip’s (2016) interpretation. **(d)** The distribution of Tioga 4
588 deglaciation durations in the vicinity of Bishop Creek Canyon, based on a 1×10^5 trial Monte
589 Carlo simulation. We define “valid” trials as those where the Tioga 4 moraine has the oldest
590 simulated deglaciation age and deglaciation’s duration as the time difference between the Tioga
591 4 moraine’s stabilization and the youngest deglaciation age from the other two sampling groups.



592 4.4. *Updated chronologies for previously published datasets*

593 Revising the age-depth model for the Swamp Lake paleoenvironmental reconstruction
594 from one based on linear interpolation between adjacent radiocarbon dates to one that permits
595 sedimentation rates to vary throughout the core suggests that age uncertainties on the core's
596 undated horizons are ~2–3 times larger than the age uncertainties on the calibrated radiocarbon
597 dates. Although these age uncertainties vary with core-depth distance to the nearest radiocarbon
598 date, representative 1 σ uncertainties for the undated horizons in the Swamp Lake core of
599 greatest relevance to the Tioga 4 deglaciation are ca. 0.40 kyr verses ca. 0.15 kyr for the
600 radiocarbon dates themselves (Fig. S23; Table S7). Note that – despite updating Swamp Lake's
601 age-depth model from IntCal04 (Reimer et al., 2004) to IntCal20 (Reimer et al., 2020) – the
602 median age estimates for the radiocarbon dates in Swamp Lake's age-depth model are only
603 slightly changed (≤ 0.15 kyr) from the values reported by Street et al. (2012); the advantage of the
604 new age-depth model that we report here for this core is in the better representing the true dating
605 uncertainties.

606 With regards to the radiocarbon constraints on the timing of Great Basin lake highstands,
607 updating the various radiocarbon calibrations previously used [i.e., IntCal09 (Reimer et al.,
608 2009) and IntCal13 (Reimer et al., 2013)] to IntCal20 (Reimer et al., 2020) results in new
609 calibrated ages ranging from 0.4 kyr younger to 0.3 kyr older than the ages reported by Munroe
610 and Laabs (2013) and Ibarra et al. (2014), with a mean adjustment of 0.1 kyr younger (Fig. S24;
611 Table S8).

612 Finally, for the paleoenvironmental reconstruction from McLean's Cave, the median age
613 estimate in Bchron's age-depth model for the various measurement depths in speleothem ML1
614 ranges from 0.147 kyr younger than the ages reported by Oster et al. (2015) to 0.731 kyr older,



615 with a mean difference of essentially zero (0.047 kyr older; Figs. S25–S26; Table S9). For the
616 portion of the speleothem with the greatest relevance to this manuscript [sampling depths
617 132.00–141.85 mm, with $^{230}\text{Th}/\text{U}$ dates of 15.433 ± 0.065 ka (1 σ uncertainty) and $16.718 \pm$
618 0.159 ka at those depths, respectively (Oster et al., 2015)], the Bchron age-depth model has
619 median ages that are 0.110–0.510 kyr older than the ages reported by Oster et al. (2015), with a
620 mean difference of 0.325 kyr. Bchron’s 1 σ age uncertainties for the undated horizons over this
621 sampling-depth interval range from ± 0.066 kyr (at the interval’s younger, shallower end) to
622 ± 0.156 kyr (at the interval’s older, deeper end).

623 5. Discussion

624 This manuscript’s goal is to place the **Sierra Nevada’s** final deglaciation in a robust
625 regional and global context. That narrative, however, depends upon the cosmogenic dates and the
626 three calculators produce exposure ages that disagree by $\sim 5\%$ (ca. 1 kyr) despite identical inputs.
627 Thus, this discussion is structured as follows. First, we compare the calculated ages for each
628 calculator and document their differences (and similarities). Second, we use the radiocarbon
629 constraints on the timing of the Tioga 4 deglaciation to assess the accuracy of the calculators for
630 these particular ^{10}Be and ^{36}Cl samples. Then, after adopting a preferred set of exposure ages, we
631 return to this manuscript’s primary focus and discuss the final deglaciation of the Sierra Nevada
632 within a regional and global context.

633 5.1. Comparison of the cosmogenic surface-exposure-age calculators

634 For the thirty-one new ^{10}Be samples presented here, CRONUScalc 2.0 and CREp (on 3
635 Mar 2024) generated surface-exposure ages that were $\sim 5\%$ older than those produced by the
636 Version 3 calculator (Fig. 6). In particular, the CRONUScalc ages averaged 5.4 % older (range:
637 3.2–6.3 %) and the CREp ages averaged 5.3 % older (range: 4.7–5.7 %). These differences



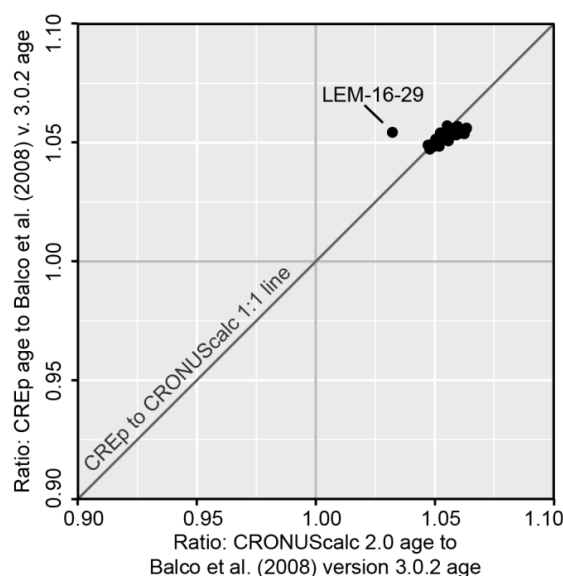
638 exceed the relative uncertainty in the ^{10}Be concentrations of the samples, which average 1.8 %,
639 and range 1.3–4.4 % (Table S3). Additionally, the age differences between the CRONUScalc 2.0
640 and the Version 3 calculator results are larger than their combined internal age uncertainties for
641 twenty-six of the thirty-one ^{10}Be samples (84 %); likewise, the age differences between the
642 results from CREp and the Version 3 calculator are larger than their combined internal age
643 uncertainties for thirty of the samples (97 %). Thus, by these measures, the age differences
644 returned by the calculators are significant.

645 This ~5 % age difference cannot be explained by the scaling or atmospheric models, as
646 all three calculators used LSDn scaling (Lifton et al., 2014) and the ERA-40 atmospheric
647 reanalysis (Uppala et al., 2005), and the ~5 % age difference also cannot be explained by the
648 calculators using different geomagnetic-field reconstructions and ^{10}Be -production-rate-
649 calibration datasets. Although the geomagnetic-field reconstruction is not constant across the
650 calculators, two lines of evidence suggest this variability is not the source of the ~5 % age
651 difference: First, the ages from the Version 3 calculator and CREp were both calculated with the
652 Lifton (2016) geomagnetic reconstruction, and yet the two sets of ages differ by ~5 %. Second,
653 recalculating the exposure ages of these thirty-one samples in CREp (the only calculator of the
654 three that readily enables users to select their preferred geomagnetic reconstruction) with the
655 Lifton et al. (2014) reconstruction (which is used by CRONUScalc) changes the CREp exposure
656 ages by <1 % on average (Table S10). Both the Version 3 calculator and CRONUScalc 2.0 used
657 the CRONUS-Earth primary ^{10}Be -calibration dataset, so the dataset used to calibrate the ^{10}Be
658 production rate also cannot be the reason for the ~5 % age difference across the calculators.
659 Lastly, we note that the corrections for topographic and snow shielding are not particularly large
660 (ranging from 1–14 %), nor are the erosion rates we infer for these samples ($\leq 1 \text{ mm yr}^{-1}$) – and,



661 in any event, these corrections are a constant for any particular sample across the three
662 calculators. Thus, the ~5 % age difference between the calculators cannot be explained by
663 scaling model, the atmospheric and magnetic reconstructions, the choice of calibration dataset, or
664 particulars about the samples (i.e., topographic shielding, snow shielding, or erosion rate).

665 We hypothesize that the ~5 % age difference is the result of the calculators using
666 different algorithms for converting a suite of calibration samples into a single value (be it a non-
667 dimensional LSDn scaling factor or a SLHL production rate) for scaling to other locations.
668 Unfortunately, assessing this hypothesis is hindered by the Version 3 calculator reporting a
669 LSDn scaling factor (and not also a SLHL ^{10}Be production rate) and CRONUScalc 2.0 and
670 CREp reporting SLHL production rates (and not also LSDn scaling factors). Fortunately,
671 determining why the calculators are returning different surface-exposure ages is not essential to
672 this paper's purpose. Instead, we focus on two tasks: (1) assessing which calculator is more
673 likely producing more accurate ages for the samples in the dataset reported here; and then (2)
674 placing these dates within the context of previous paleoclimate research.



675

676 **Figure 6.** Comparison of the ^{10}Be ages from the three calculators. The Version 3 calculator
677 produces exposure dates that are ~5% younger than the ages produced by CRONUScalc 2.0 and
678 CREp for the thirty-one ^{10}Be samples in this dataset. The outlier is the ca. 5 ka boulder from
679 Lake Edison, which is ca. 9–19 kyr younger than the other samples.

680

681 5.2 Assessment of the cosmogenic surface-exposure-age calculators

682 If we accept the interpretation that Tuolumne Meadows deglaciated before 15.4 ka (as
683 suggested by the Greenstone Lake radiocarbon date; Fig. S2; Clark et al., 2003) and that the
684 high-elevation lake basins of the Sierra Nevada deglaciated at 15.75 ± 0.5 ka (Phillips, 2016), as
685 suggested by the bulk-organic radiocarbon dates (Sect. 2.2.2), then the probability distributions
686 on the cosmogenic surface-exposure dates suggest that the CRONUScalc 2.0 and CREp dates are
687 probably more accurate than the dates from the Version 3 calculator for the limited range of
688 elevations (2300–3500 m), latitudes (37–38° N), longitudes (118–120° W), and ^{10}Be
689 concentrations ($3\text{--}6 \times 10^5$ atoms g^{-1}) represented by the thirty-one ^{10}Be samples in this
690 manuscript's dataset (Figs. 3e–g and 4f–h). We emphasize this assessment is (1) probabilistic
691 and (2) predicated on the accuracy of the bulk-sediment radiocarbon dates. Because bulk-



692 sediment radiocarbon dates can be biased toward older ages by the presence of inorganic “dead”
693 carbon, we first assess the possibility that these bulk-sediment radiocarbon dates from the Sierra
694 Nevada are contaminated with radioactively dead carbon (Sect. 5.2.1.) before returning to the
695 topic of the surface-exposure calculators and their relative accuracy for the Tioga 4 deglaciation
696 in the Sierra Nevada (Sect. 5.2.2.).

697 *5.2.1 On the accuracy of the bulk-organic radiocarbon dates*

698 Bulk-organic radiocarbon dates are problematic for accurate chronologies because trace
699 amounts of inorganic carbon, if present in the sediments, will bias the radiocarbon dates toward
700 older ages due to the “hardwater effect” (Godwin, 1951, p. 306; Deevey et al., 1954; Oana and
701 Deevey, 1960; Philippsen, 2013). However, three lines of evidence suggest dead carbon is not a
702 significant concern for these samples. First, carbonate bedrock is absent within the radiocarbon-
703 dated drainage basins; instead, these watersheds are etched into the granitic rocks of the Sierra
704 Nevada (Bateman and Wones, 1972; Bateman et al., 1983; Huber, 1983).

705 Second, Clark and Gillespie (1997) tested for dead carbon in four other granitic
706 watersheds of the Sierra Nevada by dating macrofossils (twigs, branches, and charcoal) and
707 directly adjacent bulk sediment (organic silt, gyttja, and peat) in four cores. In four of five cases,
708 these paired radiocarbon dates agree within 1 σ . In the case of the exception, the bulk sediment
709 (gyttja) is ca. 1.1 kyr older than the macrofossil, which was a piece from a “large” branch. While
710 this age offset could be explained by 10 % of the carbon in the gyttja being dead with respect to
711 ^{14}C activity, Clark and Gillespie (1997) rejected this interpretation because – crucially – one of
712 the four other radiocarbon-dated pairs in their dataset came from the same sediment core (BL-2,
713 from Upper Baboon Lake in the Bishop Creek drainage basin; Fig. 1f) and the macrofossil and
714 bulk-sediment in this other radiocarbon-date pair had indistinguishable ages: the macrofossil



715 (twig) dated to $7,900 \pm 60$ ^{14}C -yrs and the bulk sediment (gyttja) dated to $7,890 \pm 60$ ^{14}C -yrs.
716 Therefore, Clark and Gillespie (1997) interpreted the mismatched radiocarbon-date pair as
717 resulting from the large branch sinking into then-flocculent gyttja when it landed in the pond – a
718 phenomenon observable within modern ponds and interpreted for other lacustrine cores (e.g.,
719 Davis et al., 2019, Fig. 16) – and we accept their interpretation for the observed age offset in this
720 pair of radiocarbon dates.

721 Finally, Swamp Lake also occupies a granitic watershed within the Sierra Nevada and all
722 thirteen radiocarbon dates in its age-depth model were on bulk sediment; Street et al. (2012)
723 tested the core’s sediments for carbonates by fumigating samples with concentrated HCl and
724 comparing them with unfumigated samples. Street et al. (2012) found no detectable carbonates
725 within the Swamp Lake core.

726 Although a lack of compelling evidence for dead carbon within the lacustrine sediments
727 of five granitic watersheds in the Sierra Nevada [i.e., Swamp Lake plus the four investigated by
728 Clark and Gillespie (1997)] does not preclude its presence in the sediments of other granitic
729 watersheds in the Sierra Nevada, there is no evidence for dead carbon in the lacustrine sediments
730 of the Sierra Nevada’s granitic watersheds. Therefore, we accept the bulk-organic radiocarbon
731 dates reviewed in Sect. 2.2.2 as accurate minimum limits on the timing of the Tioga 4
732 deglaciation.

733 5.2.2. *On the accuracy of the cosmogenic surface-exposure-age calculators*

734 Accepting the bulk-organic radiocarbon dates as accurate minimum limits on the timing
735 of the Tioga 4 deglaciation suggests that the CRONUScalc and CREp dates are probably more
736 accurate than the Version 3 calculator’s dates for the ^{10}Be samples reported here. Our argument
737 is as follows: After excluding outliers, nine sampling locations remain (Table 2). For six of these



738 nine locations (lower Tuolumne Meadows, Pothole Dome, Lember Dome, the top of Lyell
739 Canyon, lower Mono Creek Canyon, and upper Mono Creek Canyon), the CRONUScalc and
740 CREp dates produce mean sampling group ages closely bracketing 15.75 ka (≤ 0.3 kyr). These
741 mean ages range ~~from~~ 16.0–15.5 ka (Table 2). For the three remaining locations, larger
742 deviations from 15.75 ka seem reasonable. These three exceptions are (from oldest to youngest):
743 (1) the outermost moraine beneath Lake Edison (which predates the innermost Lake Edison
744 moraine by ca. 3.4 kyr across all three calculators; Fig. 4c–e); (2) the innermost moraine beneath
745 Lake Edison, which records the start of the Tioga 4 deglaciation, and not the deglaciation of
746 high-elevation lake basins, as the radiocarbon dates do; and (3) the bottom of Lyell Canyon,
747 which has comparatively young exposure ages across all three calculators and likely hosted a
748 substantially greater Tioga 4 ice thickness than the radiocarbon-dated lake basins (Wahrhaftig et
749 al., 2019).

750 In contrast to CRONUScalc and CREp, the Version 3 calculator produces mean ages that
751 are 0.5–1.1 kyr younger than 15.75 ka for the six locations mentioned above (Figs. 3e and 4f).
752 These mean ages range from 15.2–14.7 ka (Table 2). Likewise, within this set of results, the
753 innermost Lake Edison moraine likely stabilized ca. 0.1–0.5 kyr after the start of organic
754 accumulation in the high basins of the Sierra Nevada. Additionally, the Version 3 calculator’s
755 exposure ages from locations analogous to the radiocarbon-dated lake basins [such as the top of
756 Lyell Canyon (with a mean age of 15.0 ka) and the upper reaches of Mono Creek Canyon (14.8
757 ka)] postdate the high-elevation lake-basin radiocarbon dates by ca. 0.9 kyr (Figs. 3e and 4f).
758 Shifting the bulk-organic radiocarbon ages 0.9 kyr younger, into agreement with the most
759 probably ages from the Version 3 calculator, would require 7–11 % of the carbon in the
760 sediments of Highlands, Greenstone, and East Lakes be “dead” with respect to ^{14}C activity.



761 Considering Tuolumne Meadows in particular, where the radiocarbon-dated deglacial
762 chronology is the strongest of all our field areas, CRONUScalc and CREp produce mean
763 deglaciation ages of 16.0–15.5 ka for lower Tuolumne Meadow, Pothole Dome, and Lambert
764 Dome – while the Version 3 calculator produces mean ages of 15.2–14.7 ka (Table 2). In
765 comparison, Greenstone Lake was both deglaciated and accumulating organic carbon by 15.4 ka
766 (Fig. S2; Sect. 2.2.2) – and Greenstone Lake was ≤ 4 km from the accumulation zone that fed ice
767 into Tuolumne Meadows (Huber, 2007; Wahrhaftig et al., 2019). If Greenstone Lake was
768 deglaciated and accumulating organic carbon by 15.4 ka, then it seems likely that our sampling
769 sites in lower Tuolumne Meadows (~30 m above the modern floor of Tuolumne Meadows) and
770 on Pothole Dome (~70 m) and Lambert Dome (~230 m) were also deglaciated by that time.

771 We tested whether recalculating the ^{10}Be surface-exposure ages with the most precisely
772 determined ^{10}Be production rate from western North America (the Promontory Point production
773 rate; Lifton et al., 2015) would shift the ages older – and thus bring the results of the Version 3
774 calculator into better agreement with the radiocarbon dates from the Sierra Nevada (Fig. S2). We
775 instead find that the Lifton et al. (2015) calibration dataset results in even younger exposure ages
776 (Table S11). Therefore, with the evidence available to us, we conclude that the Version 3
777 calculator is probably producing exposure ages that are ~5 % too young for the thirty-one ^{10}Be
778 samples in this location and that the CRONUScalc and CREp dates are more consistent with the
779 current radiocarbon chronology.

780 Accordingly, with the goal of streamlining the Discussion going forward, we will
781 henceforth exclusively refer to the CRONUScalc 2.0 ages, which are indistinguishable from the
782 CREp ages. This interpretive decision results in the following deglacial narrative: the innermost
783 Lake Edison moraine stabilized a few hundred years prior to the start of organic accumulation in



the high-elevation ponds of the Sierra Nevada (Fig. 4g), the six sampling locations mentioned above were then exposed to cosmic rays around the same time that the ponds began accumulating organic carbon, and deglaciation concluded with the melting of the valley-bottom ice remnants, where Tioga 4 ice thicknesses were the greatest (e.g., the bottom of Lyell Canyon; Figs. 3f). This narrative is consistent with geomorphic interpretations of rapid deglaciation and ice thinning in the Sierra Nevada at the end of the last glaciation (Clark, 1976; Clark and Clark, 1995) and with observations from Alaska (Cushing, 1891; Reid, 1896; Field, 1947; Mickelson, 1971; Syverson, 1995), and interpretations (Goldthwait, 1938; Lowell, 1985; Lowell et al., 1990) and dating (Bierman et al., 2015; Davis et al., 2015; Koester et al., 2017, 2021; Corbett et al., 2019; Drebber et al., 2023; Halsted et al., 2024) from New England and adjacent regions (Barth et al., 2019) for how rapid **deglaciation** proceeds in mountainous landscapes (Goldthwait and Mickelson, 1982).

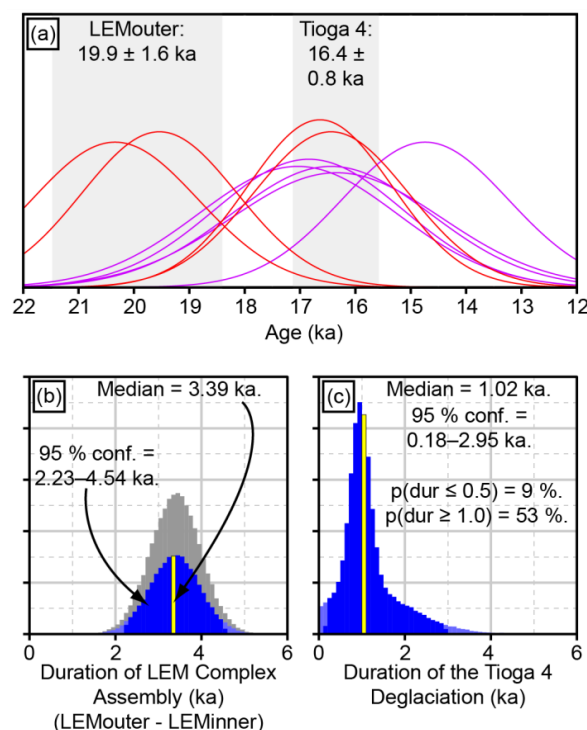
5.3 *New ^{10}Be and revised ^{36}Cl constraints on the timing and duration of the Tioga 4 deglaciation*

5.3.1. *On the timing of the Tioga 4 deglaciation*

Within this context, the best direct estimate for the culmination of the Tioga 4 readvance and the start of the Tioga 4 deglaciation is 16.4 ± 0.8 ka (1 σ external; Fig. 7a). This age is the mean and standard deviation of the seven cosmogenic surface-exposure ages from the two Tioga 4 moraines dated by this study: the two ^{10}Be dates from the innermost Lake Edison moraine (which independently dates to 16.5 ± 0.4 ka; Fig. 4g; Table 2) and the five ^{36}Cl dates from the Tioga 4 moraine in Bishop Creek Canyon (which independently dates to 16.2 ± 1.7 ka; Fig. 5c). Although the most distal sampling location in Tuolumne Meadows does not date the start of the



806 Tioga 4 deglaciation, we note that it also produces an exposure age (16.0 ± 1.3 ka) similar to the
807 stabilization ages of these two innermost moraines.



808 **Figure 7. (a)** The 68 % confidence (1σ) ranges for the outermost Lake Edison moraine
809 (LEMouter) and for the start of the Tioga 4 deglaciation (which is dated by two ¹⁰Be and five
810 ³⁶Cl dates across two innermost moraines). Red lines are the probability densities of the
811 individual ¹⁰Be dates (as calculated by CRONUScalc 2.0) and the purple lines are the same for
812 the ³⁶Cl samples. Samples constraining the end of the Tioga 4 deglaciation (rather than its
813 beginning) are omitted for clarity. **(b)** The inferred duration of moraine construction in the Lake
814 Edison moraine complex. **(c)** Duration of the Tioga 4 deglaciation in 1×10^5 Monte Carlo
815 simulations (5×10^4 from Mono Creek Canyon and 5×10^4 from Bishop Creek Canyon).
816
817

818 Prior to the start of the Tioga 4 deglaciation, regional climate experienced a few thousand
819 years that were at least episodically conducive to moderate glaciation in the Sierra Nevada. This
820 interpretation follows from two observations: first, the 3.4 kyr difference in the mean ages of the
821 outermost and innermost Lake Edison moraines (with a 95% confidence interval of 2.2–4.5 kyr;
822 Fig. 7b); second, the presence of approximately nine additional (undated) end moraines between



823 these two moraines (Fig. 4b). Although these numerous, closely spaced moraines (~11 in 2 km)
824 are suggestive of glacial advances driven by interannual climate variability (e.g., Anderson et al.,
825 2014; Barth et al., 2017), where stochastic variations in temperature and precipitation are
826 superimposed on a climate that is approximately stable over a longer time, the presence of the
827 Lake Edison moraine complex does not require this interpretation. The moraines might truly
828 represent large-magnitude and long-term variations in summer temperature and winter
829 precipitation in the Sierra Nevada over the ca. 20–16 ka interval. However – regardless of
830 whether the moraines in the Lake Edison complex represent interannual climate variability (i.e.,
831 weather), climate change, or some combination thereof – they indicate the former Mono Creek
832 Glacier’s ELA dropped to ~2800 m (Phillips, 2016) between ca. 20 ka and ca. 16.5 ka before
833 returning to higher elevations.

834 5.3.2. *On the duration of the Tioga 4 deglaciation*

835 The glaciers of the Sierra Nevada rapidly melted after the start of the Tioga 4
836 deglaciation at 16.4 ± 0.8 ka; our best estimate for the full duration of the Tioga 4 deglaciation in
837 the central Sierra Nevada from innermost moraine stabilization to the melting of the last
838 remanent ice masses is 1.0 kyr, with a 95 % confidence range of 0.2–3.0 kyr (Fig. 7c).

839 Although the original analysis of the ^{36}Cl dates from the vicinity of Bishop Creek Canyon
840 concluded that the Tioga 4 deglaciation was probably ≤ 500 years and certainly < 1000 years
841 (Phillips et al., 2009) – we find a ~50 % probability that the full duration of the Tioga 4
842 deglaciation in the central Sierra Nevada was 1000 years or longer and only a ~10 % probability
843 that it was 500 years or less (Fig. 7c). However, despite finding that the time required for
844 deglaciation was ca. 500 years longer than interpreted by Phillips et al. (2009), the ^{10}Be dates
845 from Lake Edison and Mono Creek Canyon (Fig. 4) support the fundamental conclusion of



846 Phillips et al. (2009) that the deglacial history of Bishop Creek Canyon and its vicinity (Fig. 5) is
847 representative of other locations within the Sierra Nevada.

848 Moreover, the new ^{10}Be dates are consistent with the interpretations of multiple
849 researchers (Clark, 1976; Clark and Clark, 1995; Phillips et al., 2009) that the Sierra Nevada's
850 final deglaciation was a geomorphically abrupt event. For instance, the bottom of Lyell Canyon
851 sampling location has the youngest mean surface-exposure age across all the sampling locations
852 reported here (Fig. 3c; Table 2) – and a **trimline-based ice-thickness reconstruction** (Wahrhaftig
853 et al., 2019) indicates the bottom of Lyell Canyon hosted an ice thickness greater than any other
854 location we sampled. Tioga 4 ice thicknesses over the bottom of Lyell Canyon sampling site
855 (~600 m) were ~2–4x greater than the ice thicknesses over the sampling sites in Tuolumne
856 Meadows (~300 m) and at the top of Lyell Canyon (~150 m). Additionally, ice thicknesses in
857 Lyell Canyon were also ~50 % greater than ice thicknesses over Greenstone Lake (~400 m), thus
858 explaining why the bottom of Lyell Canyon almost certainly (99.4 % probability, per the
859 radiocarbon date's probability-density distribution from Bchron (Haslett and Parnell, 2008) and
860 our Monte Carlo modeling of the surface-exposure ages) deglaciated after the beginning of
861 organic accumulation in Greenstone Lake. **The observation that the locations with the thickest**
862 **ice were the last to deglacierate, regardless of their distance from the cirque headwalls, indicates**
863 **that the deglaciation was driven by a relatively sudden and large rise in the ELA.**

864 5.4. *Geomorphic and climatological constraints on the magnitude of deglacial climate change*

865 Geomorphic and modern climatological observations suggest that this widespread and
866 rapid deglaciation (the Tioga 4 deglaciation) was driven by a summertime warming of ≥ 2 °C, a
867 wintertime drying of ≥ 35 %, or some combination thereof. The temperature-change
868 reconstruction is based on the interpretation that the deglaciation was driven by ≥ 600 m rise in



869 the ELA (as reviewed in Sect. 2.2.1.) and the observation that modern surface-temperature lapse
870 rates are $\sim 3\text{--}4\text{ }^{\circ}\text{C km}^{-1}$ in the higher elevations of the Sierra Nevada and the Cascade Range
871 (Wolfe, 1992). Importantly, the similar lapse rates in both mountain ranges indicate modern
872 high-elevation lapse rates are mostly independent of latitude and we assume a similar
873 independence for the deglaciation period (Ye et al., 2023). Combining the minimum ELA change
874 with the estimated lapse rate suggests the Sierra Nevada's final deglaciation was driven by a
875 summertime warming of $\geq 2\text{ }^{\circ}\text{C}$, **assuming no change in winter precipitation** (Leonard et al.,
876 2023).

877 Conversely, if we assume no change in summer temperatures and accept a 20 %
878 precipitation decrease as the mass-balance equivalent of a $1\text{ }^{\circ}\text{C}$ warming (Oerlemans, 2005), then
879 the Tioga 4 deglaciation could have alternatively been driven by a 35 % (or greater) reduction in
880 winter precipitation – with intermediate temperature and precipitation combinations possibly,
881 and perhaps likely.

882 5.5. *Constraints from regional paleoclimate proxies on the timing and nature of the climate* 883 *change that drove the Tioga 4 deglaciation*

884 We examine five paleoclimate records from western North America and adjacent
885 portions of the Pacific Ocean that further illuminate the timing and drivers of the Tioga 4
886 deglaciation: **(1) the lacustrine core from Swamp Lake (~40 km west of Tuolumne Meadows;**
887 **Fig. 1b; Street et al., 2012), (2) speleothem ML1 from McLean's Cave (~100 km west-northwest**
888 **of Tuolumne Meadows; Fig. 1b; Oster et al., 2015), (3) twenty-five radiocarbon dates from**
889 **seventeen Great Basin Pleistocene lakes (Fig. 1a; Munroe and Laabs, 2013; Ibarra et al., 2014),**
890 **(4) ODP core 893A from the Santa Barbara Basin (Fig. 1a; Hendy et al., 2002), and (5) the**
891 **MD02-2515 sea-surface temperature (SST) record from the Gulf of California (Fig. 1a;**



892 McClymont et al., 2012). We compare these records with the $\delta^{18}\text{O}$ record from Ostolo Cave in
893 Spain, which records the timing of Heinrich Event 1 (Bernal-Wormull et al., 2021; Pérez-Mejías
894 et al., 2021).

895 5.5.1. *Swamp Lake*

896 The paleoenvironmental proxy records from Swamp Lake (Fig. 1a) suggest the central
897 Sierra Nevada warmed at 16.4 ± 0.4 ka and that this warmth persisted for ca. 1.3–1.6 kyr. The
898 magnetic susceptibility of Swamp Lake’s sediments decreased more than thirty-fold over a ca.
899 0.1 kyr interval at 16.4 ± 0.4 ka and remained at near-zero values for ca. 1.6 kyr (Fig. 8a).
900 Simultaneously, the core’s total organic carbon (TOC) content started trending higher at $16.5 \pm$
901 0.4 ka and increased twenty-fold over ca. 1.3 kyr. Similar trends are recorded in the other proxy
902 records from Swamp Lake, such as: the tripling of the molar ratio of carbon to nitrogen, a nine-
903 fold increase in biogenic silica concentration, and a local $\delta^{13}\text{C}$ maxima (Street et al., 2012).
904 These changes reflect the return of sub-alpine conifers and associated terrestrial vegetation in
905 Swamp Lake’s small (1.3 km^2) drainage basin, which stabilized soils and allowed a near-order-
906 of-magnitude increase in diatom abundance via decreased turbidity (Street et al., 2012). Upward
907 migration of the upper treeline is usually driven by warming temperatures (e.g., LaMarche and
908 Mooney, 1967; Denton and Karlén, 1977; Kullman, 1986, 1995; Scuderi, 1987). We infer that
909 the Sierra Nevada warmed at 16.4 ± 0.4 ka and that these warmer temperatures lasted for ca. 1.3–
910 1.6 kyr.

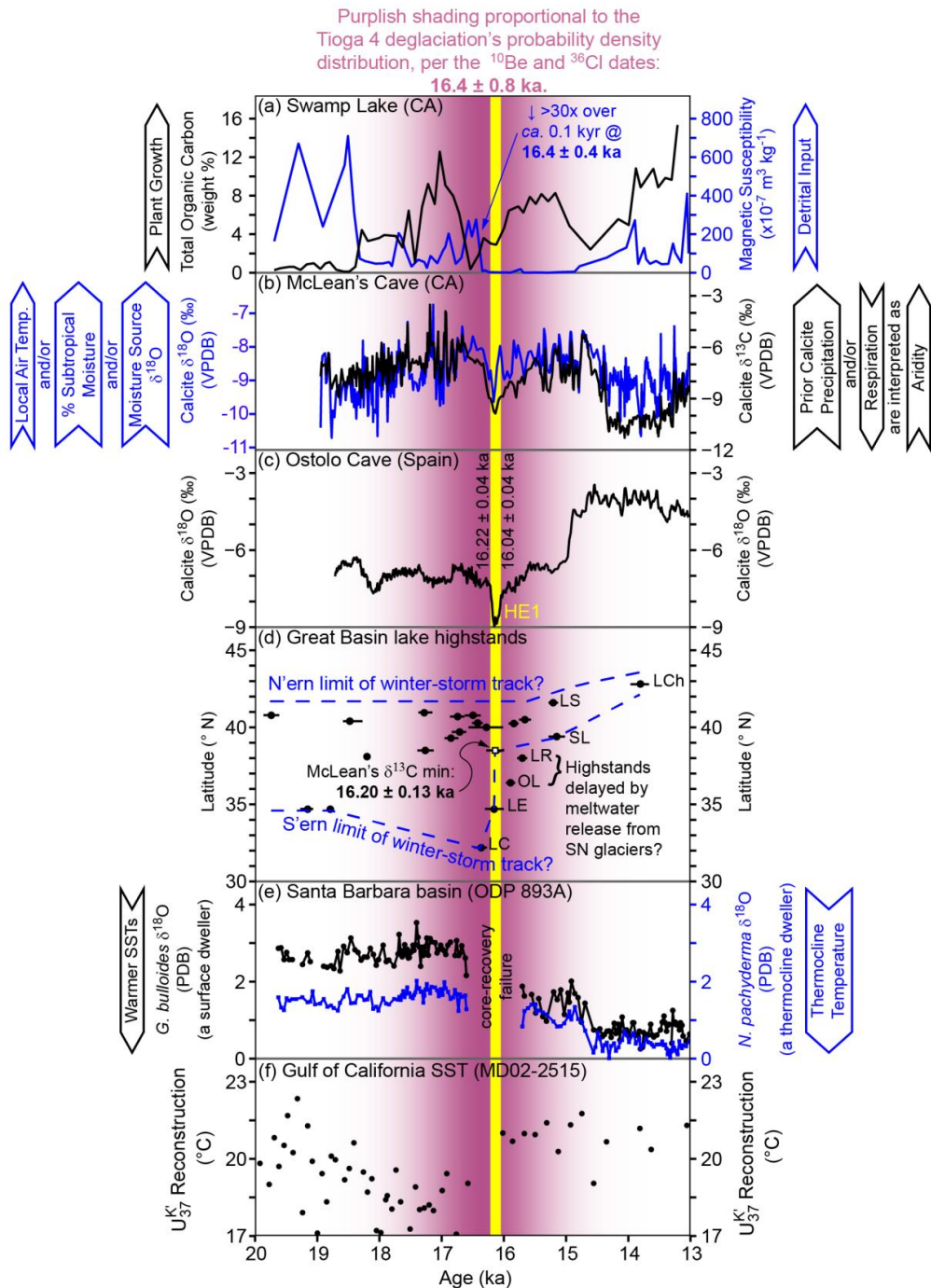


Figure 8. The ^{10}Be - and ^{36}Cl -dated Tioga 4 deglaciation (16.4 ± 0.8 ka) in the context of other paleoclimate records. (a) The total organic carbon (TOC) and magnetic susceptibility records from Swamp Lake (~40 km west of Tuolumne Meadows; Street et al., 2012) on the revised age-



depth model that we present here (Sect. S.8.; Fig. S23; Table S7). **(b)** The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ records from McLean's Cave (~100 km west-northwest of Tuolumne Meadows; Oster et al., 2015) on the revised age-depth model that we present here (Sect. S.10.; Fig. S25; Table S9). **(c)** The $\delta^{18}\text{O}$ record from speleothem OST2 (Ostolo Cave, Spain), which constrains the start of Heinrich Event 1 to 16.22 ± 0.04 ka and its end to 16.04 ± 0.04 ka (Bernal-Wormull et al., 2021). **(d)** The timings of Great Basin lake highstands (Munroe and Laabs, 2013; Ibarra et al., 2014), as recalculated here (Table S8). **(e)** The $G. bulloides$ $\delta^{18}\text{O}$ and $N. pachyderma$ $\delta^{18}\text{O}$ records from ODP core 893A from the Santa Barbara Basin (Hendy et al., 2002); note that lower $\delta^{18}\text{O}$ values record warmer temperatures. **(f)** The $U_{37}^{K'}$ -index reconstruction of sea-surface temperatures from core MD02-2514 in the Gulf of California; the precision of these temperature estimates is ± 0.6 °C (McClymont et al., 2012).

5.5.2. *McLean's Cave*

The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ records from McLean's Cave (Fig. 8b; Oster et al., 2015) suggest the west-central Sierra Nevada warmed and dried between 16.20 ± 0.13 ka and 14.71 ± 0.19 ka. Interestingly, these dates are indistinguishable from the start of Heinrich Event 1 in the North Atlantic (16.22 ± 0.04 ka; Fig. 8c; Bernal-Wormull et al., 2021; Pérez-Mejías et al., 2021) and the start of the Bølling (14.74 ± 0.06 ka; Lemieux-Dudon et al., 2010). The $\delta^{13}\text{C}$ record trends higher over that 1.5 kyr interval, driven by increased prior calcite precipitation (PCP) and/or decreased soil respiration, both of which record a drying climate (Oster et al., 2015). The $\delta^{18}\text{O}$ record reaches a local minimum nearly contemporaneously with the just mentioned $\delta^{13}\text{C}$ minimum (the $\delta^{18}\text{O}$ minimum is one isotopic-measurement-interval earlier in the core, at 16.23 ± 0.13 ka) and rises, episodically, for ca. 0.8 ka. The 2.17 ‰ $\delta^{18}\text{O}$ increase over that interval might reflect warmer temperatures in the Sierra Nevada (up to 3–4 °C; Rozanski et al., 1993), a ~40% reduction in moisture delivery to the range from the North Pacific (relative to moisture sourced from the subtropics), a change in the $\delta^{18}\text{O}$ of the moisture-source regions, or some combination thereof. Thus, the $\delta^{13}\text{C}$ record implies drying of the west-central Sierra Nevada starting at 16.20 ± 0.13 ka and the $\delta^{18}\text{O}$ record permits both it and warming.

5.5.3. *Great Basin lakes*



944 Considering the western United States more broadly, the temporal and spatial pattern of
945 Great Basin lake-level highstands (Fig. 8d) and numerical modeling suggests that these
946 highstands were fed by an invigorated subtropical jet stream and a deeper and southeastward-
947 shifted Aleutian Low, which collectively increased moisture transport into the Great Basin via
948 atmospheric rivers (McClymont et al., 2012; Chiang et al., 2014; McGee et al., 2018). Notably,
949 the southern limit of lake-level highstands shows a $\sim 6^\circ$ northward jump between ca. 16.4 ka and
950 ca. 16.2 ka, suggesting a major reorganization in atmospheric circulation over western North
951 America at that time (Fig. 8d), coincident with the deglaciation of the Sierra Nevada. In
952 particular, the $\sim 6^\circ$ northward jump is defined by (1) Lake Cochise (at 32° N; “LC” on Figs. 1a
953 and 8d) abandoning its 1274 m shoreline at 16.37 ± 0.21 ka (Waters, 1989; Munroe and Laabs,
954 2013), (2) Lake Estancia (at 35° N; “LE” on Figs. 1a and 8d) abandoning its 1890 m shoreline at
955 16.16 ± 0.15 (Allen and Anderson, 2000; Munroe and Laabs, 2013), and by (3) the abrupt rise in
956 $\delta^{13}\text{C}$ in McLean’s Cave (at 38° N; Oster et al., 2015) at 16.20 ± 0.13 ka. Note that the highstands
957 of meltwater-fed Owens Lake (at 36° N) and Lake Russell (at 38° N) post-date this atmospheric
958 reorganization due to the release of meltwater from the rapidly melting glaciers of the Sierra
959 Nevada.

960 5.5.4. *The Santa Barbara Basin and the Gulf of California*

961 The interpretation that rapid deglaciation began in the Sierra Nevada at ca. 16.2 ka is also
962 consistent with marine-sediment cores from the Santa Barbara Basin and the Gulf of California.
963 Although the Santa Barbara Basin core (ODP core 893A; Hendy et al., 2002) unfortunately lacks
964 data between ca. 16.6 ka and ca. 15.7 ka due to a core-recovery failure, the average $\delta^{18}\text{O}$ value of
965 *G. bulloides* (a surface-dwelling planktonic foraminifera) decreased approximately 1.4 ‰ over
966 this missing interval (Fig. 8e), which is consistent with warming. Changes in the core’s



967 planktonic-foraminifera assemblage suggests Santa Barbara Basin SSTs warmed $\sim 5^{\circ}\text{C}$ over this
968 missing interval. This large change in SSTs suggests that the Aleutian Low weakened and
969 migrated to the northwest, causing the California Current to weaken (Hendy, 2010), slowing the
970 flow of subpolar water into the basin (Hendy and Kennett, 2000; Hendy et al., 2002).

971 Similarly, the $U_{37}^{K'}$ reconstruction from Gulf of California core MD02-2515 (McClymont
972 et al., 2012) indicates SSTs there warmed $4.0 \pm 0.9^{\circ}\text{C}$ between 16.8 ka and 16.0 ka (Fig. 8f). A
973 parallel TEX_{86}^H reconstruction from the core demonstrates little-to-no warming over this time
974 interval at the thermocline. The divergence in these temperature proxies implies a sharp
975 reduction in upwelling, which in turn suggests a reduction in northwesterly winds over the Gulf
976 of California (Ganeshram and Pedersen, 1998), such as might accompany a northwestward
977 migration of the northwest Pacific's subtropical high (McGee et al., 2018). Such a reorganization
978 in atmospheric circulation would have shutdown upwelling in the Gulf of California and allowed
979 warm, tropical waters to flow into it, producing the warmer SSTs, as is currently observed during
980 Northern Hemisphere spring (Ganeshram and Pedersen, 1998; McClymont et al., 2012).

981 If the magnitudes of these SST warmings in the Santa Barbara Basin and the Gulf of
982 California are also representative of the summer air-temperature change in the central Sierra
983 Nevada, then the warming would have been more than enough to deglaciate the range (Sect.
984 5.4.).

985 5.6. *Hypothesized cause of the Tioga 4 deglaciation*

986 The close correspondence in timing between the start of the Tioga 4 deglaciation in
987 California (16.20 ± 0.13 ka, as indicated by the $\delta^{13}\text{C}$ data from McLean's Cave; Fig. 8d) and the
988 start of Heinrich Event 1 in the North Atlantic (16.22 ± 0.04 ka; Fig. 8c) suggests a mechanistic
989 connection between the two events. We hypothesize that Heinrich Event 1 withdrew such a



990 volume of ice from the Laurentide Ice Sheet (LIS) that atmospheric circulation reorganized over
991 North America in response. As the LIS shrinks and thins, the Aleutian Low weakens and moves
992 northward while the subtropical high in the eastern Pacific strengthens (Bartlein et al., 1998;
993 Otto-Bliesner et al., 2006; Wong et al., 2016; Jones et al., 2018). Also, as the LIS thins, it
994 becomes a less formidable obstacle to atmospheric circulation, which enables the polar jet stream
995 – formerly split by the LIS (Fig. 9a), with a weaker branch passing to the north of the ice sheet
996 and a stronger branch passing to the south (Kutzbach and Wright Jr, 1985; Manabe and Broccoli,
997 1985; Kutzbach and Guetter, 1986; Bromwich et al., 2004; Löfverström et al., 2014; Lora et al.,
998 2016; Wang et al., 2024) – to reunify (Fig. 9b). We interpret that these changes in the Aleutian
999 Low and the Subtropical High caused the ITCZ to shift northward over the eastern Pacific
1000 Ocean, weakening the subtropical jet stream (McGee et al., 2018), reducing the frequency of
1001 atmospheric rivers, and causing them to “land” on North America to the north of the central
1002 Sierra Nevada (which is at 37–38° N). Based on the timing and latitude of lake-level highstands
1003 (Fig. 8d), we interpret this northward shift in the mean latitude of landfalling atmospheric rivers
1004 to be ~6°.

1005 Interestingly, the TraCE-21k transient simulation of deglacial climate produced only one
1006 major reorganization in atmospheric circulation over North America’s west coast during the
1007 deglaciation period – and it was a 7° northward shift in the polar jet stream (He et al., 2013; Lora
1008 et al., 2016). This northward shift in the polar jet stream was coincident with polar jet
1009 reunification and that reunification was triggered by a ~1.4 km thinning of the LIS, with the
1010 TraCE-21k model switching from ICE-5G’s “15.0 ka” ice-sheet topography to ICE-5G’s “14.0
1011 ka” topography (Peltier, 2004) at 13.87 ka in the transient model. Although we interpret
1012 deglaciation of the Sierra Nevada as occurring at ca. 16.2 ka and being driven by a northward



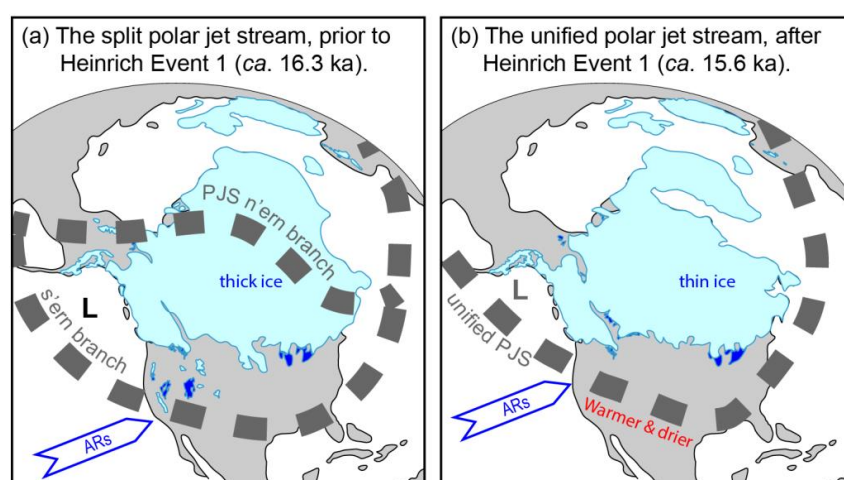
1013 expansion of Hadley Cell circulation on the eastern Pacific and a $\sim 6^\circ$ northward shift in the mean
1014 latitude of land-falling atmospheric rivers (and not directly by a northward shift in the polar jet
1015 stream), the TraCE-21k model results do underscore the sensitivity of North American
1016 atmospheric circulation to LIS thickness and contain a northward shift in atmospheric circulation
1017 that is comparable to what we see in the lake-level-highstand data (Fig. 8d).

1018 Supporting evidence for the ca. 16.2 ka deglaciation of the Sierra Nevada being driven by
1019 an atmospheric reorganization over North America in response to Heinrich Event 1 comes from
1020 the West Antarctica Ice Sheet (WAIS) Divide deuterium record (Jones et al., 2018). This record
1021 indicates interannual to decadal climate variability in the high southern latitudes was almost
1022 twice as large during the LGM as it was during the Holocene. Jones et al. (2018) link this
1023 enhanced variability to the mean location of tropical convection in the Pacific, with a thick LIS
1024 causing a deeper and south-shifted Aleutian Low that weakens tropical Pacific winds. The
1025 weaker winds then cause the western warm pool to spill eastward, as during modern El Niño
1026 events. The enhanced isotopic variability at WAIS Divide comes to an abrupt end at ca. 16 ka,
1027 implying a substantial thinning of the LIS at that time and a concomitant reorganization in
1028 atmospheric circulation over North America (and the tropical Pacific).

1029 **In summary**, we infer Heinrich Event 1 sufficiently thinned the LIS at ca. 16.2 ka to
1030 trigger an atmospheric reorganization (Fig. 9). That atmospheric reorganization brought **drier**
1031 **winters and warmer summers** to what is now the southwestern United States. In response, the
1032 central and southern Sierra Nevada essentially deglaciated and formerly expansive lakes in
1033 California, Arizona, New Mexico, and Utah desiccated (McGee et al., 2018). Offshore western
1034 North America, the weakening of the Aleutian Low reduced the influx of polar water into the
1035 Santa Barbara Basin, causing SSTs there to warm (Hendy and Kennett, 2000; Hendy et al., 2002;



1036 Hendy, 2010), and the northward repositioning of the northeastern Pacific's subtropical high
1037 shutdown upwelling in the Gulf of California, allowing subtropical water to enter the Gulf and
1038 warm SSTs there (Ganeshram and Pedersen, 1998; McClymont et al., 2012).



1039
1040 **Figure 9.** Cartoon illustrating how we propose the polar jet stream evolved in response to
1041 Heinrich Event 1 and how we envision the principal location in landfalling atmospheric rivers
1042 (ARs) changed. The removal of ice from the Laurentide Ice Sheet and the ice sheet's associated
1043 height reduction facilitated reunification of the polar jet stream (PJS) and a northward shift in its
1044 mean position (relative to its southern branch's former position). This reorganization in
1045 atmospheric circulation brought warmer and drier conditions to California and the southern Great
1046 Basin, driving the Tioga 4 deglaciation in the Sierra Nevada and the abandonment of lake-level
1047 highstands in the southern Great Basin. Ice sheet and lake reconstructions simplified from Dyke
1048 et al. (2003).



6. Conclusions

We present thirty-one new ^{10}Be and twenty-six recalculated ^{36}Cl dates (Phillips et al., 2009) on the timing and duration of the Tioga 4 deglaciation in the Sierra Nevada Mountains of California. We calculate these dates using three different surface-exposure calculators [the Version 3 calculator (Balco et al., 2008), CRONUScalc 2.0 (Marrero et al., 2016), and CREp (Martin et al., 2017)] and we interpret that the CRONUScalc and CREp results (which are essentially identical) are a few percent more accurate ($\sim 5\%$) than the results from the Version 3 calculator for the samples in this dataset. Adopting the CRONUScalc results as our preferred set of surface-exposure dates, we find that the Tioga 4 deglaciation – which followed the last major Pleistocene readvance in the Sierra Nevada and essentially deglaciated the range – began at 16.4 ± 0.8 ka ($n = 7$). Furthermore, we find that the range deglaciated in ca. 1.0 kyr (median estimate, with a 95% confidence range of 0.2–3.0 kyr).

In addition, we use Bchron 4.7.6 (Haslett and Parnell, 2008) to construct new age-depth models for the paleoenvironmental record from Swamp Lake (Fig. S23; Table S7; Street et al., 2012) and for speleothem ML1 from McLean's Cave (Fig. S25; Table S9; Oster et al., 2015). The principal benefit of these new age-depth models is that they provide age-uncertainty estimates for the undated horizons in these records, which the original age-depth models lacked. Examining the 16.4 ± 0.8 ka portions of these records, we find evidence of warming at 16.4 ± 0.4 ka in the Swamp Lake core (with no commentary on potential precipitation changes) and evidence of drying (and possibly also warming) at 16.20 ± 0.13 ka in the McLean's Cave speleothem. These three events – the onset of the Tioga 4 deglaciation, as recorded by ^{10}Be and ^{36}Cl concentrations in morainal boulders, the warming recorded at Swamp Lake, and the drying recorded at McLean's Cave – are indistinguishable in age and we interpret them to be different



1072 manifestations of the same event: a warming and drying of the central Sierra Nevada that started
1073 at 16.20 ± 0.13 ka.

1074 We place the warming and drying of the central Sierra Nevada ($36\text{--}38^\circ$ N) in a regional
1075 context by comparing it with the timing of lake-level highstands in the Great Basin (Munroe and
1076 Laabs, 2013; Ibarra et al., 2014) and with the start of rising SSTs in the Santa Barbara Basin
1077 (Hendy et al., 2002) and the Gulf of California (McClymont et al., 2012). We find evidence
1078 indicating a $\sim 6^\circ$ northward shift in the mean latitude of landfalling atmospheric rivers at ca. 16.2
1079 ka.

1080 Finally, we hypothesize that the Sierra Nevada's deglaciation and the southern Great
1081 Basin's desiccation were the result of Heinrich Event 1 (Heinrich, 1988; Hemming, 2004) –
1082 which started at 16.22 ± 0.04 ka and ended at 16.04 ± 0.04 ka (Bernal-Wormull et al., 2021;
1083 Pérez-Mejías et al., 2021) – reducing the height and extent of the Laurentide Ice Sheet such that
1084 it no longer split the polar jet stream into northern and southern branches as it passed over North
1085 America. The polar jet stream reunified in response to a thinner and smaller ice sheet, and
1086 adopted a more northerly position (as compared with the mean position of the jet stream's former
1087 southern branch), bringing warmer and drier weather to California and the southern Great Basin,
1088 driving the Tioga 4 deglaciation, lowering lake levels throughout the region, and warming SSTs
1089 in the Santa Barbara Basin and the Gulf of California.

1090



1091 **Data availability**

1092 The data necessary to recalculate the surface-exposure ages of the new ^{10}Be concentrations
1093 reported here are available in this article's online supplement. The supplement also contains field
1094 photos of the sampled boulders and the new age-depth models we report for the Swamp Lake
1095 and McLean's Cave paleoenvironmental reconstructions. The necessary files to reproduce the
1096 snow-shielding calculations are available at:

1097 <https://github.com/BerylliumBecker/SierraNevadaSnowDepths>.

1098 **Author contributions**

1099 RAB conceptualized the study. RAB, SAM, BT, and MWC secured the funding for fieldwork
1100 and lab analyses. RAB collected the boulders for ^{10}Be dating, with the aid of field assistants
1101 acknowledged below. RAB and AMB processed the samples for ^{10}Be , with the aid of lab
1102 assistants acknowledged below. MWC and PRIME Lab colleagues measured $^{10}\text{Be}/^9\text{Be}$ in the
1103 samples. RAB calculated the snow-shielding correction factors, developed the new age-depth
1104 models for the Swamp Lake and McLean's Cave paleoenvironmental reconstructions, and
1105 recalculated the ages of legacy ^{36}Cl and ^{14}C data. RAB, AMC, SAM, and BT interpreted the
1106 results. RAB wrote the manuscript's first draft and created the figures and tables. All the authors
1107 edited the manuscript.

1108 **Competing interests**

1109 The authors declare that they have no competing interests.

1110



1111 **Acknowledgements**

1112 Sampling permission was granted by the citizens of the United States, via their representatives in
1113 the National Park Service and the U.S. Forest Service. We thank Greg Stock (Yosemite National
1114 Park) and USFS District Ranger Ray Porter (Sierra National Forest) for their help in navigating
1115 the permitting process. JT Holcombe, Will Montz, and Michael Bahrmassel helped collect the
1116 ^{10}Be samples. Alexander Horvath, Levi Mitchell, and Elizabeth Ceperley assisted with the
1117 laboratory work. We thank them all. Funding was provided by the UW-Madison Department of
1118 Geoscience, AAPG Foundation's Robert and Carolyn Maby Memorial Grant, a Geological
1119 Society of America student research grant, and a Doctoral Dissertation Improvement Award
1120 from the National Science Foundation (grant #1303194).

1121



1122 7. *References*

- 1123 Ackert, R. P., Becker, R. A., Singer, B. S., Kurz, M. D., Caffee, M. W., and Mickelson, D. M.:
1124 Patagonian glacier response during the Late Glacial–Holocene transition, *Science*, 321, 392–395,
1125 2008.
- 1126 Allen, B. D. and Anderson, R. Y.: A continuous, high-resolution record of late Pleistocene
1127 climate variability from the Estancia basin, New Mexico, *Geological Society of America*
1128 *Bulletin*, 112, 1444–1458, 2000.
- 1129 Alley, R. B.: The Younger Dryas cold interval as viewed from central Greenland, *Quaternary*
1130 *Science Reviews*, 19, 213–226, 2000.
- 1131 Amos, C. B., Kelson, K. I., Rood, D. H., Simpson, D. T., and Rose, R. S.: Late Quaternary slip
1132 rate on the Kern Canyon fault at Soda Spring, Tulare County, California, *Lithosphere*, 2, 411–
1133 417, 2010.
- 1134 Bahr, A., Hoffmann, J., Schönfeld, J., Schmidt, M. W., Nürnberg, D., Batenburg, S. J., and
1135 Voigt, S.: Low-latitude expressions of high-latitude forcing during Heinrich Stadial 1 and the
1136 Younger Dryas in northern South America, *Global and Planetary Change*, 160, 1–9, 2018.
- 1137 Balco, G.: Contributions and unrealized potential contributions of cosmogenic-nuclide exposure
1138 dating to glacier chronology, 1990–2010, *Quaternary Science Reviews*, 30, 3–27, 2011.
- 1139 Balco, G.: Elevation/atmospheric pressure models, The bleeding edge of cosmogenic-nuclide
1140 geochemistry, [https://cosmognosis.wordpress.com/2015/10/16/elevationatmospheric-pressure-](https://cosmognosis.wordpress.com/2015/10/16/elevationatmospheric-pressure-models/)
1141 [models/](https://cosmognosis.wordpress.com/2015/10/16/elevationatmospheric-pressure-models/), 2015.
- 1142 Balco, G.: Saturated surfaces in Antarctica, The bleeding edge of cosmogenic-nuclide
1143 geochemistry, <https://cosmognosis.wordpress.com/2016/09/09/saturated-surfaces-in-antarctica/>,
1144 2016.
- 1145 Balco, G.: Where’s the reference production rate?, The bleeding edge of cosmogenic-nuclide
1146 geochemistry, [https://cosmognosis.wordpress.com/2018/09/06/wheres-the-reference-production-](https://cosmognosis.wordpress.com/2018/09/06/wheres-the-reference-production-rate/)
1147 [rate/](https://cosmognosis.wordpress.com/2018/09/06/wheres-the-reference-production-rate/), 2018.
- 1148 Balco, G., Stone, J. O., Lifton, N. A., and Dunai, T. J.: A complete and easily accessible means
1149 of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements,
1150 *Quaternary Geochronology*, 3, 174–195, 2008.
- 1151 Barth, A. M., Clark, P. U., Clark, J., Roe, G. H., Marcott, S. A., McCabe, A. M., Caffee, M. W.,
1152 He, F., Cuzzone, J. K., and Dunlop, P.: Persistent millennial-scale glacier fluctuations in Ireland
1153 between 24 ka and 10 ka, *Geology*, 46, 151–154, 2018.
- 1154 Barth, A. M., Marcott, S. A., Licciardi, J. M., and Shakun, J. D.: Deglacial Thinning of the
1155 Laurentide Ice Sheet in the Adirondack Mountains, New York, USA, Revealed by ^{36}Cl Exposure
1156 Dating, *Paleoceanography and Paleoclimatology*, 34, 946–953,
1157 <https://doi.org/10.1029/2018PA003477>, 2019.



- 1158 Bartlein, P. J., Anderson, K. H., Anderson, P. M., Edwards, M. E., Mock, C. J., Thompson, R. S.,
1159 Webb, R. S., Webb III, T., and Whitlock, C.: Paleoclimate simulations for North America over
1160 the past 21,000 years: features of the simulated climate and comparisons with
1161 paleoenvironmental data, *Quaternary science reviews*, 17, 549–585, 1998.
- 1162 Bateman, P. C. and Wones, D. R.: Geologic map of the Huntington Lake quadrangle, central
1163 Sierra Nevada, California, 1972.
- 1164 Bateman, P. C., Kistler, Ronald W., Peck, Dallas L., and Busacca, Alan: Geologic map of the
1165 Tuolumne Meadows quadrangle, Yosemite National Park, California, 1983.
- 1166 Benson, L. V., Burdett, J. W., Kashgarian, M., Lund, S. P., Phillips, F. M., and Rye, R. O.:
1167 Climatic and Hydrologic Oscillations in the Owens Lake Basin and Adjacent Sierra Nevada,
1168 California, *Science*, 274, 746–749, <https://doi.org/10.1126/science.274.5288.746>, 1996.
- 1169 Bernal-Wormull, J. L., Moreno, A., Pérez-Mejías, C., Bartolomé, M., Aranburu, A.,
1170 Arriolabengoa, M., Iriarte, E., Cacho, I., Spötl, C., and Edwards, R. L.: Immediate temperature
1171 response in northern Iberia to last deglacial changes in the North Atlantic, *Geology*, 49, 999–
1172 1003, 2021.
- 1173 Bierman, P. R., Davis, P. T., Corbett, L. B., Lifton, N. A., and Finkel, R. C.: Cold-based
1174 Laurentide ice covered New England’s highest summits during the Last Glacial Maximum,
1175 *Geology*, 43, 1059–1062, <https://doi.org/10.1130/G37225.1>, 2015.
- 1176 Birman, J. H.: Glacial geology across the crest of the Sierra Nevada, California, *Geological*
1177 *Society of America Special Paper*, 75, 1964.
- 1178 Blackwelder, E.: Pleistocene glaciation in the Sierra Nevada and Basin ranges, *Bulletin of the*
1179 *Geological Society of America*, 42, 865–922, 1931.
- 1180 Borchers, B., Marrero, S., Balco, G., Caffee, M., Goehring, B., Lifton, N., Nishiizumi, K.,
1181 Phillips, F., Schaefer, J., and Stone, J.: Geological calibration of spallation production rates in the
1182 CRONUS-Earth project, *Quaternary Geochronology*, 31, 188–198, 2016.
- 1183 Bromwich, D. H., Toracinta, E. R., Wei, H., Oglesby, R. J., Fastook, J. L., and Hughes, T. J.:
1184 Polar MM5 simulations of the winter climate of the Laurentide Ice Sheet at the LGM, *Journal of*
1185 *Climate*, 17, 3415–3433, 2004.
- 1186 Chiang, J. C., Lee, S.-Y., Putnam, A. E., and Wang, X.: South Pacific Split Jet, ITCZ shifts, and
1187 atmospheric North–South linkages during abrupt climate changes of the last glacial period, *Earth*
1188 *and Planetary Science Letters*, 406, 233–246, 2014.
- 1189 Clark, D., Gillespie, A. R., Clark, M., and Burke, B.: Mountain glaciations of the Sierra Nevada,
1190 in: *Quaternary Geology of the United States*, Desert Research Institute, Reno, NV, 287–311,
1191 2003.



- 1192 Clark, D. H. and Clark, M. M.: New evidence of late-Wisconsin deglaciation in the Sierra
1193 Nevada, California, refutes the Hilgard Glaciation, in: Geological Society of America, Abstracts
1194 with Programs, 1995.
- 1195 Clark, D. H. and Gillespie, A. R.: Timing and significance of Late-Glacial and Holocene cirque
1196 glaciation in the Sierra Nevada, California, *Quaternary International*, 38, 21–38, 1997.
- 1197 Clark, D. H., Bierman, P. R., and Larsen, P.: Improving in situ cosmogenic chronometers,
1198 *Quaternary Research*, 44, 367–377, 1995.
- 1199 Clark, M.: Evidence for rapid destruction of Latest Pleistocene glaciers of the Sierra Nevada,
1200 California, in: Geological Society of America, Abstracts with Programs, 361–362, 1976.
- 1201 Clark, P. U., Shakun, J. D., Baker, P. A., Bartlein, P. J., Brewer, S., Brook, E., Carlson, A. E.,
1202 Cheng, H., Kaufman, D. S., Liu, Z., Marchitto, T. M., Mix, A. C., Morrill, C., Otto-Bliesner, B.
1203 L., Pahnke, K., Russell, J. M., Whitlock, C., Adkins, J. F., Blois, J. L., Clark, J., Colman, S. M.,
1204 Curry, W. B., Flower, B. P., He, F., Johnson, T. C., Lynch-Stieglitz, J., Markgraf, V., McManus,
1205 J., Mitrovica, J. X., Moreno, P. I., and Williams, J. W.: Global climate evolution during the last
1206 deglaciation, *Proceedings of the National Academy of Sciences*, 109,
1207 <https://doi.org/10.1073/pnas.1116619109>, 2012.
- 1208 Corbett, L. B., Bierman, P. R., Wright, S. F., Shakun, J. D., Davis, P. T., Goehring, B. M.,
1209 Halsted, C. T., Koester, A. J., Caffee, M. W., and Zimmerman, S. R.: Analysis of multiple
1210 cosmogenic nuclides constrains Laurentide Ice Sheet history and process on Mt. Mansfield,
1211 Vermont’s highest peak, *Quaternary Science Reviews*, 205, 234–246,
1212 <https://doi.org/10.1016/j.quascirev.2018.12.014>, 2019.
- 1213 Cushing, H. P.: Notes on the Muir Glacier region, and its geology, *The American Geologist*, 8,
1214 207–230, 1891.
- 1215 Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gundestrup, N. S., Hammer, C.
1216 U., Hvidberg, C. S., Steffensen, J. P., Sveinbjörnsdottir, A. E., and Jouzel, J.: Evidence for
1217 general instability of past climate from a 250-kyr ice-core record, *Nature*, 364, 218–220, 1993.
- 1218 Davis, P. T., Bierman, P. R., Corbett, L. B., and Finkel, R. C.: Cosmogenic exposure age
1219 evidence for rapid Laurentide deglaciation of the Katahdin area, west-central Maine, USA, 16 to
1220 15 ka, *Quaternary Science Reviews*, 116, 95–105,
1221 <https://doi.org/10.1016/j.quascirev.2015.03.021>, 2015.
- 1222 Davis, P. T., Halsted, C. T., Rogers, J. N., Arcone, S. A., Shakun, J. D., Bierman, P. R., Corbett,
1223 L. B., and Koester, A. J.: Glacial, deglacial, and postglacial history of Franconia Notch, NH,
1224 from constructing a cosmogenic nuclide glacial dipstick to determining a landslide history from
1225 lake sediment cores and ground penetrating radar images, in: Guidebook for field trips in central
1226 Vermont and adjoining New Hampshire, vol. 111th Annual Meeting, 235–286, 2019.
- 1227 Deevey, E. S., Gross, M. S., Hutchinson, G. E., and Kraybill, H. L.: The natural C-14 contents of
1228 materials from hard-water lakes, *Proceedings of the National Academy of Sciences*, 40, 285–
1229 288, 1954.



- 1230 Denton, G. H. and Karlén, W.: Holocene Glacial and tree-line variations in the White River
1231 Valley and Skolai Pass, Alaska and Yukon Territory, *Quaternary Research*, 7, 63–111, 1977.
- 1232 Denton, G. H., Anderson, R. F., Toggweiler, J. R., Edwards, R. L., Schaefer, J. M., and Putnam,
1233 A. E.: The Last Glacial Termination, *Science*, 328, 1652–1656,
1234 <https://doi.org/10.1126/science.1184119>, 2010.
- 1235 Douglass, D. C., Singer, B. S., Kaplan, M. R., Mickelson, D. M., and Caffee, M. W.:
1236 Cosmogenic nuclide surface exposure dating of boulders on last-glacial and late-glacial
1237 moraines, Lago Buenos Aires, Argentina: Interpretive strategies and paleoclimate implications,
1238 *Quaternary Geochronology*, 1, 43–58, 2006.
- 1239 Drebber, J. S., Halsted, C. T., Corbett, L. B., Bierman, P. R., and Caffee, M. W.: In Situ
1240 Cosmogenic ^{10}Be Dating of Laurentide Ice Sheet Retreat from Central New England, USA,
1241 *Geosciences*, 13, 213, <https://doi.org/10.3390/geosciences13070213>, 2023.
- 1242 Dühnforth, M., Anderson, R. S., Ward, D., and Stock, G. M.: Bedrock fracture control of glacial
1243 erosion processes and rates, *Geology*, 38, 423–426, 2010.
- 1244 Dyke, A. S., Moore, A., and Robertson, L.: Deglaciation of North America, Geological Survey
1245 of Canada Open File Report, 1574, <https://doi.org/10.4095/214399>, 2003.
- 1246 Farber, D. L., Hancock, G. S., Finkel, R. C., and Rodbell, D. T.: The age and extent of tropical
1247 alpine glaciation in the Cordillera Blanca, Peru, *Journal of Quaternary Science*, 20, 759–776,
1248 <https://doi.org/10.1002/jqs.994>, 2005.
- 1249 Field, W. O. Jr.: Glacier recession in Muir Inlet, Glacier Bay, Alaska, *Geographical Review*, 37,
1250 349–399, 1947.
- 1251 Firestone, R. B., West, A., Kennett, J. P., Becker, L., Bunch, T. E., Revay, Z. S., Schultz, P. H.,
1252 Belgia, T., Kennett, D. J., Erlandson, J. M., Dickenson, O. J., Goodyear, A. C., Harris, R. S.,
1253 Howard, G. A., Kloosterman, J. B., Lechler, P., Mayewski, P. A., Montgomery, J., Poreda, R.,
1254 Darrah, T., Hee, S. S. Q., Smith, A. R., Stich, A., Topping, W., Wittke, J. H., and Wolbach, W.
1255 S.: Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal
1256 extinctions and the Younger Dryas cooling, *Proceedings of the National Academy of Sciences*,
1257 104, 16016–16021, <https://doi.org/10.1073/pnas.0706977104>, 2007.
- 1258 Ganeshram, R. S. and Pedersen, T. F.: Glacial-interglacial variability in upwelling and
1259 bioproductivity off NW Mexico: Implications for Quaternary paleoclimate, *Paleoceanography*,
1260 13, 634–645, 1998.
- 1261 Ganopolski, A. and Rahmstorf, S.: Rapid changes of glacial climate simulated in a coupled
1262 climate model, *Nature*, 409, 153–158, 2001.
- 1263 Godwin, H.: Comments on radiocarbon dating for samples from the British Isles, *American*
1264 *Journal of Science*, 249, 301–307, 1951.



- 1265 Goldthwait, J. W.: The uncovering of New Hampshire by the last ice sheet, *American Journal of*
1266 *Science*, 236, 345–372, 1938.
- 1267 Goldthwait, R. P. and Mickelson, D. M.: Glacier Bay, a model for the deglaciation of the White
1268 Mountains in New Hampshire, Ohio State University, Institute of Polar Studies, 1982.
- 1269 Gosse, J. C. and Phillips, F. M.: Terrestrial in situ cosmogenic nuclides: theory and application,
1270 *Quaternary Science Reviews*, 20, 1475–1560, 2001.
- 1271 Gosse, J. C., Evenson, E. B., Klein, J., Lawn, B., and Middleton, R.: Precise cosmogenic ^{10}Be
1272 measurements in western North America: Support for a global Younger Dryas cooling event,
1273 *Geology*, 23, 877–880, 1995.
- 1274 Halsted, C. T., Bierman, P. R., Shakun, J. D., Davis, P. T., Corbett, L. B., Drebbler, J. S., and
1275 Ridge, J. C.: A critical re-analysis of constraints on the timing and rate of Laurentide Ice Sheet
1276 recession in the northeastern United States, *Journal of Quaternary Science*, 39, 54–69,
1277 <https://doi.org/10.1002/jqs.3563>, 2024.
- 1278 Haslett, J. and Parnell, A.: A simple monotone process with application to radiocarbon-dated
1279 depth chronologies, *Journal of the Royal Statistical Society Series C: Applied Statistics*, 57, 399–
1280 418, 2008.
- 1281 He, F., Shakun, J. D., Clark, P. U., Carlson, A. E., Liu, Z., Otto-Bliesner, B. L., and Kutzbach, J.
1282 E.: Northern Hemisphere forcing of Southern Hemisphere climate during the last deglaciation,
1283 *Nature*, 494, 81–85, 2013.
- 1284 Heinrich, H.: Origin and consequences of cyclic ice rafting in the northeast Atlantic Ocean
1285 during the past 130,000 years, *Quaternary Research*, 29, 142–152, 1988.
- 1286 Hemming, S. R.: Heinrich events: Massive Late Pleistocene detritus layers of the North Atlantic
1287 and their global climate imprint, *Reviews of Geophysics*, 42, 2003RG000128,
1288 <https://doi.org/10.1029/2003RG000128>, 2004.
- 1289 Hendy, I. L.: The paleoclimatic response of the Southern California Margin to the rapid climate
1290 change of the last 60 ka: A regional overview, *Quaternary International*, 215, 62–73, 2010.
- 1291 Hendy, I. L. and Kennett, J. P.: Dansgaard-Oeschger cycles and the California Current System:
1292 planktonic foraminiferal response to rapid climate change in Santa Barbara Basin, Ocean
1293 Drilling Program hole 893A, *Paleoceanography*, 15, 30–42, 2000.
- 1294 Hendy, I. L., Kennett, J. P., Roark, E. B., and Ingram, B. L.: Apparent synchronicity of
1295 submillennial scale climate events between Greenland and Santa Barbara Basin, California from
1296 30–10 ka, *Quaternary Science Reviews*, 21, 1167–1184, 2002.
- 1297 Huber, N. K.: Preliminary geologic map of the Dardanelles Cone quadrangle, central Sierra
1298 Nevada, California, 1983.
- 1299 Huber, N. K.: Geological Ramblings in Yosemite, Yosemite Conservancy, 136 pp., 2007.



- 1300 Ibarra, D. E., Egger, A. E., Weaver, K. L., Harris, C. R., and Maher, K.: Rise and fall of late
1301 Pleistocene pluvial lakes in response to reduced evaporation and precipitation: Evidence from
1302 Lake Surprise, California, *Geological Society of America Bulletin*, 126, 1387–1415, 2014.
- 1303 James, L. A., Harbor, J., Fabel, D., Dahms, D., and Elmore, D.: Late Pleistocene glaciations in
1304 the northwestern Sierra Nevada, California, *Quaternary Research*, 57, 409–419, 2002.
- 1305 Jones, T. R., Roberts, W. H., Steig, E. J., Cuffey, K. M., Markle, B. R., and White, J. W. C.:
1306 Southern Hemisphere climate variability forced by Northern Hemisphere ice-sheet topography,
1307 *Nature*, 554, 351–355, 2018.
- 1308 Jouzel, J., Vaikmae, R., Petit, J. R., Martin, M., Duclos, Y., Stievenard, M., Lorius, C., Toots,
1309 M., Mélières, M. A., Burckle, L. H., Barkov, N. I., and Kotlyakov, V. M.: The two-step shape
1310 and timing of the last deglaciation in Antarctica, *Climate Dynamics*, 11, 151–161,
1311 <https://doi.org/10.1007/BF00223498>, 1995.
- 1312 Kelly, M. A., Lowell, T. V., Applegate, P. J., Phillips, F. M., Schaefer, J. M., Smith, C. A., Kim,
1313 H., Leonard, K. C., and Hudson, A. M.: A locally calibrated, late glacial ^{10}Be production rate
1314 from a low-latitude, high-altitude site in the Peruvian Andes, *Quaternary Geochronology*, 26,
1315 70–85, 2015.
- 1316 Koester, A. J., Shakun, J. D., Bierman, P. R., Davis, P. T., Corbett, L. B., Braun, D., and
1317 Zimmerman, S. R.: Rapid thinning of the Laurentide Ice Sheet in coastal Maine, USA, during
1318 late Heinrich Stadial 1, *Quaternary Science Reviews*, 163, 180–192,
1319 <https://doi.org/10.1016/j.quascirev.2017.03.005>, 2017.
- 1320 Koester, A. J., Shakun, J. D., Bierman, P. R., Davis, P. T., Corbett, L. B., Goehring, B. M.,
1321 Vickers, A. C., and Zimmerman, S. R.: Laurentide Ice Sheet thinning and erosive regimes at
1322 Mount Washington, New Hampshire, inferred from multiple cosmogenic nuclides, in:
1323 *Untangling the Quaternary Period—A Legacy of Stephen C. Porter*, vol. 548, edited by: Waitt,
1324 R. B., Thackray, G. D., and Gillespie, A. R., Geological Society of America,
1325 [https://doi.org/10.1130/2020.2548\(15\)](https://doi.org/10.1130/2020.2548(15)), 2021.
- 1326 Kullman, L.: Late Holocene reproductional patterns of *Pinus sylvestris* and *Picea abies* at the
1327 forest limit in central Sweden, *Canadian Journal of Botany*, 64, 1682–1690,
1328 <https://doi.org/10.1139/b86-225>, 1986.
- 1329 Kullman, L.: New and firm evidence for Mid-Holocene appearance of *Picea abies* in the Scandes
1330 Mountains, Sweden, *Journal of Ecology*, 439–447, 1995.
- 1331 Kutzbach, J. E. and Guetter, P. J.: The influence of changing orbital parameters and surface
1332 boundary conditions on climate simulations for the past 18 000 years, *Journal of atmospheric
1333 sciences*, 43, 1726–1759, 1986.
- 1334 Kutzbach, J. E. and Wright Jr, H. E.: Simulation of the climate of 18,000 years BP: Results for
1335 the North American/North Atlantic/European sector and comparison with the geologic record of
1336 North America, *Quaternary Science Reviews*, 4, 147–187, 1985.



- 1337 Laabs, B. J., Marchetti, D. W., Munroe, J. S., Refsnider, K. A., Gosse, J. C., Lips, E. W., Becker,
1338 R. A., Mickelson, D. M., and Singer, B. S.: Chronology of latest Pleistocene mountain glaciation
1339 in the western Wasatch Mountains, Utah, USA, *Quaternary Research*, 76, 272–284, 2011.
- 1340 Laabs, B. J., Licciardi, J. M., Leonard, E. M., Munroe, J. S., and Marchetti, D. W.: Updated
1341 cosmogenic chronologies of Pleistocene mountain glaciation in the western United States and
1342 associated paleoclimate inferences, *Quaternary Science Reviews*, 242, 106427, 2020.
- 1343 Lal, D.: Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion
1344 models, *Earth and Planetary Science Letters*, 104, 424–439, 1991.
- 1345 LaMarche, V. C. and Mooney, H. A.: Altithermal timberline advance in western United States,
1346 *Nature*, 213, 980–982, 1967.
- 1347 Lemieux-Dudon, B., Blayo, E., Petit, J.-R., Waelbroeck, C., Svensson, A., Ritz, C., Barnola, J.-
1348 M., Narcisi, B. M., and Parrenin, F.: Consistent dating for Antarctic and Greenland ice cores,
1349 *Quaternary Science Reviews*, 29, 8–20, 2010.
- 1350 Leonard, E. M., Laabs, B. J., Marcott, S. A., Crawford, E. E., Mackall, B. T., Ibarra, D. E.,
1351 Osman, M. B., Plummer, M. A., and Caffee, M. W.: Chronology and climate of the Last Glacial
1352 Maximum and the subsequent deglaciation in the northern Medicine Bow Mountains, Wyoming,
1353 USA, *Quaternary Science Advances*, 12, 100109, 2023.
- 1354 Li, C. and Born, A.: Coupled atmosphere-ice-ocean dynamics in Dansgaard-Oeschger events,
1355 *Quaternary Science Reviews*, 203, 1–20, 2019.
- 1356 Lifton, N.: Implications of two Holocene time-dependent geomagnetic models for cosmogenic
1357 nuclide production rate scaling, *Earth and Planetary Science Letters*, 433, 257–268, 2016.
- 1358 Lifton, N., Sato, T., and Dunai, T. J.: Scaling in situ cosmogenic nuclide production rates using
1359 analytical approximations to atmospheric cosmic-ray fluxes, *Earth and Planetary Science Letters*,
1360 386, 149–160, 2014.
- 1361 Lifton, N., Caffee, M., Finkel, R., Marrero, S., Nishiizumi, K., Phillips, F. M., Goehring, B.,
1362 Gosse, J., Stone, J., and Schaefer, J.: In situ cosmogenic nuclide production rate calibration for
1363 the CRONUS-Earth project from Lake Bonneville, Utah, shoreline features, *Quaternary*
1364 *Geochronology*, 26, 56–69, 2015.
- 1365 Löfverström, M., Caballero, R., Nilsson, J., and Kleman, J.: Evolution of the large-scale
1366 atmospheric circulation in response to changing ice sheets over the last glacial cycle, *Climate of*
1367 *the Past*, 10, 1453–1471, 2014.
- 1368 Lora, J. M., Mitchell, J. L., and Tripathi, A. E.: Abrupt reorganization of North Pacific and
1369 western North American climate during the last deglaciation, *Geophysical Research Letters*, 43,
1370 11–796, 2016.
- 1371 Lowell, T. V.: Late Wisconsin ice-flow reversal and deglaciation, northwestern Maine,
1372 *Geological Society of America Special Paper*, 197, 71–83, 1985.



- 1373 Lowell, T. V., Kite, J. S., Calkin, P. E., and Halter, E. F.: Analysis of small-scale erosional data
1374 and a sequence of late Pleistocene flow reversal, northern New England, Geological Society of
1375 America Bulletin, 102, 74–85, 1990.
- 1376 Manabe, S. and Broccoli, A. J.: The influence of continental ice sheets on the climate of an ice
1377 age, Journal of Geophysical Research: Atmospheres, 90, 2167–2190,
1378 <https://doi.org/10.1029/JD090iD01p02167>, 1985.
- 1379 Mangerud, J.: The discovery of the Younger Dryas, and comments on the current meaning and
1380 usage of the term, Boreas, 50, 1–5, <https://doi.org/10.1111/bor.12481>, 2021.
- 1381 Mangerud, J., Andersen, S. T., Berglund, B. E., and Donner, J. J.: Quaternary stratigraphy of
1382 Norden, a proposal for terminology and classification, Boreas, 3, 109–126,
1383 <https://doi.org/10.1111/j.1502-3885.1974.tb00669.x>, 1974.
- 1384 Marcott, S. A., Shakun, J. D., Clark, P. U., and Mix, A. C.: A reconstruction of regional and
1385 global temperature for the past 11,300 Years, Science, 339, 1198–1201,
1386 <https://doi.org/10.1126/science.1228026>, 2013.
- 1387 Marcott, S. A., Clark, P. U., Shakun, J. D., Brook, E. J., Davis, P. T., and Caffee, M. W.: 10Be
1388 age constraints on latest Pleistocene and Holocene cirque glaciation across the western United
1389 States, npj Climate and Atmospheric Science, 5, 1–7, 2019.
- 1390 Marrero, S.: Calibration of cosmogenic chlorine-36, PhD Thesis, New Mexico Institute of
1391 Mining and Technology, Socorro, NM, 365 pp., 2012.
- 1392 Marrero, S. M., Phillips, F. M., Borchers, B., Lifton, N., Aumer, R., and Balco, G.: Cosmogenic
1393 nuclide systematics and the CRONUScalc program, Quaternary Geochronology, 31, 160–187,
1394 2016.
- 1395 Martin, L. C. P., Blard, P.-H., Balco, G., Lavé, J., Delunel, R., Lifton, N., and Laurent, V.: The
1396 CREP program and the ICE-D production rate calibration database: A fully parameterizable and
1397 updated online tool to compute cosmic-ray exposure ages, Quaternary Geochronology, 38, 25–
1398 49, 2017.
- 1399 Mayewski, P. A., Rohling, E. E., Stager, J. C., Karlén, W., Maasch, K. A., Meeker, L. D.,
1400 Meyerson, E. A., Gasse, F., van Kreveld, S., and Holmgren, K.: Holocene climate variability,
1401 Quaternary Research, 62, 243–255, 2004.
- 1402 McClymont, E. L., Ganeshram, R. S., Pichevin, L. E., Talbot, H. M., Van Dongen, B. E.,
1403 Thunell, R. C., Haywood, A. M., Singarayer, J. S., and Valdes, P. J.: Sea-surface temperature
1404 records of Termination 1 in the Gulf of California: Challenges for seasonal and interannual
1405 analogues of tropical Pacific climate change, Paleoceanography, 27, 2011PA002226,
1406 <https://doi.org/10.1029/2011PA002226>, 2012.
- 1407 McGee, D., Moreno-Chamarro, E., Marshall, J., and Galbraith, E. D.: Western U.S. lake
1408 expansions during Heinrich stadials linked to Pacific Hadley circulation, Science Advances, 4,
1409 eaav0118, <https://doi.org/10.1126/sciadv.aav0118>, 2018.



- 1410 Mickelson, D. M.: Glacial geology of the Burroughs Glacier area, southeastern Alaska, Ph.D.
1411 Dissertation, The Ohio State University, Columbus, OH, 240 pp., 1971.
- 1412 Moore, J. G.: Geologic map of the Mount Whitney quadrangle, Inyo and Tulare counties,
1413 California, United States Geological Survey, 1981.
- 1414 Munroe, J. S. and Laabs, B. J.: Temporal correspondence between pluvial lake highstands in the
1415 southwestern US and Heinrich Event 1, *Journal of Quaternary Science*, 28, 49–58, 2013.
- 1416 Nishiizumi, K., Winterer, E. L., Kohl, C. P., Klein, J., Middleton, R., Lal, D., and Arnold, J. R.:
1417 Cosmic ray production rates of ^{10}Be and ^{26}Al in quartz from glacially polished rocks, *Journal of*
1418 *Geophysical Research: Solid Earth*, 94, 17907–17915,
1419 <https://doi.org/10.1029/JB094iB12p17907>, 1989.
- 1420 NOAA, NASA, and USAF: US Standard Atmosphere, 1976, National Oceanic and Atmospheric
1421 Administration, 1976.
- 1422 Oana, S. and Deevey, E. S.: Carbon 13 in lake waters, and its possible bearing on
1423 paleolimnology, *American Journal of Science*, 258-A, 253–272, 1960.
- 1424 Oerlemans, J.: Extracting a climate signal from 169 glacier records, *Science*, 308, 675–677,
1425 2005.
- 1426 Oster, J. L., Montanez, I. P., Santare, L. R., Sharp, W. D., Wong, C., and Cooper, K. M.:
1427 Stalagmite records of hydroclimate in central California during termination 1, *Quaternary*
1428 *Science Reviews*, 127, 199–214, 2015.
- 1429 Otto-Bliesner, B. L., Brady, E. C., Clauzet, G., Tomas, R., Levis, S., and Kothavala, Z.: Last
1430 glacial maximum and Holocene climate in CCSM3, *Journal of Climate*, 19, 2526–2544, 2006.
- 1431 Pedro, J. B., Jochum, M., Buizert, C., He, F., Barker, S., and Rasmussen, S. O.: Beyond the
1432 bipolar seesaw: Toward a process understanding of interhemispheric coupling, *Quaternary*
1433 *Science Reviews*, 192, 27–46, 2018.
- 1434 Peltier, W. R.: Global glacial isostasy and the surface of the Ice-Age Earth: The ICE-5G (VM2)
1435 model and GRACE, *Annual Review of Earth and Planetary Sciences*, 32, 111–149,
1436 <https://doi.org/10.1146/annurev.earth.32.082503.144359>, 2004.
- 1437 Pérez-Mejías, C., Moreno, A., Bernal-Wormull, J., Cacho, I., Osácar, M. C., Edwards, R. L., and
1438 Cheng, H.: Oldest Dryas hydroclimate reorganization in the eastern Iberian Peninsula after the
1439 iceberg discharges of Heinrich Event 1, *Quaternary Research*, 101, 67–83, 2021.
- 1440 Peteet, D., Del Genio, A., and Lo, K. K. -W.: Sensitivity of Northern Hemisphere air
1441 temperatures and snow expansion to North Pacific sea surface temperatures in the Goddard
1442 Institute for Space Studies general circulation model, *Journal of Geophysical Research:*
1443 *Atmospheres*, 102, 23781–23791, <https://doi.org/10.1029/97JD01573>, 1997.



- 1444 Philippsen, B.: The freshwater reservoir effect in radiocarbon dating, *Heritage Science*, 1, 1–19,
1445 2013.
- 1446 Phillips, F. M.: Cosmogenic nuclide data sets from the Sierra Nevada, California, for assessment
1447 of nuclide production models: I. Late Pleistocene glacial chronology, *Quaternary*
1448 *Geochronology*, 35, 119–129, 2016.
- 1449 Phillips, F. M., Zreda, M. G., Benson, L. V., Plummer, M. A., Elmore, D., and Sharma, P.:
1450 Chronology for fluctuations in Late Pleistocene Sierra Nevada glaciers and lakes, *Science*, 274,
1451 749–751, 1996.
- 1452 Phillips, F. M., Stone, W. D., and Fabryka-Martin, J. T.: An improved approach to calculating
1453 low-energy cosmic-ray neutron fluxes near the land/atmosphere interface, *Chemical Geology*,
1454 175, 689–701, 2001.
- 1455 Phillips, F. M., Zreda, M., Plummer, M. A., Elmore, D., and Clark, D. H.: Glacial geology and
1456 chronology of Bishop Creek and vicinity, eastern Sierra Nevada, California, *Geological Society*
1457 *of America Bulletin*, 121, 1013–1033, 2009.
- 1458 Phillips, F. M., Kelly, M. A., Hudson, A. M., Stone, J. O., Schaefer, J., Marrero, S. M., Fifield,
1459 L. K., Finkel, R., and Lowell, T.: CRONUS-Earth calibration samples from the Huancané II
1460 moraines, Quelccaya ice cap, Peru, *Quaternary Geochronology*, 31, 220–236, 2016.
- 1461 Power, M. J.: Paleoclimatic interpretation of an alpine lake in south central Sierra Nevada,
1462 California, multiple proxy evidence, MS thesis, Northern Arizona University, 1998.
- 1463 Praetorius, S. K., Condon, A., Mix, A. C., Walczak, M. H., McKay, J. L., and Du, J.: The role of
1464 Northeast Pacific meltwater events in deglacial climate change, *Science Advances*, 6, eaay2915,
1465 <https://doi.org/10.1126/sciadv.aay2915>, 2020.
- 1466 Putnam, A. E., Denton, G. H., Schaefer, J. M., Barrell, D. J., Andersen, B. G., Finkel, R. C.,
1467 Schwartz, R., Doughty, A. M., Kaplan, M. R., and Schlüchter, C.: Glacier advance in southern
1468 middle-latitudes during the Antarctic Cold Reversal, *Nature Geoscience*, 3, 700–704, 2010a.
- 1469 Putnam, A. E., Schaefer, J. M., Barrell, D. J. A., Vandergoes, M., Denton, G. H., Kaplan, M. R.,
1470 Finkel, R. C., Schwartz, R., Goehring, B. M., and Kelley, S. E.: In situ cosmogenic ^{10}Be
1471 production-rate calibration from the Southern Alps, New Zealand, *Quaternary Geochronology*, 5,
1472 392–409, 2010b.
- 1473 Quirk, B. J., Moore, J. R., Laabs, B. J., Caffee, M. W., and Plummer, M. A.: Termination II, Last
1474 Glacial Maximum, and Lateglacial chronologies and paleoclimate from Big Cottonwood
1475 Canyon, Wasatch Mountains, Utah, *GSA Bulletin*, 130, 1889–1902, 2018.
- 1476 R Core Team: R: A language and environment for statistical computing, 2024.
- 1477 Rasmussen, S. O., Bigler, M., Blockley, S. P., Blunier, T., Buchardt, S. L., Clausen, H. B.,
1478 Cvijanovic, I., Dahl-Jensen, D., Johnsen, S. J., and Fischer, H.: A stratigraphic framework for
1479 abrupt climatic changes during the Last Glacial period based on three synchronized Greenland



- 1480 ice-core records: refining and extending the INTIMATE event stratigraphy, *Quaternary Science*
1481 *Reviews*, 106, 14–28, 2014.
- 1482 Reid, H. F.: *Glacier Bay and its glaciers*, USGS, 1896.
- 1483 Reimer, P. J., Baillie, M. G., Bard, E., Bayliss, A., Beck, J. W., Bertrand, C. J., Blackwell, P. G.,
1484 Buck, C. E., Burr, G. S., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G.,
1485 Friedrich, M., Guilderson, T. P., Hogg, A. G., Hughen, K. A., Kromer, B., McCormac, G.,
1486 Manning, S., Ramsey, C. B., Reimer, R. W., Remmele, S., Southon, J. R., Stuiver, M., Talamo,
1487 S., Taylor, F. W., Van Der Plicht, J., and Weyhenmeyer, C. E.: IntCal04 terrestrial radiocarbon
1488 age calibration, 0–26 cal kyr BP, *Radiocarbon*, 46, 1029–1058, 2004.
- 1489 Reimer, P. J., Baillie, M. G., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B.,
1490 Buck, C. E., Burr, G. S., and Edwards, R. L.: IntCal09 and Marine09 radiocarbon age calibration
1491 curves, 0–50,000 years cal BP, *Radiocarbon*, 51, 1111–1150, 2009.
- 1492 Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B., Buck, C. E.,
1493 Cheng, H., Edwards, R. L., and Friedrich, M.: IntCal13 and Marine13 radiocarbon age
1494 calibration curves 0–50,000 years cal BP, *Radiocarbon*, 55, 1869–1887, 2013.
- 1495 Reimer, P. J., Austin, W. E., Bard, E., Bayliss, A., Blackwell, P. G., Ramsey, C. B., Butzin, M.,
1496 Cheng, H., Edwards, R. L., and Friedrich, M.: The IntCal20 Northern Hemisphere radiocarbon
1497 age calibration curve (0–55 cal kBP), *Radiocarbon*, 62, 725–757, 2020.
- 1498 Rood, D. H., Burbank, D. W., and Finkel, R. C.: Chronology of glaciations in the Sierra Nevada,
1499 California, from ^{10}Be surface exposure dating, *Quaternary Science Reviews*, 30, 646–661, 2011.
- 1500 Rozanski, K., Araguás-Araguás, L., and Gonfiantini, R.: Isotopic patterns in modern global
1501 precipitation, in: *Climate Change in Continental Isotopic Records*, vol. 78, American
1502 Geophysical Union Washington, DC, 1–36, 1993.
- 1503 Schaefer, J. M., Denton, G. H., Barrell, D. J. A., Ivy-Ochs, S., Kubik, P. W., Andersen, B. G.,
1504 Phillips, F. M., Lowell, T. V., and Schlüchter, C.: Near-synchronous interhemispheric
1505 termination of the Last Glacial Maximum in mid-latitudes, *Science*, 312, 1510–1513,
1506 <https://doi.org/10.1126/science.1122872>, 2006.
- 1507 Scuderi, L. A.: Late-Holocene upper timberline variation in the southern Sierra Nevada, *Nature*,
1508 325, 242–244, 1987.
- 1509 Shakun, J. D., Clark, P. U., He, F., Marcott, S. A., Mix, A. C., Liu, Z., Otto-Bliesner, B.,
1510 Schmittner, A., and Bard, E.: Global warming preceded by increasing carbon dioxide
1511 concentrations during the last deglaciation, *Nature*, 484, 49–54, 2012.
- 1512 Stock, G. M. and Uhrhammer, R. A.: Catastrophic rock avalanche 3600 years BP from El
1513 Capitan, Yosemite Valley, California, *Earth Surface Processes and Landforms*, 35, 941–951,
1514 <https://doi.org/10.1002/esp.1982>, 2010.



- 1515 Stone, J. O.: Air pressure and cosmogenic isotope production, *Journal of Geophysical Research:*
1516 *Solid Earth*, 105, 23753–23759, <https://doi.org/10.1029/2000JB900181>, 2000.
- 1517 Street, J. H., Anderson, R. S., and Paytan, A.: An organic geochemical record of Sierra Nevada
1518 climate since the LGM from Swamp Lake, Yosemite, *Quaternary Science Reviews*, 40, 89–106,
1519 2012.
- 1520 Stuiver, M. and Reimer, P. J.: Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration
1521 program, *Radiocarbon*, 35, 215–230, 1993.
- 1522 Syverson, K. M.: The ability of ice-flow indicators to record complex, historic deglaciation
1523 events, *Burroughs Glacier, Alaska, Boreas*, 24, 232–244, 1995.
- 1524 Tulenko, J. P., Briner, J. P., Young, N. E., and Schaefer, J. M.: The last deglaciation of Alaska
1525 and a new benchmark ^{10}Be moraine chronology from the western Alaska Range, *Quaternary*
1526 *Science Reviews*, 287, 107549, 2022.
- 1527 Uppala, S. M., Kållberg, P. W., Simmons, A. J., Andrae, U., Bechtold, V. D. C., Fiorino, M.,
1528 Gibson, J. K., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka,
1529 N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., Berg, L. V. D.,
1530 Bidlot, J., Bormann, N., Cairns, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M.,
1531 Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B. J., Isaksen, I., Janssen, P. A. E. M., Jenne, R.,
1532 McNally, A. P., Mahfouf, J. -F., Morcrette, J. -J., Rayner, N. A., Saunders, R. W., Simon, P.,
1533 Sterl, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo, P., and Woollen, J.: The ERA-40
1534 re-analysis, *Quarterly Journal of the Royal Meteorological Society*, 131, 2961–3012,
1535 <https://doi.org/10.1256/qj.04.176>, 2005.
- 1536 Wahrhaftig, C., Stock, G. M., McCracken, R. G., Sasnett, P., and Cyr, A. J.: Extent of the Last
1537 Glacial Maximum (Tioga) glaciation in Yosemite National Park and vicinity, California, US
1538 Geological Survey Scientific Investigations Series Map, 3414, 2019.
- 1539 Wang, H., An, Z., Zhang, X., Shu, P., He, F., Liu, W., Lu, H., Ming, G., Liu, L., and Zhou, W.:
1540 Westerly and Laurentide Ice Sheet fluctuations during the Last Glacial Maximum, *npj Climate*
1541 *and Atmospheric Science*, 7, 2024.
- 1542 Waters, M. R.: Late Quaternary lacustrine history and paleoclimate significance of pluvial Lake
1543 Cochise, southeastern Arizona, *Quaternary Research*, 32, 1–11, 1989.
- 1544 Wong, C. I., Potter, G. L., Montañez, I. P., Otto-Bliesner, B. L., Behling, P., and Oster, J. L.:
1545 Evolution of moisture transport to the western U.S. during the last deglaciation, *Geophysical*
1546 *Research Letters*, 43, 3468–3477, <https://doi.org/10.1002/2016GL068389>, 2016.
- 1547 Ye, S., Cuzzone, J. K., Marcott, S. A., Licciardi, J. M., Ward, D. J., Heyman, J., and Quinn, D.
1548 P.: A quantitative assessment of snow shielding effects on surface exposure dating from a
1549 western North America ^{10}Be data compilation, *Quaternary Geochronology*, 76, 2023.
- 1550