Delayed and rapid deglaciation of alpine valleys in the Sawatch Range, southern Rocky Mountains, USA

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Abstract

We quantify retreat rates for three alpine glaciers in the Sawatch Range of the southern Rocky Mountains following the Last Glacial Maximum using ^{10}Be ages from ice-sculpted, valley-floor bedrock transects and statistical analysis via the BACON program in R. Glacier retreat in the Sawatch Range from at (100%) or near (~83%) Last Glacial Maximum extents initiated between 16.0 and 15.6 ka and was complete by 14.2 – 13.7 ka at rates ranging between 35.6 to 6.8 m a^{-1}. Deglaciation in the Sawatch Range commenced ~2 – 3 kyr later than the onset of rising global CO_2, and prior to rising temperatures observed in the North Atlantic region at the Heinrich Stadial 1/Bølling transition. However, deglaciation in the Sawatch Range approximately aligns with the timing of Great Basin pluvial lake lowering. Recent data-modeling comparison efforts highlight the influence of the large North American ice sheets on climate in the western United States, and we hypothesize that recession of the North American ice sheets may have influenced the timing and rate of deglaciation in the Sawatch Range.

While we cannot definitively argue for exclusively North Atlantic forcing or North

25 American ice sheet forcing, our data demonstrate the importance of regional forcing

mechanisms on past climate records.

1. Introduction

Alpine glaciers worldwide underwent substantial retreat in response to climate

30 warming during the last deglaciation (Shakun et al., 2015; Palacios et al., 2020).

However, the general trend of warming through the last deglaciation was interrupted by

internally forced and regionally heterogeneous climate changes such as the cool

Heinrich Stadial 1 (17.5 – 14.7 ka), abrupt warming into the Bølling-Allerød period (14.7

– 12.9 ka), and the Younger Dryas cold period (12.9 – 11.7 ka) all centered in the North

35 Atlantic region (NGRIP members, 2004; Rasmussen et al., 2014). To thoroughly

characterize the influence of these climatic oscillations, their expression throughout the

Northern Hemisphere is often investigated using records of mountain glaciation (Ivy-

Ochs et al., 2006; Schaefer et al., 2006; Young et al., 2011; Shakun et al., 2015;

Marcott et al., 2019; Young et al., 2019). Mountain glacier deposits serve as suitable

40 archives since mountain glaciers are particularly sensitive to changes in climate (e.g.

Oerlemans, 2005; Roe et al., 2017). Furthermore, where deposits are carefully mapped

and dated, quantitative retreat or thinning rates of glaciers can be compared to records

of climatic forcings. Using statistical approaches to quantify retreat and thinning rates

has been previously applied to ice sheets (e.g., Johnson et al., 2014; Jones et al., 2015;

45 Koester et al., 2017; Small et al., 2018; Lesnek et al., 2020) but only for a few mountain

glaciers (e.g., Hofmann et al, 2019).

In the western United States (US; Fig. 1), mountain glaciers expanded out of the high elevations of the Rocky Mountains, the Sierra Nevada, and many other, smaller ranges during the Last Glacial Maximum (LGM; Porter et al., 1983; Pierce, 2003).

During the last deglaciation, many glaciers retreated from their extended LGM positions and eventually melted from their cirques during the late glacial-to-early Holocene (e.g., Munroe and Laabs, 2017; Marcott et al., 2019). Yet, the temporal and spatial patterns of retreat throughout the western US and their relationship to hemispheric and global forcing are still a subject of debate. Glaciers in the western US may have retreated in response to increasing global temperature forced by rising atmospheric CO_2 concentrations, thus broadly synchronous with other mountain glaciers around the world (e.g. Shakun et al., 2015; Marcott et al., 2019). However, some evidence suggests a delay of deglaciation until the Bølling due to either persistent stadial conditions (e.g., Young et al., 2011) or as a response to increased local moisture supply to some glaciers from nearby pluvial lakes (e.g. Laabs et al., 2009).

Over a decade of work has resulted in detailed moraine chronologies in three adjacent alpine valleys in the Sawatch Range of central Colorado (Fig. 2; Briner, 2009; Young et al., 2011; Shroba et al., 2014; Leonard et al., 2017b; Schweinsberg et al., 2020). While these studies primarily focused on mapping and dating the range-front moraines and associated outwash terraces, a transect of ages from bedrock samples in Lake Creek valley (Fig. 2) documented rapid retreat between 15.6 ± 0.7 ka and 13.7 ± 0.2 ka (Leonard et al., 2017b; Schweinsberg et al., 2020). Schweinsberg et al. (2020) suggested a possible link between North Atlantic climate forcing and the rapid

deglaciation observed in Lake Creek valley, but similar transects from adjacent valleys

70   are lacking to bolster or refute this hypothesis.
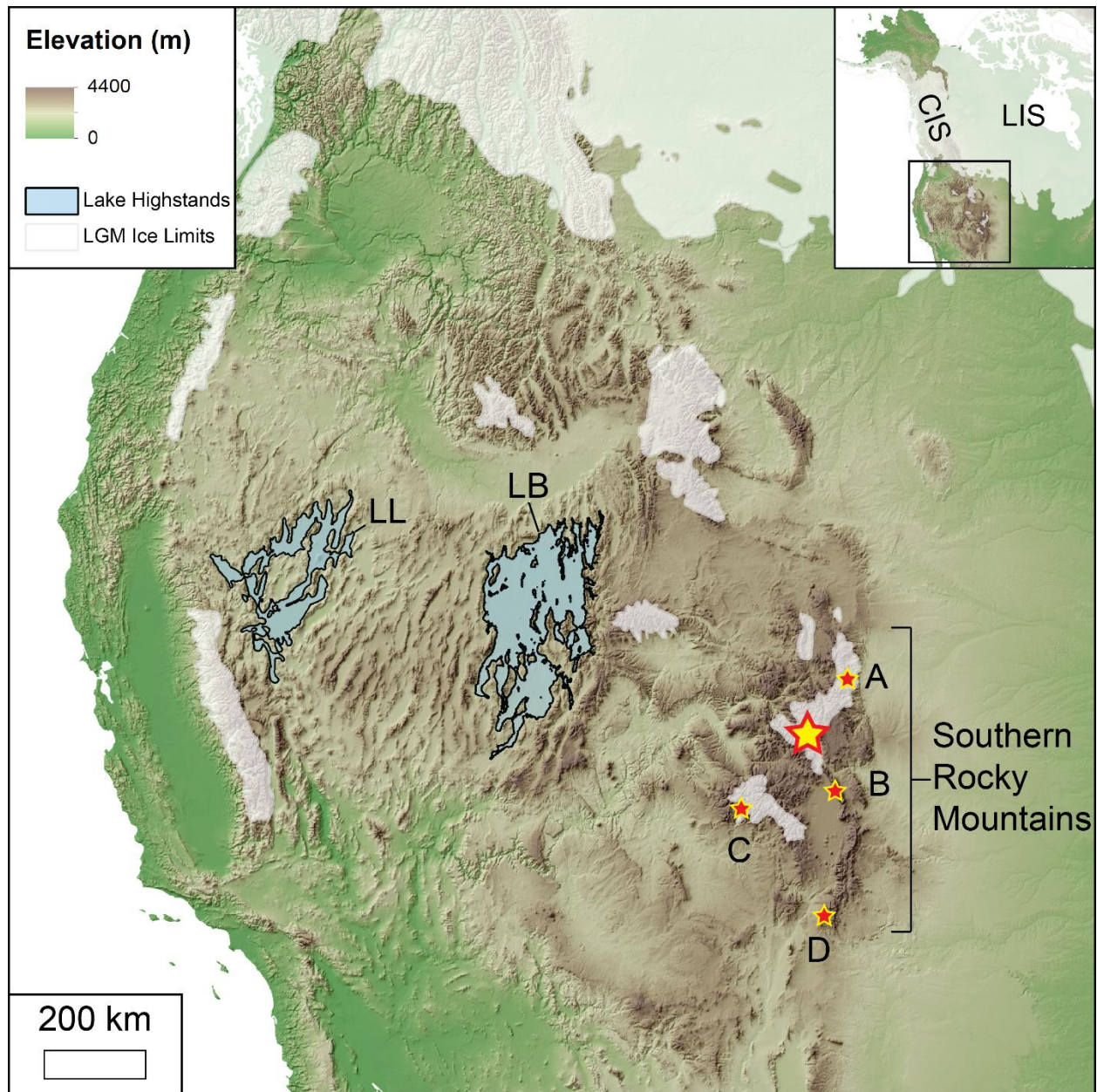
Figure 1. Key moraine chronologies from the southern Rocky Mountains and locations of glaciation centers and large pluvial lakes in the western US following the Last Glacial Maximum (LGM). LL = Lake Lahontan, LB = Lake Bonneville, A = Colorado
75   Front Range, B = Sangre de Cristo Mountains, C = San Juan Mountains, and D = Winsor Creek valley, New Mexico. The largest star corresponds to our field site in the Sawatch Range. LGM ice limits from Dalton et al. (2020). Inset is of the western portion of North America. CIS = Cordilleran Ice Sheet, LIS = Laurentide Ice Sheet.

Here, we combine 12 new cosmogenic ^{10}Be exposure ages with ten previously published ^{10}Be ages from bedrock samples along transects in three adjacent alpine valleys in the Sawatch Range, southern Rocky Mountains (Fig. 2). By dating bedrock sites along valley transects, we characterize the timing and pace of glacier retreat during the last deglaciation. We calculate rates of deglaciation for each valley with best-fit time-distance plotting using the R program BACON (Fig. 4). Our results suggest that glaciers in the Sawatch Range may have been influenced more heavily by regional forcing than by global CO_2 concentrations.

2. Setting

The high peaks of south-central Colorado and northern New Mexico compose the southern end of the Rocky Mountain Range in North America and were home to many alpine glaciers during multiple glaciations throughout the Pleistocene (Fig. 1; Pierce, 2003; Leonard et al., 2017b; Marcott et al., 2019; Laabs et al., 2020; ages discussed below are re-calculated using the promontory point production rate calibration of Lifton et al., 2015 and the LSDn scaling model of Lifton et al., 2014). Transects of ^{10}Be ages from bedrock along valley axes exist for a few valleys in the upper Boulder Creek drainage in the Front Range, Colorado (Benson et al., 2004; Ward et al., 2009; Dühnforth and Anderson, 2011). While some evidence from the Boulder Creek drainages may suggest delayed deglaciation, chronologic scatter in the ages makes it difficult to determine the exact timing and how quickly glaciers retreated to their cirques. Existing ages from one valley the Sangre de Cristo Range, south-central Colorado, suggest that a glacier there remained at or re-advanced to near its LGM terminus at ~16

ka, but then retreated to its cirque in a period of ~2 kyr (Leonard et al., 2017a). In the

Animas River valley of the San Juan Mountains, southwest Colorado, existing [10]Be ages

indicate glacier retreat began as early as ~19 ka, with complete retreat of nearly 70% of

105   the total valley length beginning ~16 ka and finishing by ~12.7 ka (Guido et al., 2007).

Relatively early initial retreat of the glacier in the Animas River valley is contingent on

dating at a single site. Near Baldy Peak in Northern New Mexico, LGM moraines and

what appear to be cirque moraines have been surveyed in the Winsor Creek valley

(Armour et al., 2002; Marcott et al., 2019). [10]Be ages from the cirque, ~4 km up-valley

110   from the LGM moraines, range from 15.8 – 14.3 ka, suggesting that the glacier

retreated to near its cirque within that interval. The recessional and LGM moraines

remain undated so it is difficult to know when the glacier began retreating. In summary,

while there is some chronologic scatter in ages from these sites, there is evidence to

suggest that some glaciers in the southern Rocky Mountains remained relatively

115   expanded through the beginning of the last deglaciation and were delayed in their

retreat. However, once retreat was underway, all sites observed thus far reveal that

glaciers completely retreated at least up to their cirques prior to the Younger Dryas cold

period with no evidence for subsequent moraine deposition.

Prominent moraines originally mapped as part of the surficial geologic map of the

120   Granite 7.5' quadrangle (updated by Shroba et al., 2014) exist at the mouths of multiple

glacially sculpted valleys within the Sawatch Range (e.g. Briner et al., 2009; Young et

al., 2011; Brugger et al., 2019a; Schweinsberg et al., 2020). Of these, moraines

deposited at the mouths of three adjacent valleys, Lake Creek, Clear Creek and Pine

Creek, have been thoroughly surveyed and dated (Fig. 2; Briner, 2009; Young et al.,

125   2011; Schweinsberg et al., 2020). The moraine chronologies reported thus far reveal

that following the LGM (which culminated between ~22 – 19 ka), a recessional moraine

at 82% of the LGM position sampled in the Lake Creek system was deposited at 15.6 ±

0.7 ka (Schweinsberg et al., 2020). There is a similar-appearing moraine at 83% of the

LGM position in Clear Creek valley. Although it is undated, we tentatively correlate this

130   moraine in Clear Creek valley to the moraine dated to 15.6 ± 0.7 ka in Lake Creek

valley. Finally, there is no recessional moraine in Pine Creek valley, but a cluster of

ages at 16.0 ± 0.9 ka from the LGM moraine suggest that the glacier re-advanced to or

remained at its LGM extent until nearly the same time when glaciers in the other two

valleys deposited recessional moraines (Briner, 2009; Young et al., 2011). Young et al.

135   (2011) argued
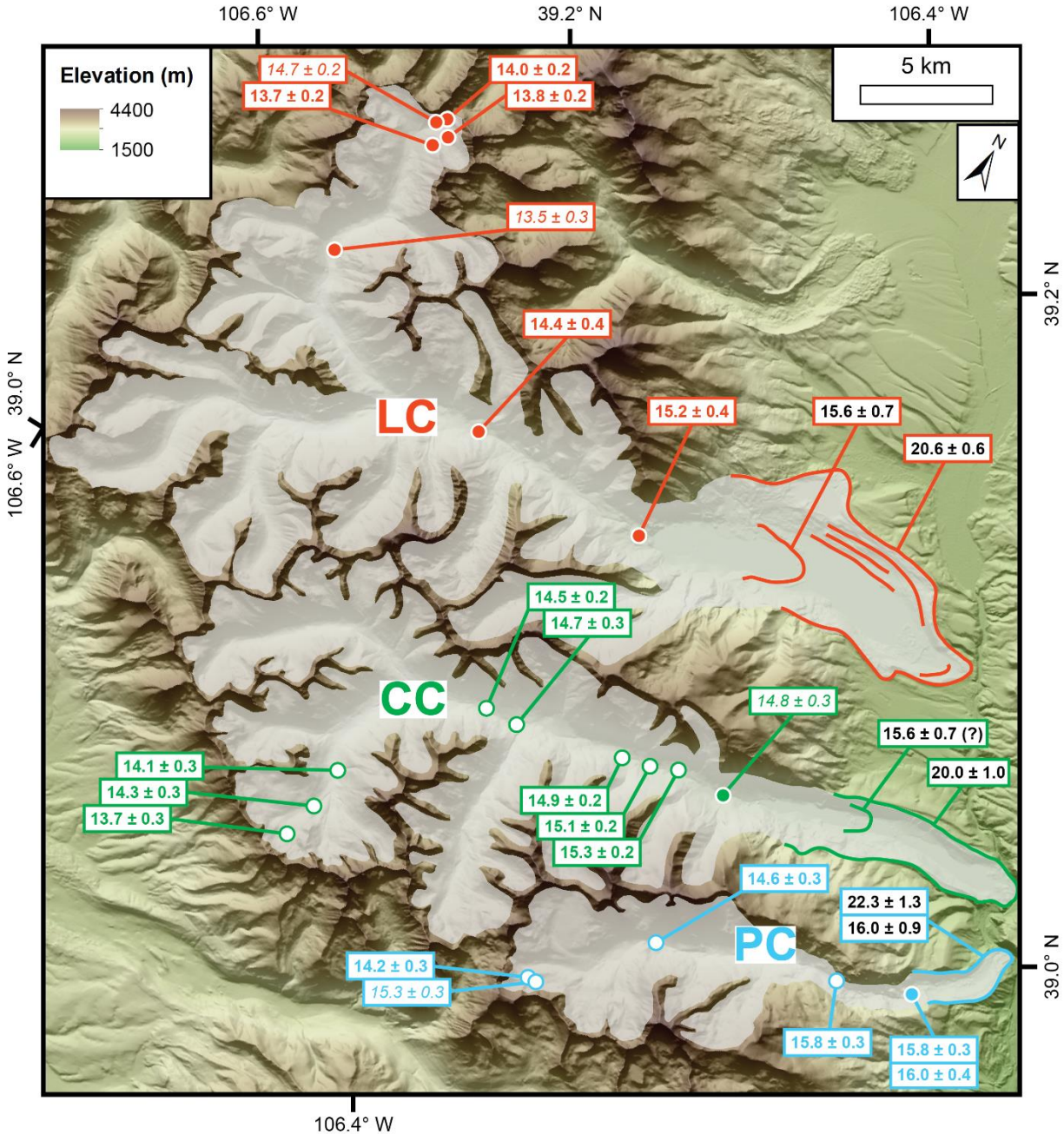
Figure 2. Ice-sculpted bedrock [10]Be ages from Lake Creek (LC; orange), Clear Creek (CC; green), and Pine Creek valleys (PC; blue). New ages are open circles and previously published ages are closed. Bedrock ages with italicized labels are suspected outliers. Included are LGM and recessional moraines (solid colored lines and labels with black text) with reported ages for the LGM moraines in all three valleys, including the younger mode in Pine Creek valley at 16.0 ± 0.9 ka (n=7; Young et al., 2011) and a recessional moraine in Lake Creek valley at 15.6 ± 0.7 ka (n=5; Schweinsberg et al., 2020). There is a similar, undated recessional moraine in Clear Creek valley that we hypothesize is also ~16 ka. Ice-sculpted bedrock ages reported here include analytical

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uncertainty, and moraine ages are reported as mean and one standard deviation. Glaciers at their mapped LGM extents are delineated in gray.

that since all three glaciers are east-facing and in close proximity—yet show differences

150   in the timing of LGM culmination between the valleys—it is possible that non-climatic

factors, such as glacier hypsometry, may have influenced the timing and extent of LGM

culminations. While there are pre-existing [10]Be ages measured in a transect along Lake

Creek Valley that track the retreat of the glacier through the last deglaciation, the other

two valleys have not yet been surveyed. As such, it remains unclear if glacier

155   hypsometry also influenced the timing and pace of deglaciation between all three

adjacent valleys.

3. Methods and materials

Sample collection for [10]Be dating from Clear Creek and Pine Creek valleys was

160   conducted in the summers of 2017 and 2018. Twelve samples were collected from

exposed, glacially sculpted bedrock surfaces along the Clear Creek (n=8) and Pine

Creek (n=4) valley floors, spanning from just within range-front moraines up to each

respective cirque (Figs. 2 and 3). Bedrock surfaces located in the bottoms of valley

floors – where glacial erosion is maximized – were specifically targeted since the

165   potential for incomplete scouring of these surfaces can lead to inherited nuclides and

ages that are older than expected.

Samples were processed at the University at Buffalo Cosmogenic Isotope

Laboratory following the versions of quartz purification and beryllium extraction

procedures refined at the University of Vermont (Corbett et al., 2016). After quartz

170   purification, samples were dissolved in acid along with a [9]Be carrier spike in two

batches each with a process blank. Beryllium was then purified and extracted, oxidized, and packed into targets for measurement at the Center for Accelerated Mass Spectrometry at Lawrence Livermore National Laboratory. $^{10}Be/^9Be$ ratios were measured and standardized to the reported 07KNSTD3110 ratio of 2.85 x 10^{-12}

175 (Nishiizumi et al., 2007). For samples collected in 2018, the process blank $^{10}Be/^9Be$ ratio was 2.96 x 10^{-15}, and for samples collected in 2017 the process blank $^{10}Be/^9Be$ ratio was 9.56 x 10^{-16} (see Table 1 for details on sample collection dates). Our 12 ages and 10 previously published ages were calculated using the Cronus Earth online calculator (developmental version 3;

180 https://hess.ess.washington.edu/math/index_dev.html; Balco et al., 2008). We calculate ages using the Promontory Point production rate (Lifton et al., 2015) and the LSD*n* scaling model (Lifton et al., 2014) – a combination used extensively throughout the western US (e.g., Licciardi and Pierce, 2018; Quirk et al., 2018; Brugger et al., 2019b; Schweinsberg et al., 2020). Below, we discuss in more detail how different production

185 rate calibrations and scaling schemes impact our results. We do not attempt to make any corrections for snow cover or post-depositional bedrock surface erosion.
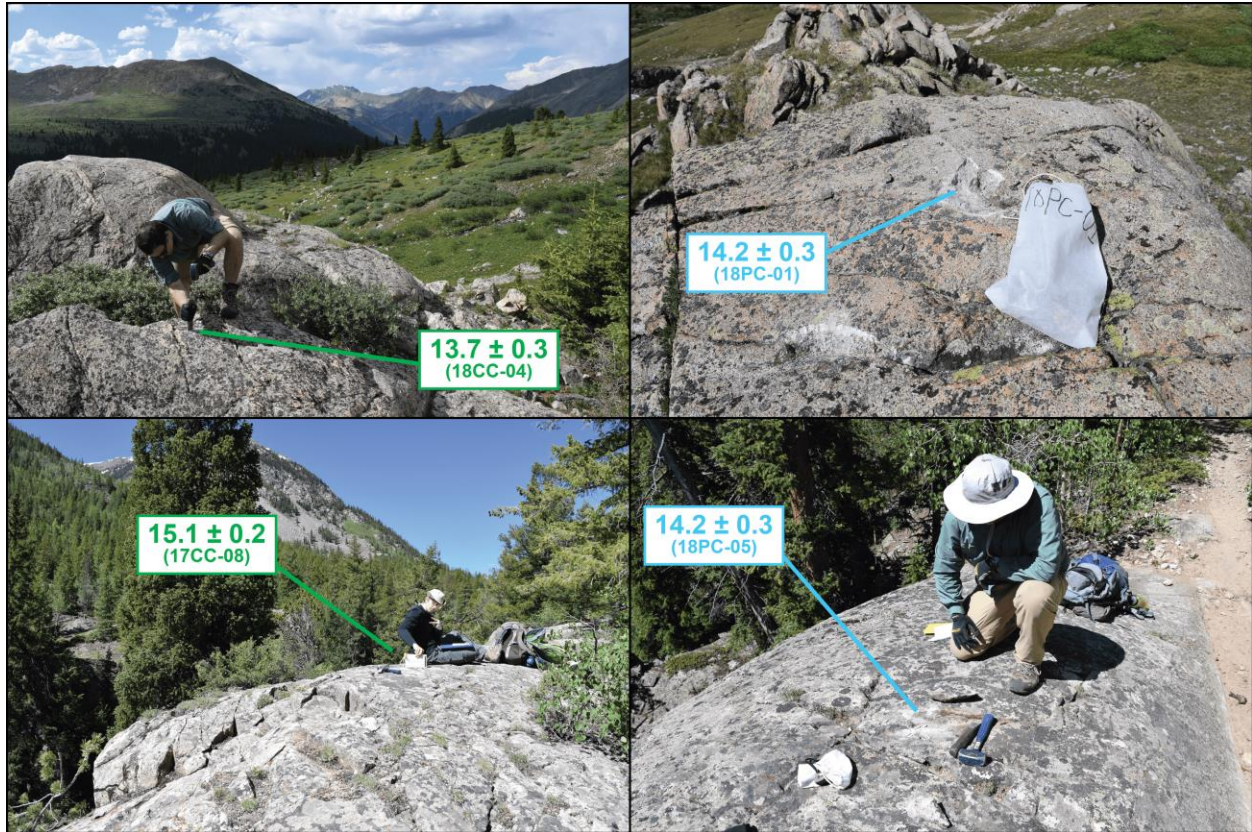
Figure 3. Field photos of ice-sculpted bedrock surfaces from selected locations. Clockwise from top left: 18CC-04, 18PC-01, 18PC-05, 17CC-08. Color scheme for ages matches Figures 2 and 4: Clear Creek valley samples = green; Pine Creek valley samples = blue.

To calculate retreat rates, we used the BACON program in R (Blaauw and Christen, 2011). This program generates age-depth models for stratigraphic records based on chronologic constraints at various depths. Here, we use the ^{10}Be ages and their 1-sigma internal uncertainties measured in each valley as the age input and the geographic coordinates of each age as the depth inputs. The position along the valley floor is scaled such that the toe of the glacier at the LGM is the starting point (e.g., 100% or maximum length), and the base of each valley's cirque wall is the end point (e.g., 0% or minimum length). The model then interpolates between each point using Bayesian analysis and the geologic principle of superposition to build an age-length

model with an unweighted statistical treatment of uncertainty. The interpolation between points is smoothed (i.e. non-linear) based on retreat rates at previous positions. The retreat rates presented here are net retreat rates, because it is possible there may have been short-lived re-advances that did not lead to significant moraine deposition. BACON outputs a time series of age-length points and non-Gaussian 95% confidence intervals. Calculated retreat rates are assumed to be linear, and we report the 95% uncertainty range.

4. Results

The 12 new sculpted-bedrock [10]Be ages reported here range 15.8 ± 0.3 – 13.7 ± 0.3 ka (Fig. 2; Table 1). Combined with the previously published samples in our study area, all 22 sculpted-bedrock [10]Be ages, which span from immediately inboard of the innermost moraine to the cirque floors, range between 16.0 ± 0.4 and 13.5 ± 0.3 ka (Fig. 2, Table 1). In Lake Creek valley, seven ages span from 67 – 1% of the distance of the valley floor, ranging between 15.2 ± 0.4 and 13.5 ± 0.3 ka. Nine [10]Be ages spanning from 68 – 1% in Clear Creek valley range between 15.3 ± 0.2 and 13.7 ± 0.2 ka. In Pine Creek valley, six [10]Be ages span from 78 – 3% and range between 16.0 ± 0.4 and 14.2 ± 0.3 ka.

Most ages in each valley are in stratigraphic order and fall within the 95% confidence interval calculated in BACON, except for four ages (Fig. 4). Ages from Lake Creek valley suggest the glacier retreated from its recessional moraine position (82%) at 15.6 ± 0.7 ka, and reached its cirque (~1%) by 13.7 ± 0.2 ka. Clear Creek valley ages suggest the glacier retreated from its recessional moraine position (83%) at 15.6 ± 0.7

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Table 1. Sample data and ^{10}Be ages.

Sample Name	Latitude (DD)	Longitude (DD)	Elevation (m asl)	Thickness (cm)	Shielding correction	^{10}Be concentration (atoms/g)	^{10}Be concentration err. (atoms/g)	^{10}Be age (ka)[a]	^{10}Be age (ka)[b]	Transect dist. (km)	Transect dist. (%)
Lake Creek transect											
AR09-01	39.06590	-106.40703	2930	1.5	0.9960	513652	12462	15.2 ± 0.4	16.5 ± 0.4	22.4	67
AR09-10	39.07059	-106.47182	3048	3.5	0.9890	508740	13867	14.4 ± 0.4	15.6 ± 0.4	16.5	49
AR09-11	39.10098	-106.54449	3261	4.0	0.9830	543494	10771	13.5 ± 0.3	15.0 ± 0.3	7.3	22
LKCK-15-3	39.15210	-106.52745	3761	3.0	0.9830	767000	10200	14.0 ± 0.2	15.8 ± 0.2	1.0	3
LKCK-15-1	39.15800	-106.53100	3740	1.5	0.9859	760192	9960	13.8 ± 0.2	15.6 ± 0.2	0.5	2
LKCK-15-2	39.15809	-106.53175	3776	4.0	0.9848	807000	11600	14.7 ± 0.2	16.5 ± 0.2	0.5	2
LKCK-15-4	39.14907	-106.52420	3774	3.0	0.9740	750000	12000	13.7 ± 0.2	15.5 ± 0.2	0.4	1
Clear Creek transect											
AR09-03	39.00260	-106.33924	2835	2.0	0.9920	462709	9308	14.8 ± 0.3	15.9 ± 0.3	18.8	68
17CC-06[1]	39.00270	-106.35680	2928	2.0	0.9821	508593	7026	15.3 ± 0.2	16.7 ± 0.2	17.1	62
17CC-08[1]	38.99920	-106.36590	2916	1.0	0.9668	490889	5908	15.1 ± 0.2	16.4 ± 0.2	16.1	58
17CC-11[1]	38.99720	-106.37550	2954	1.5	0.9643	494089	6071	14.9 ± 0.2	16.2 ± 0.2	15.3	55
17CC-09[1]	38.98970	-106.41250	3049	1.5	0.9815	523681	9768	14.7 ± 0.3	16.0 ± 0.3	11.5	42
17CC-10[1]	38.98970	-106.42410	3096	2.0	0.9780	527682	6338	14.5 ± 0.2	15.8 ± 0.2	10.5	38
18CC-01[2]	38.94677	-106.45814	3317	2.0	0.9645	583017	10873	14.1 ± 0.3	15.6 ± 0.3	3.5	12
18CC-02[2]	38.93217	-106.45944	3403	2.5	0.9863	631265	11746	14.3 ± 0.3	15.8 ± 0.3	1.8	6
18CC-04[2]	38.91955	-106.46294	3625	2.5	0.9851	691699	12979	13.7 ± 0.3	15.3 ± 0.3	0.2	1
Pine Creek transect											
AR09-07	38.97437	-106.25060	2931	3.0	0.9960	536779	14280	16.0 ± 0.4	17.5 ± 0.5	14.3	78
AR09-08	38.97437	-106.25060	2931	1.0	0.9960	537781	10676	15.8 ± 0.3	17.2 ± 0.3	14.3	78
18PC-06[2]	38.96590	-106.27515	3244	1.5	0.9816	643484	14156	15.8 ± 0.3	17.4 ± 0.4	11.4	62
18PC-05[2]	38.94764	-106.33513	3403	3.0	0.9661	631502	11710	14.6 ± 0.3	16.2 ± 0.3	5.5	30
18PC-01[2]	38.91623	-106.36673	3824	1.5	0.9899	818218	15138	14.2 ± 0.3	16.1 ± 0.3	0.5	3
18PC-02[2]	38.91648	-106.36528	3827	2.5	0.9899	880955	18751	15.3 ± 0.3	17.4 ± 0.4	0.4	2

Notes: Rock density for all samples 2.65 g/cm^3; zero surface erosion rate applied to all samples. Sample names of prevously published ages italicized, sample names for new ages in bold.

[a] Ages calculated using the Promontory Point production rate calibration (Lifton et al., 2015) and LSDn scaling (Lifton et al., 2014)

[b] Ages calculated using the Northeast North America production rate clibration (Balco et al., 2009) and Lm scaling (Lal, 1991; Stone, 2000)

[1] Process blank for the following samples was 9.56 x 10^{-16} (atoms/g)

[2] Process blank for the following samples was 2.96 x 10^{-15} (atoms/g)

225 ka and reached its cirque (~1%) by 13.7 ± 0.3 ka. Finally, Pine Creek valley ages

suggest the glacier was at its LGM extent (100%) until 16.0 ± 0.9 ka and then retreated

to its cirque (~3%) by 14.2 ± 0.2 ka.

Results from BACON analysis suggest the net retreat rate for the glacier in Lake

Creek valley between 15.6 ± 0.7 ka (Schweinsberg et al., 2020) and 13.7 ± 0.2 ka

230 ranges 35.6 – 13.8 m a^{-1} at 95% confidence (Fig. 4). The net retreat rate calculated from

BACON for the glacier in Clear Creek valley between 15.6 ± 0.7 ka and 13.7 ± 0.3 ka

ranges 15.5 – 8.2 m a^{-1} at 95% confidence. Finally, the net retreat rate for the glacier in

Pine Creek valley from the LGM position at 16.0 ± 0.9 ka (Young et al., 2011) to 14.2 ±

0.3 ranges 18.3 – 6.8 m a^{-1} at 95% confidence. Removal of potential outliers reduces

235 retreat rates by 1.7%, 2.7% and 6% for Lake Creek, Clear Creek, and Pine Creek

valleys respectively. The calculated average valley gradients for each valley –

measured as the elevation change divided by the horizontal length of each valley

bottom transect from LGM moraine up to the base of each respective cirque – are 29

m/km for Lake Creek valley, 37 m/km for Clear Creek valley, and 65 m/km for Pine
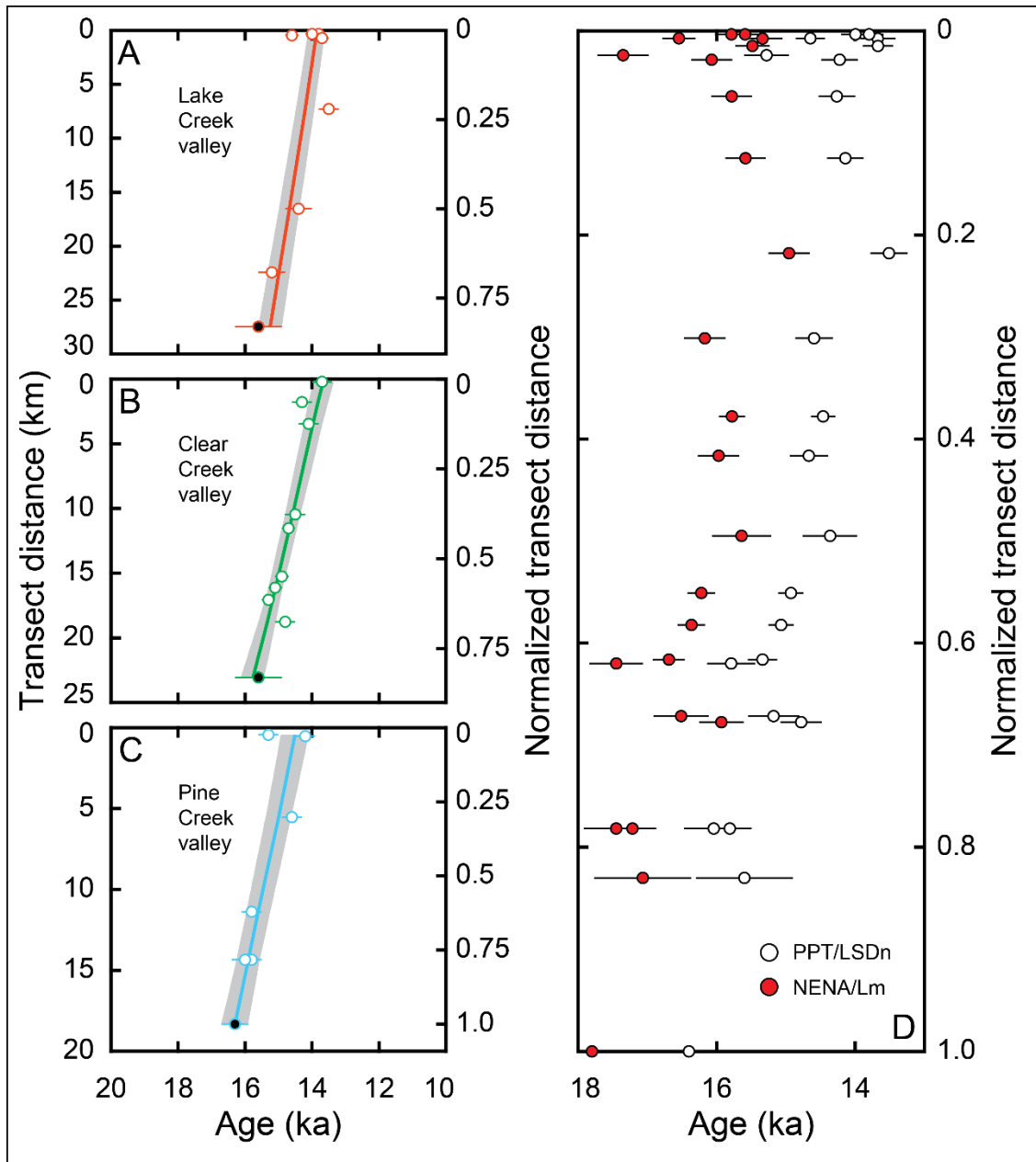
240 Creek valley.

Figure 4. Summary plots of ^{10}Be ages and BACON statistical analysis results. A) Lake Creek valley (orange), B) Clear Creek valley (green), and C) Pine Creek valley (blue). Ages in solid black fill at the bottom of each transect are from recessional moraine ages (Young et al., 2011; Schweinsberg et al., 2020). BACON results are mean (color lines) and 95% confidence intervals (gray shading). Left y-axes are total valley floor distances from the LGM moraine to the base of each respective cirque headwall (note that scales are different because valley lengths are different). Right y-axes are the same, but normalized values, where 1 = LGM moraine position and 0 = base of cirque headwall. D) Distribution of all ages using both PPT (Lifton et al., 2015) and LSD*n* (Lifton et al., 2014), and NENA (Balco et al., 2009) and Lm (Lal, 1991; Stone, 2000) production rate

calibration and scaling scheme combinations. All other reasonable combinations mentioned in the text produce ages that fall somewhere between ages calculated using the PPT/LSD*n* and NENA/Lm combinations.

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5. Discussion

5.1 Reliability of bedrock ages

While most bedrock ages along each valley transect are in stratigraphic order,

we find four ages that do not comply with stratigraphic order and fall outside the 95%

260   confidence interval of the retreat rates calculated from BACON. For example, in Lake

Creek valley, one age at 13.5 ± 0.3 ka is younger than all up-valley ages, which average

13.8 ± 0.2 ka (excluding one possible outlier outside of the BACON 95% confidence

interval). In Clear Creek valley, the age from the farthest downvalley site of 14.8 ± 0.3

ka may be a possible outlier because the next three ages up-valley are all older and in

265   stratigraphic order, the oldest of which is 15.3 ± 0.2 ka. Finally, one age from the Pine

Creek cirque of 15.3 ± 0.3 ka may be an outlier because it is older than the next age

downvalley (14.6 ± 0.3 ka) as well as a second sample from the cirque of 14.2 ± 0.3 ka.

Two suspected outliers are older than expected, which may have been caused by

insufficient glacial erosion. The two remaining potential outliers are younger than

270   expected, which could have resulted from excessive soil and snow cover, enhanced

post-depositional bedrock surface erosion, or a combination of these factors.

Although we interpret our results using the Promontory Point production rate

calibration site (Lifton et al., 2015) and the LSDn scaling scheme (Lifton et al. 2014), we

calculate exposure ages with other commonly used calibration sites (e.g. northeastern

275   North America NENA; Balco et al., 2009 and the 'global' production rate; Borchers et al.,

2016) and another commonly used scaling scheme (Lal/Stone–Lm; Lal, 1991; Stone,

15

2000). Samples used for the NENA production rate calibration range in elevation

between ~50 to 400 m asl and are located ~3000 km northeast of the Sawatch Range.

This combination produces the oldest ages given the previously mentioned reasonable

280   production rate calibrations and scaling schemes, and are between 9 to 12% older than

when using PPT/LSD*n* (all other combinations fall somewhere in between; Fig. 4; Table

1). We do not feel confident in calculating exposure ages using other production rate

calibration sites since the sites in closest proximity likely shared the most similar

exposure histories. Ultimately, we favor the Promontory Point production rate calibration

285   site (Lifton et al., 2015) because the site is closest in both location (site is ~600 km from

the Sawatch Range) and elevation (sample elevations are ~1600 m asl) to our study

area.

5.2 The last deglaciation of the Sawatch Range and the southern Rocky

290   *Mountains*

The pattern of deglaciation in both Clear Creek valley and Pine Creek valley

appears to follow the pattern previously observed in Lake Creek valley (Young et al.,

2011; Leonard et al., 2017b; Schweinsberg et al., 2020). All three glaciers remained at –

or re-advanced to – (100%) or near (82 – 83%) their LGM extents between 16.0 – 15.6

295   ka, after which all three glaciers rapidly retreated to their cirques within the next ~2 kyr,

at rates ranging between 35.6 and 6.8 m a^{-1}. It is possible that the glacier in Pine Creek

valley began retreating ~500 yr earlier than the other two glaciers, and likewise

completely deglaciated ~500 yr earlier. Pine Creek valley is shorter and steeper than

the other two valleys. Thus, it is possible that variations in valley hypsometry between

16

300 Pine Creek valley and the other two valleys may have caused the slight difference in

their deglaciation histories (Young et al., 2011). We also observe that Pine Creek valley

has the steepest average valley gradient and generally the slowest net retreat rate,

which is predictably a direct result of valley hypsometry since glacier lengths in steeper

valleys generally adjust less to equivalent changes in ELA. On the other hand, glaciers

305 occupying the lower-gradient Lake and Clear creek valleys experienced generally

higher reconstructed rates of retreat. Regardless, we find that while Pine Creek may

have initiated ~500 yr sooner than the other two, all three valleys were in a period of ~1-

1.5-kyr-long synchronous retreat once the other two glaciers began retreating. We

conclude that while there may have been some hypsometric influences on the timing of

310 deglaciation across our study site, evidence suggests these influences did not keep the

glaciers from synchronously retreating during a majority of their deglaciation. We find

that all three valley glaciers did not begin significantly retreating until ~5 – 6 kyr after the

culmination of the LGM in the Sawatch Range (since we assume boulder ages on both

LGM and recessional moraines represent the timing of moraine abandonment).

315 However, once glacier retreat initiated, deglaciation was completed within ~2 kyr.

From the existing records in the southern Rocky Mountains synthesized above,

we find that the pattern of deglaciation observed in the Sawatch Range was consistent

in a few but not all sites across the region. Collecting more records of alpine

deglaciation in the southern Rocky Mountains may be necessary to further test which

320 pattern, if any, is the dominant pattern of deglaciation in the region.

5.3 Drivers of southern Rocky Mountain deglaciation

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Records of global climate change over the last deglaciation suggest a link between rising CO_2 concentrations and global temperature (Denton et al., 2010; Shakun

325   et al., 2012; Putnam et al., 2013; Fig. 5). However, there is noticeable spatial heterogeneity in both the timing and magnitude of warming through the last deglaciation that cannot be attributed to global CO_2 forcing alone (e.g., Clark et al., 2012). We find that the initiation of significant deglaciation in some locations across the southern Rocky Mountains lagged rising CO_2 concentrations by as much as ~2 – 3 kyr (Fig. 5), which

330   suggests these glaciers were more likely influenced by regional forcings rather than global CO_2.

Ice core records—among other records—reveal a complex pattern of abrupt warming and cooling events that occurred in the North Atlantic region during the last deglaciation (Fig. 5; Buizert et al., 2014). Despite rising CO_2 concentrations beginning

335   ~18 ka, North Atlantic records reveal that cold conditions persisted until 14.7 ka, known as Heinrich Stadial 1 (HS-1). Following these sustained cold conditions, an abrupt transition to warmer conditions is marked by the HS-1/Bølling boundary at 14.7 ka (Buizert et al., 2014). We find that deglaciation at some locations in the southern Rocky Mountains encompasses the HS-1/Bølling transition.

Figure 5. Deglaciation of the Sawatch Range compared to other climate proxies. From top to bottom: Atmospheric CO_2 concentrations (Bereiter et al., 2015); Global and Southern Hemisphere temperature stacks (Shakun et al., 2012); Synthesized Greenland temperature from ice cores (Buizert et al., 2014); Lake Level reconstructions of Lake Bonneville (LB; black dashed line) and Lake Lahontan (LL; gray dashed line) from Reheis et al. (2014); Normalized BACON plots from Lake Creek (LC; orange), Clear Creek (CC; green) and Pine Creek valleys (PC; blue). Vertical lines correspond to the onset of CO_2 rise beginning ~18 ka and the Heinrich Stadial 1/Bølling transition at 14.7 ka.

Furthermore, the

relatively rapid and short-

lived nature of retreat for

glaciers in the Sawatch

Range – and some others

across the southern
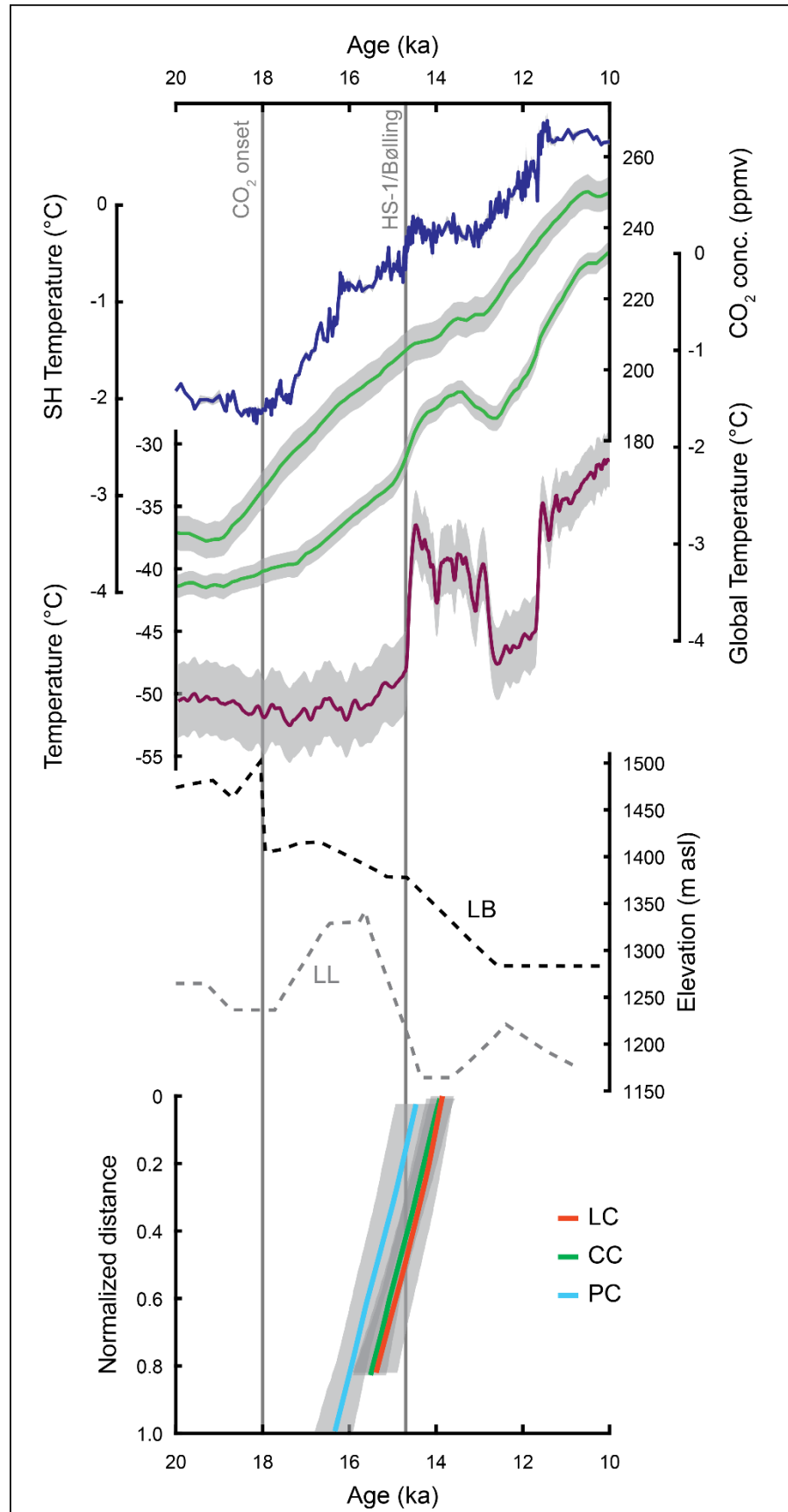
Rocky Mountains – appears to be more consistent with the abrupt manner of warming observed in the North Atlantic. However, glaciers were already retreating prior to the abrupt HS-1/Bølling transition at ~14.7 ka. Therefore, it is difficult to argue that North

380   Atlantic warming alone forced glacier retreat in the southern Rocky Mountains.

In addition to the alpine glaciers that existed in the mountainous regions of the western US during the late Pleistocene, large pluvial lakes such as Lake Lahontan and Lake Bonneville existed across the Great Basin (Fig. 1; Gilbert, 1890; Russell, 1885; Orme, 2008). These lakes could have been sustained by increased precipitation

385   delivery to the southwestern US (e.g., Munroe and Laabs, 2013; Oster et al., 2015; Lora and Ibarra, 2019) or were maintained simply by colder temperatures persisting throughout the region (e.g., Benson et al., 2013). Recent syntheses of past Great Basin lake levels reveal that Lahontan and Bonneville lakes resided at relative high stands between 15.5 and 14.5 ka (Benson et al., 2013; Reheis et al., 2014; Oviatt, 2015). After

390   this time, each lake experienced notable declines in lake level (Fig. 5), which could have been the result of reduced precipitation due to re-arranging storm tracks, warming temperature or a combination of both (Benson et al., 2013; Oster et al., 2015; Lora and Ibarra, 2019).

Recent modeling efforts have highlighted how North American ice sheets likely

395   influenced atmospheric circulation and regional climate throughout the Pleistocene (COHMAP members, 1985; Lofverstrom et al., 2014; Liakka and Lofverstrom, 2018; Lora and Ibarra, 2019). Specifically, there appears to have been drastic shift in climatologies over the western US when the Cordilleran (CIS) and Laurentide (LIS) ice sheets separated (Lofverstrom et al., 2014; Lora et al., 2016; Tulenko et al., 2020). For

400   example, during the last deglaciation, once the CIS and LIS separated, some model

results suggest the western US became warmer and drier (Lora et al., 2016). The latest

synthesis of the last deglaciation of the major North American ice sheets suggests the

separation occurred between 16 and 15 ka (Dalton et al., 2020). Thus, it is possible that

the saddle collapse and separation of the CIS and LIS and resulting atmospheric re-

405   organization may have led to both drastic pluvial lake level reductions and the rapid

deglaciation of some glaciers in the southern Rocky Mountains.

Between North Atlantic forcing and North American ice sheet forcing, it is difficult

to conclude what the primary driver of deglaciation in the Sawatch Range was; it may

be a combination of both forcings. We find that the approximate timing and rate of

410   deglaciation observed in the Sawatch Range points to abrupt warming and/or drying,

and is supported by pluvial lake level records in the western US, which have also been

tied to both North Atlantic forcing and North American ice sheet forcing (Munroe and

Laabs, 2013; Benson et al., 2013; Lora and Ibarra, 2019). Regardless, the data

synthesized here underscore the dominance of regional forcing mechanisms over global

415   forcing mechanisms on some climate records in the western US.

6. Conclusions

We constrain the timing and rate of deglaciation in three alpine valleys in the

Sawatch Range, southern Rocky Mountains. Beryllium-10 ages from ice-sculpted

420   bedrock in each valley reveal the significant retreat of glaciers from their LGM extents

(100%) or near (82 – 83%) their LGM extents was initiated shortly after 16.0 – 15.6 ka,

despite ~2 – 3 kyr of increasing global temperature forced by rising atmospheric CO_2.

Glaciers in three adjacent valleys retreated rapidly to their cirques within ~2 kyr,

culminating at ~14.2 – 13.7 ka, at rates ranging between 35.6 to 6.8 m a^{-1}. We

425   recognize that using the NENA production rate and Lm scaling produces ages 9 – 12%

older than the ages reported herein, which might change the interpretation of the

dataset. However, we favor the PPT/LSDn combination because the PPT calibration

site is closest in proximity and elevation to the Sawatch Range.

We hypothesize that one of two – or a combination of both – possible regional

430   climatic mechanisms were responsible for driving the pattern of deglaciation for some

glaciers in the southern Rocky Mountains. First, we find that for some alpine glaciers in

the region, the relatively rapid, short-lived and synchronous nature of retreat – including

those in the Sawatch Range – across the southern Rocky Mountains is more consistent

with the abrupt manner of warming observed in the North Atlantic than with steadily

435   increasing global temperature forced by CO_2 rise. However, evidence suggests glaciers

were already retreating prior to the HS-1/Bølling transition. Alternatively, lake level

records reveal that both Bonneville and Lahontan lakes lowered nearly in step with

some retreating alpine glaciers across the southern Rocky Mountains. Previous studies

have linked Great Basin pluvial lake regression to warming and the migration of

440   prevailing storm tracks due to atmospheric re-organization that may have been forced

by separation of North American ice sheets. Thus, warming and drying induced by

abrupt atmospheric re-organization at the time of LIS and CIS separation may have

driven both Great Basin lake level lowering and rapid alpine glacier retreat in some

valleys in the southern Rocky Mountains. While we cannot conclude that either one of

445   the aforementioned forcing mechanisms was solely responsible for deglaciation of the

Sawatch Range, we suggest that either one or both were stronger controls than increasing global temperature forced by CO_2 rise.

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Author contributions

JP Tulenko: Investigation (sample collection and processing), Conceptualization, Data curation, Writing – original draft, Visualization; **W Caffee:** Investigation (sample

460   collection and processing), Writing – review and editing; **AD Schweinsberg:** Investigation (sample collection and processing), Conceptualization, Writing – review and editing; **JP Briner:** Investigation (sample collection and processing), Conceptualization, Data curation, Supervision, Funding acquisition; **EM Leonard:** Investigation (sample collection), Conceptualization, Data curation, Writing – review and

465   editing.

Competing Interests

The authors declare that they have no known competing financial interests or personal

relationships that could have appeared to influence the work reported in this paper.

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