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

RC 1:

Detailed comments

Lines 123-125: It is not clear from this sentence whether the estimate that "glaciers remained at (100%) or near (82-83%) their LGM length until 16-15 ka" is derived by this study or a previous study.

While we measured the normalized moraine locations in this paper, the age ranges for the moraines between 16-15 ka were established in previous studies that dated those moraines. We have re-arranged this portion of the text, in accordance with both yours and RC 2's suggestion to read:

"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 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)."

Lines 139-145: Hypsometry is the only named non-climatic factor that is considered. Were these glaciers ever lake-terminating (e.g. Lake Creek)? What role could bed geometry have played?

While we recognize that there are lakes present in both Lake Creek and Clear Creek, these are dammed reservoirs and may or may not have been present at the time of deglaciation. Whether or not glaciers may have been lake-terminating near their terminal moraines, our focus is on glacier retreat upvalley, which would not have been influenced by terminal-moraine-area lake effects. Thus, the majority of retreat commenced in these valleys without any possible influence from lake-terminating dynamics. Even if lakes did exist, and dynamics associated with lakes is likely not among the explanations for any inter-valley variability.

To the point of bed geometry, we should be more explicit in describing how the retreat rates are influenced by valley geometries/hypsometry. We find that the retreat rates are significantly different between each valley and we wonder if this is attributable to valley geometry/hypsometry. The smallest, shortest and steepest valley (Pine Creek) retreats at the slowest rate while the other two valleys which are broader and much larger retreat at faster rates. As mentioned in our response to SC 1, we find there may have been some notable non-climatic factors that influenced when glaciers began initially retreating, and perhaps even the rates of retreat among the different valleys, but we think that the ~1 – 1.5 kyr of synchronous retreat across all three valleys is strong evidence for a climatic driver.

As mentioned in our reply to the short comment in the open discussion, we are adding in a brief discussion of retreat rates and average valley gradients and how the two scale, as well as appending the concluding statement at Line 269:

Starting at Line 217: “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 Creek valley.”

Starting at Line 269: “We also observe that Pine Creek valley has the steepest average valley gradient and 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 occupying the lower-gradient Lake and Clear creek valleys experienced 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 deglaciation across our study site, evidence suggests these influences did not keep these glaciers from synchronously retreating during a majority of their deglaciation.”

Line 150: The text refers to a “slightly modified” method. Modified from what – Corbett et al. (2016)? Modified how?

The differences in the procedure between our lab and the UVM lab are very minor and likely not worth mentioning. We have elected instead to simply remove the phrase “slightly modified”

Line 155-160: What was the ratio/10Be concentration of your procedural lab blank(s)?

We updated the text to include that information:

“After quartz purification, samples were dissolved in acid along with a 9Be carrier spike in two batches each with a process blank.”

And

“For samples collected in 2018, the process blank 10Be/9Be ratio was 2.96 x 10-15, and for samples collected in 2017 the process blank 10Be/9Be ratio was 9.56 x 10-16 (see Table 1 for details on sample collection dates).”

In addition, we added a footnote to Table 1 listing the process blank values.

Lines 175-179: This isn't the first time that Bayesian age-depth models have been used for transects of 10Be ages. Previous such work (e.g. Jones et al., 2015, Nat. Comms.; Small et al., 2018, GSA Bull.) should be acknowledged. In general, the approach to derive retreat rate estimates needs more detail. What is exactly being modelled here? Is it assuming a linear or non-linear relationship between age and depth/distance? Is the model accounting for age uncertainties? If so, are the age uncertainties included at 1 or 2 standard deviations, weighted or unweighted?

Thank you for bringing these additional citations to our attention. We tried to be as thorough in acknowledging that this type of work has been published before so we are happy to include these citations in the list cited at line x

As to describing BACON with slightly more detail, we amended the mentioned paragraph to now read:

"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 10Be 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."

Lines 183-184: Clarify what you mean by "net retreat rates".

We use the term "net" retreat rates because there may be many short-term re-advances "hidden" in our chronology, short events that are un-detectable by our chronology. Thus actual retreat rates could have been higher locally. We believe that "net" retreat rate is an appropriate way to characterize our derived retreat rates.

Results: You should initially report the results for only the new data (the 12 ages from Clear Creek and Pine Creek), even if only described briefly. After that, you can describe the results in combination with the previously published ages.

We added the following sentence to the beginning of the paragraph:

"The 12 new sculpted-bedrock 10Be ages reported here range 15.8 ± 0.3 – 13.7 ± 0.3 ka (Fig. 2; Table 1)."

Line 190 (and elsewhere): How confident are you in the precision of your distance measurements? Would rounding to the nearest whole percent be more suitable?

We measured profiles along valley floors in ArcGIS to get precise numbers, but we agree that rounding to the nearest whole percent is more realistic. We fixed this throughout the text and in Table 1.

Line 214 (and elsewhere): Please clarify here whether the retreat rate result is reported at 68% or 95% confidence. Additionally, the format of reporting is probably not suitable, as the model output distribution is likely non-Gaussian. Such results are therefore typically reported as an uncertainty range, rather than mean with uncertainty.

We appreciate the insight on reporting model outputs that you correctly pointed out are non-Gaussian. We now report the 95% uncertainty range throughout the text.

Lines 233-243: The identification of likely outliers is based on the general stratigraphic relationship of ages within the dataset. These outliers also happen to fall outside of the 95% confidence bounds from the BACON model. But, as far as I can tell, BACON was not used to systemically identify (and remove) outliers. In which case, the estimated retreat rates from BACON will be influenced by these apparent outliers. So, how do the retreat rates differ when these outliers are excluded?

When calculating the resulting retreat rates if we remove outliers and in all three valleys, the retreat rates decrease by 1.7, 2.7 and 6% for Lake Creek, Clear Creek and Pine Creek valleys respectively. We have added the following sentence:

"Removal of potential outliers reduces retreat rates by 1.7%, 2.7% and 6% for Lake Creek, Clear Creek, and Pine Creek valleys respectively."

Lines 247-252: More of a discussion point than a criticism: While it seems fairly well justified to use the Promontory Point calibration site instead of NENA site based on locality and elevation range, it is also worth considering the time period used for the calibration sites. The Promontory Point site is calibrating the production rate at 18.9-18.0 ka, while the NENA site is calibrating for 16.8-13.8 ka. The dataset reported here best correlates to the time period covered by the NENA site, which could be an argument to use this production rate instead of that from Promontory Point.

This is a good point – production rate choice is always a topic of discussion. Fundamentally, this is why we provide our ages with two reasonable production rate choices. As the reviewer knows, ultimately, you have to choose one to go with for the main text. While we agree that there are advantages to dating features close in age to a calibration site, it is likely that other factors (as mentioned in the text) like site elevation, are also important. Ultimately, the age ranges at the PPT and NENA calibration sites are fairly close in age to ours. That said, because PPT is the closest in elevation to our field area, and is a rate that others are using in their papers for Rocky Mountain cosmogenic nuclide chronologies, we chose to report PPT in our text.

Lines 266-269: Explain how glacier hypsometry and/or steepness would influence differing glacier behaviour during deglaciation.

We are adding in a brief discussion of retreat rates and average valley gradients and how the two scale, as well as appending the concluding statement highlighted at the beginning of our response:

Starting at Line 217: "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 Creek valley."

Starting at Line 269: "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 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 deglaciation across our study site, evidence suggests these influences did not keep these glaciers from synchronously retreating during a majority of their deglaciation."

Lines 285-288: Glaciers don't respond to CO2, so directly comparing to CO2 seems a little irrelevant. Of course, there is a close relationship between CO2 and temperature, but why not compare your glacier retreat records to proxy global temperature (e.g. Shakun et al., 2012)?

We thank the reviewer for highlighting this. We have changed the text and Figure 5 to show the proxy global temperature curve compiled in Shakun et al., 2012. We also recognize that the compilation curves from Shakun et al. are clearly influenced by more than just greenhouse gas forcing, particularly in the Northern Hemisphere. It may be argued that the southern hemisphere compiled record is more closely tied to atmospheric CO_2 concentrations so we are including both the global record and the southern hemisphere records in figure 5.

Lines 327-334: The argument that there is similarity between records, and "possible teleconnections", isn't particularly convincing. The majority of the recorded retreat occurred before the North Atlantic climate shift; your ages indicate retreat initiated 1-2 kyr earlier that the climate shift at 14.7 ka. I'd like to see the text rephrased, without mention of teleconnections.

As you observe, the glaciers in our field site do begin retreating prior to the onset of North Atlantic abrupt warming. Originally we were more focused on the fact that the rate and short-lived nature of retreat was most similar to the abrupt North Atlantic warming even though the timing was not perfect. And so, we removed mention of teleconnection since it is difficult to argue that glaciers retreated in response to N. Atlantic warming if they were already retreating prior to the abrupt warming event.

Rather, we reworded the section to read:

"We find that deglaciation at some locations in the southern Rocky Mountains encompasses the HS-1/Bølling transition. 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 apparently were already retreating prior to the abrupt HS-1/Bølling transition at ~14.7 ka. Therefore, it is difficult to argue that North Atlantic warming alone forced glacier retreat in the Southern Rocky Mountains."

We also appended a few sentences in the abstract to read:

"Deglaciation in the Sawatch Range commenced ~2 – 3 kyr later than the onset of rising global CO2, and prior to rising temperatures observed in the North Atlantic region at the Heinrich Stadial 1/Bølling transition."

Lines 329-330: What is this period of relative glacier stability based on?

Our original line of thought was that, based off of the previous moraine chronologies at our field site, it is possible that glaciers remained at relatively stable positions from the culmination of the LGM up until they began retreating at 16 – 15 ka. However, it is also possible that glaciers retreated in this time frame and then re-advanced to form the moraines deposited at 16 – 15 ka. We do not know which scenario is correct so we elected to remove this sentence.

Line 383: "one of two", or both mechanisms, as you state below. Reword this, as these are not mutually exclusive explanations.

We rephrased the sentence with the following: "we hypothesize that one of two – or a combination of both – possible regional climatic mechanisms…"

Lines 385-386: As mentioned above, it is a difficult to accept that the glaciers "began retreating around the time of abrupt warming" when the data indicate retreat started at least 1-2 kyr before the climate transition. There is only correlation here if you doubt the accuracy (or precision) of the retreat ages, in which case you should discuss more thoroughly.

Re-worded the text here to read as follows:

"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 increasing global temperature forced by CO2 rise. However, evidence suggests glaciers were already retreating prior to the HS-1/Bølling transition."

Lines 387-390: I like the comparison of the rates of glacier and climate change, as it makes use of your estimated retreat rates and it can be effective if there is any doubt in the absolute timing. However, a number of non-climatic, glaciological processes can also contribute to faster rates, even with a gradual forcing. Such processes also need to be considered.

We agree that the rate of retreat can be modified by non-climatic factors. And this is in fact supported by the relationship between retreat rates and valley gradients that we previously discussed. However, that all three neighboring glaciers evacuated their valleys in the same 1-2 kyr interval in time, relatively quickly despite the variation in retreat rate, we believe must be climatically forced.

Line 400: Sorry to be pedantic, but as above, glaciers don't respond to gas concentrations. Refer to global temperature instead.

Changed the wording here and elsewhere to say, "increase in global temperature forced by CO_2 rise"

Table 1: Transact distances are reported to the nearest metre over many thousands of metres. This seems unrealistically precise.

As previously stated, we now round.

Figure 2: Need to make clear what are the new data and what are previously published data. There are also two references to "n=x", which I presume need values added.

Closed circles are now previously published ages and open circles are new ages in the figure.

The references to n = x in both cases have been resolved.

RC2:

Line-by-line comments:

Line 50: the Uinta Mountains are part of the Middle Rocky Mountains physiographic province and probably do not need to be singled out here (although they are awesome and have a fantastic glacial record).

Removed the Uinta Mountains as a singled out entity

Line 53: could probably state “Latest Pleistocene or Early Holocene” here, as Marcott et al. found that some cirque floor moraines were abandoned as early as 15 ka. Additionally, basal 14C ages from lake sediments inboard of cirque-floor moraines are Pleistocene in age in some mountains (see records published by J. Munroe for the Uinta Mountains (Munroe and Laabs, 2017) and by J. Munroe and others in the Ruby Mountains).

Replaced “by the start of the Holocene” with “during the late glacial-to-early Holocene”

Lines 90-93: should cite some of the earlier, original reports on the glacial record in southern Colorado and northern New Mexico. Jim McCalpin did some work in the region (mostly the Sangres) in the 1980s and Keith Brugger has done more recent mapping in the Sawatch.

Thank you for bringing these citations to our attention. We felt it would be most appropriate to add the following citation to the list since we are only citing summary papers here:

Laabs, B. J. C., Licciardi, J. M., Leonard, E. M., Munroe, J. S., and Marchetti, D. W.: Updated cosmogenic chronologies of Pleistocene mountain glaciation in the western United States and associated paleoclimate inferences, Quaternary Science Reviews, 242, 106427, https://doi.org/10.1016/j.quascirev.2020.106427, 2020.

Although we did include the following citation to the section specifically discussing the Sawatch Range:

Brugger, K. A., Ruleman, C. A., Caffee, M. W., and Mason, C. C.: Climate during the Last Glacial Maximum in the Northern Sawatch Range, Colorado, USA, Quaternary, 2, 36, 2019a.

Lines 101-104: the Guido et al. cosmo ages are pre-CRONUS (and also pre-really good AMS measurements) and probably should be recalculated in order to accurately compare with more recently published cosmo ages from southern Colorado. If you’ve already done this, then it’s worth specifying here. If not, the Guido et al. ages are available in ICE-D.

Thank you for the suggestion, we recalculated the ages and updated some of the text to reflect those changes. In addition, we added the following phrase at the beginning of the section:

“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”

Line 174: prior to this paragraph, consider adding a paragraph about how exposure ages of glacially scoured bedrock are related to ice margin position and some potential limitations of dating these to track ice retreat compared to moraines. As you know, glacially scoured bedrock surfaces that protrude above the valley floor (forming smooth and easy-to-sample surfaces) represent places of minimal scour depth, which can result in an inheritance problem. The Bayesian approach helps to sort this out by accounting for relative age differences, but even so, the potential for inheritance is greater than for most other applications of cosmogenic dating and should be acknowledged. Snow cover is another important consideration along valley floors and should be acknowledged if not assessed.

Thank you for the suggestion. We added the following sentence to the end of the first paragraph in the section to acknowledge that incomplete erosion is an issue when it comes to exposure ages on glacially sculpted bedrock:

“Bedrock surfaces located in the bottoms of valley floors – where glacial erosion is maximized – were specifically targeted since the potential for incomplete scouring of these surfaces can lead to inherited nuclides and ages that are older than expected.”

In addition, we did not choose to make any corrections for snow shielding nor post-depositional bedrock erosion and we acknowledge that with the following sentence at the end of the second paragraph in the section:

“We do not attempt to make any corrections for snow cover or post-depositional bedrock surface erosion.”

Lines 189-211: consider reorganizing the reporting of ages here. The bedrock exposure ages are reported first, then the exposure ages of recessional moraines/young modes of terminal moraines, and then the bedrock ages are described again. Perhaps starting with the moraine ages (or including them in a previous section) and focusing just on the bedrock exposure ages here would improve the flow of this section and a smoother transition to the retreat rates in the subsequent paragraph.

Thank you for the suggestion. We agree that it is a little awkward reporting the moraine ages here in the results when we did not date them in this study. So we decided to move this paragraph to the previous section (2. Setting).

Lines 233-242: the statistical reasons for excluding four exposure ages are explained well here, but the most likely reason that some exposure ages fall out of stratigraphic order, inconsistent exposure between sample sites, is not. As noted in a previous comment, the potential limitations of bedrock exposure ages should be acknowledged.

We added in the following sentences to the end of the paragraph that hopefully convey the potential issues associated with each suspected outlier:

"Two suspected outliers are older than expected, which may have been caused by insufficient glacial erosion leading to inheritance. The two remaining potential outliers are younger than expected, which could have resulted from excessive soil and snow cover, enhanced post-depositional bedrock surface erosion, or erosion and removal of overlying sediments, or a combination of these factors."

Lines 243-255: I can't see the reason for using NENA-Lm as an example of another production/scaling model for high altitude sites in western NA. The NENA calibration site is far away and much lower in elevation, and I think the reason for using it in some earlier studies in the mountain west was to illustrate the effects of lower SLHL production rate (which started to appear in the literature circa 2010) on exposure ages. Perhaps a better option would be to compare the ages computed with the Promontory Point calibration/LSDn scaling with ages computed with a globally averaged production rate and LSDn scaling, or just show the effects of using different scaling models with the Promontory Point calibration? This would better illustrate the degree to which the choice of production rate affects exposure ages, which I assume is what the authors are doing here.

The goal of using NENA here was to show it as a sort of an 'end-member' production rate since it is relatively low (especially compared to PPT). In addition, it is the other production rate (or series of rates) that exist from North America. We did originally calculate the ages using the default PR in CRONUS and those ages fall somewhere between PPT and NENA. We wanted to emphasize that even if we used a relatively low PR that produces ages which are 9 – 12% older (e.g. NENA), there is still a significant delay in deglaciation compared to the time of global warming and CO_2 rise.

We rephrased the beginning of the final paragraph in section 5.1 to read:

"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 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, 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 production rate calibrations and scaling schemes, and are between 9 to 12% older than when using PPT/LSDn (all other combinations fall somewhere in between; Fig. 4; Table 1)."

Lines 267-269: should probably cite Young et al. (2011) at the end of this sentence.

Done

Fig. 1: this is a beautiful map! As you reference some other glaciated mountains in the western U.S. in the introductory paragraphs, consider labeling some of the ones shown on the map along with pluvial lakes.

We originally chose not to label all of the other glacial centers in the western US since we did not discuss chronologies from any other location outside the southern Rocky Mountains.

Fig. 2: seems like a good idea to show all the terminal moraine cosmo ages instead of just the young mode at Pine Creek, given that the terminals are the "starting point" for ice retreat? Just a suggestion; I understand that you're emphasizing the onset of ice recession in this paper, not the glacier maxima.

While we do agree that this might be valuable, we did not originally report individual moraine ages in the text (rather an approximate age range) for the culmination of the LGM in our field area since, as you mention here, we are only focusing on deglaciation rather than the LGM. That said, we will report the LGM moraine ages on the figure and mention in caption that the ages are mean ages from moraine boulders reported in Schweinsberg et al. (2020).

Lake Creek terminal moraine: 20.6 ± 0.6 ka
Clear Creek terminal moraine: 20.0 ± 1.0 ka
Pine Creek terminal moraine: 22.3 ± 1.3 ka

Fig. 5: may want to consider a more recent and focused assessment of the Bonneville hydrograph in Oviatt (2015) or some of the specific discussions about the duration of the Provo phase of the lake by D. Miller (2016).

We did not find large enough differences between the Reheis et al. (2014) lake level curves and those from Oviatt et al. (2015) and D. Miller (2016) that would significantly alter our interpretations since the timing of North American ice sheet separation, lake level lowering and Sawatch Range deglaciation are currently only loosely correlated.

EC1:

Ln 271-2: "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". You cannot jump over the gun like above because you are based on the different types of samples (i.e. Moraine erratics VS bedrock). Moraine boulders can indicate advance or stagnation (As you know there is some debate on the implication of ages of boulders on a moraine. Polished bedrock usually indicates the timing of deglaciation as you did. There should be differentiation on the interpretation of ages of two types sampled (Reviewer 2 told about this problem). You may want to make more explanation and discussion on this matter.

We, along with other groups working on moraine dating, interpret moraine boulder ages as the culmination of a glacier advance. We think that the boulders on top of a moraine are the last to be deposited, thus represent the end of the advance. And when the moraine, and the uppermost layer of sediment (the surface boulders that we often choose to date), becomes abandoned, the boulder clocks begin. Thus, we think that the 16 ka moraines in our study valleys ought to be a suitable starting point for our up-valley bedrock transects.

We added in the following phrase to the highlighted sentence:

"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 LGM moraines represent the timing of moraine abandonment)."

Figure 2: Can you separate the type of samples for 10Be dating? For example, erratics (open circle) Vs bedrock (filled circle).

In figure 2, all of the samples with circles are from sculpted bedrock. The only ages from moraine boulders are the ones that are averages for the recessional moraines in Lake Creek and younger mode of ages on the terminal moraine in Pine Creek. We thank you for the comment, it will help clarify for our readers should the manuscript be accepted. We changed the label for the moraine ages in all three valleys to better distinguish moraine boulder ages from sculpted bedrock ages.

Figure 3: How about showing the sample number on the picture (or on the sampled boulder or bedrock), which is better to readers?

Great – this also helps to clarify. We now include sample names in the images along with the reported ages.

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.

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While we cannot definitively argue for exclusively North Atlantic forcing or North 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 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 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 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; 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).

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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 are lacking to bolster or refute this hypothesis.

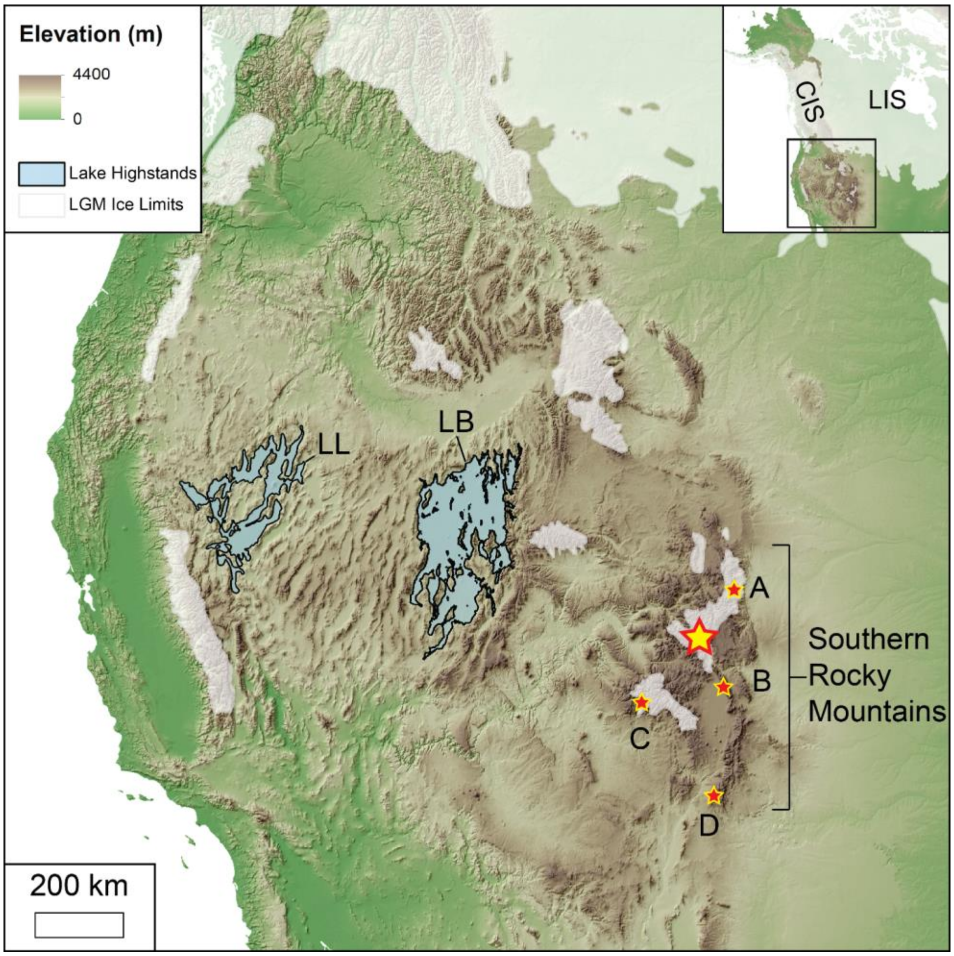

Figure 1. Key moraine chronologies from the southern Rocky Mountains and locations of glaciation centers and large pluvial lakes in the western US following the Last Glacial Maximum (LGM). LL = Lake Lahontan, LB = Lake Bonneville, A = Colorado Front Range, B = Sangre de Cristo Mountains, C = San Juan 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 LSD*n* 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

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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 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 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 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.

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Prominent moraines originally mapped as part of the surficial geologic map of the 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., 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 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. (2011) argued

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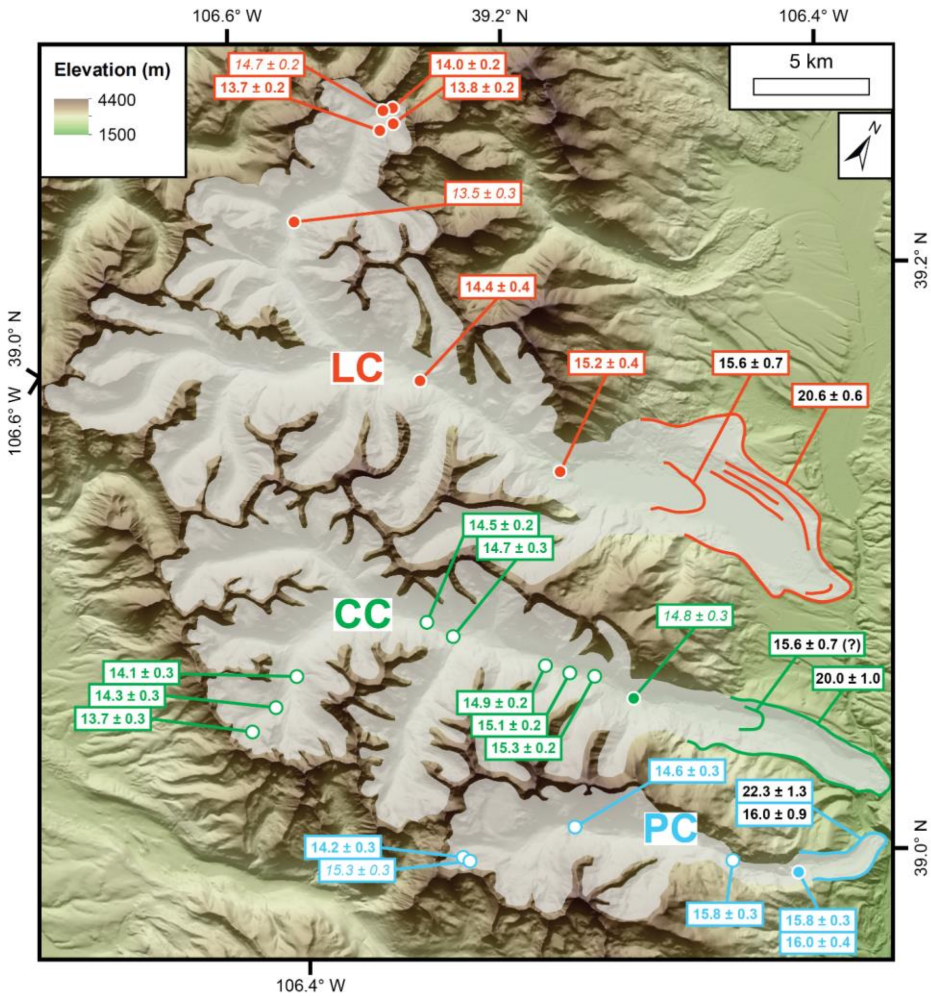

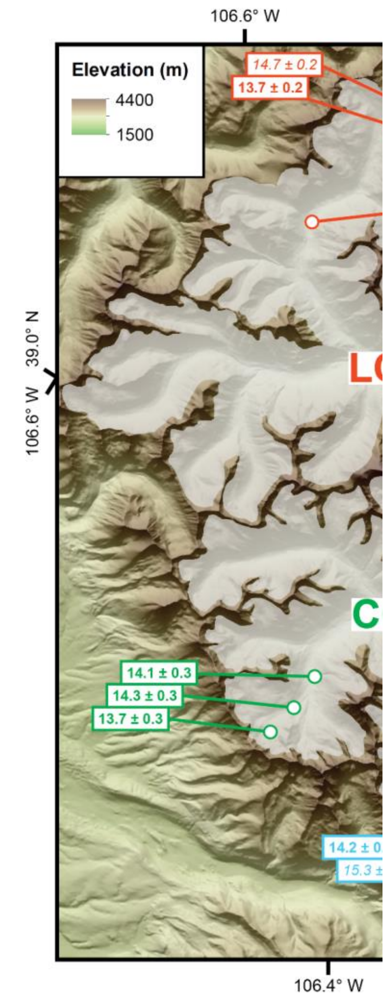

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Figure 2. Ice-sculpted bedrock ^{10}Be ages from Lake Creek (LC; orange), Clear Creek (CC; green), and Pine Creek valleys (PC; blue). New ages are open circles and previously published ages are closed. Bedrock ages with italicized labels are suspected 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 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 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 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 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 purification, samples were dissolved in acid along with a ^{9}Be carrier spike in two

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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. $^{10}Be/^{9}Be$ ratios were measured and standardized to the reported 07KNSTD3110 ratio of 2.85 x 10^{-12} (Nishiizumi et al., 2007). For samples collected in 2018, the process blank $^{10}Be/^{9}Be$ ratio was 2.96 x 10^{-15}, and for samples collected in 2017 the process blank $^{10}Be/^{9}Be$ 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; 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 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.

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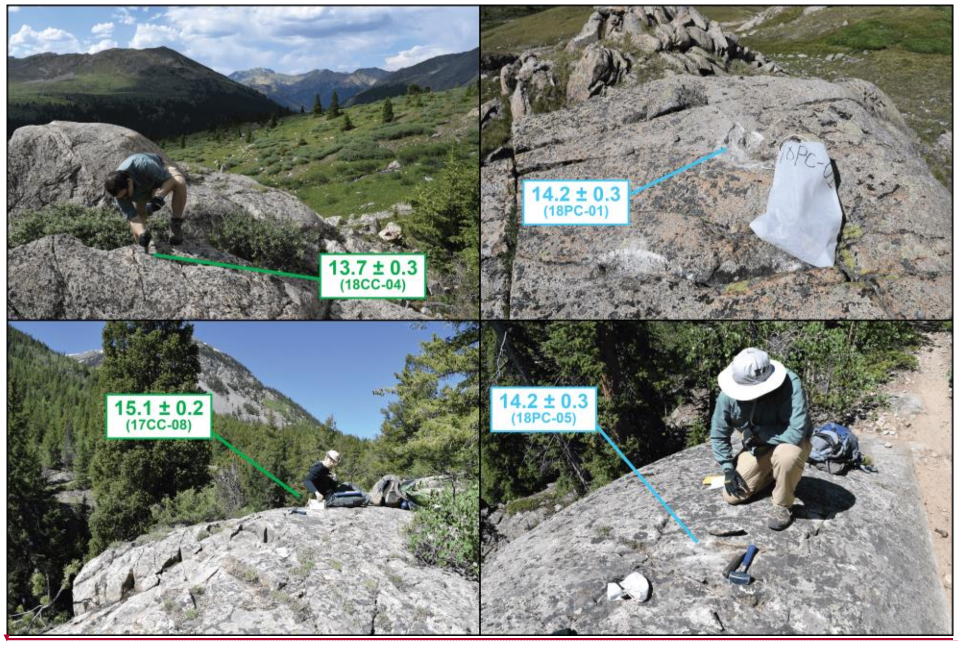


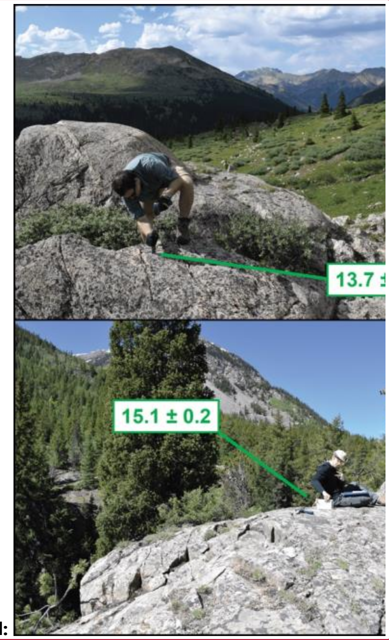
Deleted: 

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

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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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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 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 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 Creek valley.

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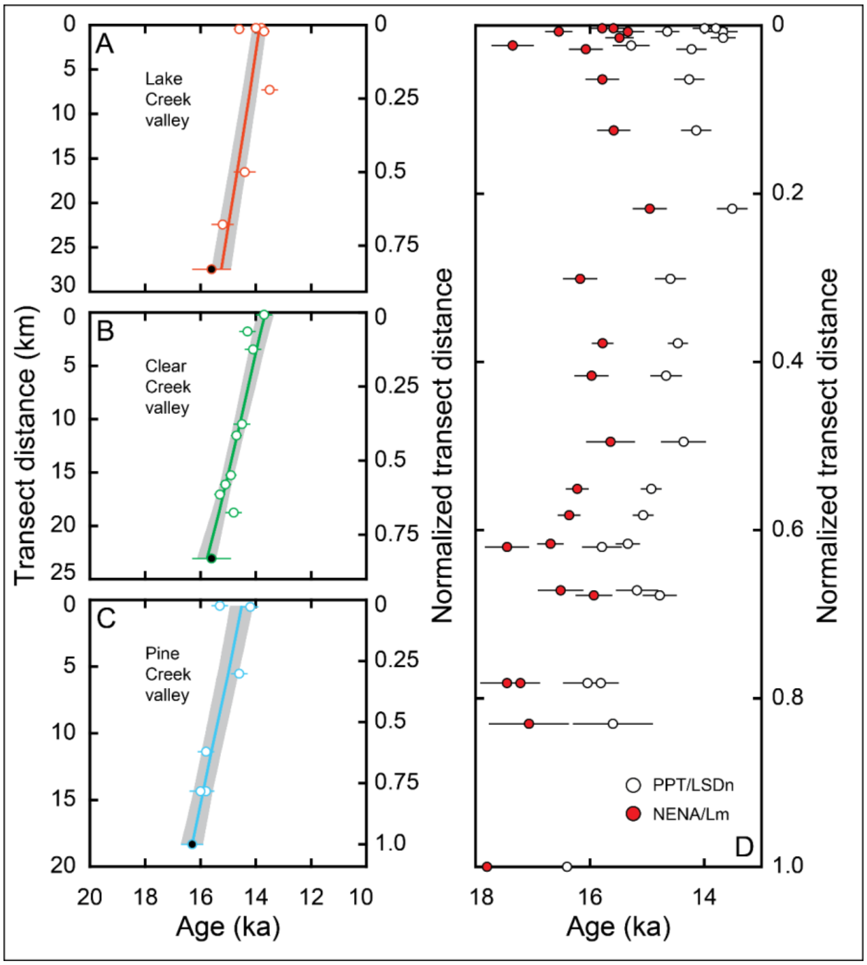

Figure 4. Summary plots of ^{10}Be ages and BACON statistical analysis results. A) Lake Creek valley (orange), B) Clear Creek valley (green), and C) Pine Creek valley (blue). Ages in solid black fill at the bottom of each transect are from recessional moraine ages (Young et al., 2011; Schweinsberg et 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% 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 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 expected, which could have resulted from excessive soil and snow cover, enhanced post-depositional bedrock surface erosion, or a combination of these factors.

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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 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,

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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 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 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 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 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

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

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

5.3 Drivers of southern Rocky Mountain deglaciation

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 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 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 ~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.

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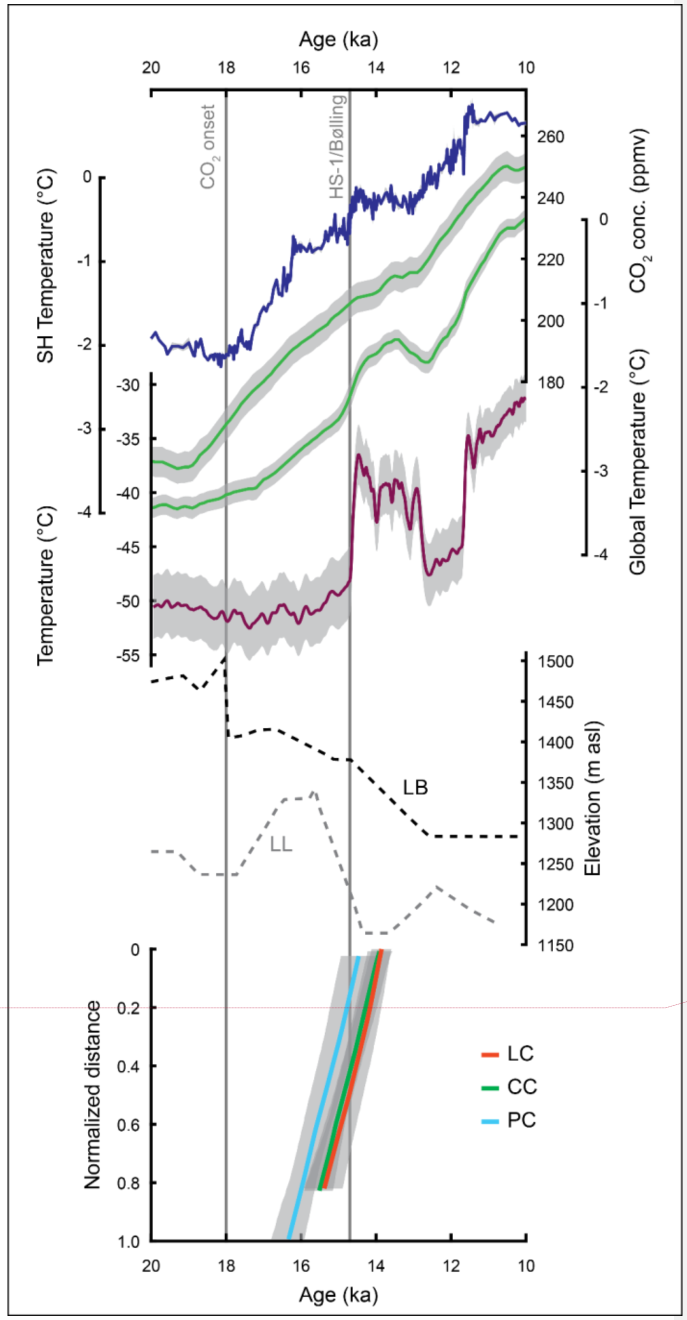
Figure 5. Deglaciation of the Sawatch Range compared to other climate proxies. From top to bottom: Atmospheric CO_2 concentrations (Bereiter et al., 2015); Global and Southern Hemisphere temperature stacks (Shakun et al., 2012); Synthesized Greenland temperature from ice cores (Buizert et al., 2014); 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

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

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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 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 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 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 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-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 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 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 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.

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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 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/LSD*n* 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 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 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 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 the aforementioned forcing mechanisms was solely responsible for deglaciation of the

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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 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 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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