Quaternary Research

doi:10.1017/qua.2020.21

Cosmogenic ^{10}Be exposure dating of Bull Lake and Pinedale moraine sequences in the upper Arkansas River valley, Colorado Rocky Mountains, USA

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(Received October 15, 2019; Accepted February 27, 2020)

Abstract

Many formerly glaciated valleys in the western United States preserve detailed glacial features that span the penultimate glaciation through the last deglaciation; however, numerical age control is limited in many of these systems. We report 35 new cosmogenic ^{10}Be surface exposure ages of moraine boulders in the Sawatch Range, Colorado. Eight ages suggest Bull Lake moraines in Lake Creek (range: 132–120 ka, $n = 4$) and Clear Creek (range: 187–133 ka, $n = 4$) valleys may correlate with Marine Isotope Stage 6. In Lake Creek valley, 22 ^{10}Be ages from Pinedale end moraines average 20.6 ± 0.6 ka, and 5 ^{10}Be ages from a recessional moraine average 15.6 ± 0.7 ka, indicating that glaciers occupied two extended positions at ∼21–20 and ∼16 ka. The glacial extent dated to ∼16 ka was nearly as great as that of the earlier glacial phase, suggesting that climate conditions in the Colorado Rocky Mountains at this time were similar to those of the last glacial maximum. Combining these moraine ages with seven previously published ^{10}Be ages from cirque and valley-bottom bedrock reveals that the Lake Creek paleoglacier lost 82% of its full glacial length in ∼1.5 ka and was completely deglaciated by ∼14 ka.

Keywords: Pleistocene; Glaciation; Cosmogenic isotopes; ^{10}Be dating; Moraines; Pinedale; Bull Lake; Rocky Mountains; Deglaciation; Colorado; Sawatch Range

INTRODUCTION

Reconstructing the timing and pattern of Pleistocene glaciation and deglaciation helps to enhance our understanding of past climate drivers and dynamics (e.g., Thackray et al., 2008; Davis et al., 2009; Owen et al., 2009; Shakun et al., 2015). Many studies have developed detailed Pleistocene glacial chronologies in the western United States, revealing both synchronous and asynchronous glacial behavior across the region (Licciardi et al., 2004; Thackray et al., 2004; Young et al., 2011). Aspects of these glacial histories have been interpreted to reflect climate forcings at a range of spatial scales, from global to local (e.g., Hostetler and Clark, 1997; Licciardi et al., 2001, 2004; Munroe et al., 2006; Licciardi and Pierce, 2008, 2018; Thackray, 2008; Refsnider et al., 2008; Laabs et al., 2009; Young et al., 2011; Shakun et al., 2015; Marcott et al., 2019). Asynchronous glacial behavior may reveal the influence of regional- or local-scale climatic factors or internal dynamics driving glacial responses that are superimposed on global-scale climate change, such as insolation or CO_2 forcings (Shakun et al., 2015). For example, variable glacial behavior has been attributed to differences in glacial hypsometry, local climate, and/or glacial response times (e.g., Licciardi et al., 2004; Thackray et al., 2008; Laabs et al., 2009; Young et al., 2011; Leonard et al., 2017b) and shifting orographic precipitation influences (Licciardi and Pierce, 2018). Alterations in moisture delivery patterns driven by former North American ice sheets or large paleolakes have also been postulated to modulate mountain glaciation in the western United States (e.g., Licciardi et al., 2004; Laabs et al., 2006; Munroe et al., 2006; Oster et al., 2015).

Glacial deposits corresponding to the Bull Lake (penultimate Pleistocene glaciation, Marine Isotope Stage [MIS] 6) and Pinedale (MIS 2) glaciations in the Rocky Mountains

Cite this article: Schweinsberg, A. D., Briner, J. P., Licciardi, J. M., Shroba, R. R., Leonard, E. M. 2020. Cosmogenic ^{10}Be exposure dating of Bull Lake and Pinedale moraine sequences in the upper Arkansas River valley, Colorado Rocky Mountains, USA. *Quaternary Research* 1–15. https://doi.org/10.1017/qua.2020.21

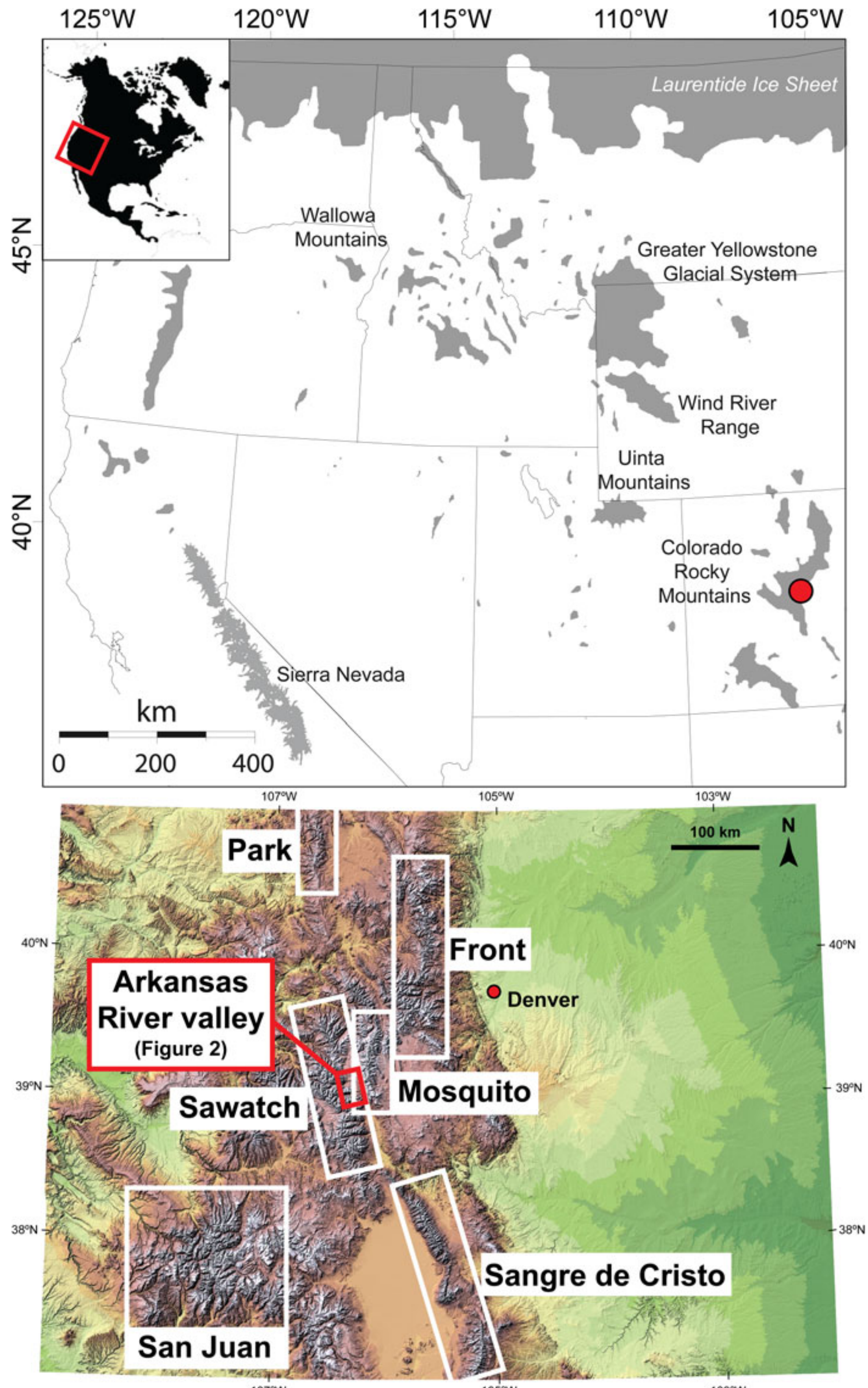

Figure 1. (Top) Last glacial maximum glacial extents in the western United States (gray shading; adopted from Porter et al. [1983] and Young et al. [2011]). Red circle denotes location of the upper Arkansas River valley in the Colorado Rocky Mountains. Inset map (top left) indicates the western United States in the context of North America. (Bottom) Map of Colorado showing the mountain ranges discussed in the text. (For interpretation of the reference to color in this figure caption, the reader is referred to the web version of this article.)

have been a focus of ongoing study since the early twentieth century (e.g., Blackwelder, 1915; Richmond, 1965; Porter et al., 1983; Pierce, 2004). Similar to glacial chronologies throughout the western United States, the timing of Pinedale maxima and the onset of deglaciation vary between mountain ranges within Colorado (Leonard et al., 2017b). To our knowledge, Colorado glacial chronologies derived from cosmogenic nuclide exposure dating methods are available from six mountain ranges (Fig. 1; Park, Front, Sawatch, Mosquito, Sangre de Cristo, and San Juan Ranges) (Leonard et al., 2017b, and references therein; Brugger et al., 2019a). These chronologies highlight differences in glacial and deglacial patterns. Numerical modeling studies have also been conducted for several paleoglacier systems, providing quantitative limits on temperature and precipitation conditions that drove Pinedale glaciation and deglaciation (Brugger, 2006, 2010; Brugger et al., 2009, 2019b; Ward et al., 2009; Dühnforth and Anderson, 2011; Schweinsberg et al., 2016; Leonard et al., 2017b) as well as Bull Lake glaciation (Leonard et al., 2014).

Established glacial chronologies suggest that glaciers throughout Colorado reached their maximum Pinedale extents before ~23.5–19.5 ka, with near-complete deglaciation in most valleys by ~15–13 ka (all previously published ^{10}Be ages are recalculated using the Promontory Point production rate [Lifton et al., 2015] and LSD*n* scaling scheme [Lifton et al., 2014], unless noted otherwise). However, evidence exists from the Sangre de Cristo Mountains and Sawatch Range for extensive glaciers at or near their Pinedale maxima as late as ~16 ka (Young et al., 2011; Leonard et al., 2017a), which is similar to findings in the Wasatch Range, Utah (Laabs et al., 2011). By contrast, some glaciers in the San Juan Mountains may have retreated significantly from their Pinedale maximum extents as early as ~21 ka and were considerably reduced in size by ~16 ka (Guido et al., 2007; Ward et al., 2009). Except in the San Juan Mountains, moraine chronologies throughout Colorado support the concept of two Pinedale glacial culminations at ~21–20 and ~17–16 ka (Briner, 2009; Ward et al., 2009; Leonard et al., 2017a).

The timing of deglaciation in Colorado is also variable, initiating earlier in the San Juan and Front Ranges and slightly later in the Sawatch and Sangre de Cristo Ranges (Leonard et al., 2017b). Several proposed hypotheses called upon global and/or regional drivers of glacial behavior to explain these inter-range asynchronies in the western United States (Licciardi et al., 2004; Young et al., 2011; Shakun et al., 2015). For example, Young et al. (2011) attributed the dominant phase of glacial recession in the Sawatch Range to the temperature changes associated with the North Atlantic Bølling-Allerød warm interval (~14.7–12.9 ka; Stuiver and Grootes, 2000), although refined cosmogenic isotope production rates and scaling models leave open the possibility that the initial rise in atmospheric CO_2 at ~18 ka may be the major factor driving glacial retreat (e.g., Shakun et al., 2012, 2015; Parrenin et al., 2013; Leonard et al., 2017b). However, in the San Juan and Front Ranges, as well as in other mountain ranges across the western United States (Fig. 1; e.g., Shakun et al., 2015), evidence exists for earlier (pre–18 ka) glacial recession that is not readily ascribed to global or hemispheric forcings. Alternatively, regional- to local-scale mechanisms, such as precipitation forcing (e.g., Oster et al., 2015; Laabs and Munroe, 2016), may play a role in regulating glacial behavior in the Colorado Rocky Mountains, but the importance of regional forcing remains unclear.

To provide insight into forcings driving the spatial and temporal patterns of glacial behavior, detailed chronologies that not only mark the timing of glacial culminations but also span the onset and entirety of deglaciation are required. Although many locations in the western United States afford these dating opportunities, the upper Arkansas River valley contains some of the most extensive sequences of till and outwash in central Colorado, including well-preserved recessional moraines, many of which are in the valleys on the eastern side of the Sawatch Range (Fig. 2). Building on previous studies (Briner, 2009; Young et al., 2011; Shroba et al., 2014; Schweinsberg et al., 2016), we construct a detailed ^{10}Be chronology for Bull Lake and Pinedale terminal moraines, Pinedale recessional moraines, and upvalley bedrock and cirque sites (Young et al., 2011; Leonard et al., 2017b). In this paper, we present 35 new cosmogenic ^{10}Be exposure ages that, when combined with prior work in the upper Arkansas River valley, yield a total of 82 ^{10}Be ages that collectively constrain the middle and late Pleistocene glacial history of this region.

REGIONAL SETTING

Previous work

During the Bull Lake and Pinedale glaciations, Sawatch Range glaciers extended beyond the range front, forming large lateral and end-moraine complexes tied to extensive outwash sequences (Nelson and Shroba, 1998; Shroba et al., 2014). The preservation of these surficial deposits and their associated landforms has attracted many geological investigations (e.g., Hayden, 1874; Capps and Leffingwell, 1904; Davis, 1905; Westgate, 1905; Capps, 1909; Ray, 1940; Richmond and Tweto, 1965; Tweto and Case, 1972; Nelson and Shroba, 1998; Schildgen, 2000; Briner, 2009; Young et al., 2011; Ruleman et al., 2013; Shroba et al., 2014; Schweinsberg et al., 2016; Kellogg et al., 2017; Brugger et al., 2019b). Although the relative ages of these moraines can be distinguished by morphostratigraphic features, such as the sharpness of moraine crests as well as boulder abundance and weathering (Nelson and Shroba, 1998), numerical age constraints were recently established with cosmogenic ^{10}Be exposure dating. Thus far, the sole attempt to date the Bull Lake glaciation in the upper Arkansas River valley was conducted in Dry Creek Gulch (Pine Creek valley), yielding ^{10}Be ages ($n = 10$) from boulders and pebble collections on the left lateral moraine that range from 72 to 4 ka, all of which were interpreted to be anomalously young (Fig. 2; Briner, 2009). Although multiple relative-age criteria suggest the possibility of a glacial advance between MIS 6 and MIS 2 in the Rocky Mountains (e.g., Colman and Pierce, 1986), the majority of studies reveal deposits limited to MIS 6 and/or MIS 2 in age (e.g., Pierce, 2004; Licciardi and Pierce, 2008). It is therefore likely that the ^{10}Be ages from Dry Creek Gulch reflect post-depositional erosional processes, such as moraine degradation, rather than the age of the Bull Lake culmination (Briner, 2009).

More recent dating efforts have focused on identifying the timing of Pinedale glacier culminations and subsequent upvalley glacial retreat in the upper Arkansas River valley.

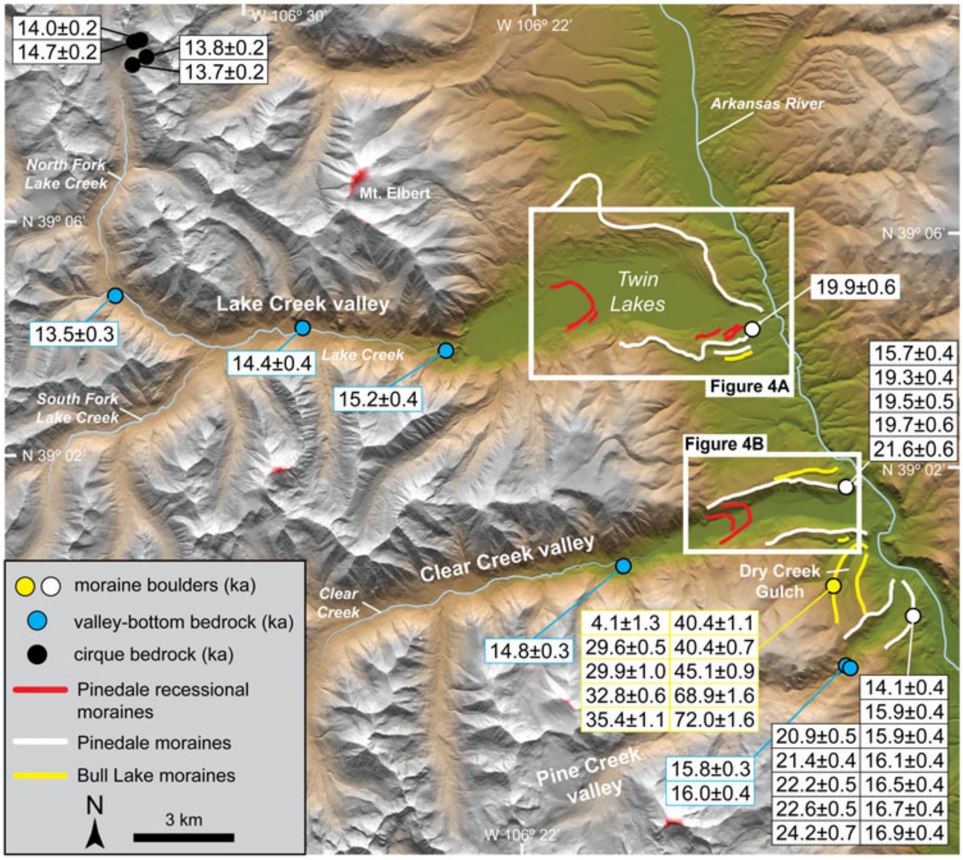

Figure 2. (color online) Previously published ^{10}Be ages of glacial features in the upper Arkansas River valley. White boxes denote the locations of new ^{10}Be ages reported in this study (see Fig. 4). ^{10}Be ages reported with 1σ uncertainty. Circles provide approximate locations of previously sampled boulders and bedrock within the study area. All ^{10}Be ages displayed here are recalculated using the production rate calibrated at Promontory Point (Lifton et al., 2015) and the LSD*n* scaling framework (Lifton et al., 2014) and have been previously published (Schildgen, 2000; Briner, 2009; Young et al., 2011; Leonard et al., 2017b).

Previously published ^{10}Be ages indicate asynchronous Pinedale maxima at 22.3 ± 1.3, 20.0 ± 1.0, 18.4 ± 0.6, and 16.0 ± 0.9 ka for adjacent valley glaciers, which were interpreted to reflect the influence of differing glacial hypsometries and nonclimatic factors intrinsic to individual valley glacial systems (Young et al., 2011; Fig. 2). By contrast, ^{10}Be ages of glacially sculpted bedrock upvalley of the Pinedale terminal moraines in the upper Arkansas River valley suggest near-synchronous retreat of all three paleoglaciers between 16 and 15 ka and point to regional-scale climate forcings stimulating widespread glacial recession (Young et al., 2011).

Building on three ^{10}Be ages from glacially sculpted bedrock upvalley of the range front in Lake Creek valley (Young et al., 2011), Leonard et al. (2017b) generated four ^{10}Be ages from bedrock within the Lake Creek cirque (Fig. 2). Some disagreement between the available ages affords two possible interpretations for the timing of near-complete deglaciation of Lake Creek valley: (1) as early as ~15 ka or (2) ~14 ka or later. Although prior numerical paleoglacier modeling provides insight into the magnitude and rate of deglaciation of the Lake Creek paleoglacier (Schweinsberg et al., 2016), the two aforementioned interpretations lead to different conclusions regarding rates of ice retreat and the alignment between deglaciation and independently dated climate events, prompting further investigation. The main objective of our current study was to expand on these existing ages to develop a more complete and precisely dated chronology of the Lake Creek valley glacial system as a means of further evaluating rates of glacial retreat and connections to climatic and nonclimatic influences.

Study area

This study focuses primarily on glacial deposits in Lake Creek valley, particularly on the extensive suite of moraines surrounding the Twin Lakes Reservoir that include multiple Pinedale moraines and a Bull Lake moraine remnant (Fig. 2; Shroba et al., 2014). Adding to the Pinedale chronology established by Young et al. (2011), we report new ^{10}Be ages for the left lateral moraine mapped as Bull Lake in Clear Creek valley, immediately south of the Lake Creek system (Fig. 2). The only numerical age control for moraines in Lake Creek valley before this work is from two (recalculated) ^{10}Be ages of 21.0 ± 0.6 ka (original sample ID: DC-91-3) and 19.9 ± 0.6 ka (original sample ID: DC-91-2) for boulders on the Bull Lake and Pinedale right lateral moraines,

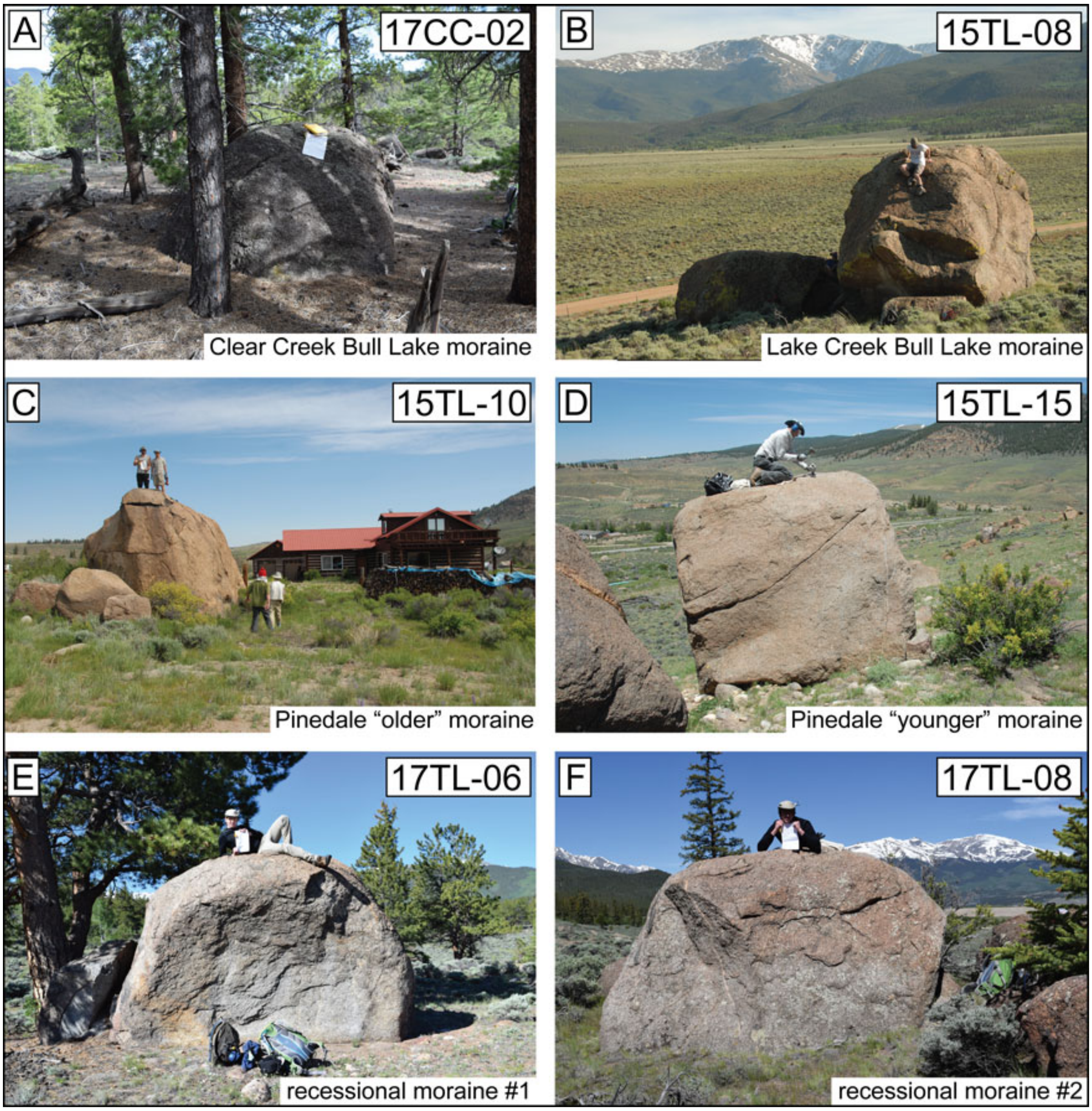

Figure 3. (color online) Photographs of selected boulders sampled in Lake Creek and Clear Creek valleys. Boulders sampled on Bull Lake moraines in Clear and Lake Creek valleys (A and B), sampled boulders from the Pinedale "outer" (C) and "younger" (D) moraines in Lake Creek valley, and boulders sampled from recessional moraine 1 (E) and recessional moraine 2 (F) in Lake Creek valley. Note weathering of Bull Lake boulder surfaces (A and B).

respectively (Schildgen, 2000). The ^{10}Be age of the Bull Lake boulder is considered erroneously young, which may be due to post-depositional disturbance (Schildgen, 2000). Alternatively, this boulder may in fact be Pinedale in age, as recent surficial mapping (Shroba et al., 2014) indicates extensive till mapped as Pinedale throughout the area; however, ambiguities in the reported locations of these previously dated boulders leave this issue unresolved.

The Bull Lake and Pinedale moraines reflect the most extensive positions associated with the penultimate and last glaciation, respectively (Shroba et al., 2014; Schweinsberg et al., 2016). Till of Pinedale age is mapped as two separate units in Lake Creek valley, denoted as Pinedale "older" and Pinedale "younger," reflecting relative age differences (Shroba et al., 2014). The "older" moraine is a thin (few meters thick) drape of till that mantles a low, subdued Bull Lake moraine (Lee, 2010; Shroba et al., 2014). Directly inboard of the Pinedale "older" moraine is the much bulkier "younger" Pinedale moraine crest, ~50 m high. Recently acquired LiDAR coverage provides a high-resolution view of the moraine morphology of this complex. Given that many of the recessional moraines are preserved only as small segments, our dating efforts focused on the more prominent and continuous moraines with abundant surface boulders suitable for ^{10}Be dating. Specifically, we report new ^{10}Be ages for boulders on the Bull Lake left lateral moraine in Clear Creek valley ($n = 4$; Figs. 3A and 4B). In addition, in Lake Creek valley, we generated ^{10}Be ages from the Bull Lake right lateral moraine ($n = 4$; Figs. 3B and 4A), Pinedale "older" ($n = 7$) and "younger" moraines ($n = 7$), and three

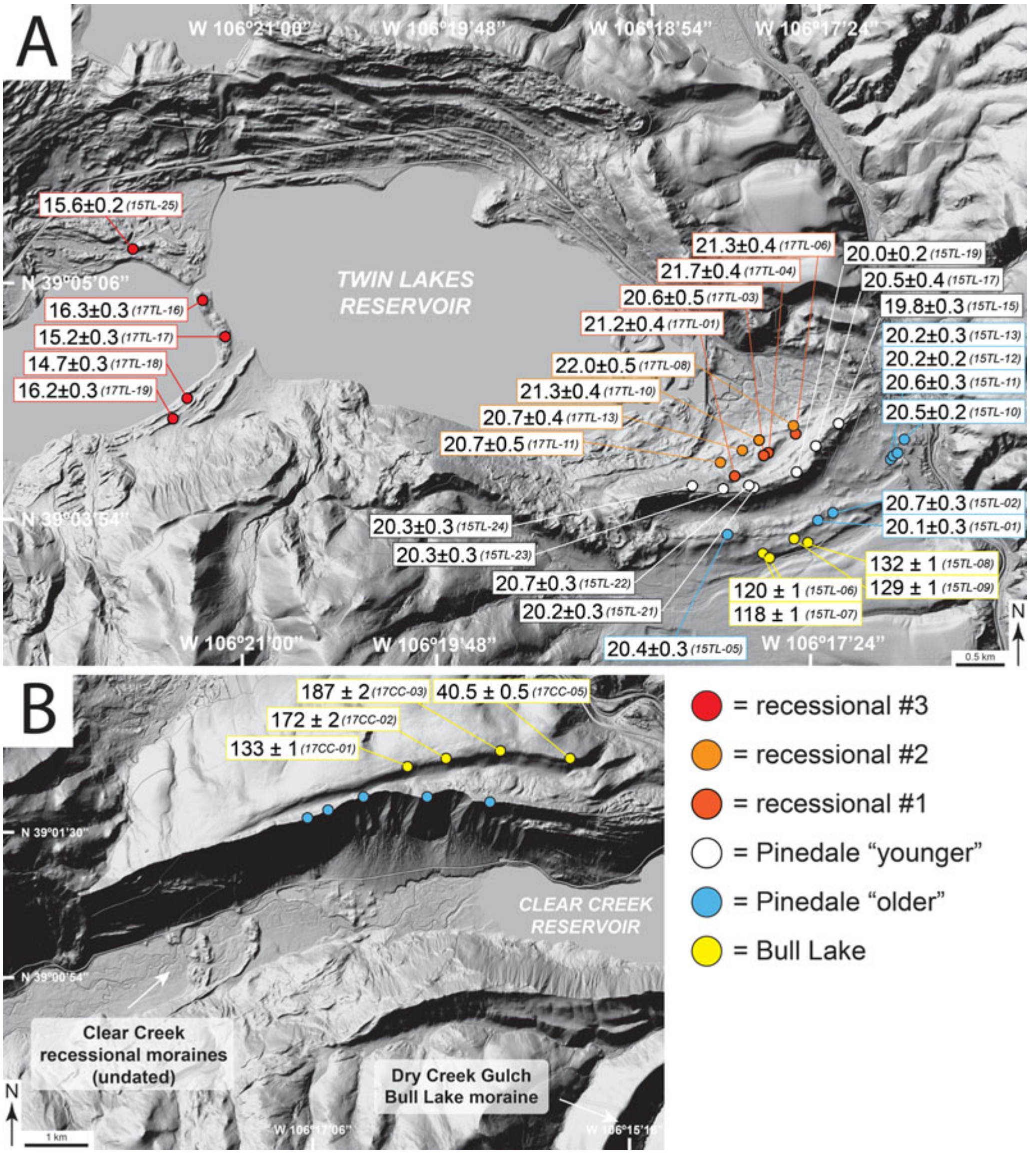

Figure 4. Summary of ^{10}Be ages from moraine complexes in Lake and Clear Creek valleys. All ^{10}Be ages are new, except for the ages denoted by the blue circles in Clear Creek valley (Young et al., 2011). Individual ^{10}Be ages and 1σ uncertainties are expressed in thousands of years (ka). (A) ^{10}Be ages of boulders on moraine crests enclosing the Twin Lakes Reservoir in Lake Creek valley. (B) ^{10}Be ages of boulders on the left-lateral Bull Lake moraine in Clear Creek valley. (For interpretation of the reference to color in this figure legend, the reader is referred to the web version of this article.)

recessional ridges, denoted as recessional 1 ($n = 4$), recessional 2 ($n = 4$), and recessional 3 ($n = 5$; Figs. 3C–F and 4A).

METHODS

Sampling for ^{10}Be dating was conducted in 2015 and 2017 (Fig. 3). Samples were collected from large boulders resting on moraine ridge crests, using a cordless angle grinder equipped with a diamond cutting disk and a hammer and chisel. Samples underwent physical and chemical processing at the University at Buffalo Cosmogenic Isotope Laboratory following previously published procedures (Licciardi, 2000; Corbett et al., 2016). Samples were crushed and sieved to isolate the 425–850 µm size fraction, all magnetic minerals were removed, and the remaining material was etched in dilute HCl and HF/HNO_3 acid solutions. Quartz was further isolated via froth flotation techniques and additional HF/HNO_3 etches until pure quartz was obtained. Beryllium was extracted to produce purified BeO target material for accelerator mass spectrometry (AMS) analysis. A commercially available ^{9}Be carrier was added to the purified quartz samples before dissolution in concentrated HF. All ^{10}Be/^{9}Be ratios were measured at the Center for AMS at Lawrence Livermore National Laboratory and normalized to standard 07KNSTD3110 (^{10}Be/^{9}Be ratio of 2.85×10^{-12}; Nishiizumi et al., 2007).

All new and previously reported ^{10}Be exposure ages (Table 1) were calculated using the CRONUS-Earth online

Table 1. Sample information, cosmogenic isotope data, and surface exposure ages for Lake Creek and Clear Creek valleys.

Sample ID	Lat. (°N)	Long. (°W)	Elev. (m asl)	Sample thickness (cm)	Shielding correction	Erosion rate (cm/yr)	Quartz (g)	^{10}Be/^{9}Be ratio (E-13)[a]	[^{10}Be] (1E + 05 atoms/g)	^{10}Be exposure age (ka)[b]
Bull Lake (Lake Creek valley)										
72-15TL-06	39.065	106.297	2826	3.0	0.9994	0.0001	20.4658	49.40 ± 0.42	36.3 ± 0.31	119.6 ± 1.2 (± 5.3)
72-15TL-07	39.064	106.297	2818	3.0	0.9994	0.0001	20.6263	48.65 ± 0.33	35.5 ± 0.24	117.5 ± 0.9 (± 5.1)
72-15TL-08	39.066	106.294	2816	2.0	0.9994	0.0001	21.0807	56.26 ± 0.39	40.0 ± 0.28	132.3 ± 1.1 (± 5.9)
72-15TL-09	39.066	106.293	2808	1.8	0.9991	0.0001	20.1398	52.33 ± 0.36	39.0 ± 0.27	129.2 ± 1.0 (± 5.7)
Mean ^{10}Be age (ka ± 1σ):										124.7 ± 7.2
Bull Lake (Clear Creek valley)										
92-17CC-01	39.030	106.276	2926	1.5	0.9995	0.0001	10.2022	29.38 ± 0.26	43.5 ± 0.04	133.4 ± 1.4 (± 6.0)
92-17CC-02	39.031	106.273	2919	2.5	0.9995	0.0001	10.0426	35.16 ± 0.31	52.9 ± 0.05	171.7 ± 1.8 (± 8.0)
92-17CC-03	39.032	106.267	2908	1.0	0.9997	0.0001	10.0992	38.36 ± 0.35	57.4 ± 0.05	186.9 ± 2.1 (± 8.0)
92-17CC-05	*39.031*	*106.259*	*2873*	*2.0*	*0.9996*	*0.0001*	*10.1059*	*9.14 ± 0.11*	*13.6 ± 0.02*	*40.5 ± 0.5 (± 1.7)*
Mean ^{10}Be age (ka ± 1σ):										164.0 ± 27.5
Pinedale "older"										
72-15TL-01	39.067	106.292	2806	3.0	0.9995	0.0000	20.4838	8.71 ± 0.12	6.36 ± 0.09	20.1 ± 0.3 (± 0.8)
72-15TL-02A	39.068	106.291	2801	2.5	0.9995	0.0000	22.8013	9.98 ± 0.14	6.59 ± 0.09	20.7 ± 0.3 (± 0.8)
72-15TL-05	39.066	106.301	2849	1.5	0.9953	0.0000	20.1133	8.96 ± 0.11	6.69 ± 0.09	20.4 ± 0.1 (± 0.8)
72-15TL-10	39.074	106.283	2775	2.0	0.9995	0.0000	20.1271	8.64 ± 0.92	6.44 ± 0.07	20.5 ± 0.2 (± 0.8)
72-15TL-11	39.072	106.285	2779	1.5	0.9995	0.0000	20.0991	8.72 ± 0.12	6.52 ± 0.09	20.6 ± 0.3 (± 0.8)
72-15TL-12	39.072	106.286	2777	1.5	0.9995	0.0000	20.0788	8.49 ± 0.10	6.36 ± 0.08	20.2 ± 0.3 (± 0.8)
72-15TL-13	39.073	106.285	2778	2.0	0.9995	0.0000	19.9807	8.37 ± 0.11	6.32 ± 0.09	20.2 ± 0.3 (± 0.8)
Mean ^{10}Be age (ka ± 1σ):										20.4 ± 0.2
Pinedale "younger"										
74-15TL-15	39.075	106.290	2824	2.0	0.9997	0.0000	25.6239	10.84 ± 0.16	6.38 ± 0.10	19.8 ± 0.3 (± 0.8)
74-15TL-17	39.073	106.292	2840	2.5	0.9997	0.0000	25.0445	11.08 ± 0.20	6.69 ± 0.12	20.5 ± 0.4 (± 0.9)
74-15TL-19	39.071	106.294	2846	1.5	0.9997	0.0000	25.3730	11.13 ± 0.13	6.59 ± 0.08	20.0 ± 0.2 (± 0.8)
74-15TL-21	39.070	106.300	2855	2.0	0.9997	0.0000	25.0215	11.04 ± 0.14	6.67 ± 0.08	20.2 ± 0.3 (± 0.8)
74-15TL-22	39.070	106.298	2859	1.5	0.9997	0.0000	25.2629	11.51 ± 0.14	6.89 ± 0.09	20.7 ± 0.3 (± 0.8)
74-15TL-23	39.069	106.301	2866	1.0	0.9995	0.0000	25.0669	11.29 ± 0.14	6.80 ± 0.09	20.3 ± 0.3 (± 0.8)
74-15TL-24	39.070	106.303	2884	2.0	0.9995	0.0000	25.1827	11.40 ± 0.14	6.83 ± 0.09	20.3 ± 0.3 (± 0.8)
Mean ^{10}Be age (ka ± 1σ):										20.3 ± 0.3
Recessional moraine 1										
90-17TL-01	39.071	106.301	2854	1.5	0.9994	0.0000	14.0597	6.56 ± 0.12	7.05 ± 0.13	21.2 ± 0.4 (± 0.9)
90-17TL-03	39.073	106.297	2840	1.0	0.9983	0.0000	15.0757	6.79 ± 0.15	6.80 ± 0.15	20.6 ± 0.5 (± 0.9)
90-17TL-04	39.072	106.297	2834	2.0	0.9994	0.0000	15.0786	7.13 ± 0.13	7.13 ± 0.13	21.7 ± 0.4 (± 0.9)
90-17TL-06	39.074	106.294	2830	1.0	0.9996	0.0000	15.0544	6.97 ± 0.13	7.03 ± 0.13	21.3 ± 0.4 (± 0.9)
Mean ^{10}Be age (ka ± 1σ):										21.2 ± 0.4
Recessional moraine 2										
92-17TL-08	39.075	106.294	2815	2.0	0.9886	0.0000	20.0466	9.43 ± 0.21	7.09 ± 0.16	22.0 ± 0.5 (± 1.0)
92-17TL-10	39.074	106.297	2822	1.0	0.9664	0.0000	20.1836	9.02 ± 0.15	6.76 ± 0.12	21.3 ± 0.4 (± 0.9)
92-17TL-11	39.072	106.302	2841	1.5	0.9996	0.0000	19.9662	8.99 ± 0.15	6.82 ± 0.13	20.7 ± 0.4 (± 0.9)
92-17TL-13	39.073	106.300	2831	1.0	0.9994	0.0000	20.1248	8.98 ± 0.20	6.80 ± 0.15	20.7 ± 0.5 (± 0.9)
Mean ^{10}Be age (ka ± 1σ):										21.2 ± 0.6
Recessional moraine 3 (moraine loop bisecting Twin Lakes reservoir)										
76-15TL-25	39.088	106.362	2812	1.0	0.9896	0.0000	25.1011	8.13 ± 0.12	4.89 ± 0.07	15.6 ± 0.2 (± 0.6)
90-17TL-16	39.084	106.355	2817	3.0	0.9989	0.0000	20.1138	6.76 ± 0.11	5.08 ± 0.08	16.3 ± 0.3 (± 0.7)
90-17TL-17	39.081	106.353	2811	1.5	0.9909	0.0000	19.9891	6.26 ± 0.12	4.73 ± 0.09	15.2 ± 0.3 (± 0.6)
90-17TL-18	39.075	106.358	2820	2.0	0.9970	0.0000	20.0598	6.11 ± 0.12	4.60 ± 0.09	14.7 ± 0.3 (± 0.6)
90-17TL-19	39.073	106.360	2839	1.5	0.9961	0.0000	20.0041	6.86 ± 0.13	5.18 ± 0.10	16.2 ± 0.3 (± 0.7)
Mean ^{10}Be age (ka ± 1σ):										15.6 ± 0.7
Lake Creek cirque[c]										
75-LKCK-15-1	39.158	106.531	3740	1.5	0.9859	0.0000	20.4795	10.27 ± 0.14	7.60 ± 0.10	13.8 ± 0.2 (± 0.6)
76-LKCK-15-2	39.158	106.532	3776	4.0	0.9848	0.0000	18.0309	9.63 ± 0.14	8.07 ± 0.12	14.7 ± 0.2 (± 0.6)
76-LKCK-15-3	39.152	106.528	3761	3.0	0.9830	0.0000	18.0945	9.22 ± 0.12	7.67 ± 0.10	14.0 ± 0.2 (± 0.6)
76-LKCK-15-4	39.149	106.524	3774	3.0	0.9740	0.0000	18.1295	9.03 ± 0.14	7.50 ± 0.12	13.7 ± 0.2 (± 0.6)
Mean ^{10}Be age (ka ± 1σ):										14.0 ± 0.4

[a] ^{10}Be/^{9}Be ratios are batch-specific, blank-corrected, and reported with 1σ (internal) uncertainty. Batch-specific process blanks yielded values of 4.3×10^{-16} (72-Blank), 3.1×10^{-15} (74-Blank), 2.4×10^{-15} (90-Blank), and 9.6×10^{-16} (92-Blank). AMS uncertainties ranged from 0.7% to 1.2%, 1.1% to 2.2%, and 1.3% to 1.6% for all Bull Lake, Pinedale, and Lake Creek cirque samples, respectively.

[b] All samples, including the Lake Creek cirque data (Leonard et al., 2017b), were spiked with ~225–230 μg of ^{9}Be prepared by the GFZ German Research Center for Geosciences ("Phenakite" standard, ^{9}Be concentration: 372 ± 3.5 ppm) at the University at Buffalo. ^{10}Be ages are calculated using a sample density of 2.65 g/cm^3 and an effective attenuation length of 160 g/cm^2. ^{10}Be ages are reported with 1σ uncertainty; the value in the parentheses reflects the external uncertainty. Negligible erosion is assumed for samples of Pinedale age and younger. Bull Lake samples are reported with an erosion rate of 1 mm/ka. Sample in italics are considered outliers and are not included in the mean ^{10}Be age calculation.

[c] Data published by Leonard et al. (2017b).

 https://doi.org/10.1017/qua.2020.21

^{10}Be exposure age calculator (v. 3.0, http://hess.ess.washington.edu/math/index_dev.html; Balco et al., 2008). To ensure comparability of our ages with those of recent publications (e.g., Licciardi and Pierce, 2018; Brugger et al., 2019a), we use the regionally calibrated Promontory Point ^{10}Be production rate (Lifton et al., 2015) and LSD*n* scaling model (Lifton et al., 2014). The Promontory Point measurements include data from sites relatively close in proximity and elevation to our study area; thus, the use of this production rate minimizes uncertainties related to scaling. For comparison, ^{10}Be exposure ages were also calculated using alternative production rates and scaling models (Table 2).

RESULTS

Bull Lake glaciation

Unlike Pinedale boulders and glacially sculpted bedrock in the upper Arkansas River valley, which preserve evidence of original glacial smoothing and striations, boulders associated with Bull Lake deposits exhibit signs of weathering, including grain-to-grain relief and local spalling near the base of the boulders, presumably due to wildfires. As a result, the impact of erosion must be considered in the exposure age calculations. The Bull Lake ages are calculated with an assumed erosion rate of 1 mm/ka (Tables 1 and 3), which has been previously estimated for granitic boulders in similar climates within the western United States (Benedict, 1993; Gosse et al., 1995) and used for calculating Bull Lake ^{10}Be ages in adjacent mountain ranges (Brugger et al., 2019a).

^{10}Be ages from Bull Lake moraine boulders in Lake Creek range from 132 to 120 ka and yield a mean age of 125 ± 7 ka ($n = 4$). With a ^{10}Be age well outside the 2σ range of the ^{10}Be age population, we excluded one boulder age as a young outlier (sample 92-17CC-05, 40.5 ± 0.5 ka) from the Bull Lake unit in Clear Creek valley; thus, ^{10}Be ages from the Bull Lake moraine in Clear Creek valley are 187 ± 2, 172 ± 2, and 133 ± 1 ka (Table 1).

Pinedale glaciation

In total, 27 new ^{10}Be ages were developed from large crystalline boulders on moraines mapped as Pinedale near the Twin Lakes Reservoir in Lake Creek valley (Fig. 3, Table 1). The ages of boulders on the Pinedale "older" moraines range from 20.7 ± 0.3 to 20.1 ± 0.3 ka, averaging 20.4 ± 0.2 ka ($n = 7$). ^{10}Be ages of boulders on the Pinedale "younger" moraines range from 20.7 ± 0.3 to 19.8 ± 0.3 ka, and average 20.3 ± 0.3 ka ($n = 7$). The mean ^{10}Be ages for the Pinedale "older" and "younger" moraines overlap within 1σ uncertainty. Directly inboard of the Pinedale "younger" moraine is the oldest recessional moraine (recessional 1), from which we obtained ^{10}Be ages ranging from 21.7 ± 0.4 to 20.6 ± 0.5 ka, yielding a mean age of 21.2 ± 0.4 ka ($n = 4$). Similarly, the ^{10}Be ages for recessional moraine 2 range from 22.0 ± 0.5 to 20.7 ± 0.4 ka, averaging 21.2 ± 0.6 ka ($n = 4$). Although the ^{10}Be ages of boulders on recessional moraines 1 and 2 are older than ^{10}Be ages on the outboard Pinedale "older" and "younger" moraines, all ^{10}Be ages overlap within 2 SDs (see "Interpretation and Discussion"). Finally, five boulders from recessional moraine 3, which bisects the Twin Lakes Reservoir, range from 14.7 ± 0.3 to 16.3 ± 0.3 ka, yielding a mean ^{10}Be age of 15.6 ± 0.7 ka.

INTERPRETATION AND DISCUSSION

Bull Lake glaciation

Our ^{10}Be ages of Bull Lake moraine boulders in Clear Creek and Lake Creek valleys build on the few other dated Bull Lake glacial deposits in Colorado. Bull Lake deposits dated with cosmogenic isotopes have been reported in six other studies, two of which reported anomalously young boulders on Bull Lake deposits. After flagging four boulders as outliers due to problematic issues with erosion, sediment/snow shielding, and/or ^{36}Cl complications, Benson et al. (2004) reported a single, interpreted as reliable, ^{10}Be age of ∼144 ka for a boulder in the Front Range (data not recalculated). Similarly, ^{10}Be ages of deposits mapped as Bull Lake in age from Pine Creek valley in the upper Arkansas River valley were also determined to be anomalously young (Briner, 2009). In contrast, Brugger et al. (2019a) dated a Bull Lake moraine in Iowa Gulch in the adjacent Mosquito Range, yielding a mean age of 130 ± 5 ka ($n = 2$), which is consistent with our mean ^{10}Be age of 125 ± 7 ka in Lake Creek valley. Results from Lake Creek valley are also broadly consistent with mean ^{10}Be and ^{26}Al ages of 101 ± 21 and 122 ± 26 ka, respectively, from boulders on Bull Lake moraines in the Front Range (Dethier et al., 2000; data not recalculated), and with ^{10}Be and ^{26}Al ages of 133 ± 28 and 139 ± 31 ka, respectively, on a Bull Lake terrace in the same range (Schildgen et al., 2002; data not recalculated, insufficient sample information available). Ages from Iowa Gulch and Lake Creek valley are younger than ^{10}Be ages from Clear Creek valley, which range from 187 to 133 ka, suggesting possible isotopic inheritance for the two oldest Clear Creek samples.

Although some ^{10}Be ages of Bull Lake boulders in Clear Creek valley are older than other Bull Lake moraines in Colorado, relatively older age constraints on Bull Lake deposits have been reported from the Zeigler Reservoir fossil site in Colorado (158 ± 9 ka; Mahan et al., 2014), the Greater Yellowstone Glacial System (150 ± 4 ka; Licciardi and Pierce, 2018) and the Wind River Range in Wyoming (>130 ka; Phillips et al., 1997; Gosse and Phillips, 2001). After excluding the anomalously young ages, ^{10}Be age estimates from Clear and Lake Creek valleys, in conjunction with other dated Bull Lake deposits, indicate that most dated Bull Lake moraines were deposited during MIS 6. We note, however, that the range of ages limits our ability to confirm that moraine deposition was regionally synchronous throughout the penultimate glaciation.

Table 2. ^{10}Be exposure ages and alternative production rates and scaling schemes.

	^{10}Be ages: Promontory Point production rate (ka)[a]			^{10}Be ages: Default CRONUS production rate (ka)[b]		
Sample ID	Constant (St)	Lm	LSD*n*	Constant (St)	Lm	LSD*n*
Bull Lake (Lake Creek valley)						
72-15TL-06	138.0 ± 1.4	127.8 ± 1.3	119.6 ± 1.2	143.5 ± 1.4	128.6 ± 1.3	123.4 ± 1.2
72-15TL-07	135.3 ± 1.1	125.4 ± 1.0	117.5 ± 0.9	140.6 ± 1.1	126.2 ± 1.0	121.3 ± 1.0
72-15TL-08	154.3 ± 1.3	142.7 ± 1.2	132.3 ± 1.1	160.5 ± 1.3	143.6 ± 1.2	137.1 ± 1.1
72-15TL-09	150.4 ± 1.2	139.0 ± 1.1	129.2 ± 1.0	156.4 ± 1.3	139.9 ± 1.1	133.8 ± 1.1
Bull Lake (Clear Creek valley)						
92-17CC-01	157.0 ± 1.6	145.0 ± 1.5	133.4 ± 1.4	163.3 ± 1.7	146.0 ± 1.5	138.3 ± 1.4
92-17CC-02	202.3 ± 2.2	185.8 ± 2.0	171.7 ± 1.8	210.9 ± 2.3	186.9 ± 2.0	178.1 ± 1.9
92-17CC-03	222.6 ± 2.6	202.2 ± 2.3	186.9 ± 2.1	232.3 ± 2.8	203.6 ± 2.3	192.9 ± 2.2
92-17CC-05	45.3 ± 0.6	42.8 ± 0.5	40.5 ± 0.5	46.9 ± 0.6	43.1 ± 0.5	41.5 ± 0.5
Pinedale "older"						
72-15TL-01	21.3 ± 0.3	20.9 ± 0.3	20.1 ± 0.3	22.0 ± 0.3	21.0 ± 0.3	20.7 ± 0.3
72-15TL-02A	22.0 ± 0.3	21.6 ± 0.3	20.7 ± 0.3	22.8 ± 0.3	21.7 ± 0.3	21.3 ± 0.3
72-15TL-05	21.7 ± 0.3	21.2 ± 0.3	20.4 ± 0.1	22.4 ± 0.3	21.3 ± 0.3	20.9 ± 0.3
72-15TL-10	21.8 ± 0.2	21.4 ± 0.2	20.5 ± 0.2	22.5 ± 0.2	21.5 ± 0.2	21.1 ± 0.2
72-15TL-11	21.9 ± 0.3	21.5 ± 0.3	20.6 ± 0.3	22.7 ± 0.3	21.6 ± 0.3	21.2 ± 0.3
72-15TL-12	21.4 ± 0.3	21.0 ± 0.3	20.2 ± 0.3	22.1 ± 0.3	21.1 ± 0.3	20.8 ± 0.3
72-15TL-13	21.3 ± 0.3	21.0 ± 0.3	20.2 ± 0.3	22.1 ± 0.3	21.1 ± 0.3	20.7 ± 0.3
Pinedale "younger"						
74-15TL-15	20.9 ± 0.3	20.6 ± 0.3	19.8 ± 0.3	21.7 ± 0.3	20.7 ± 0.3	20.3 ± 0.3
74-15TL-17	21.8 ± 0.4	21.4 ± 0.4	20.5 ± 0.4	22.6 ± 0.4	21.5 ± 0.4	21.1 ± 0.4
74-15TL-19	21.3 ± 0.3	20.9 ± 0.3	20.0 ± 0.2	22.0 ± 0.3	21.0 ± 03	20.6 ± 0.3
74-15TL-21	21.5 ± 0.3	21.1 ± 0.3	20.2 ± 0.3	22.2 ± 0.3	21.2 ± 0.3	20.8 ± 0.3
74-15TL-22	22.1 ± 0.3	21.6 ± 0.3	20.7 ± 0.3	22.8 ± 0.3	21.7 ± 0.3	21.2 ± 0.3
74-15TL-23	21.6 ± 0.3	21.2 ± 0.3	20.3 ± 0.3	22.3 ± 0.3	21.3 ± 0.3	20.9 ± 0.3
74-15TL-24	21.6 ± 0.3	21.2 ± 0.3	20.3 ± 0.3	22.4 ± 0.3	21.3 ± 0.3	20.9 ± 0.3
Recessional moraine 1						
90-17TL-01	22.7 ± 0.4	22.1 ± 0.4	21.2 ± 0.4	23.4 ± 0.4	22.2 ± 0.4	21.7 ± 0.4
90-17TL-03	22.0 ± 0.5	21.5 ± 0.5	20.6 ± 0.5	22.7 ± 0.5	21.6 ± 0.5	21.2 ± 0.5
90-17TL-04	23.3 ± 0.4	22.7 ± 0.4	21.7 ± 0.4	24.1 ± 0.5	22.8 ± 0.4	22.3 ± 0.4
90-17TL-06	22.8 ± 0.4	22.2 ± 0.4	21.3 ± 0.4	23.6 ± 0.5	22.4 ± 0.4	21.9 ± 0.4
Recessional moraine 2						
92-17TL-08	23.7 ± 0.5	23.0 ± 0.5	22.0 ± 0.5	24.5 ± 0.6	23.1 ± 0.5	22.6 ± 0.5
92-17TL-10	22.8 ± 0.4	22.2 ± 0.4	21.3 ± 0.4	23.6 ± 0.4	22.3 ± 0.4	21.9 ± 0.4
92-17TL-11	22.1 ± 0.4	21.6 ± 0.4	20.7 ± 0.4	22.8 ± 0.4	21.7 ± 0.4	21.3 ± 0.4
92-17TL-13	22.1 ± 0.5	21.6 ± 0.5	20.7 ± 0.5	22.8 ± 0.5	21.7 ± 0.5	21.3 ± 0.5
Recessional moraine 3 (moraine loop bisecting Twin Lakes)						
76-15TL-25	16.2 ± 0.2	16.2 ± 0.2	15.6 ± 0.2	16.7 ± 0.3	16.3 ± 0.2	16.1 ± 0.2
90-17TL-16	16.9 ± 0.3	16.9 ± 0.3	16.3 ± 0.3	17.5 ± 0.3	17.0 ± 0.3	16.7 ± 0.3
90-17TL-17	15.7 ± 0.3	15.7 ± 0.3	15.2 ± 0.3	16.2 ± 0.3	15.8 ± 0.3	15.6 ± 0.3
90-17TL-18	15.2 ± 0.3	15.2 ± 0.3	14.7 ± 0.3	15.7 ± 03	15.3 ± 0.3	15.1 ± 0.3
90-17TL-19	16.8 ± 0.3	16.8 ± 0.3	16.2 ± 0.3	17.4 ± 0.3	16.9 ± 0.3	16.7 ± 0.3
Lake Creek cirque						
75-LKCK-15-1	14.9 ± 0.2	15.0 ± 0.2	13.8 ± 0.2	15.4 ± 0.2	15.0 ± 0.2	14.2 ± 0.2
76-LKCK-15-2	15.9 ± 0.2	15.8 ± 0.2	14.7 ± 0.2	16.4 ± 0.2	15.9 ± 0.2	15.0 ± 0.2
76-LKCK-15-3	15.1 ± 0.2	15.1 ± 0.2	14.0 ± 0.2	15.6 ± 0.2	15.2 ± 0.2	14.4 ± 0.2
76-LKCK-15-4	14.8 ± 0.2	14.9 ± 0.2	13.7 ± 0.2	15.3 ± 0.2	14.9 ± 0.2	14.1 ± 0.2

[a]Lifton et al. (2015).
[b]Balco (2017).
Note: Abbreviation "St" refers to time-independent scaling (constant production rate) after Lal (1991) and Stone (2000). "Lm" is the time-dependent version of St based on time-variation in the dipole magnetic field intensity, as formulated by Nishiizumi et al. (1989).

Table 3. Erosion rates and ^{10}Be exposure age calculations for Bull Lake samples.

Sample ID	Zero erosion	0.5 mm/ka	1 mm/ka
Lake Creek valley			
72-15TL-06	109.1 ± 1.0	114.0 ± 1.1	119.6 ± 1.2
72-15TL-07	107.4 ± 0.8	112.1 ± 0.8	117.5 ± 0.9
72-15TL-08	119.1 ± 0.8	125.1 ± 1.0	132.3 ± 1.1
72-15TL-09	116.8 ± 0.8	122.5 ± 0.9	129.2 ± 1.0
Clear Creek valley			
92-17CC-01	120.0 ± 1.1	129.1 ± 1.2	133.4 ± 1.4
92-17CC-02	148.2 ± 1.3	158.8 ± 1.5	171.7 ± 1.8
92-17CC-03	160.6 ± 1.5	173.2 ± 1.8	186.9 ± 2.1
92-17CC-05	39.4 ± 0.5	39.9 ± 0.5	40.5 ± 0.5

Note: All ^{10}Be exposure ages calculated using the Promontory Point production rate (Lifton et al., 2015) and LSD*n* scaling framework (Lifton et al., 2014).

Pinedale glaciation and subsequent retreat

Chronology and geomorphology

^{10}Be ages obtained on end moraines mapped as Pinedale in age in Lake Creek valley range from 21.7 to 19.8 ka (Fig. 4). Four distinct moraine positions returned essentially identical ^{10}Be age populations, suggesting that these moraines were deposited within a short time period. The ^{10}Be ages of boulders on recessional moraines 1 and 2 do not obey chronological expectation at face value; however, uncertainties within 2 SDs allow for the interpretation that all four moraines (recessional moraines 1 and 2 and the Pinedale "older" and "younger" moraines) were deposited within ~1000 yr or less. We do not believe that the age reversal is due to geologic uncertainties, as we cannot envision a scenario that would give rise to a ~1000 yr apparent age difference between the two outer Pinedale moraines and the two recessional moraines. Such a scenario would either require samples on the outer moraines to have experienced systematic, enhanced erosion or partial exhumation, or for samples on the inner moraines to systematically contain isotopic inheritance. Laboratory and/or analytical complications were also considered, as samples from the two recessional moraines were processed in the laboratory later than, and separately from, the samples from the two outer Pinedale moraines. Similarly, the data were measured via AMS at different times. The difference in moraine ages does not lie in process-blank subtraction; whether using the laboratory average or batch-specific values, the resulting age differences are less than 100 yr. The ^{9}Be carrier was the same for all samples, and the carrier concentration would not have changed in the months of time elapsed between chemistry batches. Finally, technicians at the AMS facility did not report any issues related to the primary and secondary standards (Zimmerman, S., personal communication, 2019). Thus, we see no obvious explanation for the age reversal.

The positions of the landforms—four closely spaced moraines overlapping in age, in addition to a considerably less bulky outer moraine (Pinedale "older") adjacent to a large, well-defined moraine (Pinedale "younger")—could be interpreted to support the influence of interannual climate variability on glacial fluctuations. Some models suggest that climate noise (weather) may potentially drive kilometer-scale oscillations in glacial extent that are beyond climatically driven glacier behavior (Anderson et al., 2014). It is surprising that the larger and more prominent "younger" Pinedale moraine was not statistically younger than the thin drift comprising the Pinedale "older" moraine, as we would have expected that more time was needed to construct a moraine of that size. As such, we propose two possible interpretations for the deposition of the Pinedale-age moraines dated in this study: (1) the Lake Creek paleoglacier deposited each moraine in stratigraphic order, initially depositing the Pinedale "older" and then "younger" moraine, followed by recessional moraines 1 and 2, all within a period of ~1000 years or less; or (2) the Lake Creek paleoglacier initially stabilized at the Pinedale "younger" position, depositing till and building that moraine, and then advanced briefly to the Pinedale "older" position without removing the inner moraine. The glacier would have then retreated back to reoccupy the "younger" position, depositing till and ultimately the boulders we collected for ^{10}Be dating. In the latter scenario, there would have been a near-maximum extent of the Lake Creek paleoglacier achieved at an unknown time before ~21 ka.

The timing of the Pinedale maximum extent in Lake Creek valley is consistent with the timing of other Pinedale maxima in the upper Arkansas River valley, although not all phases of Pinedale maxima are expressed in each valley (Fig. 5A). The oldest Pinedale ice limit is preserved in Pine Creek valley (22.3 ± 1.3 ka; Young et al., 2011), whereas ^{10}Be ages from Lake and Clear Creek valleys suggest that ice initially retreated from its Pinedale maximum extent at 20.6 ± 0.6 and 20.0 ± 1.0 ka, respectively. The synchronicity in Lake Creek and Clear Creek valleys suggests regional-scale climate forcing driving glacial behavior. Furthermore, considering uncertainties, the glacial culmination dated to 22.3 ± 1.3 ka in Pine Creek valley is essentially synchronous with the timing of Pinedale maxima in Lake and Clear Creek valleys, an interpretation inconsistent with that of Young et al. (2011). Moreover, the younger mode of ^{10}Be ages at 16.0 ± 0.9 ka in Pine Creek valley (Young et al., 2011) overlaps with the recessional moraine in Lake Creek valley dating to 15.6 ± 0.7 ka, potentially demonstrating synchronous behavior of two valley glacial systems at this point during the last deglaciation. Undated recessional moraines in Clear Creek valley (Fig. 4B) may correspond to this age as well. Overall, the glacial chronologies from Pine Creek and Lake Creek valleys support the concept of at least two periods of near-maximum ice extent during Pinedale times, one at ~21–20 ka and another at ~16 ka (Licciardi et al., 2001, 2004; Munroe et al., 2006; Refsnider et al., 2008; Ward et al., 2009; Leonard et al., 2017b).

Deglaciation of Lake Creek valley

Our data indicate that the Lake Creek paleoglacier culminated at ~21–20 ka, followed by several glacial readvances and/or

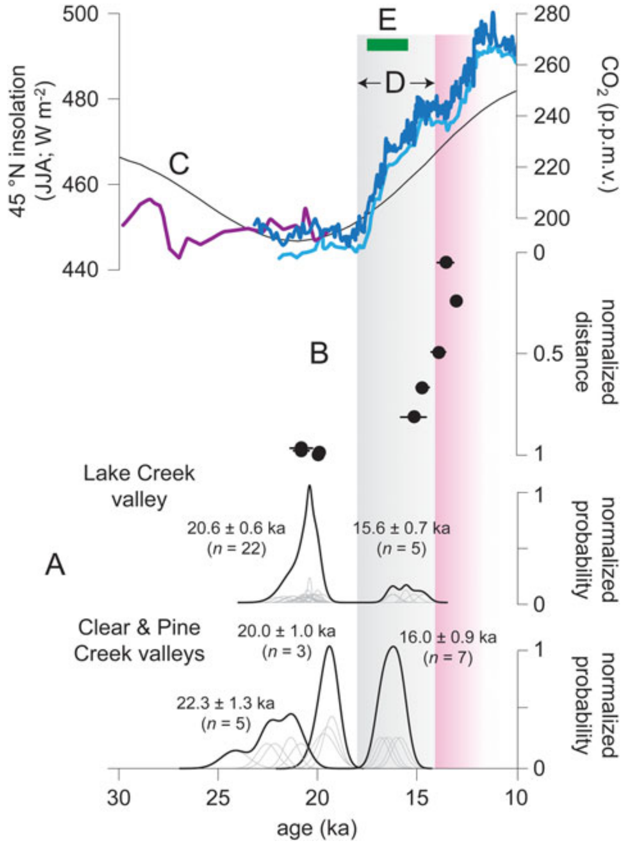

Figure 5. Comparison of upper Arkansas River valley Pinedale ^{10}Be chronologies with climate forcings. (A) Probability density plots of ^{10}Be ages for individual moraines (black curves) and boulders (light gray curves) in Lake, Clear, and Pine Creek valleys (this study and Young et al., 2011). (B) Normalized glacial length history in Lake Creek valley. (C) Summer (June, July, and August) insolation curve at 45°N (Berger and Loutre, 1991). (D) Interval of deglacial CO_2 rise adopted from Shakun et al. (2015); shown by the gray vertical bar. (E) Timing of the dominant high stand of a compilation of paleolakes in the Great Basin (Munroe and Laabs, 2013, and references therein); shown by green horizontal bar. Vertical pink bar indicates the Bølling-Allerød warm interval (~14.7–12.9 ka). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

stillstands that are indistinguishable in age from the maximum position. Subsequently, there was either recession or a retreat and readvance to the innermost recessional moraine, which was abandoned at ~15.6 ± 0.7 ka.

By combining our results with previously dated samples, we reconstruct the pattern of deglaciation for the entirety of Lake Creek valley (Fig. 5B). We consider the final deglaciation of Lake Creek valley to have initiated at 15.6 ± 0.7 ka (mean age of boulders from recessional 3, $n = 5$) and ended at 14.0 ± 0.4 ka (mean age of cirque bedrock samples, $n = 4$). Thus, if we consider the first valley-bottom bedrock age downvalley from the cirque to be anomalously young (13.5 ± 0.3 ka; Fig. 2), there was a 82% reduction in glacier length between ~15.6 and 14.0 ka in Lake Creek valley. In comparison, the Lake Creek paleoglacier lost only 18% of its length between ~21 and ~15.6 ka (Fig. 5B), and Pine Creek glacier was at nearly 100% of its maximum length at ~20 and ~16 ka.

The timing of deglaciation spans a broad interval throughout Colorado, with downvalley age constraints placing the initiation of widespread ice retreat between ~20 and 16 ka, and most records revealing that valleys were nearly ice free by ~15–13 ka (Leonard et al., 2017b). Deglaciation began as early as ~20 ka in valleys in the San Juan Mountains and Front Range, with nearly complete deglaciation in these ranges by ~14–13 ka (Guido et al. 2007; Ward et al., 2009). Prior studies suggest that the oldest ^{10}Be ages in these valleys may reflect ^{10}Be inheritance rather than early deglaciation (Leonard et al., 2017b). In the Front Range, asynchronous deglaciation has been reported in adjacent valleys, with the onset and completion of deglaciation differing between valleys by ~2–3 ka; Ward et al. (2009) attributed this difference to valley hypsometry.

In contrast to the valleys in the Front Range and San Juan Mountains, major deglaciation in the Sangre de Cristo Mountains (Leonard et al., 2017a) and in the upper Arkansas River valley did not occur until ~16–15 ka (Young et al., 2011; Table 1). New data from Lake Creek valley similarly indicate an interval of rapid ice recession that resulted in nearly complete deglaciation occurring from ~16 to 14 ka. No clear evidence for a glacial readvance or stabilization during the Younger Dryas interval was identified in Lake Creek valley, likely due to the cirque floors being lower than the regional equilibrium-line altitude at that time in the Sawatch Range. This result is similar to those reported for other sites in Colorado (Leonard et al., 2017b), except for some sites in the Front Range (Menounos and Reasoner, 1997; Marcott et al., 2019).

Regional Pinedale glaciation patterns and paleoclimatic implications

Evidence for two phases of near-maximum Pinedale ice extent is now identified in multiple valleys in the upper Arkansas River valley (Fig. 5A), supporting the concept of two phases of extensive mountain glaciation in the U.S. Rocky Mountains (~21–20 and 17–16 ka; Licciardi et al., 2001, 2004; Munroe et al., 2006; Refsnider et al., 2008; Ward et al., 2009; Leonard et al., 2017b). Although Pine Creek and Lake Creek valleys exhibit evidence for till deposition and moraine development at similar times (16.0 ± 0.9 and 15.6 ± 0.7 ka, respectively), the moraine morphologies and associated glacial fluctuations differ between valleys. Pine Creek glacier likely reoccupied the same (terminal) ice limit, generating a composite feature that resulted in a bimodal ^{10}Be age distribution (Briner, 2009). In contrast, Lake Creek glacier retreated and then readvanced to a position ~5 km upvalley from its prior Pinedale ice extent (at ~80% of its maximum glacial length; Figs. 4 and 5B). Thus, our results suggest a synchronous glacial response to external climate forcing that resulted in variable moraine morphologies due to the influence of local topographic factors (e.g., hypsometry, valley gradient).

Despite the steady increase in CO_2 concentration initiated at ~18 ka (Fig. 5D), relatively extensive ice at ~16 ka has been documented in various mountain ranges across the U.S. Rocky Mountains (e.g., Laabs et al., 2009; Leonard et al., 2017b; Licciardi and Pierce, 2018). These stable glacial configurations existed during Heinrich stade 1 (~18.0–14.7 ka), when depressed temperatures in the North Atlantic (Clark et al., 2001), and perhaps in the western United States, modulated by the Laurentide Ice Sheet (Clark and Bartlein, 1995), were favorable for glacial growth. However, previous studies have also postulated that regional precipitation changes during this interval may have influenced glacial behavior (Thackray et al., 2004; Thackray, 2008). Highstands of many pluvial lakes in the southwestern United States about 17–16 ka (Fig. 5E; Munroe and Laabs, 2013; Ibarra et al., 2014, 2018), as well as speleothem records from the southwestern United States (Wagner et al., 2010; Asmerom et al., 2010; Moseley et al., 2016), suggest generally wetter and/or cooler conditions during this time period. Thus, enhanced moisture delivery may have contributed to glacial stabilization in some ranges of the Colorado Rocky Mountains. In addition, glaciers immediately downwind from the enlarged Great Basin pluvial lakes may have experienced further local precipitation enhancement (Laabs et al., 2009; Birkel et al., 2012), but it is unlikely this effect would have extended into Colorado. Climate models and proxy records suggest that a moisture boundary existed across the Great Basin (Oster et al., 2015) during the last glacial maximum. This implies that changing moisture conditions during deglaciation may have affected precipitation patterns through the Rocky Mountains in different ways, which may provide an explanation for the observed asynchronies in deglaciation (Leonard et al., 2017b). Following the latter phase of Pinedale ice extent in these systems, rapid ice recession likely occurred in response to region-wide warming associated with rising atmospheric CO_2 concentrations combined with increasing insolation (Fig. 5C). Whether this pulse of deglaciation in our study valleys coincided with the abrupt Oldest Dryas–Bølling transition in the North Atlantic remains an open question for future investigations.

CONCLUSIONS

We report 35 new ^{10}Be ages from boulders on seven moraine crests spanning the Bull Lake and Pinedale glaciations in Lake and Clear Creek valleys, thereby expanding on previous work and increasing the total number of ^{10}Be ages to 82 from three adjacent valleys that constrain the glacial history in the upper Arkansas River valley (Schildgen, 2000; Briner, 2009; Young et al., 2011; Schweinsberg et al., 2016; Leonard et al., 2017b). Bull Lake boulders in Lake and Clear Creek valleys range from 132 to 120 ka and 187 to 133 ka, respectively, providing the first direct ages suggesting that mapped Bull Lake moraines in this area may correlate to MIS 6. Four distinct moraine crests previously mapped as Pinedale units of different age (Shroba et al., 2014) date to (in order) 20.4 ± 0.2 ka (Pinedale "older"), 20.3 ± 0.3 ka (Pinedale "younger"), 21.2 ± 0.4 ka (recessional 1), and 21.2 ± 0.6 ka (recessional 2), suggesting till deposition and moraine formation in rapid succession. Collectively, our chronology suggests that the Lake Creek paleoglacier was at or near its maximum Pinedale extent until 20.6 ± 0.6 ka ($n = 22$), then experienced a readvance and/or stillstand to 80%–85% of its Pinedale maximum length at 15.6 ± 0.7 ka ($n = 5$), and then underwent rapid ice retreat that was completed by ~15–14 ka.

The results of this study are consistent with the model of two regional intervals of near-maximum glacial extent during Pinedale times. Our data also support previous suggestions that relative glacial lengths during these two episodes differ among valleys due to nonclimatic factors such as glacial hypsometry (Ward et al., 2009; Young et al., 2011). These results highlight the need for additional data sets constraining the last deglaciation in the western United States, particularly regarding the magnitude and rate of ice retreat expressed not only through geochronological data, but also in combination with numerical modeling and paleoclimate records to provide insight on regional-scale climate forcing.

ACKNOWLEDGMENTS

Funding was provided by the Colorado Scientific Society and by the Center for GeoHazard Studies at the University at Buffalo for cosmogenic measurements and fieldwork. The authors gratefully acknowledge K. Brugger, R. Kroner, C. Russell, C. Porreca, J. Tulenko, and W. Caffee for support in the field and C. Sbarra for assistance in the laboratory. We also thank all 2016 Geological Society of America field trip attendees for their thoughtful discussions.

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