

THE LAST PLEISTOCENE GLACIATION IN THE UINTA MOUNTAINS: UPDATED CHRONOLOGY AND CONNECTIONS TO LAKE BONNEVILLE

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ABSTRACT

Mountain glaciation in the vicinity of Lake Bonneville included numerous valley glaciers and ice fields in the Uinta and Wasatch Mountains, and some smaller glaciers in mountains of the western Lake Bonneville basin. Understanding of glacial chronologies in these mountains has lagged that of the last cycle of Lake Bonneville, due in part to the lack of preserved organic matter suitable for radiocarbon dating in most glacial deposits. Cosmogenic exposure dating of moraines has helped constrain the timing of mountain glaciation, but has been limited until recently by uncertainty of the in situ production of beryllium-10 (^{10}Be). Previously reported cosmogenic ^{10}Be exposure ages of moraines in mountains neighboring Lake Bonneville are recalculated here using newer production rates and scaling models. Recalculated cosmogenic exposure ages are 10–14% older than reported in previous studies, which significantly shifts the apparent relative timing of mountain glaciation and the phases of Lake Bonneville. In the Uinta Mountains, glaciers in eastern valleys last occupied their terminal moraines prior to the overflowing phase of Lake Bonneville, whereas glaciers in the central and western valleys occupied their terminal moraines while the lake overflowed. Glaciers in the western Wasatch Mountains attained their maxima prior to and during the overflowing phase of Lake Bonneville. The updated cosmogenic glacial chronologies still permit the possibility that Lake Bonneville impacted glacier mass balance in neighboring mountains. Ice retreat began by ~18–17 ka while the lake overflowed, suggesting a climatic shift that initiated ice retreat but still supported a high lake.

INTRODUCTION

The rich record of Pleistocene mountain glaciation in the Lake Bonneville basin (LBB) affords an opportunity to study the possible hydrologic and climatic connections between mountain glaciers and Lake Bonneville. Glacial mapping and reconstructions in the Uinta Mountains (Munroe and Mickelson, 2002; Munroe and others, 2006; Munroe and Laabs, 2009), which featured the vast majority of ice in the LBB, and in other mountains around Lake Bonneville (figure 1; Laabs and others, 2011; Laabs and Munroe, 2016; Quirk and others, 2018) reveal the following pattern of glaciation in space and time: (1) the total volume of mountain glaciers in the LBB was less than 5% of the volume of Lake Bonneville, (2) mountain glaciers expanded before and during the overflowing phase of Lake Bonneville, and (3) glacier equilibrium-line altitudes were lowest in mountains surrounded by and immediately east (downwind) of Lake Bonneville. These observations support the possibility that Lake Bonneville impacted regional climate and was a local moisture source for mountain glaciers (Munroe and Mickelson, 2002) if mountain glaciers persisted through the Last Glacial Maximum (ending at 19 ka) to the overflowing phase of Lake Bonneville at 18.0–15.5 ka (Oviatt, 2015).

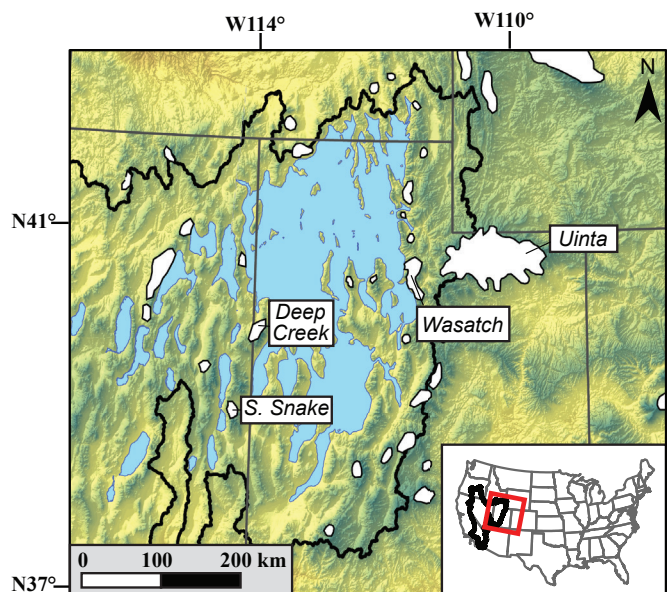


Figure 1. Shaded relief map of the northeastern Great Basin, western United States with extents of Great Basin lakes (blue) and mountain glacier systems (white) produced from a 30-m DEM from the National Elevation Dataset (<https://catalog.data.gov/dataset/usgs-national-elevation-dataset-ned>). Lake extents are from Reheis (1999) and glacier systems are from Pierce (2003). Mountain glacier systems with cosmogenic ^{10}Be exposure chronologies are labeled.

Until recently, understanding the relative timing of mountain glaciation and the transgressive (30–18 ka), overflowing (18.0–15.5 ka), and regressive (15.5–12.0 ka) phases of Lake Bonneville (as outlined by Oviatt, 2015) has been limited by several factors. Chiefly, age limits on mountain glacial deposits in the Uinta Mountains and elsewhere in the LBB have been few, due in large part to the lack of preserved organic matter available for radiocarbon dating in glacial deposits, and the fact that nearly all mountain glaciers in the LBB terminated high above the lake shoreline, thereby limiting to a single location at Little Cottonwood Canyon, at the western front of the Wasatch Mountains, where stratigraphic relations between glacial and lacustrine deposits can be observed. There, privatization and modification of the land surface have resulted in removal of outcrops displaying stratigraphic relations of lacustrine and glacial sediment described in previous studies (Madsen and Curry, 1979; Scott, 1988). More recent work by Godsey and others (2005) at a new exposure describes interlayering of glacial sediment with nearshore deposits of Lake Bonneville near the mouth of Little Cottonwood Canyon, suggesting that the glacier was at or near its known terminus during the Bonneville highstand.

The application of cosmogenic nuclide surface exposure dating to Pleistocene glacial deposits in the Uinta Mountains and elsewhere in the LBB has started to reveal the relative timing of mountain glaciation and the last cycle of Lake Bonneville. Several studies, all focusing on deposits of the last glaciation in the Uinta Mountains, report cosmogenic beryllium-10 (^{10}Be) exposure ages of erratic boulders atop terminal moraines (Munroe and others, 2006; Laabs and others, 2007; Refsnider and others, 2008; Laabs and others, 2009). Additionally, cosmogenic ^{10}Be exposure dating has been applied to terminal moraines in the western Wasatch Mountains (Laabs and others, 2011; Quirk and others, 2018) and in mountains west of Lake Bonneville (Laabs and Munroe, 2016). All of these studies have reported cosmogenic ^{10}Be exposure ages of terminal moraines that closely correspond to the late transgressive or early overflowing phase of Lake Bonneville.

Until recently, the direct comparison of cosmogenic ^{10}Be exposure ages of moraines with age limits on the last Lake Bonneville cycle (chiefly based on calendar-corrected radiocarbon dates) was complicated by a limited understanding of *in situ* production of cosmogenic ^{10}Be . Specifically, determining the sea-level high-latitude production rate of *in situ* ^{10}Be had been limited by the small number of locations where the production rate could be calibrated (Balco and others, 2008). Further, the most commonly used models for scaling *in situ* ^{10}Be production for altitude, geomagnetic latitude, and time yielded variable production rates in mountains of the LBB, and some of these models performed poorly in a recent statistical analysis by Borchers and others (2016). An important step forward was provided by recent work calibrating the ^{10}Be production rate at an independently dated surface in the LBB (Lifton and others, 2015, 2016), and development of a new model for scaling *in situ* production of ^{10}Be in space and time (Lifton and others, 2014). Such improvements to cosmogenic nuclide production models reduce variability among cosmogenic ^{10}Be exposure age estimates and permit more accurate comparison of cosmogenic ^{10}Be exposure ages of moraines to the chronology of Lake Bonneville. These newer ^{10}Be production models are now incorporated into online exposure age calculators (Balco and others, 2008; Marrero and others, 2016; Martin and others, 2017), providing accessible and consistent calculation and comparison of cosmogenic ^{10}Be exposure ages in the LBB and elsewhere.

This paper updates the cosmogenic chronology of glacial deposits in the Uinta Mountains based on newer models of *in situ* production of ^{10}Be . Although no new cosmogenic ^{10}Be exposure ages are available since the reporting on this subject by Laabs and Munroe (2016), the incorporation of newer ^{10}Be production models in online cosmogenic exposure age calculators affords a more consistent comparison of the cosmogenic exposure ages of moraines to the chronology of Lake Bonneville. Additionally, cosmogenic ^{10}Be exposure ages of moraines are updated in parts of the western Wasatch Mountains (not including Big Cottonwood Canyon; the reader is referred to Quirk and others [2018] for a report on this area), and in two ranges in the western LBB, the South Snake and Deep Creek Ranges. The updated cosmogenic chronologies of glacial deposits support our previous reporting (Laabs and Munroe, 2016) that Pleistocene glaciers in the LBB reached expanded positions before and during the overflowing phase of Lake Bonneville, and began retreating before the lake ceased overflowing at the Provo shoreline.

METHODS

Cosmogenic ^{10}Be exposure ages of terminal moraines of the last glaciation in the LBB are recalculated here using newer production models for *in situ* ^{10}Be that take advantage of a calibrated spallogenic production rate from within the LBB (Lifton and others, 2015, 2016) and an updated version of the time-dependent production scaling model of Lifton and others (2014), termed “LSDn” in a statistical analysis of the model by Borchers and others (2016). The production rate calibration site in the LBB is an erosional surface below the highest shoreline of Lake Bonneville at the southern end of the Promontory Mountains in northern Utah. The surface formed by wave cutting along the mountain front during the transgressive phase of Lake Bonneville and was exposed during the Bonneville flood at ca. 18.0 ka (Lifton and others, 2015). The calibration at this site yields a sea-level, high-latitude spallogenic production rate of *in situ* ^{10}Be statistically similar to other calibration sites worldwide and represents the only ^{10}Be production rate calibration of an independently dated surface in western North America. Given the geographic and

temporal proximity of this calibration site to late Pleistocene moraines in the LBB, it provides the best available production model for computing cosmogenic ^{10}Be exposure ages associated with the moraines. We combined this calibration set with the LSDn scaling model of Lifton and others (2014) as implemented in Version 3.0 of the online calculator formerly known as the CRONUS calculator (Balco and others, 2008) to compute cosmogenic ^{10}Be exposure ages of moraines in the LBB excluding those in Big Cottonwood Canyon of the western Wasatch Mountains. The reader is referred to Quirk and others (2018) for cosmogenic ^{10}Be exposure ages and data for that location, which were calculated in the same way as the cosmogenic exposure ages reported here.

RESULTS AND DISCUSSION

Recalculated cosmogenic ^{10}Be exposure ages in the Uinta and Wasatch Mountains are 10–14% (about 2 kyr) older than originally reported by Laabs and others (2009, 2011). Older exposure ages are to be expected because the production rates used here are proportionately less than those used in the original studies. The newly calculated older exposure ages prompt reconsideration of the relative timing of moraine occupation and the last cycle of Lake Bonneville.

In most studies of cosmogenic moraine chronologies, the mean of boulder exposure ages of terminal moraines is considered the best estimate of when ice last occupied the moraine (figure 2). This interpretive approach is based on the observation that cosmogenic ^{10}Be exposure ages atop a single moraine are normally distributed and vary as expected given measurement errors (e.g., internal uncertainty shown in table 1). This is the case for 8 or 10 dated terminal moraines in the Uinta Mountains. Individual exposure ages of boulders atop the moraines at Smiths Fork and North Fork Provo (terminal) show a bimodal distribution (even after outliers identified by Laabs and others [2009] are removed), suggesting that the moraines are either degrading or were occupied twice during the last glaciation. Other moraines have a single mode (figure 3), with ages varying as expected as indicated by reduced chi-squared values (χ^2_r in table 1) close to or slightly greater than unity (c.f., Rood and others, 2011). In these cases, the mean age (table 1, figure 2) closely corresponds to the most probable age as indicated by relative probability plots (figure 3). In cases where cosmogenic ^{10}Be exposure age distributions are bimodal, it is unclear whether (1) the moraines were occupied twice, (2) have undergone a period of degradation (represented by the younger mode) since the time of ice abandonment, or (3) some other factor has contributed to the apparent bimodal exposure history of boulders atop the Smiths Fork and North Fork Provo moraines. For this reason, the mean exposure ages of these two moraines are considered the best estimates of the time when ice last occupied the moraines. For all other moraines in the Uinta Mountains and elsewhere in the LBB, the mean exposure age is also considered the best limit on the time when ice last occupied the moraines.

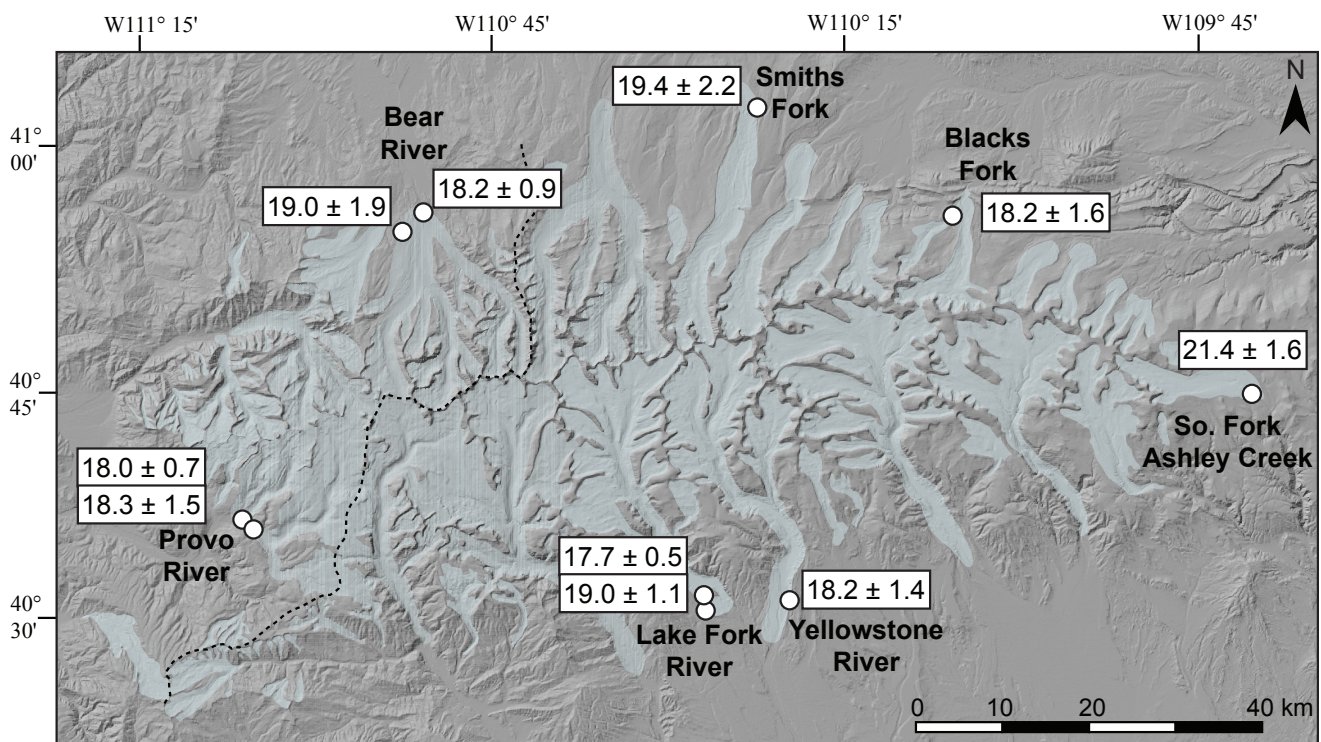


Figure 2. Shaded relief with reconstructed maximum ice extents of the last glaciation in the Uinta Mountains, Utah produced from a 30-m DEM from the National Elevation Dataset (<https://catalog.data.gov/dataset/usgs-national-elevation-dataset-ned>). Recalculated mean cosmogenic ^{10}Be exposure ages (ka) of terminal moraines in glacial valleys are described in the text (see table 1 for individual cosmogenic exposure ages).

Mean and maximum probable cosmogenic ^{10}Be exposure ages of moraines in the Uinta Mountains, Wasatch Mountains, and western LBB mountains overlap, with some variability relative to the overflowing phase of Lake Bonneville (figure 3). In the Uinta Mountains, terminal moraines were last occupied by ice prior to or during the overflowing phase of Lake Bonneville. Ice retreat began earliest in the South Fork Ashley Creek valley in the eastern Uinta Mountains, where the mean cosmogenic ^{10}Be exposure age of the terminal moraine is 21.4 ± 1.6 ka. This valley was farthest from Lake Bonneville and had one of the highest equilibrium-line altitudes (ELAs) in the Uinta Mountains, suggesting that its mass balance was less impacted by a lake effect from Lake Bonneville compared to other valleys closer to the lake. In the Burnt Fork valley, also far from Lake Bonneville compared to other glacial valleys, cosmogenic exposure ages are highly variable (table 1, figure 3). If, as Laabs and others (2009) suggested, such high variability suggests the oldest exposure age of this moraine best represents the time when it was last occupied by ice, then the ice retreat here also began prior to the overflowing phase of Lake Bonneville.

Terminal moraine exposure ages are generally younger in the middle and western valleys of the Uinta Mountains, corresponding to the overflowing phase of Lake Bonneville. In the middle valleys of the Uinta Mountains, exposure ages of terminal moraines range from 19.4 ± 2.2 ka in the Smiths Fork valley to 18.2 ± 1.4 ka in the Yellowstone River valley. In western valleys, exposure ages range from 19.0 ± 1.9 ka in the East Fork Bear River valley to 18.0 ± 0.7 ka in the North Fork Provo River valley.

Changes in mountain glacier length immediately after the time when terminal moraines were abandoned is difficult to assess in these areas, except in the Lake Fork valley of the southern Uinta Mountains (figure 2). There, an ice proximal crest nested into the ice-distal crest of the terminal moraine has a mean exposure age of 17.7 ± 0.5 ka. The moraine age suggests that ice re-advanced to or persisted at its maximum length during the early part of the overflowing phase of Lake Bonneville, but like glaciers elsewhere in the Uinta Mountains, began retreating while the lake continued to overflow. This observation differs significantly from the original reports of Laabs and others (2009) and Laabs and others (2011), where cosmogenic ^{10}Be exposure ages of moraines (calculated with the consensus production rate at the time) suggested that ice persisted at terminal moraines until the end of the overflowing phase of Lake Bonneville at ca. 15.5 ka.

In the Wasatch Mountains, cosmogenic ^{10}Be exposure ages of terminal moraines differ across three valleys. Terminal moraines in American Fork and Little Cottonwood Canyons are younger than the small number ($n = 3$) of boulder exposure ages from atop the ice-distal crest of the terminal moraine in Bells Canyon (figure 3). The exposure ages from atop the ice-distal moraine crest in Bells Canyon suggest that ice occupied the terminal moraine at 21.9 ± 2.0 ka, prior to the overflowing phase of Lake Bonneville during the global Last Glacial Maximum. The younger terminal moraine exposure ages from American Fork Canyon (16.8 ± 1.4 ka) and Little Cottonwood Canyon (17.3 ± 0.7 ka) overlap with exposure ages from the ice-proximal moraine crest in Bells Canyon (16.8 ± 0.7 ka), indicating that glaciers occupied terminal moraines during the overflowing phase of Lake Bonneville.

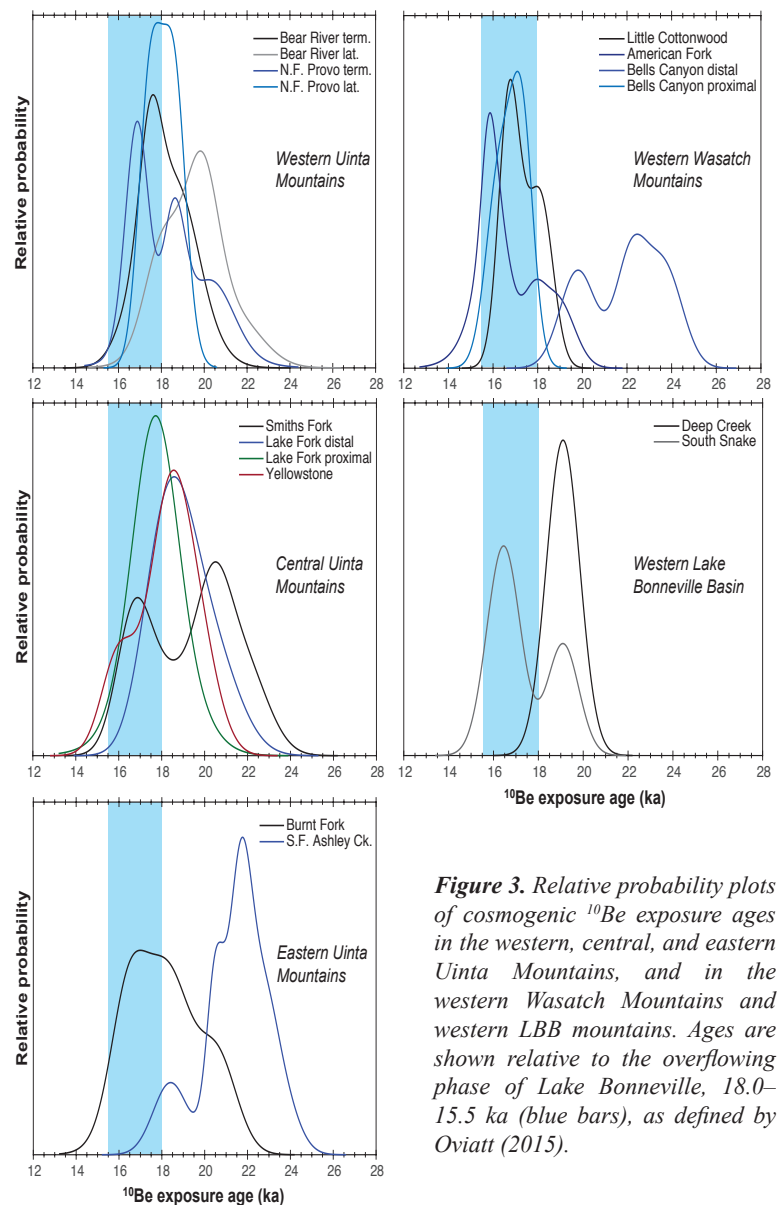


Figure 3. Relative probability plots of cosmogenic ^{10}Be exposure ages in the western, central, and eastern Uinta Mountains, and in the western Wasatch Mountains and western LBB mountains. Ages are shown relative to the overflowing phase of Lake Bonneville, 18.0–15.5 ka (blue bars), as defined by Oviatt (2015).

Table 1. Cosmogenic beryllium-10 exposure ages of moraines in the Lake Bonneville basin.

Mountains	Valley/Moraine	Sample ID	Cosmogenic Exposure Age (ka)	Internal uncertainty (kyr)	External uncertainty (kyr)
<i>Uinta west</i>	Bear River - Main Valley	EBBF-1	17.0	0.9	1.1
		EBBF-2	18.9	0.9	1.2
		EBBF-3	17.5	0.5	0.8
		EBBF-4	18.3	1.0	1.2
		EBBF-5	19.2	1.2	1.4
			18.2 ± 0.9	χ²r = 1.28	
	Bear River - East Fork	EFBR-1	15.0	1.5	1.6
		EFBR-4A	22.2	4.1	4.2
		EFBR-4B	19.9	0.8	1.1
		EFBR-5	19.8	0.9	1.2
		EFBR-7	19.5	1.8	2.0
		EFBR-8	19.9	0.7	1.0
		EFBR-9A	18.3	0.8	1.1
		EFBR-9B	21.6	1.2	1.5
		EFBR-9C	17.8	0.8	1.1
			19.0 ± 1.9	χ²r = 1.83	
	N.F. Provo terminal	NFP-1	12.9	0.6	0.8
		NFP-4C	14.7	0.7	0.9
		NFP-4B	15.2	0.8	1.0
		NFP-2B	16.8	0.6	0.9
		NFP-5	16.9	0.5	0.8
		NFP-4A	18.6	0.5	0.9
		NFP-3A	19.0	2.0	2.2
		NFP-4D	20.4	1.0	1.2
			18.3 ± 1.5	χ²r = 5.32	
	N.F. Provo lateral	NFP-12	17.3	0.5	0.8
		NFP-13	17.7	0.5	0.9
		NFP-14	18.6	0.5	0.9
		NFP-15	18.6	0.6	0.9
			18.0 ± 0.7	χ²r = 1.58	
<i>Uinta middle</i>	Smiths Fork	EFSF-2	18.5	1.3	1.5
		EFSF-4	20.4	0.8	1.1
		EFSF-5	16.7	0.8	1.0
		EFSF-7	30.3	1.7	2.1
		EFSF-8	21.8	1.1	1.3
		EFSF-9	51.8	3.8	4.3
		EFSF-10	27.0	1.2	1.6
			19.4 ± 2.2	χ²r = 5.90	
	Lake Fork distal	LF04-3	11.2	0.6	0.8
		LF04-1	17.5	0.9	1.1
		LF04-2	18.3	0.9	1.1
		LF04-5B	18.6	1.0	1.2
		LF04-5A	19.1	1.0	1.2
		LF-RK-5	19.9	1.4	1.6
		LF04-4	20.5	1.2	1.4
			19.0 ± 1.1	χ²r = 1.15	
	Lake Fork proximal	LFR-1	17.8	0.9	1.1
		LFR-3	18.7	1.3	1.4
		LFR-4	17.2	1.0	1.2
		LFR-5	17.4	1.8	1.9
		LFR-6	17.3	1.1	1.2
		LFR-7	17.9	1.0	1.2
		LFR-9	17.9	1.0	1.2
			17.7 ± 0.5	χ²r = 0.24	

Table 1. Continued

Yellowstone	YS-RK-11	12.8	0.6	0.8	
	YS-RK-6	14.2	0.7	0.9	
	YS-RK-7	16.0	0.8	1.0	
	YS-RK-9	18.3	0.9	1.1	
	YS-RK-3	18.2	1.0	1.2	
	YS-RK-10	18.6	0.9	1.1	
	YS-RK-8	19.8	0.9	1.1	
			18.2 ± 1.4	χ ² r = 4.45	
Uinta east	Burnt Fork	BF-13	14.1	0.7	0.8
		BF-15	16.4	0.8	1.0
		BF-16	17.3	1.2	1.4
		BF-9	18.0	1.6	1.8
		BF-17	18.5	0.9	1.1
		BF-12	20.6*	0.9	1.2
			18.2 ± 1.6	χ ² r = 3.28	
	S.F. Ashley	SFA-9	18.4	0.8	1.0
		SFA-10	20.5	0.4	0.9
		SFA-5	21.3	0.9	1.2
		SFA-1	21.6	0.5	1.0
		SFA-8	21.8	0.5	1.0
		SFA-4	22.7	0.6	1.0
		SFA-2	23.4	0.8	1.2
		SFA-7	39.2	1.0	1.8
		SFA-11	53.9	2.4	3.2
	SFA-6	56.2	1.7	2.8	
		21.4 ± 1.6	χ ² r = 5.37		
Wasatch	American Fork	AF-7	13.9	0.6	0.8
		AF-2	15.5	0.7	0.9
		AF-6	15.6	1.2	1.4
		AF-11	15.8	0.3	0.7
		AF-9	16.0	0.5	0.8
		AF-10	16.2	0.7	0.9
		AF-1	16.3	0.6	0.9
		AF-4	17.8	0.5	0.8
		AF-3	18.7	0.8	1.0
	AF-8	19.0	0.7	1.0	
			16.8 ± 1.4	χ ² r = 4.80	
	Little Cottonwood	02-UT-LCC-01	17.8	0.6	0.9
		02-UT-LCC-02	16.7	0.5	0.8
		02-UT-LCC-04	17.0	0.5	0.8
		02-UT-LCC-05	18.0	0.5	0.9
		02-UT-LCC-06	16.7	0.4	0.8
		02-UT-LCC-07	16.6	0.5	0.8
		02-UT-LCC-08	18.4	0.5	0.9
			17.3 ± 0.7		
	Bells distal	BCR-1	19.8	0.8	1.1
		BCR-2	23.7	0.8	1.2
		BCR-4	22.2	0.7	1.1
				21.9 ± 2.0	χ ² r = 6.13
Bells proximal	BCLR-1	16.3	0.6	0.9	
	BCLR-2	17.3	0.5	0.8	
			16.8 ± 0.7	---	

Table 1. Continued

Western LBB	Deep Creek Range	DC-02	11.5	0.5	0.6
		DC-05	18.8	0.7	1.0
		DC-06	19.1	0.7	1.0
		DC-03	19.4	0.7	1.0
		DC-04	30.4	5.0	5.1
			19.1 ± 0.3	$\chi^2_r = 0.22$	
	South Snake Range	DL-1	16.7	0.7	1.0
		DL-2	19.1	0.7	1.0
		DL-4	16.2	0.7	0.9
		DL-6	13.5	0.5	0.7
			17.3 ± 1.6	$\chi^2_r = 5.40$	

Note: all ages are calculated using version 3.0 of the online calculator formerly known as CRONUS (Balco and others, 2008) based on a calibrated production rate at Promontory Point, Utah (Lifton and others, 2015) and LSDn scaling (Lifton and others, 2014). Mean exposure ages of moraines with 1s are shown in bold. Internal uncertainty is based on the AMS measurement of beryllium-10 concentration and external uncertainty is based on the measurement uncertainty and the uncertainty of the scaled production rate. Ages shown in gray were identified as outliers by Laabs and others (2009). Sample data are given in Laabs and others (2009) and Laabs and Munroe (2016).

*Considered by Laabs and others (2009) to be the best estimate of the moraine age.

As reported by Laabs and Munroe (2016), the preservation of multiple crests (ice-proximal and ice-distal) along the Bells Canyon terminal moraine affords an opportunity to more precisely identify temporal changes in glacier length. The distinct cosmogenic exposure ages of the distal and proximal moraine crests in Bells Canyon suggest multiple intervals of ice occupation of the terminal moraine complex; one interval prior to the overflowing phase of Lake Bonneville and one interval during the overflowing phase. New cosmogenic exposure age limits from Big Cottonwood Canyon of Quirk and others (2018) also reveal evidence of an earlier glacial maximum prior to the overflowing phase of Lake Bonneville. There, ice occupied a lateral moraine delimiting the time of maximum glacier length at 20.2 ± 1.1 ka. To summarize, evidence that glaciers were expanded to their terminal moraine positions during the overflowing phase of Lake Bonneville is present in American Fork, Little Cottonwood, and Bells Canyons. In contrast, a moraine representing a later glacial maximum in the Wasatch Mountains was not found in Big Cottonwood Canyon. There, Quirk and others (2018) report an exposure age of 17.9 ± 0.5 ka for a bedrock surface just above the dated lateral moraine, which suggests that overall ice retreat began during the overflowing phase of Lake Bonneville, as was the case in neighboring glacial valleys in the Wasatch Mountains.

Cosmogenic exposure ages of terminal moraines in mountains in the western LBB are few but are consistent with exposure ages of moraines in the Uinta and Wasatch Mountains. The bimodal distribution of exposure ages of the moraine in the South Snake Range suggests multiple intervals of ice occupation, although more data are needed to more accurately determine the age of this single crested moraine, and to evaluate if it was constructed by multiple episodes of ice advance to the same position. Cosmogenic exposure ages of the moraine in the Deep Creek Range indicate that ice last occupied the terminal moraine at 19.1 ± 0.3 ka, prior to the overflowing phase of Lake Bonneville.

CONCLUSIONS

Overall, the recalculated cosmogenic chronology of terminal moraines in the Uinta, Wasatch, and western LBB mountains displays some correspondence between the time when mountain glaciers last occupied terminal moraines and the overflowing phase of Lake Bonneville. Only a small number of instances suggest that terminal moraines were abandoned prior to the overflowing phase of Lake Bonneville; these are far downwind of the lake in the eastern Uinta Mountains, terminal moraines of an earlier glacial maximum in Big Cottonwood Canyon of the Wasatch Mountains, and in the Deep Creek Range, where more data are needed to better assess the timing of glaciation. In most valleys, glaciers occupied (or reoccupied) terminal moraines during the overflowing phase of Lake Bonneville. Mean exposure ages of terminal moraines in the central and western Uinta Mountains correspond to the late transgressive/early overflowing phase (20–18 ka), whereas exposure ages of terminal moraines in the Wasatch Mountains closer to the lake suggest that moraines were occupied until ~17 ka. No terminal moraines correspond

to the end of the overflowing phase of Lake Bonneville as originally reported by Laabs and others (2009, 2011), unless the lake dropped from the Provo shoreline earlier than suggested in recent reports by Oviatt (2015) and Miller (2016).

An impact by Lake Bonneville on glacier mass balance in the Uinta and Wasatch Mountains remains possible based on the updated moraine chronology reported here. If the lake was near its maximum size just prior to the start of its overflow at 18 ka, as suggested by the hydrograph of Oviatt (2015), then it may have been a moisture source for glaciers in the Uinta and Wasatch Mountains even prior to 18 ka. If so, lake-effect precipitation in the central and western Uinta Mountains, where paleo-glacier ELAs were among the lowest in the range (Munroe and Mickelson, 2002) and recalculated cosmogenic ages range from ~20–18 ka, could have impacted glacier mass balance. Ice retreat during the overflowing phase in the central and western Uinta Mountains could have been caused by a reduced lake effect resulting from a 25% decline in lake surface area at the Provo shoreline. Even in the valleys of the western Wasatch Mountains immediately downwind of Lake Bonneville, glaciers began retreating at ~17 ka while the lake overflowed. This observation supports the possibility of a climatic shift during the overflowing phase of the lake to conditions that no longer favored glacier maxima.

Although the potential impact of Lake Bonneville on glacier mass balance in the Uinta and Wasatch Mountains is supported by ELA reconstructions and the recalculated chronology summarized here, it is still complicated by several uncertainties. First, whether the lake was seasonally frozen during the latter part of the transgressive phase and the overflowing phase is uncertain, although clumped isotope data from Mering (2015) suggest that the average lake temperature was warm enough to remain ice free. Additionally, the frequency of lake-effect storms to enhance moisture, the impact of the lake on near surface lapse rates in neighboring mountains, and seasonal differences in temperature and precipitation changes relative to the modern climate are unclear. Ongoing reconstructions of hydroclimate in the LBB during the last glaciation and Bonneville lake cycle (e.g., Oster and Ibarra, 2019) and refinements to the chronologies of Lake Bonneville and Pleistocene mountain glaciers may help resolve remaining questions regarding the hydrologic and climatic relationship of the lake and mountain glaciers.

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