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THE LAST DEGLACIATION OF ALASKA

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ABSTRACT. *We review available chronologies that constrain the timing of glacier fluctuations during the last deglaciation in Alaska. We address three questions relating to the last glacial termination: (i) How did the timing of glacier recession relate to buildup of global CO_2, such as during the onset of CO_2 rise at ~18 ka? (ii) Did glaciers fluctuate in synchrony with Heinrich Stadial 1 (18-14.6 ka)? And, (iii) what is the spatio-temporal pattern of glacier change during the climatically turbulent late glacial interval (14.6-11.7 ka)? The existing record is incomplete, yet reveals that most Alaskan glaciers experienced significant retreat (~40% of their Last Glacial Maximum lengths) prior to the onset of CO_2 rise ~18 ka. This points to stronger insolation forcing of Alaskan glaciers compared to mid-latitude glaciers. Despite some glacier re-advances and standstills during Heinrich Stadial 1, most glaciers continued to recede. This suggests that glaciers in Alaska were relatively immune to the far-field effects of Atlantic meridional overturning circulation. Finally, the majority of glaciers (9 out of 14 available records) were up-valley of their late Holocene glacier extents during the Younger Dryas. Most of the sites with evidence for relatively extensive glaciers during the Younger Dryas are in southern Alaska, which may relate to moisture changes associated with the flooding of Bering Strait as much as it does to changes in North Atlantic Ocean circulation.*

La última deglaciación de Alaska

RESUMEN. *Revisamos las cronologías disponibles que identifican la temporalidad de las fluctuaciones glaciares durante la última deglaciación en Alaska. Nos centramos en tres cuestiones relacionadas con el final de la última glaciación: (i) ¿Cómo se relaciona el momento de la recesión glaciar con el aumento global de CO_2 hacia ~18ka? (ii) ¿Fluctuaron los glaciares en sincronía con el Stadial 1 de Heinrich (18-14.6 ka)? Y (iii) ¿Cuál es el patrón espacio-temporal del cambio glaciar durante el último intervalo glaciar climáticamente turbulento (14.6-11.7 ka)? El registro existente es incompleto y revela que la mayoría de los glaciares de*

Alaska experimentaron un retroceso significativo (~40% de su longitud durante el Último Máximo Glaciar) anterior al inicio de aumento de CO_2 hacia 18 ka. Esto apunta a una mayor insolación en los glaciares de Alaska en comparación con los glaciares de las latitudes medias. A pesar de algunos reavances glaciares durante el Stadial 1 de Heinrich, la mayoría de los glaciares continuaron retrocediendo. Esto sugiere que los glaciares de Alaska fueron relativamente inmunes a los efectos de la circulación meridional atlántica de retorno. Finalmente, durante el Younger Dryas la mayoría de los glaciares (9 de 14 registros) estaban por encima de su posición de finales del Holoceno. La mayoría de los lugares con evidencia de glaciares relativamente extensos durante el Younger Dryas están en el sur de Alaska, lo que puede relacionarse con cambios de humedad asociados a la inundación del estrecho de Bering tanto como a los cambios en la circulación del Atlántico Norte.

Keywords: Alaska, deglaciation, glacier, geochronology, paleoclimate.

Palabras clave: Alaska, deglaciación, glaciar, geocronología, paleoclima.

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1. Introduction

Facing a major episode of global deglaciation today (Roe *et al.*, 2017), lessons learned from the last deglaciation are relevant for enriching our understanding of glacier sensitivity to climate forcing. The last deglaciation refers to the transition from glacial maximum conditions between 26 and 19 ka (Clark *et al.*, 2009) to the Holocene interglaciation period (the past 11,700 years). Detailed reconstructions of mountain glacier change from the last deglaciation exist from around the globe (e.g., Shakun *et al.*, 2015), although complete, high-resolution records of glacier fluctuations through the last deglaciation from single valleys remain sparse (e.g., Putnam *et al.*, 2010, 2013). Alaska fills an important spatial gap in the available records of mountain glacier change during the last deglaciation. Unlike elsewhere across the high northern latitudes, which was mostly smothered by continental ice sheets during glacial maxima, Alaska remained only partially glaciated (Fig. 1). Thus, Alaska is one of few high latitude regions with detailed geomorphic records of mountain glacier extent during the last deglaciation.

Presently several outstanding questions about glacier behavior during the last deglaciation remain unresolved. For example, how did the timing of glacier recession relate to buildup of global CO_2, such as during the onset of CO_2 rise at ~18 ka? What was the expression of glacier change during Heinrich Stadial 1 (~18-14.6 ka)? Finally, what is the spatio-temporal record of glacier change during the climatically turbulent late glacial interval, such as during the Bølling-Allerød (14.6-12.9 ka), Antarctic Cold Reversal (~14-13 ka), and Younger Dryas (12.9-11.7 ka) periods? These three questions can be addressed with high-resolution and precise glacial chronologies from around the globe spanning the last deglaciation. Embedded within these questions is the role of polar amplification, an underlying feature of the climate system that may influence high-latitude glacier change differently than elsewhere. However, there are currently very few complete mountain glacier chronologies from the high northern latitudes. Despite some chronological constraints of mountain glacier fluctuations from Alaska, they are still mostly scattered data points from different mountain ranges around the state. Nevertheless, adequate information is available from a few places to begin to address the above questions.

This paper summarizes some key records of glacier change in Alaska spanning the last deglaciation. We build from the most recent review of the Pleistocene glacier history of Alaska (Kaufman *et al.*, 2011). There have been some new glacial chronology studies published since that time, and furthermore, unlike past reviews spanning the Late Pleistocene (Briner and Kaufman, 2008; Kaufman *et al.*, 2011) and spanning the Holocene (Barclay *et al.*, 2009; Kaufman *et al.,* 2016), this paper focuses solely on the last deglaciation. This is the first review paper on the glaciation history of Alaska to do so. Our goal is not to provide an exhaustive review of all publications on glacier history in Alaska during this interval, but rather to focus on select records that are most useful for addressing outstanding questions about the last glacial termination in the state.

2. Key glacial chronologies

To address the three questions outlined in the introduction, we seek the best available continuous glacial histories from single mountain ranges, or more ideally, high-resolution chronologies from single glacier systems. Glacier chronologies that most closely meet this goal exist in the Brooks Range, Alaska Range, Ahklun Mountains and southern Alaska (Fig. 1), and these records have allowed us to build glacier histories spanning the last deglaciation in these select areas. Below, we review some of the key records from these locations and summarize the glacier history from each. All cosmogenic ^{10}Be exposure ages reported in this paper have been calculated using the same parameters: the Arctic ^{10}Be production rate of Young *et al*. (2013) using version 3.0 of the calculator from Balco *et al.* (2008; http://hess.ess.washington.edu) with Lm scaling (see Balco *et al*., 2008). Table 1 shows all samples discussed here, and includes ages calculated using alternative production rates and scaling schemes. A Google Earth KMZ supplemental file shows the location all of the samples discussed here, and when coupled with the Arctic DEM KMZ file (https://elevation2.arcgis.com/arcgis/rest/services/Polar/ArcticDEM/ImageServer), one can see the all ages discussed and their geomorphic context. All ^{14}C ages reported here (Table 2) are in calendar years BP and re-calculated using Calib 7.1 (Stuiver *et al*., 2017; http://calib.org/calib). All marine samples have been calibrated using the standard marine reservoir correction; there is no overwhelming information available from southern Alaska that suggests otherwise (Reger *et al*., 2008a; Kopczynski *et al*., 2017).

Table 1. Cosmogenic nuclide exposure ages discussed in text.

Sample name	Latitude (DD)	Longitude (DD)	elevation (m asl)	Thickness (cm)	Shielding correction	[Be-10] atoms g-1	+/- atoms g-1	Be AMS standard	[Al-26] atoms g-1	+/- atoms g-1	Al AMS standard	Age (ka) Arctic Lm	Age (ka) Arctic LSDn	Age (ka) Global Lm	Age (ka) Global LSDn
Briner et al., 2005															
LGM terminal moraine, western Alaska Range															
SR2-00-2	61.481	-154.5353	650	5.0	1.0000	196000	8000	KNSTD	1101000	67000	KNSTD	22.8±0.9 19.4±1.2	23.4±1 18.8±1.2	21.8±0.9 19.4±1.2	21.4±0.9 18.8±1.2
SR2-00-5	61.47453	-154.5036	641	3.0	1.0000	176000	9000	KNSTD	1103000	67000	KNSTD	20.3±1 19.3±1.2	20.8±1.1 18.7±1.1	19.4±1 19.3±1.2	19.1±1 18.7±1.1
SR2-00-3	61.48586	-154.5675	613	5.0	1.0000	174000	7000	KNSTD	0	0	KNSTD	20.9±0.8	21.5±0.9	20±0.8	19.7±0.8
SR2-00-4	61.45944	-154.466	655	4.0	1.0000	172000	7000	KNSTD	0	0	KNSTD	19.7±0.8	20.3±0.8	18.9±0.8	18.6±0.8
Balascio et al., 2005															
Recessional moraine, Brooks Range															
NB05-1	69.33863	-143.5783	779	2.0	1.0000	214000	18000	KNSTD	0	0	KNSTD	22±1.9	22.5±1.9	21.1±1.8	20.6±1.7
NB05-2	69.3375	-143.57505	768	2.0	1.0000	166000	14000	KNSTD	0	0	KNSTD	17.3±1.5	17.6±1.5	16.5±1.4	16.1±1.4
NB05-3	69.3491	-143.5762	686	2.0	1.0000	175000	16000	KNSTD	0	0	KNSTD	19.6±1.8	20.1±1.8	18.8±1.7	18.4±1.7
NB05-4	69.3429	-143.56098	702	2.0	1.0000	213000	19000	KNSTD	0	0	KNSTD	23.6±2.1	24.1±2.2	22.6±2	22.1±2
LGM terminal moraine, Brooks Range															
NB05-5	69.4447	-143.78667	779	2.0	1.0000	231000	20000	KNSTD	0	0	KNSTD	23.8±2.1	24.3±2.1	22.8±2	22.3±1.9
NB05-6	69.4582	-143.80105	772	2.0	1.0000	263000	22000	KNSTD	0	0	KNSTD	27.3±2.3	27.9±2.4	26.2±2.2	25.5±2.1
NB05-7	69.4596	-143.80033	758	2.0	1.0000	274000	23000	KNSTD	0	0	KNSTD	28.8±2.4	29.5±2.5	27.6±2.3	27±2.3
NB05-8	69.45985	-143.7943	754	2.0	1.0000	569000	48000	KNSTD	0	0	KNSTD	60.6±5.2	62±5.3	58±5	56.7±4.8
NB05-9	69.4611	-143.7956	749	2.0	1.0000	210000	19000	KNSTD	0	0	KNSTD	22.2±2	22.7±2.1	21.3±1.9	20.8±1.9
Young et al., 2009															
LGM terminal moraine, Alaska Range															
FL06-01	63.54898	-144.35723	1064	3.0	1.0000	283500	7100	07KNSTD	0	0	KNSTD	25.3±0.6	25.8±0.7	24.2±0.6	23.6±0.6
FL06-02	63.53728	-144.36893	1058	2.0	1.0000	118100	5100	07KNSTD	0	0	KNSTD	10.5±0.5	10.6±0.5	10±0.4	9.7±0.4
FL06-03	63.54522	-144.41628	1234	2.0	1.0000	243100	7000	07KNSTD	0	0	KNSTD	18.6±0.5	18.9±0.5	17.9±0.5	17.3±0.5
FL06-04	63.54557	-144.42693	1262	2.0	1.0000	246800	6400	07KNSTD	0	0	KNSTD	18.5±0.5	18.7±0.5	17.7±0.5	17.1±0.4
FL06-05	63.54443	-144.45505	1333	2.5	1.0000	263600	7400	07KNSTD	0	0	KNSTD	18.7±0.5	18.9±0.5	17.9±0.5	17.3±0.5
FL06-06	63.53808	-144.46902	1347	2.0	1.0000	269800	7000	07KNSTD	0	0	KNSTD	18.8±0.5	19±0.5	18.1±0.5	17.4±0.5
FL06-12	63.55167	-144.39142	1129	2.0	1.0000	129300	3800	07KNSTD	0	0	KNSTD	10.8±0.3	11±0.3	10.4±0.3	10±0.3
Recessional erratics, Alaska Range															
US07-09	63.50463	-144.52625	1595	2.0	0.9950	296700	11500	07KNSTD	0	0	KNSTD	17.1±0.7	17.1±0.7	16.4±0.6	15.6±0.6
US07-10	63.50472	-144.52617	1593	3.0	0.9950	272100	7600	07KNSTD	0	0	KNSTD	15.8±0.4	15.8±0.4	15.2±0.4	14.5±0.4
US07-11	63.50443	-144.52673	1598	3.0	0.9950	258800	6700	07KNSTD	0	0	KNSTD	15±0.4	15±0.4	14.4±0.4	13.7±0.4
FL07-01	63.51025	-144.51593	1449	3.0	0.9930	114700	3800	07KNSTD	0	0	KNSTD	7.5±0.2	7.5±0.2	7.2±0.2	6.9±0.2
FL07-02	63.51003	-144.51762	1458	3.0	0.9940	199000	5400	07KNSTD	0	0	KNSTD	12.9±0.4	13±0.4	12.3±0.3	11.8±0.3
FL07-06	63.5111	-144.53538	1544	2.5	0.9970	100000	3600	07KNSTD	0	0	KNSTD	6±0.2	6±0.2	5.8±0.2	5.5±0.2
FL07-07	63.5105	-144.53925	1576	2.5	0.9980	156700	7800	07KNSTD	0	0	KNSTD	9.1±0.5	9.1±0.5	8.8±0.4	8.3±0.4
FL07-08	63.5104	-144.53725	1546	2.5	0.9970	216700	12900	07KNSTD	0	0	KNSTD	13±0.8	13±0.8	12.5±0.7	11.9±0.7
US07-04	63.5003	-144.52267	1689	3.0	0.9950	244800	16900	07KNSTD	0	0	KNSTD	13.2±0.9	13.2±0.9	12.7±0.9	12±0.8
US07-05	63.49992	-144.5234	1687	2.0	0.9940	149400	3800	07KNSTD	0	0	KNSTD	8±0.2	7.9±0.2	7.7±0.2	7.3±0.2
Matmon et al., 2010															
LGM terminal moraine, Alaska Range															
DDDN-1	63.78428333	-145.7423333	649	4.0	1.0000	155000	5000	07KNSTD	0	0	KNSTD	20±0.6	20.5±0.7	19.2±0.6	18.8±0.6
DDDN-1-SD	63.78428333	-145.7423333	649	2.0	1.0000	150000	5000	07KNSTD	0	0	KNSTD	19.1±0.6	19.6±0.7	18.3±0.6	17.9±0.6
DDDN-2	63.77765	-145.7633333	716	4.0	1.0000	217000	7000	07KNSTD	0	0	KNSTD	26.4±0.9	27.1±0.9	25.3±0.8	24.8±0.8
DDDN-2-SD	63.77765	-145.7633333	716	2.0	1.0000	156000	5000	07KNSTD	0	0	KNSTD	18.7±0.6	19.1±0.6	17.9±0.6	17.5±0.6
DDDN-3	63.77363333	-145.7740167	736	4.0	1.0000	167000	6000	07KNSTD	0	0	KNSTD	19.9±0.7	20.4±0.7	19.1±0.7	18.7±0.7
DDDN-3-SD	63.77363333	-145.7740167	736	2.0	1.0000	160000	5000	07KNSTD	0	0	KNSTD	18.8±0.6	19.3±0.6	18±0.6	17.6±0.6
DR1-1	63.77718333	-145.7559833	683	2.0	1.0000	113000	10000	07KNSTD	0	0	KNSTD	13.9±1.2	14.3±1.3	13.3±1.2	13.1±1.2
DR1-2	63.77721667	-145.7566833	681	2.0	1.0000	144000	12000	07KNSTD	0	0	KNSTD	17.8±1.5	18.2±1.5	17±1.4	16.7±1.4
DR1-3	63.77933333	-145.7526833	687	2.0	1.0000	103000	8000	07KNSTD	0	0	KNSTD	12.6±1	13±1	12.1±0.9	11.8±0.9
DR1-4	63.77973333	-145.7526167	669	2.0	1.0000	111000	10000	07KNSTD	0	0	KNSTD	13.8±1.3	14.2±1.3	13.3±1.2	13±1.2
DR1-5	63.7792	-145.7557	679	2.0	1.0000	573000	50000	07KNSTD	0	0	KNSTD	71.7±6.4	73.6±6.5	68.7±6.1	67.2±6
Dortch et al., 2010b															
Carlo end moraine, Alaska Range															
Ala-126A	63.61	-148.777	682	2.0	1.0000	150600	19100	07KNSTD	0	0	KNSTD	18.5±2.4	19±2.4	17.7±2.3	17.4±2.2
Ala-126B	63.61	-148.777	682	2.0	1.0000	144400	18200	07KNSTD	0	0	KNSTD	17.7±2.2	18.2±2.3	17±2.2	16.7±2.1
Ala-127	63.606	-148.799	672	5.0	1.0000	197700	28400	07KNSTD	0	0	KNSTD	25.2±3.6	25.8±3.7	24.1±3.5	23.6±3.4
Ala-128	63.605	-148.799	673	5.0	1.0000	144400	15300	07KNSTD	0	0	KNSTD	18.3±2	18.8±2	17.6±1.9	17.2±1.8
Ala-130	63.603	-148.8	670	4.0	1.0000	122400	21600	07KNSTD	0	0	KNSTD	15.5±2.7	15.9±2.8	14.8±2.6	14.5±2.6
Ala-132	63.599	-148.799	695	5.0	1.0000	158200	23200	07KNSTD	0	0	KNSTD	19.7±2.9	20.2±3	18.9±2.8	18.5±2.7
Ala-133	63.598	-148.799	685	5.0	1.0000	126700	38300	07KNSTD	0	0	KNSTD	15.9±4.8	16.3±5	15.3±4.6	14.9±4.5
Ala-134	63.597	-148.799	675	5.0	1.0000	152100	19700	07KNSTD	0	0	KNSTD	19.3±2.5	19.8±2.6	18.5±2.4	18.1±2.4
Reindeer Hills site, Alaska Range															
Ala-151	63.404	-148.843	1108	3.0	1.0000	175800	32600	07KNSTD	0	0	KNSTD	15±2.8	15.3±2.8	14.4±2.7	14±2.6
Ala-152	63.403	-148.843	1109	5.0	1.0000	180300	20700	07KNSTD	0	0	KNSTD	15.6±1.8	15.9±1.8	15±1.7	14.6±1.7
Ala-153	63.401	-148.847	1034	4.0	0.9990	191900	20800	07KNSTD	0	0	KNSTD	17.6±1.9	18±2	16.9±1.8	16.4±1.8
Ala-154	63.401	-148.84	1032	5.0	0.9990	173600	21300	07KNSTD	0	0	KNSTD	16.1±2	16.4±2	15.4±1.9	15±1.8
Ala-155	63.4	-148.847	1023	5.0	0.9990	178800	21400	07KNSTD	0	0	KNSTD	16.7±2	17±2	16±1.9	15.6±1.9
Ala-158	63.402	-148.858	972	5.0	1.0000	143500	12900	07KNSTD	0	0	KNSTD	14±1.3	14.3±1.3	13.4±1.2	13.1±1.2
Ala-159	63.401	-148.858	965	4.0	1.0000	198900	26200	07KNSTD	0	0	KNSTD	19.4±2.6	19.8±2.6	18.6±2.5	18.1±2.4
Ala-160	63.401	-148.858	964	5.0	1.0000	210800	48200	07KNSTD	0	0	KNSTD	20.7±4.8	21.1±4.9	19.8±4.6	19.3±4.4
Ala-161	63.899	-148.866	914	5.0	1.0000	189500	35600	07KNSTD	0	0	KNSTD	19.4±3.7	19.9±3.7	18.6±3.5	18.2±3.4
Ala-162	63.899	-148.866	915	4.0	1.0000	153500	26800	07KNSTD	0	0	KNSTD	15.6±2.7	15.9±2.8	14.9±2.6	14.6±2.6
Ala-164	63.893	-148.86	875	3.0	1.0000	185200	38400	07KNSTD	0	0	KNSTD	19.3±4	19.8±4.1	18.5±3.9	18.1±3.8
Ala-165	63.893	-148.86	869	4.0	1.0000	155400	21000	07KNSTD	0	0	KNSTD	16.4±2.2	16.8±2.3	15.8±2.1	15.4±2.1
Ala-166	63.893	-148.86	869	3.0	1.0000	189200	41100	07KNSTD	0	0	KNSTD	19.9±4.3	20.3±4.4	19±4.2	18.6±4.1
Monahan Flat East site, Alaska Range															
Ala-140	63.238	-147.778	945	3.0	1.0000	158700	20100	07KNSTD	0	0	KNSTD	15.6±2	15.9±2	15±1.9	14.6±1.9
Ala-141	63.238	-147.777	936	3.0	1.0000	152900	18200	07KNSTD	0	0	KNSTD	15.1±1.8	15.5±1.8	14.5±1.7	14.2±1.7
Ala-143	63.238	-147.774	949	4.0	1.0000	148700	19800	07KNSTD	0	0	KNSTD	14.7±2	15±2	14.1±1.9	13.7±1.8
Howley 2008															
Recessional erratics, Alaska Range															
MH07-22	63.39599	-145.70778	884	1.8	0.9868	136776	3098	07KNSTD	0	0	KNSTD	14.3±0.3	14.6±0.3	13.7±0.3	13.3±0.3
MH07-24	63.3919	-145.74134	818	1.8	0.9943	144179	2811	07KNSTD	0	0	KNSTD	15.8±0.3	16.2±0.3	15.2±0.3	14.8±0.3
MH07-26	63.39233	-145.74364	814	2.5	0.9983	137233	3290	07KNSTD	0	0	KNSTD	15.1±0.4	15.5±0.4	14.5±0.3	14.2±0.3
MH07-28	63.39586	-145.70746	888	1.9	0.9254	139523	3344	07KNSTD	0	0	KNSTD	15.5±0.4	15.8±0.4	14.8±0.4	14.5±0.3
Matmon et al., 2006															
DFCR site, Alaska Range															
DFCR-1	63.21038	-144.83175	1369	2.0	1.0000	204000	4000	KNSTD	0	0	KNSTD	12.7±0.2	12.8±0.3	12.1±0.2	11.6±0.2
DFCR-2	63.21038	-144.83175	1367	2.0	1.0000	182000	6000	KNSTD	0	0	KNSTD	11.3±0.4	11.4±0.4	10.8±0.4	10.4±0.3
DFCR-3	63.21038	-144.83175	1352	2.0	1.0000	204000	7000	KNSTD	0	0	KNSTD	12.8±0.4	13±0.4	12.3±0.4	11.8±0.4
DFCR-4	63.21038	-144.83175	1328	2.0	1.0000	173000	3000	KNSTD	0	0	KNSTD	11.1±0.2	11.2±0.2	10.6±0.2	10.2±0.2
DFCR-5	63.21038	-144.83175	1326	2.0	1.0000	191000	6000	KNSTD	0	0	KNSTD	12.3±0.4	12.4±0.4	11.8±0.4	11.3±0.4
DFCR-6	63.21038	-144.83175	1318	2.0	1.0000	184000	6000	KNSTD	0	0	KNSTD	11.9±0.4	12±0.4	11.4±0.4	11±0.4
DFCR-7	63.21038	-144.83175	1336	2.0	1.0000	174000	3000	KNSTD	0	0	KNSTD	11.1±0.2	11.2±0.2	10.6±0.2	10.2±0.2
DFCR-8	63.21038	-144.83175	1223	2.0	1.0000	173000	6000	KNSTD	0	0	KNSTD	12.1±0.4	12.3±0.4	11.6±0.4	11.2±0.4
DFCR-9	63.21038	-144.83175	1224	2.0	1.0000	172000	6000	KNSTD	0	0	KNSTD	12±0.4	12.2±0.4	11.5±0.4	11.1±0.4
DFCRSD-1	63.21038	-144.83175	1369	2.0	1.0000	189000	6000	KNSTD	0	0	KNSTD	11.7±0.4	11.8±0.4	11.2±0.4	10.8±0.3
DFCRSD-2	63.21038	-144.83175	1336	2.0	1.0000	185000	6000	KNSTD	0	0	KNSTD	11.8±0.4	11.9±0.4	11.3±0.4	10.8±0.4
DFMF site, Alaska Range															
DFMF-1	63.1541	-144.59018	1173	2.0	1.0000	196000	6000	KNSTD	0	0	KNSTD	14.3±0.4	14.5±0.4	13.7±0.4	13.3±0.4
DFMF-2	63.1541	-144.59018	1170	2.0	1.0000	191000	6000	KNSTD	0	0	KNSTD	14±0.4	14.2±0.4	13.4±0.4	13±0.4
DFMF-3	63.1541	-144.59018	1162	2.0	1.0000	184000	6000	KNSTD	0	0	KNSTD	13.6±0.4	13.8±0.5	13±0.4	12.6±0.4
DFMF-4	63.1541	-144.59018	1153	2.0	1.0000	209000	7000	KNSTD	0	0	KNSTD	15.5±0.5	15.8±0.5	14.9±0.5	14.4±0.5
DFMF-5	63.1541	-144.59018	1165	2.0	1.0000	173000	6000	KNSTD	0	0	KNSTD	12.7±0.4	12.9±0.4	12.2±0.4	11.8±0.4
DFMFSD-1	63.1541	-144.59018	1173	2.0	1.0000	154000	5000	KNSTD	0	0	KNSTD	11.2±0.4	11.4±0.4	10.8±0.4	10.4±0.3
DFMFSD-2	63.1541	-144.59018	1165	2.0	1.0000	162000	6000	KNSTD	0	0	KNSTD	11.9±0.4	12.1±0.4	11.4±0.4	11±0.4
DFSC site, Alaska Range															
DFSC1	63.46295	-148.64813	919	2.0	1.0000	179000	4000	KNSTD	0	0	KNSTD	16.1±0.4	16.5±0.4	15.5±0.3	15.1±0.3
DFSC2	63.46295	-148.64813	926	2.0	1.0000	194000	4000	KNSTD	0	0	KNSTD	17.4±0.4	17.7±0.4	16.6±0.3	16.2±0.3
DFSC3	63.46295	-148.64813	927	2.0	1.0000	182000	6000	KNSTD	0	0	KNSTD	16.3±0.5	16.6±0.6	15.6±0.5	15.2±0.5
DFSC7	63.46295	-148.64813	892	2.0	1.0000	188000	7000	KNSTD	0	0	KNSTD	17.3±0.6	17.7±0.7	16.6±0.6	16.2±0.6
DFSC8	63.46295	-148.64813	886	2.0	1.0000	184000	6000	KNSTD	0	0	KNSTD	17.1±0.6	17.4±0.6	16.4±0.5	16±0.5
Briner et al., 2002															
Waskey Mountain moraines, Ahklun Mountains															
MB1-99-1	59.87000	-159.22222	240	2.0	1.0000	69539	12000	07KNSTD	0	0	KNSTD	12.8±2.2	13.3±2.3	12.2±2.1	12.1±2.1
MB1-99-2	59.87056	-159.22361	236	2.0	1.0000	96440	10000	07KNSTD	531980	83000	KNSTD	17.8±1.8 13.4±2.1	18.4±1.9 13.2±2.1	17±1.8 13.4±2.1	16.9±1.8 13.2±2.1
MB1-99-3	59.87306	-159.22722	200	2.0	1.0000	96633	13000	07KNSTD	605620	83000	KNSTD	18.4±2.5 15.8±2.2	19.1±2.6 15.5±2.1	17.7±2.4 15.8±2.2	17.5±2.4 15.5±2.1

MB1-00-4	59.86750	-159.21972	276	2.0	1.0000	70714	4000	07KNSTD	0	0	KNSTD	12.5±0.7	13.1±0.7	12±0.7	11.9±0.7
MB4-00-1	59.86944	-159.27611	274	2.0	1.0000	0	0	07KNSTD	458822	45000	KNSTD	11.1±1.1	10.8±1.1	11.1±1.1	10.8±1.1
MB4-00-2	59.86944	-159.27639	273	2.0	1.0000	0	0	07KNSTD	371517	60000	KNSTD	9±1.5	8.8±1.4	9±1.5	8.8±1.4
MB4-00-3	59.87028	-159.27056	274	2.0	1.0000	65326	5000	07KNSTD	0	0	KNSTD	11.6±0.9	12±0.9	11.1±0.9	11±0.8
MB6-00-1	59.86778	-159.21667	270	2.0	1.0000	62681	4000	07KNSTD	0	0	KNSTD	11.1±0.7	11.5±0.7	10.7±0.7	10.5±0.7
MB6-00-2	59.86833	-159.21833	273	2.0	1.0000	72182	3000	07KNSTD	0	0	KNSTD	12.8±0.5	13.4±0.6	12.3±0.5	12.2±0.5
Pendleton et al., 2015															
Recessional erratics, north-central Brooks Range															
BR05	68.07318	-150.8418	1075	1.0	0.9895	179973	3635	07KNSTD	0	0	KNSTD	15.6±0.3	15.9±0.3	15±0.3	14.5±0.3
BR06	68.07318	-150.8418	1075	1.0	0.9895	182721	3690	07KNSTD	0	0	KNSTD	15.9±0.3	16.1±0.3	15.2±0.3	14.7±0.3
BR16	68.20175	-150.94714	1108	1.0	0.9840	175391	4378	07KNSTD	0	0	KNSTD	14.9±0.4	15.1±0.4	14.3±0.4	13.8±0.3
BR20	68.23363	-150.92308	1023	3.0	0.9733	166636	3922	07KNSTD	0	0	KNSTD	15.7±0.4	15.9±0.4	15±0.4	14.6±0.3
BR12-25	68.27451	-150.97301	955	2.0	0.9780	229588	4611	07KNSTD	0	0	KNSTD	22.7±0.5	23.1±0.5	21.7±0.4	21.1±0.4
BR12-26	68.27427	-150.97223	946	3.0	0.9780	181023	3690	07KNSTD	0	0	KNSTD	18.2±0.4	18.5±0.4	17.4±0.4	16.9±0.3
BR39	68.27957	-150.78742	1362	2.0	0.9728	222188	4186	07KNSTD	0	0	KNSTD	15.4±0.3	15.5±0.3	14.8±0.3	14.2±0.3
BR42	68.26593	-150.80287	1414	2.0	0.9685	233899	4405	07KNSTD	0	0	KNSTD	15.6±0.3	15.7±0.3	15±0.3	14.3±0.3
LGM moraine, north-central Brooks Range															
BR12-28	68.28628	-150.89815	1278	3.0	0.9940	271938	11508	07KNSTD	0	0	KNSTD	20±0.9	20.2±0.9	19.2±0.8	18.5±0.8
BR12-29	68.2859	-150.89816	1270	3.0	0.9940	220496	8421	07KNSTD	0	0	KNSTD	16.3±0.6	16.5±0.6	15.7±0.6	15.1±0.6
BR12-30	68.28587	-150.89915	1265	3.0	0.9940	204665	3257	07KNSTD	0	0	KNSTD	15.2±0.2	15.4±0.2	14.6±0.2	14±0.2
BR12-31	68.28601	-150.89961	1266	3.0	0.9940	290268	5817	07KNSTD	0	0	KNSTD	21.6±0.4	21.8±0.4	20.7±0.4	20±0.4
BR12-33	68.29144	-150.89571	1226	4.0	0.9980	283846	5420	07KNSTD	0	0	KNSTD	22±0.4	22.2±0.4	21±0.4	20.3±0.4
BR12-34	68.2916	-150.89607	1239	3.0	0.9980	316838	6043	07KNSTD	0	0	KNSTD	24.1±0.5	24.3±0.5	23.1±0.4	22.2±0.4
BR12-35	68.29185	-150.89606	1238	3.0	0.9980	222139	4187	07KNSTD	0	0	KNSTD	16.9±0.3	17±0.3	16.2±0.3	15.6±0.3
BR12-36	68.29102	-150.89745	1241	2.5	0.9980	274985	5252	07KNSTD	0	0	KNSTD	20.7±0.4	21±0.4	19.9±0.4	19.2±0.4
BR12-37	68.29072	-150.89694	1244	4.0	0.9980	262326	4967	07KNSTD	0	0	KNSTD	20±0.4	20.2±0.4	19.1±0.4	18.5±0.4
Recessional erratics, Arregetch peaks, southern Brooks Range															
BR57	67.40328	-154.18384	1193	2.0	0.9267	190429	3797	07KNSTD	0	0	KNSTD	16.1±0.3	16.2±0.3	15.4±0.3	14.9±0.3
BR58	67.40327	-154.18386	1190	3.0	0.9267	176582	3317	07KNSTD	0	0	KNSTD	15±0.3	15.2±0.3	14.4±0.3	13.9±0.3
BR59	67.40615	-154.17809	1165	3.5	0.9662	177207	4974	07KNSTD	0	0	KNSTD	14.9±0.4	15.1±0.4	14.2±0.4	13.8±0.4
Badding et al., 2013															
Recessional erratics, north-central Brooks Range															
10KRV-03	68.22772	-154.50264	1267	2.0	0.9930	215000	6220	07KNSTD	0	0	KNSTD	15.8±0.5	16±0.5	15.2±0.4	14.6±0.4
10KRV-05	68.21104	-154.49136	1296	2.0	0.9830	209000	3900	07KNSTD	0	0	KNSTD	15.2±0.3	15.3±0.3	14.5±0.3	14.0±0.3
10KRV-07	68.20375	-154.48836	1318	2.0	0.9720	191000	3540	07KNSTD	0	0	KNSTD	13.7±0.3	13.8±0.3	13.2±0.2	12.6±0.2
10KRV-08	68.20383	-154.48865	1314	3.0	0.9720	190000	3500	07KNSTD	0	0	KNSTD	13.8±0.3	13.9±0.3	13.3±0.2	12.7±0.2
10KRV-09	68.19965	-154.52574	1476	3.0	0.9810	218000	4050	07KNSTD	0	0	KNSTD	13.7±0.3	13.7±0.3	13.1±0.2	12.5±0.2
11RMV-02	68.30927	-149.14107	1246	4.0	0.9830	200000	3710	07KNSTD	0	0	KNSTD	15.4±0.3	15.6±0.3	14.8±0.3	14.3±0.3
11RMV-07	68.33232	-149.15842	1242	1.0	0.9900	195000	6540	07KNSTD	0	0	KNSTD	14.6±0.5	14.8±0.5	14±0.5	13.5±0.5
11RMV-08	68.33235	-149.1579	1235	1.5	0.9900	224000	4150	07KNSTD	0	0	KNSTD	17±0.3	17.2±0.3	16.3±0.3	15.7±0.3
11RMV-13	68.36522	-149.25767	1019	1.5	0.9950	246000	4550	07KNSTD	0	0	KNSTD	22.5±0.4	22.9±0.4	21.6±0.4	20.9±0.4
11RMV-15	68.38003	-149.31113	876	1.0	0.9960	482000	10900	07KNSTD	0	0	KNSTD	50.2±1.2	51.4±1.2	48.2±1.1	46.9±1.1
Unpublished data, Greyling Lake pre-Holocene moraine															
16GRE-1	61.39429	-145.74466	1056	2.0	0.9629	153923	12804	KNSTD	0	0	KNSTD	12.8±1.1	13.1±1.1	12.3±1	11.9±1
16GRE-2A	61.39432	-145.7459	1082	2.0	0.977	142527	12145	KNSTD	0	0	KNSTD	11.4±1	11.6±1	10.9±0.9	10.6±0.9
17GRE-3	61.39419	-145.74875	1107	2.0	0.999	200566	41268	KNSTD	0	0	KNSTD	15.4±3.2	15.7±3.2	14.8±3.1	14.4±3
17GRE-4	61.39324	-145.7543	1127	1.0	0.997	146870	114918	KNSTD	0	0	KNSTD	11±8.7	11.2±8.8	10.6±8.3	10.2±8

Notes: sample density is 2.65 g/cc for all samples; ages are caculated with no surface erosion, and no snow cover. For samples with both ^{10}Be and ^{26}Al ages, ^{10}Be ages are listed in the top row, ^{26}Al ages are listed in the bottom row.

Table 2. Radiocarbon ages used for time-distance diagrams reported on Figure 2.

Lab ID	14C age	2 sigma range	2 sigma mid-point	location	source
Ahklun Mountains					
AA-23082	16,890±120	20,050-20,670	20,360±310	Goodnews River valley	Manley *et al.* (2001)
NSRL-11058	9710±90	10,760-11,250	11,010±250	Waskey Lake	Levy *et al*. (2004)
Alaska Range, McKinley River sequence					
USGS-656	19,700±200	23172-24195	23,680±510	MP1 maximum age	Ten Brink and Waythomas (1985)
I-11228	17,800±290	20794-22288	21,540±750	MP1 minimum age	Ten Brink and Waythomas (1985)
Not available	17,150±150	20276-21098	20,690±410	MP2 maximum age	Werner *et al.* (1993)
CAMS-11704	14,110±150	16658-17576	17,120±460	MP2 minimum age	Child (1995)
CAMS-15638	12,780±170	14448-15793	15,120±670	MP3 maximum age	Child (1995)
GX-6284	12,340±205	14050-15130	14,560±540	MP3 minimum age	Ten Brink and Waythomas (1985)
I-10536	10,370±150	11629-12144	12,140±520	MP4 maximum age	Ten Brink and Waythomas (1985)
I-10535	9860±140	11147-11919	11,530±390	MP4 minimum age	Ten Brink and Waythomas (1985)

2.1. Brooks Range

Glacial geomorphic features formed during the Last Glacial Maximum (LGM, locally termed the Itkillik II glaciation) are widespread in the Brooks Range (e.g., Hamilton *et al.*, 1986; Hamilton, 2003). These deposits have been used to generate a relatively complete outline of LGM glacier extent (Fig. 1; Kaufman *et al.*, 2011). The age of LGM moraines are constrained loosely with radiocarbon dating in downvalley outwash sequences to 27-25 cal ka and shortly following 23 cal ka (Hamilton *et al.,* 1986). LGM terminal moraines have been dated directly with cosmogenic ^{10}Be exposure dating in two locations: 25.6±3.1 ka (n=4, excluding one outlier) in the northeastern portion of the range (Balascio *et al.,* 2005), and 21.0 ± 0.8 ka (n=5, excluding 4 outliers) in the north-central Brooks Range (Pendleton *et al.*, 2015). Despite a high degree of scatter in both ^{10}Be chronologies, the two ages are markedly different. The geologic and analytical sources of scatter in cosmogenic nuclide exposure dating are described by Balco (2011) and Heyman *et al.* (2011). It is possible that the two-fold terminal moraine sequence that Hamilton (1986) described is expressed differently in different parts of the Brooks Range. For example, perhaps the older LGM advance is the outermost in the northeastern Brooks Range, and the younger LGM advance is the outermost in the north-central Brooks Range. Alternatively, the moraine boulders might have been influenced by isotopic inheritance and/or exhumation, yielding scatter or perhaps a systematic offset from their true age.

A number of moraines situated between extant glacier termini and LGM moraines are present throughout the Brooks Range, but these moraines have been directly dated in only two valleys. In the northeastern Brooks Range, Balascio *et al.* (2005) dated a moraine downvalley of the Hubley Glacier to 20.7 ± 2.8 ka (n=4). In the north-central Brooks Range, Pendleton *et al.* (2015) dated a moraine to 17.2 ± 1.0 ka (n=4, excluding one outlier). In both locations, these moraine ages are consistent with their respective terminal moraine ages. It is possible that the Hubley Glacier moraine is equivalent to the terminal moraine dated by Pendleton *et al.* (2015), and together with the LGM terminal moraine dated by Balascio *et al.* (2005) represents the two-fold LGM moraine sequence described by Hamilton (1986).

In terms of the subsequent deglaciation, even less is known. Hamilton (2003) interpreted alluviation near the north-central Brooks Range front as a glacier advance between ~15 and ~13 cal ka. However, subsequent ^{10}Be dating of upper valley reaches in the same area reveal that glaciers were retreating into their cirques during this interval. Thus, the alluviation event that Hamilton (2003) dated was likely not related to a glacier advance. In fact, in three different valleys throughout the north-central Brooks Range, and one valley in the Arregetch Peaks area of the southern Brooks Range, published ^{10}Be ages on moraine boulders closest (directly adjacent in most cases) to extant glacier termini (or just beyond late Holocene moraines) average 15.0 ± 0.8 ka (n=6; Badding *et al.*, 2013; Pendleton *et al.*, 2015). Collectively, these chronologies indicate that glaciers in the Brooks Range retreated into their cirques near or slightly prior to the onset of the Bølling-Allerød period. These ages also reveal that all subsequent glacier fluctuations, if any, were restricted to within the footprint of late Holocene glacier fluctuations.

Taken together, we assemble a continuous glacier timeline for the central Brooks Range (excluding the northeastern Brooks Range data), where most of the existing chronology is from. We include the information above, in addition to ^{10}Be ages from erratic boulders and bedrock along the middle reaches of a glacial valley investigated by Pendleton *et al.* (2015). The time-distance diagram (Fig. 2) encompasses the glacial

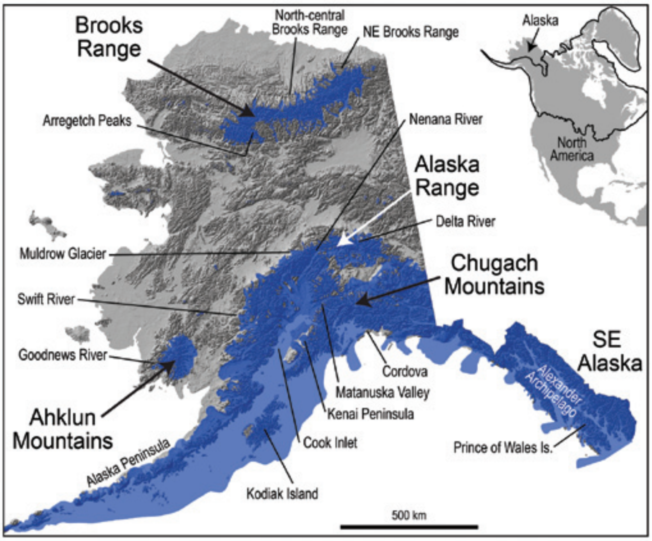

Figure 1. Map of Alaska showing extent of LGM ice in blue (Kaufman et al.*, 2011) and key place names mentioned in text; inset shows LGM ice sheet extent in North America (Dyke* et al.*, 2003).*

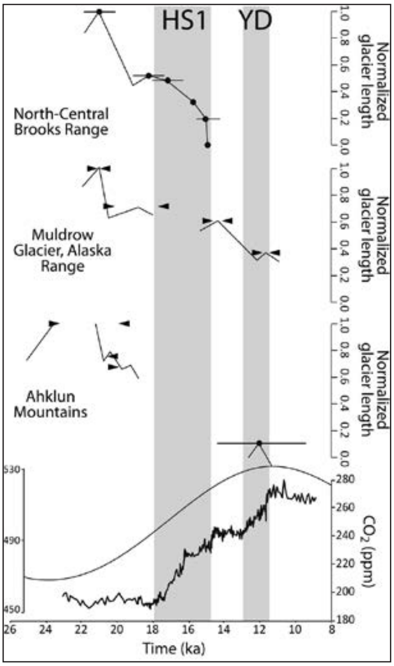

Figure 2. Glacier time-distance diagrams showing best available chronology (triangles = radiocarbon ages; right-pointing arrows = maximum age; left-pointing arrows = minimum age; circles = cosmogenic nuclide exposure ages. Sample positions are normalized using the distance between present glacier termini or paleo-ice divide and the maximum LGM ice extent. At bottom, CO_2 (Marcott et al.*, 2014) and 61° N June 21 insolation (Laskar* et al.*, 2004) WM-2, are shown.*

history outlined above; it reveals significant retreat between ~21 and ~17 ka, a glacier standstill or re-advance ~17 ka, and subsequent glacier recession to within late Holocene glacier limits by ~15 ka.

2.2. Alaska Range

The Alaska Range was heavily glaciated during the last glacial cycle. Despite being connected to the Cordilleran Ice Sheet complex, ice fields fed valley glaciers that flowed into the unglaciated terrain north and west of the Alaska Range crest (Kaufman *et al*., 2011). South of the divide, much more extensive glaciers converged to form broad lobes that filled lowlands and coastal areas. Moraines within and north of the Alaska Range have been dated, although generally only one or two moraines per valley, and not continuous glacier chronologies that span from LGM moraines to modern glacier termini, with the exception of Muldrow Glacier deposits in Denali National Park.

Porter *et al*. (1983) provide the most detailed review to date, although not the most recent (Hamilton, 1994), on existing ^{14}C ages for the timing of late Pleistocene glacier advances in the Alaska Range. Several maximum-limiting ^{14}C ages constrain the initial late Pleistocene advance to sometime after ca. 27 ka (Porter *et al*., 1983). In Denali National Park, the maximum late Pleistocene (McKinley Park [MP] I) moraine of the Muldrow Glacier was emplaced between 21.5 ± 0.7 and 20.7 ± 0.4 cal ka, based on ^{14}C ages of organic remains below and above till (Ten Brink and Waythomas, 1985; Werner *et al*., 1993). Based on ^{14}C dated sediment cores in and near Wonder Lake, two younger phases of ice advance occurred between 20.7±0.4 and 17.1±0.5 cal ka (MP II; Werner *et al*., 1993; Child, 1995), 15.1 ± 0.7 and 14.6 ± 0.5 cal ka (MP III; Child, 1995; Ten Brink and Waythomas, 1985). The youngest moraine (MP IV) is constrained by ^{14}C ages on the initiation of peat growth down-valley of the moraine (12.1 ± 0.5 cal ka) and on the moraine (11.5 ± 0.4 cal ka; Ten Brink and Waythomas, 1985). Dortch *et al*. (2010a) attempted to use ^{10}Be dating on the Muldrow Glacier moraines, but their results are too scattered to determine the timing of deglacial ice-marginal positions. We use the existing chronological information to construct a time-distance history of the paleo-Muldrow Glacier (Fig. 2).

Additional chronological control from elsewhere in the northern Alaska Range includes the headwaters of the Nenana River valley where Dortch *et al*. (2010b) dated several moraines and sets of erratic boulders, although not all sample sites yielded coherent results. At the Carlo Moraine, which they interpret to be within the LGM limit, they report an average ^{10}Be age of 17.9 ± 1.6 ka (n=7, excluding one outlier). At sites they interpret to be morpho-stratigraphically inboard of the Carlo limit, Dortch *et al.* (2010b) report clusters of erratics that date to 17.4 ± 2.2 ka (n=13; their Reindeer Hills site) and 15.2 ± 0.5 ka (n=3; their Monahan Flat East site), although given that these sites are not in a single valley, it is difficult to know where they should be plotted in time-distance space. Similarly, Matmon *et al*. (2006) provide five ^{10}Be ages from a site (their site DFSC) near Dortch *et al*.'s (2010b) Reindeer Hills site that average 16.9 ± 0.6 ka (n=5). It is not entirely clear where this site lies in relation to the LGM ice extent other than somewhere within it. Finally, Ten Brink and Waythomas (1985) reported a ^{14}C age from sediments beneath a recessional moraine in the Nenana River valley of 16.3 ± 1.2 cal ka, suggesting that at least one of the recessional moraines is from a re-advance that occurred after ~16.3 ka. Taken together, the available chronology from the Nenana River catchment is insufficient to precisely determine the age of the LGM terminal moraine, although some scattered locations upvalley were ice free during the middle stages of deglaciation; one recessional moraine dates to ~18 ka, and another post-dates ~16.3 ka.

Farther east, Matmon *et al*. (2010) obtained a ^{10}Be age of 19.4 ± 0.9 ka (n=6, excluding 5 outliers) for the terminal moraine along the Delta River valley. Slightly east of the Delta River valley, Young *et al*. (2009) dated a terminal moraine that yielded an average ^{10}Be age of 18.7 ± 0.2 ka (n=4, excluding three outliers). Both of these ages are consistent with a minimum-limiting ^{14}C age of ~17.9 cal ka for an LGM terminal moraine in the region reported by Reger *et al*. (2008b). One additional site with known direct ages of the LGM terminal moraine deposited by glaciers flowing out of the Alaska Range is the Swift River valley, where Briner *et al*. (2005) report an average ^{10}Be age of 20.4 ± 0.7 ka (n=4).

In terms of deglaciation to within modern glacial limits in the Alaska Range, Young *et al*. (2009) obtained ^{10}Be ages on erratic boulders from two additional sites in the valley east of the Delta River. Erratics from one site well upvalley from the terminal moraine yielded an average ^{10}Be age of 15.9 ± 1.1 ka (n=3), and erratics from the other site lie just beyond late Holocene glacier deposits and yielded an average ^{10}Be age of 12.9 ± 0.2 ka (n=3, excluding 4 outliers). Nearby, but on the south side of the divide, Matmon *et al*. (2006) dated moraines offset by the Denali Fault just beyond late Holocene glacier deposits at two locations. One site (their site DFCR) yielded an average ^{10}Be age of 11.9 ± 0.6 ka (n=11), and their other site (DFMF) yielded an average ^{10}Be age of 13.4±1.5 ka (n=5). Finally, Howley (2008) reported ^{10}Be ages from four erratic boulders just beyond late Holocene moraines in the Delta River valley, which average 15.2 ± 0.7 ka. Taken together, these existing ages from sites near extant glaciers suggest that glaciers retreated to within their late Holocene footprints roughly during the Bølling-Allerød period, with the exception of an apparently later re-advance between ~12.3 and ~11 cal ka (MP IV; Ten Brink and Waythomas, 1985) and a moraine dated by Matmon *et al*. (2006) to 11.9 ± 0.6 ka.

2.3. Ahklun Mountains

The Ahklun Mountains, southwestern Alaska, supported an ice cap independent of the Cordilleran Ice Sheet (Kaufman *et al*., 2011; Fig. 1). Firm chronological constraints on LGM deposits and subsequent deglaciation are sparse and scattered across the region, but in the southwestern Ahklun Mountains, the timing of the maximum LGM extent is reasonably well constrained. There, Kaufman *et al*. (2003) dated lacustrine sediments related to the LGM ice extent of a major outlet glacier that flowed down the Goodnews River valley. The LGM sediment unit, dated by a macrofossil-based ^{14}C age-depth model that was updated in Kaufman *et al*. (2012), spans from 23.9 to 19.4 cal ka. Closer to the ice cap center in that same valley, a ^{14}C age from a sediment section constrains one recessional moraine to be older than ~20.4 cal ka, and a recessional moraine farther upvalley to be younger than ~20.4 cal ka (Manley *et al*., 2001).

In the high, eastern-central portion of the Ahklun Mountains, not far downvalley from present-day glaciers, a moraine sequence (the Waskey Mountain moraines) dates to the late glacial period. Moraine boulders yield an average ^{10}Be/^{26}Al age of 12.0 ± 2.4 ka (n=9; Briner *et al*., 2002). A lake that is impounded by the moraines has a basal ^{14}C age of ~11.0 cal ka, consistent with the ^{10}Be age for the Waskey Mountain moraines (Levy *et al*., 2004). To summarize, there seems to have been significant glacier recession early in the last deglacial period in the Ahklun Mountains, but glaciers lingered until the late glacial period (Fig. 2); the Waskey Mountain moraines may date to within the Younger Dryas period.

2.4. Southern Alaska

A few relevant ages scattered across southern Alaska help address this paper's key questions. Dating the LGM extent is difficult given that glaciers terminated mostly on the continental shelf (Kaufman *et al*., 2011). To date, the best constraints on the timing of the LGM are from Mann and Peteet (1994), who obtained several maximum and minimum ^{14}C ages from Kodiak Island (Fig. 1). Their data indicate that the LGM extent on Kodiak Island occurred between 26.9 and 17.9 cal ka. Cook Inlet, which was occupied by ice during the LGM, was inundated by the sea as early as ~19.4 cal ka, and peat formed within the LGM ice extent mapped by Kaufman *et al*. (2011) as early as ~18.5 cal ka (Reger *et al*., 2008a). Reger *et al*. (2008a) outline a subsequent glacial history of the Kenai Peninsula that includes several glacial advances occurring ~18.5 to ~17.5 cal ka (Killey Stade), ~17.5 to ~16.0 cal ka (Skilak Stade) and ~15.0 ka (Elmendorf Stade). The age control for these advances is relatively sparse and from widely distributed sites, and have been updated in a few places (see below).

Kopczynski *et al*. (2017) compiled ^{14}C ages associated with the Elmendorf Moraine in the Anchorage Lowlands and subsequent recession up the Matanuska valley, in the western Chugach Mountains. The moraine was emplaced ~ 16.5 cal ka as bracketed by ^{14}C ages on marine material (Bootlegger Cove Formation) from below, and organic-rich sediments from above. Their age assignment is slightly older than that of Reger *et al*.'s (2008a), who probably relied on ^{14}C ages of shells and barnacles in the Bootlegger Cove Formation that were re-worked during emplacement of the Elmendorf Moraine, the youngest of which is 15.9±1.6 cal ka. A basal ^{14}C age from Hidden Lake (Ager and Sims, 1981; Kaufman, unpublished) of ~15 cal ka provides a new minimum age for the Skilak Stade, somewhat younger than Reger *et al*.'s (2008a) timeline for Kenai Peninsula glaciation. Taken together, these dated deposits reveal that, following the LGM advance, there were three additional moraine-forming glacial events that occurred prior to the Bølling-Allerød period. It is difficult to know how much recession occurred prior to the CO_2 rise ~18 ka, but mapping from Reger *et al*. (2008a) shows significant ice recession by 18-19 cal ka prior to the Killey Stade.

In terms of the subsequent glacial history, not much is known from a single location, but there are a few scattered locations across southern Alaska with age control. We review these sites from west to east. On Kodiak Island, Mann and Peteet (1994) ^{14}C dated a package of glaciotectonized sediments to 13.4 to 13.1 cal ka; this location is ~40 km downvalley from the nearest glaciers. On the Kenai Peninsula, lake sediments from Emerald Lake, which lies across a low topographic threshold from a present-day glacier, transition from pro-glacial to non-glacial slightly before 11.2 cal ka (LaBrecque and Kaufman, 2016). Furthermore, there is a layer of pro-glacial sediments dating from ~10.8 to ~9.8 cal ka; the sediment record suggests ice was slightly more extensive than it is today before ~11.2 cal ka and between ~10.8 and ~9.8 cal ka. Following emplacement of the Elmendorf Moraine, subsequent recession up the Matanuska valley is constrained by a transect of basal lake sediment ^{14}C ages, which document deglaciation up to the present Matanuska Glacier terminus by ~13.7 cal ka (Kopczynski *et al*., 2017). Greyling Lake, Chugach Mountains, not far downvalley from late Holocene glacier deposits, has a basal ^{14}C age of 15.2 ± 1.7 cal ka (McKay and Kaufman, 2009). A pre-Holocene moraine that abuts the lake could be younger than this, but there is no sedimentological record in the lake supporting this interpretation. Four unpublished ^{10}Be ages from the pre-Holocene moraine are scattered (Table 1), ranging in age from 15.4 to 11.0 ka. The sampled boulders are a weakly indurated greywacke, and part of a thick blanket of boulders. Given the abundance of boulders from what must have been a very actively eroding headwall, inheritance is unlikely, and the oldest age of ~15.4 ka might be closest to the true moraine age. Although not directly tied to glacier change, a basal ^{14}C age from a lake along the southern coast near Cordova of ~14.6 cal ka reveals deglaciation of the coastline at this time (Garrett *et al*., 2015). And nearby, Zander *et al*. (2013) provide lake sediment evidence to indicate glacier extent similar to today from 11.2 to 11.0 ka.

To summarize, data available from southern Alaska are mixed about when glaciers retreated to within their late Holocene footprints. Data from most locations suggest this occurred prior to the Younger Dryas, with one site on the Kenai Peninsula and one site near Cordova indicating that ice was near its present extent potentially during the Younger Dryas and even later. The young age (~13 ka) and distal location of glaciotectonized sediments on Kodiak Island is anomalous.

2.5. Southeast Alaska

To date, focused research defining the detailed timing of glaciation in Southeast Alaska is in its infancy. However, several efforts thus far have yielded results that have provided some general information on the maximum LGM extent and of the history of subsequent deglaciation. Previous overviews of glaciation in Southeast Alaska discuss how poorly the region's glacial history is understood (Mann, 1986; Mann and Hamilton, 1995). Much of the discussion centered on the timing and extent of LGM ice onto the continental shelf, but was based on little evidence. During the LGM, the Cordilleran glacier complex flowed westward from the crest of the coastal mountains to the coast; Cordilleran ice coalesced with local glaciers from high mountains throughout the Alexander Archipelago (Fig. 1). Parts of the continental shelf were exposed by lower eustatic sea level (Carrara *et al.,* 2007), and much of the evidence for LGM ice extent is now submerged due to postglacial sea level rise. It is thought that some portions of the continental shelf now submerged likely were ice free during the LGM (Carrara *et al*., 2003, 2007).

Caves in Southeast Alaska contain a varied fauna (>50,000 specimens) ranging in age from >57,260±720 (U-Th age from speleothem that entombs a bone) to the present

(Heaton and Grady, 2003; Dorale, 2003). Among the 176 ^{14}C-dated specimens are many that lived during the LGM, implying that cave entrances were open and not ice-covered. However, a lack of dated specimens between ~19,500 and ~17,000 cal yr BP implies that the western Alexander Archipelago may have been occupied by ice during this time (Heaton and Grady, 2004). Furthermore, recent ^{10}Be ages on erratic boulders and bedrock from small coastal islands west of Prince of Wales Island (Fig. 1) average 16.9 ka (Lesnek *et al*., 2016). Combined, the cave data and the ^{10}Be ages point to a phase of maximum ice cover between ~19.5 and ~17 ka.

A compilation of ^{14}C ages, largely unpublished, from shells in raised marine deposits throughout Southeast Alaska expands our understanding of the timing of ice retreat (Baichtal, 2010; Carlson and Baichtal, 2015; J. Baichtal unpublished data). In addition to pinpointing the zero-meter isobase and reconstructing relative sea level history in a number of locations, including the history of forebulge migration, the ^{14}C ages reveal the timing of widespread ice retreat through the Alexander Archipelago. It appears that all of Southeast Alaska's major fjords and sounds became ice free sometime between around 13.6 and 14.8 cal ka. The marine reservoir correction is largely unconstrained in this region for samples older than ~11 ka; the above age assignment uses a correction of 1100 years (Kovanen and Easterbrook, 2002).

3. Discussion

3.1. How did the timing of glacier recession relate to buildup of global CO_2, such as during the onset of CO_2 rise at ~18 ka?

We now return to the three questions that we set out to address in the Introduction. The first is how did the timing of glacier recession relate to buildup of global CO_2, such as during the onset of CO_2 rise at ~18 ka (Marcott *et al*., 2014)? It is currently debated whether the primary cause of glacier recession during the last deglaciation was greenhouse gas forcing or local factors such as insolation, ice sheet influences or ocean circulation effects. Shakun *et al.* (2015) suggested that mid-latitude glaciers were largely forced by fluctuations in CO_2, but other workers in the Southern Hemisphere pinpoint warming due to the bipolar expression of Heinrich Stadial 1 as an explanation for glacier retreat (e.g., Putnam *et al*., 2013). In any case, this debate has yet to draw significantly on the alpine glacier record from high northern latitudes such as in Alaska.

It seems that statewide, significant glacier recession took place prior to the global increase in CO_2, but much retreat occurred after this. The information available from Southeast Alaska shows a different trend, but this temperate location likely had a different climate regime than the majority of the state. The time-distance diagram from the Brooks Range has room for improvement, because the data come from more than one valley, and we are not confident where to place the recessional moraine dating to 17 ka. Nevertheless, based on our best estimate, it appears that the 17 ka moraine is well upvalley from the LGM terminal moraine dating to ~21 ka (Fig. 2; Pendleton *et al*., 2015). In the Ahklun Mountains, the uncertainty in the time-distance diagram revolves around the unknown location of the ice divide that fueled the outlet lobe that flowed down the Goodnews

River valley. Regardless, the first recessional moraine upvalley from the LGM terminal moraine, which was deposited prior to ~20.4 ka, indicates significant glacier recession prior to global CO_2 increase (Fig. 2). The McKinley Park sequence also requires some recession prior to 18 ka (Fig. 2). Furthermore, the oldest ^{14}C age on marine sediments at the head of Cook Inlet, near the Elmendorf Moraine, is ~17.6 cal ka (Kopczynski *et al*., 2017). Based on mapping that shows the occupation of Cook Inlet by ice during the LGM (Kaufman *et al*., 2011), that the head of Cook Inlet was clear of ice by 17.6 ka implies significant ice recession prior to 18 ka.

What drove pre-18 ka glacier retreat in Alaska? Perhaps early glacier recession was due to increasing high northern latitude insolation beginning ~23 ka (Berger and Loutre, 1991), which has been hypothesized to have initiated melting of Northern Hemisphere ice sheets (e.g., Alley *et al*., 2002; Denton *et al*., 2010; Ullman *et al*., 2015). Pendleton *et al.* (2015) suggested that early deglaciation in the Brooks Range may have also been related to the impact that the expanded Laurentide Ice Sheet had on atmospheric circulation. Indeed, simulations by global climate models show that the Laurentide Ice Sheet caused significant warming and drying in the Alaska-Yukon region during the LGM (Roe and Lindzen, 2001; Otto-Bliesner *et al*., 2006), which agrees with very little LGM temperature depressions based on chironomids (Kurek *et al*., 2009) and pollen (Bartlein *et al*., 2011). Regardless, among the eight sites in Alaska reviewed here that have sufficient existing chronology to address this question, data from seven sites support significant glacier recession prior to ~18 ka. Based on the glacier histories compiled in Figure 2, glaciers retreated up to ~40% of their LGM lengths by ~18 ka. This amount of retreat is generally greater than the amount of pre-18 ka retreat reported in the compilation of Shakun *et al*. (2015), suggesting that perhaps insolation forcing has an important effect on high northern latitude glaciers, potentially exacerbated by Arctic amplification.

3.2. What was the expression of glacier change during Heinrich Stadial 1 (18-15 ka)?

The second question we aim to address is what was the expression of glacier change during Heinrich Stadial 1 (~18-14.6 ka; Barker *et al*., 2009)? There is little doubt that strong cooling in the North Atlantic region related to ocean circulation during Heinrich Stadial 1 affected much of the globe (e.g., Cheng *et al*., 2009; Barker *et al*., 2009). It is also a time period of increasing CO_2, thus leaving open the possibility for competing cooling and warming climate forcing in some parts of the Northern Hemisphere.

In most locations where recessional moraines have been dated in Alaska, some standstills or re-advances occurred during Heinrich Stadial 1, despite the consistent increase in CO_2 between ~18 and 14.6 ka. In the Brooks Range, a prominent recessional moraine is dated to ~17 ka, and the Elmendorf Moraine dates to ~16.5 ka. On the other hand, given the number of recessional moraines in most valleys, for example throughout the Alaska Range, the Ahklun Mountains, and the Kenai Peninsula, it is difficult to know if these glacial stabilizations necessarily relate to cooling triggered in the North Atlantic Ocean. Rather, they could be related to any number of factors that would cause glacier recession to be interrupted by re-advances or stillstands (e.g., isostatic rebound, solar variability, glacier hypsometric effects). In fact, despite interruptions, there was significant recession of glaciers overall through Heinrich Stadial 1 in Alaska. As overviewed above, most paleo-glaciers with secure chronological constraints experienced the majority of their recession during Heinrich Stadial 1.

Clark *et al*. (2012) suggested that the global pattern of temperature change during the last deglaciation has two expressions: one of increasing temperature that generally mimics atmospheric CO_2 concentration, and one more aligned with North Atlantic Ocean forcing. For Beringia, both of these modes are expressed in a compilation of 11 temperature records (Clark *et al*., 2012), the former being the primary pattern, and the latter being the secondary pattern. In terms of the glacier records presented here, it appears that they too seem mostly influenced by the global pattern of temperature and CO_2 rise (Shakun *et al*., 2012), because they look more like glacial records from around the globe during this interval than climate records from the North Atlantic region.

3.3. What is the spatio-temporal record of glacier change during the climatically turbulent late glacial interval, such as during the Bølling-Allerød, Antarctic Cold Reversal, and Younger Dryas periods?

The final goal of this paper is to address the spatio-temporal record of glacier change during the climatically turbulent late glacial interval, such as during the Bølling-Allerød, Antarctic Cold Reversal, and Younger Dryas periods. In Southeast Alaska, available evidence suggests widespread glacier collapse throughout fjords and sounds during the Bølling. However, throughout most of Alaska, this question boils down to whether or not there is evidence for glacier re-advances during late glacial times. The existing glacial records reveal very limited evidence for glacier re-advances during the Younger Dryas, and no obvious glacier re-advances during the Antarctic Cold Reversal. The Waskey Mountain moraines in the central Ahklun Mountains are the best evidence to date for glacier response in Alaska during the Younger Dryas, although the chronology is imprecise. Elsewhere, there is evidence for glaciers extending beyond their present footprints during the Younger Dryas in Denali National Park (Muldrow Glacier), in the Kenai Mountains (Emerald Lake) and near Cordova. Out of the 14 glaciers throughout Alaska discussed above, nine retreated upvalley of their late Holocene extent prior to the Younger Dryas period.

In terms of climate conditions in Alaska during the Younger Dryas, a summary by Kokorowski *et al*. (2008) concluded that evidence for Younger Dryas cooling was mostly absent outside of southern Alaska. Kaufman *et al*. (2010) also found evidence for Younger Dryas climate change in southern Alaska, notably that the coldest temperature occurred at the beginning of, and was followed by warming throughout, the Younger Dryas. Denton *et al*. (2005) hypothesized that Younger Dryas cooling was mostly a wintertime phenomenon, and hence may have had limited influence on positive glacier mass balance. This is supported in Arctic Alaska with the documentation of extreme winter temperature depression during the Younger Dryas (Meyer *et al*., 2010), whereas most pollen records summarized by Kokorowski *et al*. (2008) show no significant cooling. Adding to the hemispheric climate forcing transmitted from the North Atlantic region was the time-transgressive flooding of Bering Strait around the time of the

Younger Dryas (England and Furze, 2008), although the land bridge may not have been completed severed until around 11 ka (Jakobsson *et al*., 2017). This flooding event may have led to regional forcing, such as an increase in precipitation due to more northerly storm tracks (Kaufman *et al*., 2010) that may have influenced glacier mass balance. Of course, there could have been more glacier fluctuations during the Younger Dryas than are currently recognized because they may have occurred during a climate state that was warmer than the late Holocene (e.g., Kurek *et al*., 2009; Kaufman *et al.,* 2016), and hence moraines were later obscured by subsequent glacier advances during the Holocene.

4. Conclusion

In this brief overview of the deglaciation of Alaska, we sought to address three questions about the last glacial termination. Despite there being a lack of complete, well-dated and precise glacial chronologies from single valleys, the existing record is nonetheless useful. There is overwhelming evidence that glaciers throughout Alaska experienced significant retreat prior to the global increase in atmospheric CO_2 at ~18 ka. The exact amount is difficult to quantify, but glaciers at seven out of the eight sites summarized here experienced significant recession prior to ~18 ka. Data from the three time-distance diagrams compiled here suggest that glaciers retreated about 40% of their LGM lengths. Despite multiple recessional moraines in most valleys that date to within Heinrich Stadial 1, overall glacier recession during this interval is more consistent with global forcing than with the influence of North Atlantic Ocean circulation changes. Finally, nine out of 14 records throughout the state that relate to glacier re-advance during the Younger Dryas suggest that a re-advance, if any, must have been restricted to within late Holocene glacier extents. Most of the sites with evidence for relatively extensive glaciers during the Younger Dryas are in southern Alaska. More firm answers to the questions we set out to address must await additional well-constrained glacial chronologies from multiple locations within single valleys. The chronological tools are available, and the geomorphological record of glacier change during the last glaciation is spectacular across much of the state. Together they warrant continued, focused efforts in well-chosen locations.

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