Using Cosmogenic 10Be Exposure Dating and Lichenometry to Constrain Holocene Glaciation in the Central Brooks Range, Alaska

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Using cosmogenic $^{10}$Be exposure dating and lichenometry to constrain Holocene glaciation in the central Brooks Range, Alaska

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ABSTRACT

We compile new and previously published lichenometric and cosmogenic $^{10}$Be moraine ages to summarize the timing of Holocene glacier expansions in the Brooks Range, Arctic Alaska. Foundational lichenometric studies suggested that glaciers likely grew to their Holocene maxima as early as the middle Holocene, followed by several episodes of moraine building prior to, and throughout, the last millennium. Previously published $^{10}$Be ages on Holocene moraine boulders from the north-central Brooks Range constrain the culmination of maximum Holocene glacier advances between 4.6 ka and 2.6 ka. New $^{10}$Be ages of moraine boulders from two different valleys in the central Brooks Range published here show that maximum Holocene glacial extents in these valleys were reached by 3.5 ka and ca. 2.6 ka, supporting previous studies showing that Holocene maximum, or near-maximum, glacial extents in the Brooks Range occurred prior to the Little Ice Age. However, in-depth reconciliations between glacier extent and local and regional climate are hampered by uncertainties associated with both lichenometry and $^{10}$Be dating.

INTRODUCTION

Declining high-latitude summer insolation through the Holocene should have driven alpine glaciers to steadily expand in the Arctic, culminating in their most extensive state during the Little Ice Age (LIA; A.D. ca. 1300–1850), prior to the recent reversal in overall Holocene cooling (Kaufman et al., 2004). In many sectors of the Arctic, the record of Holocene glaciation supports this concept, with LIA moraines most commonly being the outermost Holocene glacier deposits on the landscape. However, in the Brooks Range, well-preserved pre-LIA moraines seem to be particularly abundant. Thus, an extensive Holocene moraine record exists in the Brooks Range, providing an opportunity to develop glacier histories over a longer portion of the Holocene than is usually the case on the basis of moraine records elsewhere in the Arctic.

In light of this opportunity, we combine decades of work utilizing lichenometry (Ellis et al., 1981; Ellis and Calkin, 1981, 1984; Solomina and Calkin, 2003) and more recent cosmogenic $^{10}$Be exposure dating (hereafter $^{10}$Be dating; Badding et al., 2013) efforts in order to provide the most up-to-date compilation of data regarding Holocene glacier activity in the central Brooks Range. Our compilation expands on recent reviews of global Holocene glaciation by Solomina et al. (2015) and Holocene glaciation in Alaska by Kaufman et al. (2016), and follows scrutiny of the lichenometry method by Osborn et al. (2015). This study integrates previously published and new lichenometry and $^{10}$Be data from moraine sequences located in the central
Brooks Range (Fig. 1). The comparison of data sets allows for the evaluation of the strengths and weaknesses of each dating technique as well as advancing our ability to interpret both data sets.

**BACKGROUND**

Stretching ~1000 km from the Chukchi Sea in the west to the Beaufort Sea at the Alaska-Yukon border in the east, the Brooks Range forms a significant east-west physiographic and climatological barrier in Arctic Alaska (Fig. 1). The Brooks Range reaches more than 2700 m above sea level (a.s.l.) and is composed primarily of up-thrust and highly deformed Devonian sedimentary and meta-sedimentary rocks (Brosge et al., 1979). The range is heavily dissected and contains ~1000 glaciers restricted to the highest peaks and sheltered in north-facing cirques (Ellis and Calkin, 1981; Molnia, 2007). Mean annual temperatures range from –4 to –12 °C, although recent summer temperatures at McCall Glacier, in the northeastern sector of the range, average ~2 °C (Klok et al., 2005). The central Brooks Range receives ~500 mm of precipitation annually (Serreze and Hurst, 2000). With most moisture coming from the southwest, precipitation rates decrease to the northeast across the range (Porter et al., 1983; Hamilton, 1986). Accordingly, the modern equilibrium-line altitudes (ELAs) of glaciers rise from ~1766 ± 149 m a.s.l. in the west to 2027 ± 25 m a.s.l. in the east (Sikorski et al., 2009), likely because of limited moisture from the Beaufort Sea (Balascio et al., 2005).

Following the Last Glacial Maximum (LGM), glaciers in the Brooks Range retreated upvalley to, or even within, their modern limits by ca. 15 ka (Hamilton, 1986; Badding et al., 2013; Pendleton et al., 2015). Given the small extent of Brooks Range glaciers prior to the Holocene thermal maximum, during which some glaciers in southern Alaska disappeared entirely (Barclay et al., 2009), it is possible that Brooks Range glaciers may have disappeared as well. Detterman et al. (1958) and Porter and Denton (1967) first documented the existence of Holocene glacial landforms in the Brooks Range and provided a general timeline of Holocene glacier fluctuations beginning late in the Holocene. Subsequent research utilizing extensive moraine mapping and lichenometric analysis suggested that Brooks Range glaciers experienced multiple advances throughout the middle and late Holocene (Calkin and Ellis, 1980; Ellis and Calkin, 1981, 1984; Ellis et al., 1981; Haworth et al., 1986; Calkin, 1988; Sikorski et al., 2009). Despite exhaustive work carried out in the Brooks Range to reconstruct the history of Holocene glaciation, the existing lichenometric record remains largely uncorrobo-
rated by absolute dating methods, and the method has recently come under pointed scrutiny (Osborn et al., 2015).

Previously Published \(^{10}\)Be Ages and Lichenometry Data

Lichenometry

Lichenometric ages have been determined for Holocene moraines throughout the central Brooks Range (Appendix Table A1; Ellis et al., 1981; Ellis and Calkin, 1984; Haworth et al., 1986; Calkin, 1988; Sikorski et al., 2009). Most studies relied on the single-largest-lichen (SLL) approach, and suggested multiple pre-LIA glacier advances; some as early as ca. 4.5 ka, though most moraine activity dates to the past ca. 2 ka.

\(^{10}\)Be Dating

In recent years, \(^{10}\)Be dating has been applied to Holocene moraines in the Brooks Range. Budding et al. (2013) investigated late Holocene moraines in Kurupa River valley and at the Triple East Glacier, both on the northern flank of the central Brooks Range (Fig. 1). They were the first to apply \(^{10}\)Be exposure dating to Holocene moraines in the Brooks Range and confirmed the presence of pre-LIA Holocene moraines indicated by lichenometry. The outermost moraines (the most extensive Holocene advance) in the Kurupa River Valley and at Triple East glacier (Fig. 1, Table 1) date to 2.7 ± 0.2 and 4.6 ± 0.5 ka, respectively. \(^{10}\)Be dating of moraine boulders can provide an independent chronology, providing that certain conditions are met, but the method has yet to be applied as widely as lichenometry in the Brooks Range.

Methods

Lichenometry

Lichenometric studies in the Brooks Range have largely utilized the genus *Rhizocarpon* because of its relative ease of identification, assumed steady growth rate, and pervasiveness across the Brooks Range. Following Calkin and Ellis (1980), all subsequent lichenometric studies applied the SLL approach (including this study), where the maximum thallus diameter of the single largest lichen measured on a moraine is used to characterize the age of each moraine using a growth curve based on radiocarbon dating of the growing surface. We interpret the “moraine age” obtained through both lichenometry and \(^{10}\)Be dating to reflect initial moraine stabilization following the culmination of a glacier advance. For the SLL approach, lichen measurements are taken along a traverse of the entire length of the moraine.

Several lichen growth curves are available for the Brooks Range (Fig. 2). The growth curve of Calkin and Ellis (1980) was updated by Solomina and Calkin (2003) and is independently constrained by radiocarbon ages for 12 lichen diameters ranging from 2 to 50 mm on surfaces dated between 20 and 1260 cal. yr B.P. (Fig. 2). Sikorski et al. (2009) produced the latest iteration of the Brooks Range growth curve by fitting a least-squares second-order polynomial to the published lichen-growth calibration data and applying a \(y\)-intercept of 30 years to account for the colonization time of *Rhizocarpon* lichens (Calkin and Ellis, 1980). Sikorski et al. (2009) argued for the polynomial fit as it produces slightly younger and more realistic lichen ages (beyond 2000 cal. yr B.P.) than the logarithmic model of Solomina and Calkin (2003). In addition, it provides a better fit to the control points than the composite curve (Solomina and Calkin, 2003; Fig. 2).

We use the growth curve of Sikorski et al. (2009) to estimate ages for lichen diameters up to 150 mm. The ±20\% error on lichen ages proposed by Calkin and Ellis (1980) is meant to incorporate uncertainty from moraine lithology, stability, and the effect of microclimate on lichen growth; we adopt the 20\% uncertainty for all lichen ages reported herein. Because of the limited range of calibration, ages for lichens with diameters larger than ~50 mm are considered highly uncertain because they are based on an extrapolation well beyond the control points. Furthermore, assumptions about the shape of the lichen growth curve can result in severe under- or overestimation of lichen age (Osborn et al., 2015).

\(^{10}\)Be Dating

We used moraine morphology and lichenometric surveys in the upper Erratic Creek valley to distinguish among late Holocene moraine crests and to evaluate boulder stability for \(^{10}\)Be dating (Fig. 3, part a). At the Arrigetch Peak sites, we used previously published lichenometric data (Ellis et al., 1981) and new lichen surveys from this study to guide \(^{10}\)Be sampling (Fig. 3, part b). Moraine-crest boulders were selected based on the following characteristics: maximum height above surface, lack of apparent post-depositional movement by permafrost or mass wasting, maximum boulder size (to minimize boulder tipping or exhumation), and lichen cover and SLL diameter.
New and previously published (Badding et al., 2013) \(^{10}\)Be moraine boulder ages and pertinent analytical data. Erratic boulders and bedrock are associated with the deglaciation of the Arrigetch valley prior to Neoglacialization (Pendleton et al., 2015).

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<th>(^{10})Be/(^{9})Be uncertainty (atoms g(^{-1}))</th>
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aLatitude and longitude in WGS 84 Datum.

bBe carrier concentration: 372.5 ± 3.5 ppm.

c$^{10}$Be/$^{9}$Be ratios normalized against standard 07KNSTD3110 (Nishiizumi et al., 2007).

dLawrence Livermore National Laboratory ID Number.
The largest moraine boulders with the maximum height above the surrounding surface are the least likely to be a product of exhumation or to be affected by sediment/snow cover. Other processes, such as rock fall and glacier readvances can deposit boulders on moraines with an inherited concentration of $^{10}\text{Be}$; however, it is difficult to identify these boulders in the field, although post-sampling statistical analysis can sometimes be used to identify samples with inheritance. We collected all samples with hammer and chisel to a depth of ≤4 cm from tabular boulders with horizontal or nearly horizontal surfaces; corners and edges were avoided.

Samples were processed at the University at Buffalo Cosmogenic Isotope Laboratory following standard procedures (Kelley et al., 2012; Young et al., 2013). Following crushing and sieving to 250–850 μm, samples were pretreated in HCl and HF-HNO$_3$ acid baths. Heavy-liquid mineral separation and successive heated HF-HNO$_3$ acid baths were used to purify quartz. $^9\text{Be}$ carrier was added to quartz prior to dissolution in concentrated HF acid. Beryllium was isolated using ion-exchange chromatography and selective precipitation with NH$_4$OH before final oxidation to BeO.

Beryllium isotope ratios were measured at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, and normalized against standard 07KNSTD3110 (Nishizumi et al., 2007). Ratios of $^{10}\text{Be}/^{9}\text{Be}$ for process blanks averaged 1.46 ± 0.95 × 10$^{-15}$ ($n = 3$). $^{10}\text{Be}$ ages were calculated using the CRONUS-Earth exposure-age calculator 2.3 (Balco et al., 2008) assuming no snow shielding and no erosion, and using the constant-production scaling scheme (Lm) of Lal (1991) and Stone (2000).

Because there is no $^{10}\text{Be}$ production-rate-calibration site in Alaska, we must use a production-rate value from elsewhere. The most suitable production rate currently available is the Arctic production rate of Young et al. (2013), which was calibrated from sites in Arctic Canada, Greenland, and Scandinavia. The arctic production rate is indistinguishable from the $^{10}\text{Be}$ production rate from northeastern North America (Balco et al., 2009), and from other recent derivations of global $^{10}\text{Be}$ production rates (Heyman, 2014; Shakun et al., 2015). Finally, because the magnetic field at high latitudes is relatively constant, there is little need to temporally scale the production rate; similarly, the comparably high latitudes and moderate elevations of our sites relative to the arctic calibration sites limit the need for spatial scaling. Together, these factors increase our confidence in applying the arctic production rate in Alaska. $^{10}\text{Be}$ ages are reported with 1-σ internal and external uncertainties (Table 1).

**RESULTS**

**Moraine Mapping and Lichenometry**

Erratic Creek glacier is located at the headwaters of Erratic Creek, a tributary of the Anaktuvuk River in the north-central Brooks Range (Fig. 1). A sur-
vey of the Erratic Creek moraine revealed multiple nested crests backed by a sheer headwall (composed of tilted and deformed Devonian marine sediments, interbedded with the quartz-rich Kanayut and Middle Shainin Lake conglomerates [Moore et al., 1994]), and surrounded by steep, talus-covered slopes (Fig. 3, part a). The moraine complex has an over-steepened front with two distinct moraine crests just inboard of the front. Up-valley of these two moraine crests, the ground moraine is characterized by melt ponds, collapse features, and other obvious signs of a melting ice core. Farther up-valley is the modern ice limit, just a few tens of meters from the headwall. The moraines are boulder-dominated with little fine-grained matrix.

At the Arrigetch Peaks location we followed Ellis et al.’s (1981) nomenclature and resurveyed and mapped the Arr-1 and Arr-2, Arr-3, and Arr-4 glaciers. In the Arr-1 cirque, we found an intact inner moraine crest with two outboard, successively older, and partially overrun moraine remnants (Fig. 3, part b). The moraine complex is ~700 m across near the terminus, has over-steepened fronts, and contains within the complex multiple melt ponds. The moraines of Arr-1 are nestled between steep walls of granitic orthogneiss that make up the Arrigetch Peaks complex (Till et al., 2008). The Arr-2, Arr-3, and Arr-4 glaciers emanate from three cirques just south of Arr-1, but coalesce into a single tongue, which extends ~3 km downvalley. The Arr-2, Arr-3, and Arr-4 moraine complex is composed of hummocky till deposits, multiple decomposed moraine crests, and several melt ponds all within a single over-steepened moraine crest. Both moraine suites are dominantly boulder-rich, with little matrix.

We measured lichens on moraines at both field sites and derived lichenometric ages using the growth curve of Sikorski et al. (2009). The late Holocene moraines ($n = 2$) of East Erratic glacier have SLL diameters of 88 and 76 mm, which yield age estimates of ca. 2.4 and 2.1 ka, respectively (Fig. 3, part a). In the Arrigetch Peaks area (Fig. 3, part b), the late Holocene moraines ($n = 5$) have SLL diameters of 138, 107, 71, and 58 mm, yielding ages that range from ca. 4.0, 3.0, 1.8, and 1.5 ka, respectively. We note that all measured lichens were greater than 50 mm and thus outside the lichen growth curve calibration period.

$^{10}$Be Ages

In the Erratic Creek valley, moraine boulders from the outermost Holocene moraine, with a lichen diameter of 88 mm, yielded $^{10}$Be ages of 2.5 ± 0.1, 3.2 ± 0.2, 6.5 ± 0.3, and 7.4 ± 0.4 ka (Table 1; Fig. 3, part a). Boulders from the first moraine inboard of the outer-
most moraine with a lichen diameter of 76 mm yield 
$^{10}$Be ages of 2.5 ± 0.1 and 2.6 ± 0.1 ka.

In the Arrigetch Peaks area, boulders from the outer-
most Holocene moraine on glacier Arr-1, with a lichen
 diameter of 138 mm, yielded $^{10}$Be ages of 3.3 ± 0.2 and
3.6 ± 0.2 ka (Fig. 3, part b; Table 1). A second moraine
fronting glacier Arr-1, just inboard of the outermost
Holocene moraine, has a lichen diameter of 107 mm
and a single boulder $^{10}$Be age of 1.2 ± 0.1 ka (Fig. 3, part
b). Boulders from a third moraine of Arr-1, which lies
just inboard of the outer two moraines and has a lichen
diameter of 71 mm, yields $^{10}$Be ages of 0.8 ± 0.1, 3.2 ±
0.2, and 3.7 ± 0.2 ka. Lastly, the outermost Holocene
moraine of glaciers Arr-2, -3, and -4, which has a lichen
diameter of 58 mm, yielded $^{10}$Be ages of 1.2 ± 0.1 and
2.3 ± 0.1 ka.

**Discussion**

**Interpreting the New $^{10}$Be Chronologies**

Many Brooks Range moraines, including the ones
in this study, are ice-cored, which can complicate $^{10}$Be
dating. Melting out of the ice core following deposition
causes moraine degradation, formation of melt ponds,
and the continued movement of boulders (Johnson,
1971; Lukas et al., 2005). This post-depositional boulder
movement leads to $^{10}$Be ages that are younger than the
true age of moraine deposition. Therefore, many ice-
cored moraines have $^{10}$Be age populations ranging from
the actual age of the moraine (oldest age excluding ob-
vious older outliers due to inheritance) to progressively
younger ages. $^{10}$Be ages on moraine boulders can also be
older than the true timing of moraine deposition, partic-
ularly in environments with moraines in close proxim-
ity to headwalls (increasing the chance for inheritance).
Though the field sites in this study are backed by steep
headwalls, the moraine crests are far enough downvalley
to avoid direct rockfall. Therefore, we treat the oldest,
noninherited ages (as best as we can determine) as the
minimum moraine age (representing the culmination
of a glacial advance). These processes described above
would also similarly affect lichenometric ages.

Utilizing the above criteria for boulder selection
(and keeping in mind the post-depositional processes
inherent to ice-cored moraines), suitable boulders were
not common at either the Erratic Creek or the Arri-
getch Peaks locations. Under these circumstances, the
boulders sampled at each location represent the highest
quality samples at each site using the selection criteria
(Appendix Figs. A1–A3).

The ages from the outermost Holocene moraine of
the East Erratic glacier range from 7.4 to 2.5 ka (Fig.
3, part a). The abutment of the two outermost Holoc-
ene moraines against each other with no significant
intercrest trough between, and the similarity in lichen
diameters (88 vs. 76 mm) suggest that the outer two
moraines are similar in age and possibly represent small
fluctuations of the same overall advance (Fig. 3, part a).
Under this scenario, the two oldest ages on the outer
moraine appear to be outliers, and the average of the
four remaining $^{10}$Be ages is 2.7 ± 0.3 ka. The outliers
may be boulders recycled from an older glacial deposit,
or may include excess $^{10}$Be inherited from exposure in
the cirque headwall. Our preferred interpretation is that
the pair of nested moraines was deposited sometime be-
tween ca. 3.2 and ca. 2.5 ka, which delimits the outer-
most Holocene extent of the East Erratic glacier.

The wide range of $^{10}$Be ages on the moraine crests
fronting the Arrigetch Peaks glaciers Arr-1 and Arr-
2 also presents challenges when interpreting moraine
age. Multiple processes could lead to this wide range
of boulder ages. First, as the glacier expanded into older
moraine deposits, it could have incorporated previously
emplaced moraine boulders into younger moraines. This
recycling of boulders from older moraines into younger
moraines could account for some scatter of $^{10}$Be ages
from a single moraine. A second possibility involves
the incorporation of talus boulders into moraines, which
could account for older $^{10}$Be ages in moroastrographi-
ically younger moraines. Depending that the moraine
is ice-cored, we prefer post-depositional modification as
the most likely explanation for the presence of younger
$^{10}$Be ages in younger lichen zones. Interpreted this way,
the maximum Holocene glacial extent in the Arrigetch
Peaks likely culminated by at least ca. 3.5 ka, as evi-
denced by a cluster of $^{10}$Be ages around this time; addi-
tional moraine deposition occurred during subsequent
millennia (Fig. 3, part b).

**Uncertainty in Lichenometry**

The lichenometric data provide a framework for late
Holocene glacier fluctuations in the Brooks Range, al-
beit with complications when used as a numerical dat-
ing technique (Osborn et al., 2015). While previous
workers in the Brooks Range have used the SLL to infer
moraine age (e.g., Calkin and Ellis, 1980), others prefer
age estimations based on larger data sets of lichen sizes
(≥500) (e.g., McKinzey et al., 2004). Aside from differ-
ent sampling methods, variability in growth rates from
valley to valley could potentially result in large age un-
certainties. Factors influencing modelled growth rates
include environmental changes over time, differences
between species, ongoing mortality, and inaccurate age
control on calibration points (Osborn et al., 2015). Fur-
thermore, the fitting of mathematical models to growth rates is somewhat tenuous as the general shape of growth curves is variable and poorly constrained, and different fits of the same data set can produce substantially different curves that result in significant differences in lichen age, especially beyond the calibration period.

With the above caveats in mind, Figure 4 shows the cumulative lichenometric moraine data from the Brooks Range, including moraines from this study (Ellis et al., 1981; Calkin, 1988; Sikorski et al., 2009; Badding et al., 2013; Table A1). The data set indicates that glaciers were depositing moraines by at least ca. 4 ka (and likely before) followed by periods of increased moraine building at ca. 2–3, 1.5, and 1.0 ka and through the LIA (Fig. 4). The lichenometric moraine ages from this study generally agree with these periods of increased activity in the Brooks Range. However, note that the frequency distribution reflects the influence of a moraine preservation bias (older moraines overrun by younger advances) in favor of younger moraines.

Disagreement between $^{10}$Be and Lichenometry

Given the sparse $^{10}$Be ages combined with the complications discussed above, and additional factors affecting lichen growth rates, moraine ages based on lichenometry and $^{10}$Be are unlikely to agree. Nevertheless, we explore the comparison of the two dating methods here. Figure 5 shows the $^{10}$Be moraine ages plotted against their corresponding lichen diameter, overlain on the two lichen growth curves widely used in the central Brooks Range (Solomina and Calkin, 2003; Sikorski et al., 2009). It is apparent that boulders from the same moraine crest (i.e., represented by the same lichen diameter) can have strikingly different $^{10}$Be ages (e.g., Erratic Creek). Conversely, moraines that yield similar $^{10}$Be ages can have inconsistent lichen diameters (e.g., Erratic Creek and Arrigetch Peaks).

These conflicts within and between the two dating methods suggest that perhaps neither one is superior in this study area; both dating methods are influenced by complications common to both, and also unique to both. Figure 5 also highlights the disagreement of lichen growth curve extrapolations beyond the calibration period, and shows how the resulting age depends on which curve is chosen (e.g., Osborn et al., 2015). This disagreement between $^{10}$Be and lichen ages highlights the challenge of dating Holocene moraines in the Brooks Range using moraine boulder surface-exposure dating techniques.

Paleoclimatic Interpretation of Late Holocene Moraines in the Brooks Range

Under ideal circumstances, moraines are interpreted as records of climate fluctuations. However, in the Brooks Range, climate interpretations have two main limiting factors. First, as discussed above, the accuracy and precision of the lichenometric and $^{10}$Be dating techniques are limited by both shared and unique processes. Second, the size of the glaciers and the morphology of the moraines themselves could influence the exposure ages of moraine boulders in the Brooks Range. In general, Brooks Range glaciers are polythermal (Rabus and Echelmeyer, 1998; Sikorski et al., 2009), and many are

![Figure 4](https://bioone.org/journals/images/Arctic-Antarctic-Alpine-Research/48/4/fig4.jpg)

**FIGURE 4.** Summary of moraine ages in the central Brooks Range based on lichenometry, normalized to total number of moraines sampled (using median age; $n = 301$; 50 yr bins). Ages were calculated using the polynomial fit of Sikorski et al. (2009) and lichen diameters reported by Calkin (1988), Sikorski et al. (2009), Badding et al. (2013), and this study.
relatively short and debris rich. They form voluminous moraines that small glaciers have difficulty overriding or removing from the landscape during successive advances. Thus, topographic steering of subsequent glacier advances by previously deposited, bulky moraines may result in their preservation. Therefore, the presence or absence of pre-LIA moraines may be due to characteristics intrinsic to the glaciers and not necessarily climate. Nevertheless, the abundance of pre-LIA moraines suggests that pre-LIA glaciers were at least of comparable size, if not larger, than their LIA counterparts.

Regardless of their origin and despite the associated uncertainties, the frequency of moraines dating between ca. 2 and 5 ka provides strong evidence for pronounced pre-LIA glacial activity in the Brooks Range (Fig. 5). While the presence of pre-LIA glacial activity is common in the northern hemisphere, the apparent larger magnitude of pre-LIA advances in the Brooks Range is somewhat unusual. More commonly, glaciers in the northern hemisphere reached their maximum Holocene extent during the LIA (Karlén, 1973; Matthews, 1991; Svendsen and Mangerud, 1997) because they were driven by decreasing northern high-latitude summer insolation. For example, the most extensive Holocene glacier advance in southern Alaska occurred during the LIA (Barclay et al., 2009). Although the chronology of moraines in the Brooks Range remains uncertain, the contrasting timing of maximum Holocene glacier expansion suggests that glaciers did not respond similarly across Alaska. It is possible that drying throughout the Holocene due to arctic sea-ice cover (Funder et al., 2011) or shifting atmospheric patterns (Stone et al., 2002) restricted glacier extent during the LIA in the Brooks Range. However, the lack of tightly constrained glacier histories compounded by uncertainties related to nonclimatic processes hinders comparison with regional climate records and hampers identification of the dominant climatic controls on glacier evolution in the central Brooks Range.

**Conclusions**

We compiled and updated existing lichenometry data (301 moraines) and $^{10}$Be ages (21 ages from eight
moraines) to summarize the chronology of middle-to-late Holocene glacier fluctuations in the central Brooks Range. The compilation of moraine lichen ages from across the Brooks Range provides a relative indicator of regional glacier history during the late Holocene. However, concerns with the method of lichen data collection, growth-rate constraints, and interpretation of ages yield large (and unquantifiable) uncertainties with lichenometry as an absolute chronometer of moraine age. The inventory of all $^{10}$Be ages of Brooks Range moraines suggests that glaciers reached their maximum Holocene extent as early as ca. 4.6 ka and experienced numerous advances throughout the late Holocene prior to the LIA. Similar to lichenometry, the $^{10}$Be method is hampered by processes intrinsic to the morphology of central Brooks Range glaciers and characteristics of their moraines. Regardless, both methods agree on the presence of relatively extensive middle and late Holocene glacier advances followed by smaller advances culminating in the LIA.

Despite decreasing northern hemisphere summer insolation throughout the Holocene, which led to most northern hemisphere glaciers reaching their Holocene maxima during the LIA, the abundance of pre-LIA moraines is conspicuous in the Brooks Range, especially compared to elsewhere in Alaska. Relative to southern Alaska, in particular, Brooks Range glaciers may have been influenced by differing climate circumstances, intrinsic morphological processes, or a combination of both. Further study and improved age constraints on Holocene glacial features are needed to better reconcile glacier chronologies and climate records.

ACKNOWLEDGMENTS

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*MS accepted 2 December 2016*
## APPENDIX

### TABLE A1

Brooks Range lichenometry.

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Moraine lichen data from Calkin (1988), Sikorski et al. (2009), Badding et al. (2013), and this study.

1Lichen age calculated using polynomial growth curve from Sikorski et al. (2009).

2Estimated 20% uncertainty from Calkin et al. (1988).
FIGURE A1. $^{10}$Be sampling.
FIGURE A2. $^{10}$Be sampling (continued).
FIGURE A3. $^{10}$Be sampling (continued).