A REVIEW OF LICHENOMETRIC DATING OF GLACIAL MORAINES IN ALASKA

BY
GREGORY C. WILES[1], DAVID J. BARCLAY[2] AND NICOLÁS E.YOUNG[3]

[1]Department of Geology, The College of Wooster, Wooster, USA
[2]Geology Department, State University of New York at Cortland, Cortland, USA
[3]Department of Geology, University at Buffalo, Buffalo, NY, USA

Wiles, G.C., Barclay, D.J. and Young, N.E., 2010: A review of lichenometric dating of glacial moraines in Alaska. *Geogr. Ann.*, 92 A (1): 101–109.

ABSTRACT. In Alaska, lichenometry continues to be an important technique for dating late Holocene moraines. Research completed during the 1970s through the early 1990s developed lichen dating curves for five regions in the Arctic and subarctic mountain ranges beyond altitudinal and latitudinal treelines. Although these dating curves are still in use across Alaska, little progress has been made in the past decade in updating or extending them or in developing new curves. Comparison of results from recent moraine-dating studies based on these five lichen dating curves with tree-ring based glacier histories from southern Alaska shows generally good agreement, albeit with greater scatter in the lichen-based ages. Cosmogenic surface-exposure dating of Holocene moraines has the potential to test some of the assumptions of the lichenometric technique and to facilitate the development of a new set of improved lichen dating curves for Alaska.

Key words: Alaska, lichenometry, lichen dating curves, tree rings, Late Holocene

Introduction

Well-dated glacier histories are crucial for understanding Holocene climate change. In Alaska, fluctuations of cirque and valley glacier termini have been used to reconstruct changes in temperature and solar variability over recent millennia (Wiles *et al*. 2004, 2008) and a 5000-year long moraine record from the Brooks Range in northern Alaska was included in the IPCC Fourth Assessment Report to help provide a baseline for contemporary warming (Jansen *et al*. 2007). The best-constrained glacier histories in Alaska are from the coastal mountains in the south of the state (Fig. 1). Termini in this maritime region have made multiple advances into coastal forests and so tree-ring cross dates on glacially killed and scarred trees provide high precision records spanning the past 2000 years (Barclay *et al*. 2009). However, many other glacier forefields in Alaska are beyond the latitudinal or altitudinal tree line in locations where tree-ring based dating methods cannot be applied.

Lichenometry is a key method for dating Alaskan Holocene glacier histories beyond the tree line. Some of the earliest well-replicated glacier histories in Alaska were based on lichen dates of moraines (Denton and Karlén 1973a, b, 1977; Calkin and Ellis 1980, 1984; Ellis and Calkin 1984) and the method continues to be applied today (e.g. Young *et al*. 2009). In addition to moraine chronologies, lichens in Alaska have also been used to date rockfalls associated with earthquakes (Keskinen and Beget 2005) and in a study of shorelines abandoned by drainage of an ice-marginal glacial lake (Loso and Doak 2006).

In this paper we review the status of lichenometry in Alaska with emphasis on the dating of glacier moraines. We build on a recent review evaluating regional lichen growth curves (Solomina and Calkin 2003) and update this work with studies published more recently. We also compare moraine ages based on lichen with independent records based on other dating methods.

The areas considered in our review are from between 59°N and 69°N and span all five climate regions of Alaska (Fig. 1). The maritime influence is strongest in the Southern and West coast regions, while mean annual temperatures decrease northwards to reach a minimum in the Arctic Region (Shulski and Wendler 2007: Table 1). In all regions, the dramatic elevation changes in Alaska's mountain ranges cause large variability in both precipitation and temperature (Table 1); similarly each of the mountain ranges includes a wide range of rock types and substrates that can also affect lichen colonization and growth.

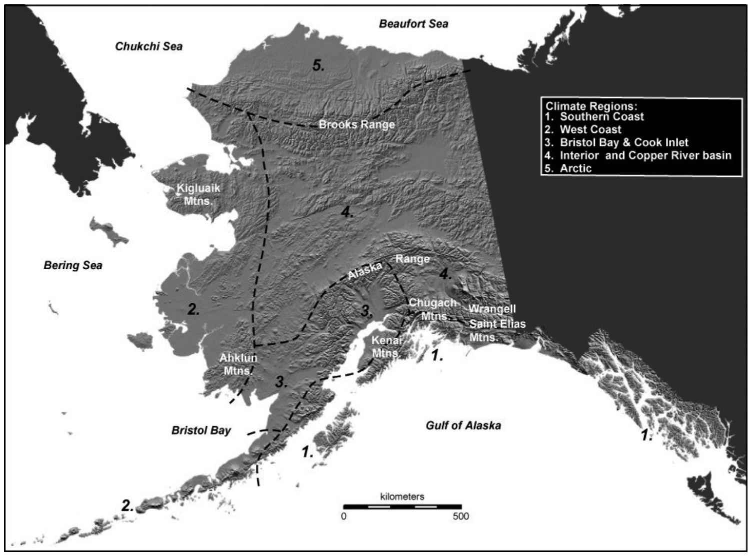

Fig.1. Shaded relief map showing the areas discussed in the text. Dashed lines separate climate regions of Shulski and Wendler (2007)

Lichen dating curves

Lichen dating curves exist for five areas in Alaska (Table 2; Fig. 2) and all are well constrained by many control points over the past several centuries. However, there are very few control points more than 400 years old leaving considerable uncertainty in older ages derived from these curves. Solomina and Calkin (2003) follow Ellis and Calkin (1984) in suggesting that dates based on these curves have a ± 20% accuracy; this uncertainty accounts for the larger error with increasing age and less confidence in the curves due to loss of control points as the curves are extended back in time.

The lichen genus most often used is *Rhizocarpon*. The species *R. geographicum* has been identified as the target lichen for moraine dating studies more frequently than section *R. alpicola*. However, because of the difficulty in differentiating to the species level in the field, in many cases, it is likely that a mix of *Rhizocarpon* lichens have actually been measured and most studies now report *Rhizocarpon sensu lato (s. l.)* to reflect this (Benedict 2008). Control points for lichen dating curves in Alaska have mostly been based on the single largest lichen on the control surface after rejection of obvious outliers, with the exception of the Kigluaik

Table 1. Climate data from weather stations near the regions of the lichen studies (from Skulski and Wendler 2007).

Station (region)	Average July Maximum (° C)	Average January Minimum (° C)	Mean Annual Precipitation (mm)	Average Annual Snowfall (cm)
Kenai (*Kenai Mountains*)	14	–15	483	155
Anchorage (*Chugach Mountains*)	18	–13	406	178
Gulkana (*Wrangell-St. Elias*)	21	–25	279	145
McKinley Park (*Alaska Range*)	20	–22	381	206
Bettles (Brooks Range)	22	–28	356	224
Bethel (Ahklun Mts.)	17	–17	406	135
Nome (*Kigluaik Mountains*)	14	–19	432	173

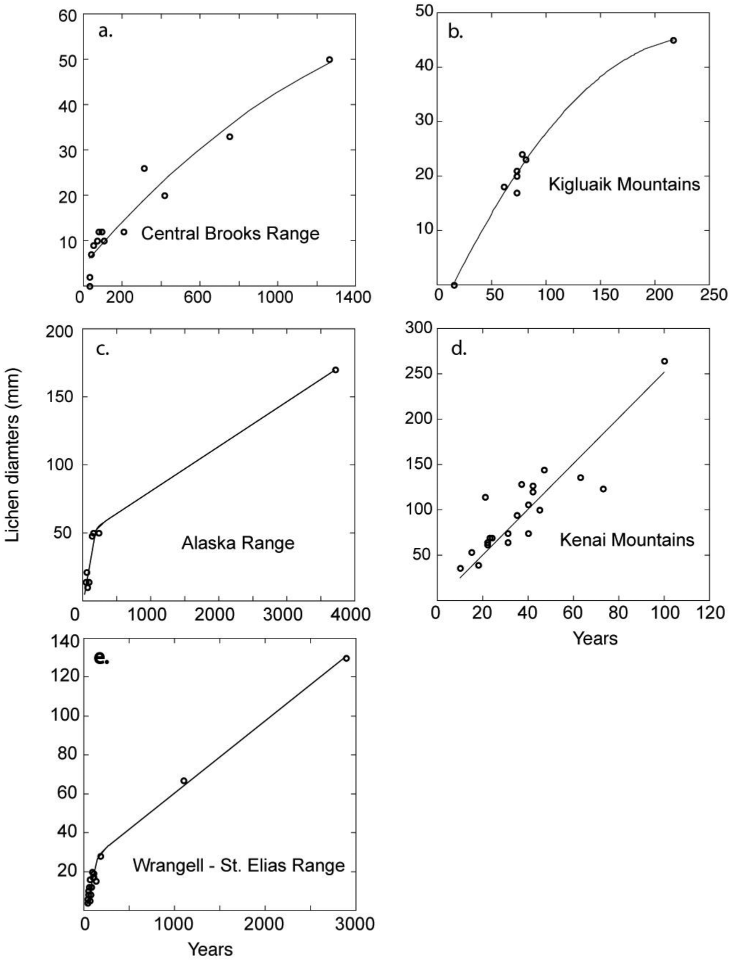

Fig. 2. Five lichen calibration curves discussed in the text. a – Curve used by Sikorski *et al*. (2009), after Calkin and Ellis (1980). The curve fit is a 2nd order polynomial. b – Curve for the Kigluaik Mountains (after Calkin *et al*. (1998)). c – Lichen curve for the Alaska Range (after Solomina and Calkin (2003)); here, as in 'e', a composite curve is used that is made up of a 'great growth' interval and a linear function describing older lichen growth. d – Straight line fit to lichen control points for the Kenai Mountains (from Wiles and Calkin, 1994). e – Lichen curve of Denton and Karlén (1973a) combined with control points from Wiles *et al*. (2002)

Mountains curve (Table 2; Fig. 2) which uses control points based on the mean diameter of the five largest lichen (Solomina and Calkin 2003).

Across Alaska, control points for constraining lichen dating curves have been based on sites dated by historical data (e.g. photographs, mine tailings, gravestones), tree-rings, tephrochronology, and ^{14}C dating (Solomina and Calkin 2003). Only modest improvements have been made to these control point datasets in the past decade. Wiles *et al*. (2002) obtained new control points to update the Wrangell-Saint Elias curve of Denton and Karlén (1973a), and Solomina and Calkin (2003) re-evaluated and discarded one control point from the central Alaska Range curve of Beget (1994). Solomina and Calkin (2003) also noted the importance of calibrating radiocarbon ages of control points prior to their use in developing growth curves and provided dendro-calibrated ages for all radiocarbon ages used in their synthesis.

Curves fitted to the lichen-dating control points have traditionally been a composite of a logarithmic or semilogarithmic model applied to the initial fast growth ('great growth') period and then a linear model used for the subsequent slower period of growth (Armstrong 1983; Innes 1985). In their review of Alaskan calibration curves and different curve fits, Solomina and Calkin (2003) suggested that these traditional composite curves (i.e. logarithmic and linear models) might be best suited for slow growing lichen and continental interior climates. Solomina and Calkin (2003) also show that logarithmic models applied to the full period of growth can be equally valid as the composite

Table 2. Summary of the lichen studies, methods, and calibration curves used

Location	Method	Taxon*	Calib. Curve**	Curve Fit	Age Range***	Reference
Kenai Mountains	Largest	Ra	1	linear	LIA	Daigle and Kaufman, 2009
Chugach Mountains	Largest	Rg s.l.	2,6	2 stage	FMA/LIA	McKay and Kaufman, 2009
Wrangell-St. Elias	Largest	Rg s.l.	2	2 stage	LIA	Wiles *et al*. 2002
Alaska Range	Largest	Rg s.l.	3,6	2 stage	FMA/LIA	Young *et al*. 2009
Brooks Range	5 largest	Rg s.l.	4,6	2nd order polynomial	FMA/LIA	Sikoski *et al*. 2009
Ahklun Mountains	5 largest	Rg s.l.	5	2 stage	FMA/LIA	Levy *et al*. 2004
Kigluaik Mountains	5 largest	Rg s.l.	5	2 stage	LIA	Calkin *et al*. 1998

Notes: *Ra = *R. alpicola*; Rg s.l. = *R.geographicum sensu lato*. **Calibration curve used. 1 = Wiles and Calkin 1994; 2 = Denton and Karlén 1973; 3 = Beget 1994; 4 = Calkin and Ellis 1980; 5 = Calkin *et al*. 1998; 6 = as modified by Solomina and Calkin 2003; see Fig. 2; ***LIA=Little Ice Age (*c*. AD 1250–1880); FMA = First Millennium AD (*c*. AD 450–850).

curves in some cases. Sikorski *et al*. (2009) used a second-order polynomial curve fit to the Brooks Range control data and suggested that this may provide more realistic ages for surfaces older than 2000 years than the formerly used composite curve.

Loso and Doak (2006) addressed the biological basis of the shape of Alaskan lichen dating curves using data from Iceberg Lake in the Chugach Mountains. Diameters of all lichen on boulders on abandoned lake shorelines were measured and used to model population dynamics for *R. geographicum* and *Pseudophebe pubescens*. They found that the apparent 'great growth' pattern of lichen curves could be explained by mortality rates in the populations, and that members of the initial colonizing cohort were likely to be very rare on old surfaces.

Regional studies

A significant number of glacial history studies have been performed since the review of Solomina and Calkin (2003). These studies have used lichen to varying degrees to date glacier moraines and only in one case in the Brooks Range have lichen been used alone as the chronological tool. Lichens of the *Rhizocarpon* genus were used in all studies and dates were derived using either the single largest or the mean of the five largest lichens (Table 2).

Kenai Mountains

In a multiproxy glacial geological study in the northern reaches of the southern Kenai Mountains (Table 1; Fig. 1), Daigle and Kaufman (2009) used lichens to estimate the age of moraines from two cirques and a valley glacier (North Goat Glacier). They used the *Rhizocarpon* dating curve developed from the region that was calibrated primarily from tree-ring-dated control surfaces (Wiles and Calkin 1994; Solomina and Calkin 2003). A linear fit to the control points made a dating curve for the past 250 years (Fig. 2a).

Moraine ages from the outer ridges at the two cirque glaciers yielded age estimates of AD 1820 and 1890 whereas one inner ridge was dated at AD 1930. For the larger North Goat Glacier the outer moraine had a 46-mm lichen that corresponds to an age of AD 1890. These times of moraine formation (Fig. 3) fall within the interval considered to be the late **Little Ice Age (LIA)** and are consistent with other glacier histories from the southern Kenai Mountains (Wiles and Calkin 1994) and elsewhere in southern Alaska (Fig. 3, Barclay *et al*. 2009).

Daigle and Kaufman (2009) also used lacustrine sediments to show that North Goat Glacier was extensive in the mid AD 1600s during the middle LIA interval (Fig. 3). Reconstructions of the LIA **equilibrium line altitudes (ELAs)** of 12 cirque glaciers surrounding their study site showed ELA depression was less than expected relative to the magnitude of cooling inferred from independent records, and Daigle and Kaufman (2009) suggested that a late LIA decrease in precipitation could account for this discrepancy.

Chugach Mountains

To the north and east of the Kenai Mountains are the Chugach Mountains (Fig. 1). McKay and Kaufman (2009) measured lichens on moraines of ten cirque glaciers surrounding Hallet and Greyling lakes on the north side of the range crest as part of a multiproxy study of glacier histories. No lichen dating curve has been developed for the Chugach Mountains so the composite (logarithmic 'great growth'

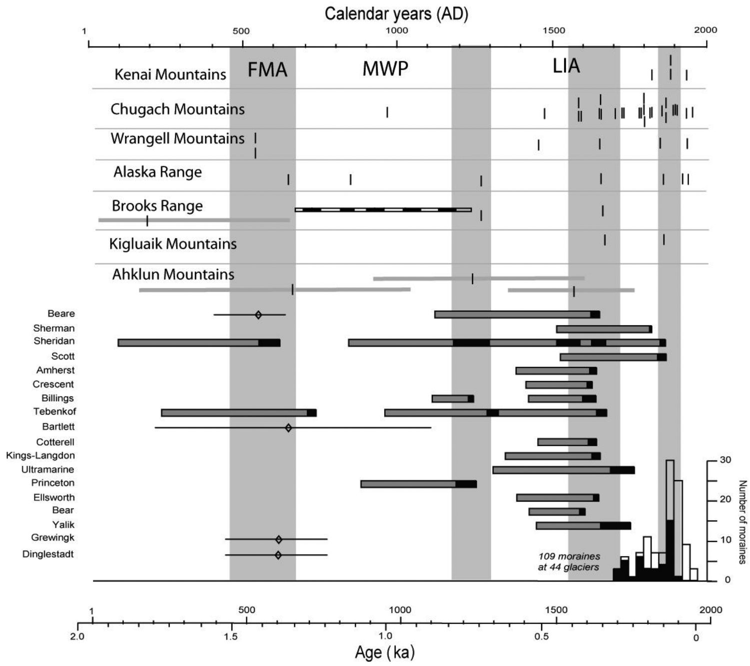

Fig. 3. Lichen-dated moraines discussed in the text (top) compared with the glacial record from southern Alaska. Small vertical lines in the lichen data represent single moraines and, in the case of the Chugach Mountains, individual stations on moraines. Horizontal bars for the Brooks Range and Ahklun Mountains data depict possible age ranges of moraines. The broken bar in the Brooks Range data represents the range of lichen ages that are not present at the sites. Horizontal bars in the record from southern Alaska indicate tree-ring crossdated intervals of forest growth and have dark ends that signify intervals when advancing termini were killing trees. Horizontal lines with diamonds are radiocarbon ages on glacially killed logs. Moraines summarized in the histogram are dated with tree-rings (primarily) and lichens

and linear slower growth) Wrangell-Saint Elias Mountain curve as updated and modified by Solomina and Calkin (2003) was used to convert lichen diameters to age estimates (Table 1).

One moraine with a maximum lichen diameter of 68 mm was dated to AD 980, whereas most other moraines had lichens between 51 and 17 mm and dated to the middle to late LIA (McKay and Kaufman 2009). Sediment cores from Hallet and Greyling lakes indicated that Neoglaciation started in these basins around 4.5 to 4.0 ka, which suggests that the LIA advances of these cirque glaciers must have overrun and destroyed moraines of earlier and less extensive late Holocene advances. From these chronological data, and glacier reconstruction and ELA studies, McKay and Kaufman (2009) inferred that winter precipitation was enhanced from AD 1300 to AD 1500 and helped force glacier advances, whereas between AD 1800 and AD 1900 less extensive advances were linked to times of cold and decreased winter precipitation.

Wrangell-St. Elias

The Wrangell-Saint Elias region has received considerable attention in lichenometry. Denton and Karlén (1973a, 1977) developed 13 control points based on single largest thalli of *Rhizocarpon* in the northern Saint Elias Mountains, and drew a growth curve with a 'great growth' period for about 200 years and a linear model for slower growth back to about 3.0 ka. This curve has subsequently been used to date surfaces in widely spaced studies in interior southern and southwestern Alaska (e.g. Levy *et al*. 2004; McKay and Kaufman 2009). Wiles *et al*. (2002) developed eight new control points using the same methods and lichen genus as Denton and Karlén (1973a, 1977) from tree-ring dated surfaces and cemetery headstones in the adjacent Wrangell Mountains, and used a linear growth model for the 200-year span of their data.

Here we combine these two control point data sets to provide an updated lichen dating curve for the Wrangell-Saint Elias region (Fig. 2). Following the original work in the region we fit a 'great growth' period and a later linear function to the data. Using this updated curve, a moraine at Copper Glacier reported in Wiles *et al*. (2002) with a single largest lichen of 85 mm dates to about AD 550, which is about 160 years later than previously reported (Wiles *et al*. 2002). This revised date corresponds more closely with other glacier advances in southern Alaska during the **First Millennium AD (FMA)** interval (Reyes *et al*. 2006, Barclay *et al*. 2009). Denton and Karlén (1977) also noted 84 mm lichen on morainal boulders at Natazhat Glacier in the White River Valley of adjacent Yukon Territory, suggesting that the Copper Glacier moraine is not the only moraine marking the FMA advance in the Wrangell-Saint Elias region. Using the updated lichen dating curve, other moraines dated by Denton and Karlén (1977) in the northern Saint Elias Mountains cluster in age around AD 1430, 1650, 1860 and 1930 (Fig. 3).

Alaska Range

Young *et al*. (2009) assembled a glacier chronology spanning the late Pleistocene though the LIA for Fish Lake valley in the northeastern Alaska Range. Lichen sizes were converted to ages using a composite curve fit to the *Rhizocarpon geographicum* dataset of Beget (1994) as modified by Solomina and Calkin (2003); this curve is comprised of a logarithmic 'great growth' period and then a linear equation for thallus diameters greater than 50 mm. Surface exposure ages using ^{10}Be were also obtained and provide a direct check on lichenometrically derived ages.

Lichenometric ages suggest that the Fish Lake valley moraines date to about 3.0 ka, the FMA (AD 610, 840, 970), the LIA (AD 1290, 1640, 1860) and AD 1910 and 1930, and the ^{10}Be surface exposure ages show good agreement. For example, the FMA moraine lichenometrically dated to AD 610 returned a single ^{10}Be age of 1.2 ± 0.1 ka (AD 700–900) and ^{10}Be ages ranging from 2.2 – 3.3 ka were obtained on the outermost Holocene moraine dated by lichenometry to 3.0 ka. The general agreement between ^{10}Be ages and lichenometric ages derived from the older (i.e. > 500 yrs) long-term growth period of the regional calibration curve adds confidence for its use on surfaces pre-dating the better constrained 'great growth' portion of the curve.

Similarly, Howley and Licciardi (2008) are using multiple dating techniques to re-examine the moraines at Canwell Glacier in the central Alaska Range. They also used the Beget lichen curve for the region as modified by Solomina and Calkin (2003) and determined that moraines dated to 3150 yr. BP, and to phases of the LIA about AD 1200 and 1835. Similar to the work of Young *et al*. (2009), ^{10}Be surface exposure dates are being processed that will hopefully test these lichenometric ages (Howley and Licciardi 2008).

Farther west in the central Alaska Range's McKinley River region, Dortch *et al*. (in press) obtained ^{10}Be surface exposure dates on moraines that were previously dated using lichens. Work by Werner (1982) used the lichen dating curve of Denton and Karlén (1973a, 1977) to date two late Holocene drifts to 1.8 and 0.9 ka. Dortch *et al*. (in press) used ^{10}Be analysis on the same surfaces and estimated an age for the older surface that was *c*.1.3 ka younger than the lichen age. They suggested a possible explanation for the age discrepancy may be due to the difference in time between the formation and the early stabilization of the moraine. The younger 0.9 ka surface dated with lichens was ice-cored and the ^{10}Be analysis suggested that the surface continues to stabilize and thus yielded a great scatter of ages. Although one age did overlap with the lichen estimate at 0.9 ka, the authors point out that determining the history of the surface based on a single boulder is problematic.

Brooks Range

The pioneering work at 97 cirque and valley glaciers in the Brooks Range by Ellis and Calkin (1984) and Evison *et al*. (1996) was recently added to by Sikorski *et al*. (2009) who obtained lichenometric ages on moraines at five cirque glaciers that had not previously been studied. They used the average of the five largest lichens on the moraine surface as the best estimate for the age of the surface. As in the earlier work, the lichen *Rhizocarpon s.l.* was used and a least squares second-order polynomial curve was fitted to the Brooks Range control point data in Solomina and Calkin (2003). This modified Brooks Range lichen curve was suggested by Sikorski *et al*. (2009) to better model the older ages and deviated only slightly from the early portions of the curve published by Calkin and Ellis (1980).

In this new work, two intervals of LIA moraine formation were identified centered on AD 1250 and 1650 (Fig. 3). These ages are slightly more recent than the ages of LIA maxima suggested by Ellis and Calkin (1984) and are more consistent with LIA moraine ages elsewhere in Alaska (Barclay *et* *al*. 2009). Based on their moraine ages and glacier ELA reconstructions, Sikorski *et al*. (2009) suggested that a decrease in precipitation accompanied LIA cooling in the Brooks Range. They also recognized that there was a gap in lichen sizes between 35 and 50 mm, corresponding with the interval from AD 650 to 1250, which encompasses the **Medieval Warm Period (MWP**, Fig. 3).

Kigluaik Mountains

The Kigluaik Mountains are located on the Seward Peninsula in northwestern Alaska (Fig. 1). Calkin *et al*. (1998) developed a local lichen dating curve for *R. geographicum s.l.* that showed significantly faster growth than the curves developed for the Wrangell-Saint Elias or Brooks Range regions (Solomina and Calkin 2003). Moraines at three cirque glaciers were dated to between AD 1645 and 1895 using this curve (Figs 2 and 3), and a linear extrapolation of the curve based on the form of curves from Swedish Lapland and the Wrangell-Saint Elias region was used to assign early Neoglacial ages to additional moraines, protalus ramparts and rock glaciers (Calkin *et al*. 1998).

Ahklun Mountains

The Ahklun Mountains are located in southwestern Alaska (Fig. 1). Levy *et al*. (2004) measured *R. geographicum s. l.* at five cirque glaciers in the Waskey Lake area and used the average of the five largest lichens to cluster the moraines into three groups with, respectively, lichen sizes of 97 ± 4, 70 ± 10, and 55 ± 10 mm. The lack of a local lichen dating curve precluded these three lichen size clusters from being dated absolutely. However, based on the lichen species used and local climate, Levy *et al*. (2004) suggested that the Kigluaik Mountains and Wrangell-Saint Elias growth curves were most appropriate for application in their study area and tentatively dated the three groups of moraines to AD 150–1050, 900–1600, and 1300–1750.

Discussion

The best-constrained glacier histories in Alaska are from the south coast where termini have made multiple advances into forefield forests (Barclay et al. 2009). Durations of forefield forest growth, tree-ring cross dates of when glacier termini were killing trees, and moraine minimum ages based on tree germination dates collectively show four intervals of glacier advance in the last 2000 years (Fig. 3); a first millennium AD (FMA) expansion and then three phases of advance during the Little Ice Age (LIA). We compare this tree-ring dated record here to lichenometric ages from the studies reviewed earlier.

The lichen-dated moraines from the Kenai and Chugach mountains are located closest to the southern tree-ring dated fore fields and show generally good agreement, with almost all moraines dating to the middle to late LIA. However, several LIA moraines from the crest of the Chugach Mountains date to the AD 1570s to 1610 (McKay and Kaufman 2009), which is when the tree-ring dated termini at the coast were still advancing. The Chugach crest data also have a moraine dated to AD 980 and there are no moraines of this age in the coastal data (Barclay *et al*. 2009).

The other lichen-dated moraines from interior, northern and western Alaska (Fig. 3) also show fairly good agreement with the southern coastal tree-ring dated record. Moraines dated to the FMA occur in the Wrangell Mountains and Alaska Range, and there is more scatter to the lichenometric dates than the tree-ring data. Unfortunately, it cannot be resolved from this comparison whether the moraine date differences between these areas reflect the different dating methods used (tree-rings versus lichen) or real spatial differences within Alaska of glacier responses to late Holocene climate change.

Recent studies in the Alaska Range suggest that an increasingly promising way to assess the validity of lichenometric ages for moraines beyond the tree line in Alaska will be with cosmogenic surface-exposure ages. The errors reported by Young *et al*. (2009) for late Holocene ^{10}Be ages in Fish Lake valley are between 3% and 9% of the 3.3 to 1.1 ka ages, which is substantially better than the 20% error generally assumed for lichenometric ages. Moreover, the surface exposure ages are independent of the lichen ages and are from the same landforms. More studies such as that by Young *et al*. (2009) are needed, particularly in the Alaska and Brooks ranges where there are already extensive lichenometric data sets on Holocene moraines.

Cosmogenic surface-exposure ages may also be able to resolve two additional issues. Firstly, some surfaces can be erroneously dated as too young when lichenometric saturation occurs. This is when lichens fully cover a rock surface, thereby effectively limiting the size that individual thalli can grow; this was noted in the Fish Lake valley where some surfaces dated with ^{10}Be as greater than 10 ka had apparent lichen ages of only *c*. 3–4 ka (N. Young, unpublished data). Secondly, many control points for lichen growth curves are based on partially forested or settled areas that are removed in both space and elevation from the moraines that are being dated. Surface exposure ages may be able to provide control points for lichen growth curves from settings that are more similar to the glacier fore fields being studied.

Although cosmogenic surface-exposure ages are a new and powerful tool, it is unlikely that lichenometric ages in Alaska will be rendered obsolete in the foreseeable future. Cosmogenic surface-exposure dating depends on the presence of boulders of suitable lithology and stability whereas lichens colonize a wider range of substrates. Hundreds of moraines have been dated with lichens over widely spread areas of Alaska and it is unlikely that all of these sites will be re-sampled for cosmogenic surface-exposure ages any time soon. An achievable goal for the next several years will be to use cosmogenic surface-exposure ages to refine the lichenometric method in Alaska and then to re-assess published lichen-dated moraine records.

In terms of lichenometric field methods, the general failure in recent studies to identify *Rhizocarpon* to the section or species level is probably introducing some of the scatter in lichen dates. However, so long as the lichens measured for both dating-curve control points and on moraines to be dated are the largest and therefore fastest growing in the *Rhizocarpon* genus, then these errors are probably tolerable. Problems are more likely to occur when sampling strategies for dating moraines differ from the methods used to constrain the dating curves.

It is common practice when using tree ages to date moraines, to sample living trees beyond the moraine of interest. This establishes that older trees are in the immediate area and that there is a temporal discontinuity between the moraine of interest and the landscape beyond. It also demonstrates that trees on the moraine are not at their biological age limit, which increases the likelihood that they are first-generation colonizers of the moraine substrate. Routine application of this practice when collecting lichen data for moraine studies would perhaps increase the confidence in ages assigned to outermost moraines that often date in the poorly constrained intervals of lichen growth curves.

Conclusions

Lichenometry continues to be an important dating method for Holocene glacier histories in areas beyond the tree line in Alaska. Since a review and assessment of Alaskan lichen growth curves by Solomina and Calkin (2003), a number of regional studies have applied lichenometry to date moraines and to integrate glacier fore field histories with lake cores and other paleoclimate proxy data. These new lichen-based studies show good agreement with tree-ring dated glacier histories in southern Alaska that span the last 2000 years.

The lichenometric method can be improved in Alaska by combining lichen studies with cosmogenic surface-exposure ages. Specifically, the latter can be used to develop better control points for lichen dating curves and to test the validity of older lichen ages. Moraine studies based on both methods are likely to be better than studies based on either method used alone. Sampling of lichens beyond the outermost moraines will help establish whether lichen ages on these outermost moraines are indeed true ages for these landforms or whether these older substrates have reached the effective age limit for lichenometric dating.

Acknowledgements

We wish to thank Parker E. Calkin for his contributions to the field of lichenometry and to understanding of the Holocene glaciation of Alaska. Helpful reviews by Olga Solomina and an anonymous reviewer are also acknowledged. This work in part was supported by the National Science Foundation grants 9912124, 9910805 and 9905493.

Dr Gregory C. Wiles, Department of Geology, The College of Wooster, Wooster, OH 44691, USA
E-mail: gwiles@wooster.edu

Dr David. J. Barclay, Geology Department, State University of New York at Cortland, Cortland, NY 13045, USA
E-mail: barclayd@cortland.edu

Nicolás E. Young, Department of Geology, University at Buffalo, Buffalo, NY 14260, USA
E-mail: nyoung2@buffalo.edu

References:

Armstrong, R.A., 1983: Growth curve of the lichen *Rhizocarpon geographicum*. *New Phytologist*, 94: 619–622.

Barclay, D.J., Wiles, G.C. and Calkin, P.E., 2009: Holocene glacier fluctuations in Alaska. *Quaternary Sciences Reviews*, 28: 2034–2048.

Beget, J. E., 1994: Tephrochronology, lichenometry and radiocarbon dating at Gulkana Glacier, central Alaska Range, USA. *The Holocene*, 4: 307–313.

Benedict, J.B., 2008: Experiments on lichen growth, III: The shape of the age-size curve. *Arctic, Antarctic and Alpine Research*, 40: 15–26.

Calkin, P.E. and Ellis, J.M., 1980: A lichenometric dating curve and its application to Holocene glacier studies in the central Brooks Range, Alaska. *Arctic and Alpine Research*, 12: 245–264.

Calkin, P.E. and Ellis, J.M., 1984: Development and application of a lichenometric dating curve, Brooks Range, Alaska. *In:* Mahaney, W.C., (ed.): Quaternary Dating Methods. Amsterdam: Elsevier, 227–246.

Calkin, P.E., Kaufman, S. Przybyl, B.J., Whitford, W.B. and Peck, B.J., 1998: Glacier regimes, periglacial landforms, and Holocene climate change in the Kigluaik Mountains, Seward Peninsula, Alaska, USA. *Arctic, Antarctic and Alpine Research*, 30: 154–165.

Daigle, T.A. and Kaufman, D.S., 2009: Holocene climate inferred from glacier extent lake sediment and tree rings at Goat Lake, Kenai Mountains, Alaska, USA. *Journal of Quaternary Research*, 24: 33–45.

Denton, G.H. and Karlén, W., 1973a: Lichenometry: its application to Holocene moraine studies in southern Alaska and Swedish Lapland. *Arctic and Alpine Research*, 5: 347–372.

Denton, G.H. and Karlén, W., 1973b: Holocene climatic variations – Their pattern and possible cause. *Quaternary Research*, 3: 155–205.

Denton, G.H. and Karlén, W., 1977: Holocene glacial and tree-line variations in the White River Valley and Skolai Pass, Alaska and Yukon Territory. *Quaternary Research*, 7: 63–111.

Dortch, J.M., Owen, L.A., Caffee, M.W. and Brease, P., 2009: Late Quaternary glaciation and equilibrium-line altitude variations of the McKinley River region, central Alaska Range. *Boreas*.

Ellis, J.M. and Calkin, P.E., 1984: Chronology of Holocene glaciation, central Brooks Range, Alaska. *Geological Society of America Bulletin*, 95: 897–912.

Evison, L.H., Calkin, P.E. and Ellis, J.M., 1996: Late-Holocene glaciation and twentieth century retreat, northeastern Brooks Range, Alaska. *The Holocene*, 6: 17–24.

Howley, M.W. and Licciardi, J.M., 2008: A neoglacial and Little Ice Age chronology from the Castner Glacier in the central Alaska Range. *Arctic Workshop* 38th Annual Meeting: p. 3.

Hu, F.S., Ito, E., Brown, T.A., Curry, B.B. and Engstrom, D.R., 2001: Pronounced climatic variations in Alaska during the last two millennia. *Proceedings of the National Academy of Sciences*, 98: 10552–10556.

Innes, J.L., 1985: Lichenometry. *Progress in Physical Geography*, 9: 187–254.

Jansen, E., Overpeck, J., Briffa, K.R., Duplessy, J.C., Joos, F., Masson-Delmotte, V., Olago, D., Otto-Bliesner, B., Peltier, W.R., Rahmstorf, S., Ramesh, R., Raynaud, D., Rind, D., Solomina, O., Villalba, R. and Zhang, D., 2007: Palaeoclimate. *In*: Solomon, S.,Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds): Climate change 2007: the physical science basis. contribution of working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Keskinen, M. and Beget, J., 2005: Age of most recent motion on the Western Denali Fault from lichenometric dating of a large rockfall avalanche and offset moraines. *AGU Abstract, American Geophysical Union*, Fall Meeting 2005, abstract #S13B-0189.

Levy, L.B., Kaufman, D.S. and Werner, A., 2004: Holocene glacier fluctuations, Waskey Lake, northeastern Ahklun Mountains, southwestern Alaska. *The Holocene*, 14: 185–193.

Loso, M.G. and Doak, D.F., 2006: The biology behind lichenometric dating curves. *Population Ecology*, 147: 223–229.

McKay, N.P. and Kaufman, D.S., 2009: Holocene climate and glacier variability at Hallet and Greyling Lakes, Chugach Mountains, south-central Alaska. *Journal of Paleolimnology*, 41: 143–159.

Reyes, A.V., Wiles, G.C., Smith, D.J., Barclay, D.J., Allen, S., Jackson, S., Larocque, S., Laxton, S., Lewis, D., Calkin, P.E. and Clague, J.J., 2006: Expansion of alpine glaciers in Pacific North America in the first millennium AD. *Geology*, 34: 57–60.

Shulski, M. and Wendler, G., 2007: Climate of Alaska. University of Alaska Press, 214 p.

Sikorski, J.J., Kaufman, D.S., Manley, W.F. and Nolan, M., 2009: Glacial-geologic evidence for decreased precipitation during the Little Ice Age in the Brooks Range, Alaska. *Arctic, Antarctic and Alpine Research*, 41: 138–150.

Solomina, O. and Calkin, P.E., 2003: Lichenometry as applied to moraines in Alaska, USA, and Kamchatka, Russia. *Arctic, Antarctic and Alpine Research*, 35: 129–143.

Werner, A., 1982: Glacial geology of the McKinley River area, Alaska with an evaluation of various relative-age dating techniques. Masters thesis, Southern Illinois University, 146 p.

Wiles, G.C. and Calkin, P.E., 1994: Late Holocene, high-resolution glacial chronologies and climate, Kenai Mountains, Alaska. *Geological Society of America Bulletin*, 106: 281–303.

Wiles, G.C., Jacoby, G.C., Davi, N.K. and McAllister, R.P., 2002: Late Holocene glacial fluctuations in the Wrangell Mountains, Alaska. *Geological Society of America Bulletin*, 114: 896–908.

Wiles, G.C., D'Arrigo, R.D., Villalba, R., Calkin, P.E. and Barclay, D.J., 2004: Century-scale solar variability and Alaskan temperature change over the past millennium. *Geophysical Research Letters* 31, L15203. doi:10.1029/2004GL020050.

Wiles, G.C., Barclay, D.J., Calkin, P.E. and Lowell, T.V., 2008: Century to millennial-scale temperature variations for the last two thousand years inferred from glacial geologic records of southern Alaska. *Global and Planetary Change*, 60: 115–125.

Young, N.E., Briner, J.P. and Kaufman, D.S., 2009: Late Pleistocene and Holocene glaciation of the Fish Lake valley, northeastern Alaska Range. *Journal of Quaternary Science*, 24: 677–689.

Manuscript received July 2009 revised and accepted Nov. 2009 .