RE-DATING THE MORAINES AT SKÁLAFELLS-JÖKULL AND HEINABERGSJÖKULL USING DIFFERENT LICHENOMETRIC METHODS: IMPLICATIONS FOR THE TIMING OF THE ICELANDIC LITTLE ICE AGE MAXIMUM

BY
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ABSTRACT. Little Ice Age (LIA) moraines along the margins of Skálafellsjökull and Heinabergsjökull, two neighbouring outlet glaciers flowing from the Vatnajökull ice-cap, have been re-dated to test the reliability of different lichenometric approaches. During 2003, 12 000 lichens were measured on 40 moraine fragments at Skálafellsjökull and Heinabergsjökull to provide surface age proxies. The results are revealing. Depending on the chosen method of analysis, Skálafellsjökull either reached its LIA maximum in the early 19th century (population gradient) or the late 19th century (average of five largest lichens), whereas the LIA maximum of Heinabergsjökull occurred by the mid-19th century (population gradient) or late-19th century (average of 5 largest lichens). Discrepancies (*c.* 80 years for Skálafellsjökull and *c.* 40 years for Heinabergsjökull) suggest that the previously cited AD 1887 LIA maxima for both glaciers should be reassessed. Dates predicted by the lichen population gradient method appear to be the most appropriate, as mounting evidence from other geochronological reconstructions and sea-ice records throughout Iceland tends to support an earlier LIA glacier maximum (late 18th to mid-19th century) and probably reflects changes in the North Atlantic Oscillation. These revised chronologies shed further light on the precise timing of the Icelandic LIA glacier maximum, whilst improving our understanding of glacier–climate interactions in the North Atlantic.

Key words: Iceland, Little Ice Age, glacier fluctuations, lichenometry, geomorphology

Introduction

The **Little Ice Age (LIA)**, the most recent global episode of glacier expansion, commenced *c.* AD 1300 (Grove 2001). It was not a sustained period of cold or prolonged glacier advance. Rather, climate was extremely variable, and, as a consequence, glacier termini fluctuated around advanced positions for several centuries, although the timing and magnitude of fluctuations were not necessarily synchronous worldwide (e.g. Gellatly *et al.* 1988; Karlén 1988; Guðmundsson 1997; Luckman and Villalba 2001). However, widespread and rapid glacier retreat during the 19th and 20th centuries signalled the end of the LIA (Grove 1988). Emphasis has been placed upon unravelling LIA glacier chronologies because prediction of future climatic change requires better understanding of climatic variability in the recent past.

Iceland is ideally located to study the timing of LIA glacier response to climate change. It lies astride the Arctic Front, the convergence zone between temperate-maritime and cold-polar air masses, and is also affected by the oceanic Polar Front, the boundary between warm waters of the Atlantic and cold Arctic waters (Björnsson 1979; Ogilvie 1992). Consequently, Icelandic glaciers have shown sensitivity to boundary shifts through fluctuations of ice margin positions due to mass balance changes (Guðmundsson 1998; Kirkbride and Dugmore 2001). Accurate age dating of moraine fragments associated with the former extent of these ice margins should, therefore, reflect changes

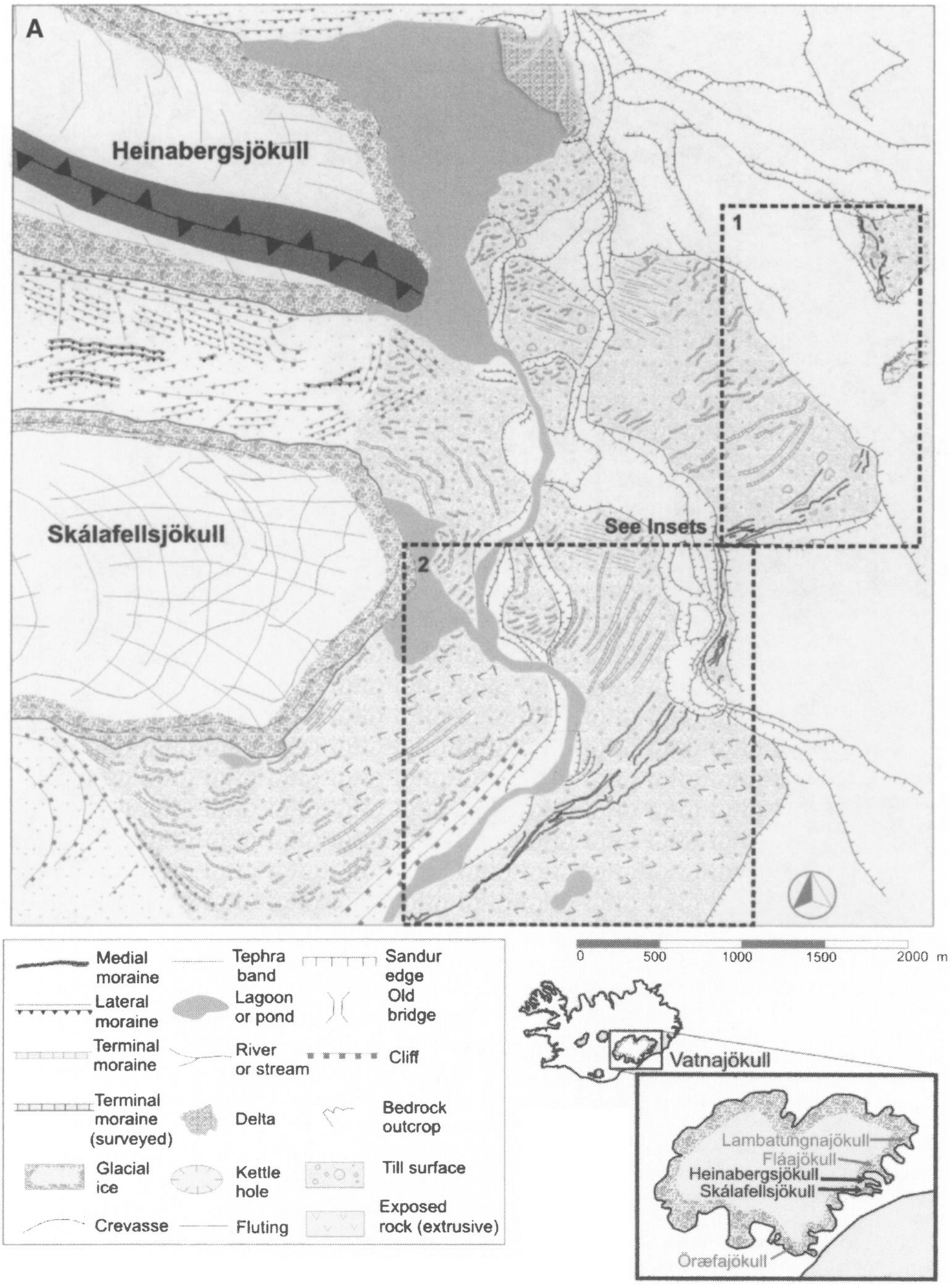
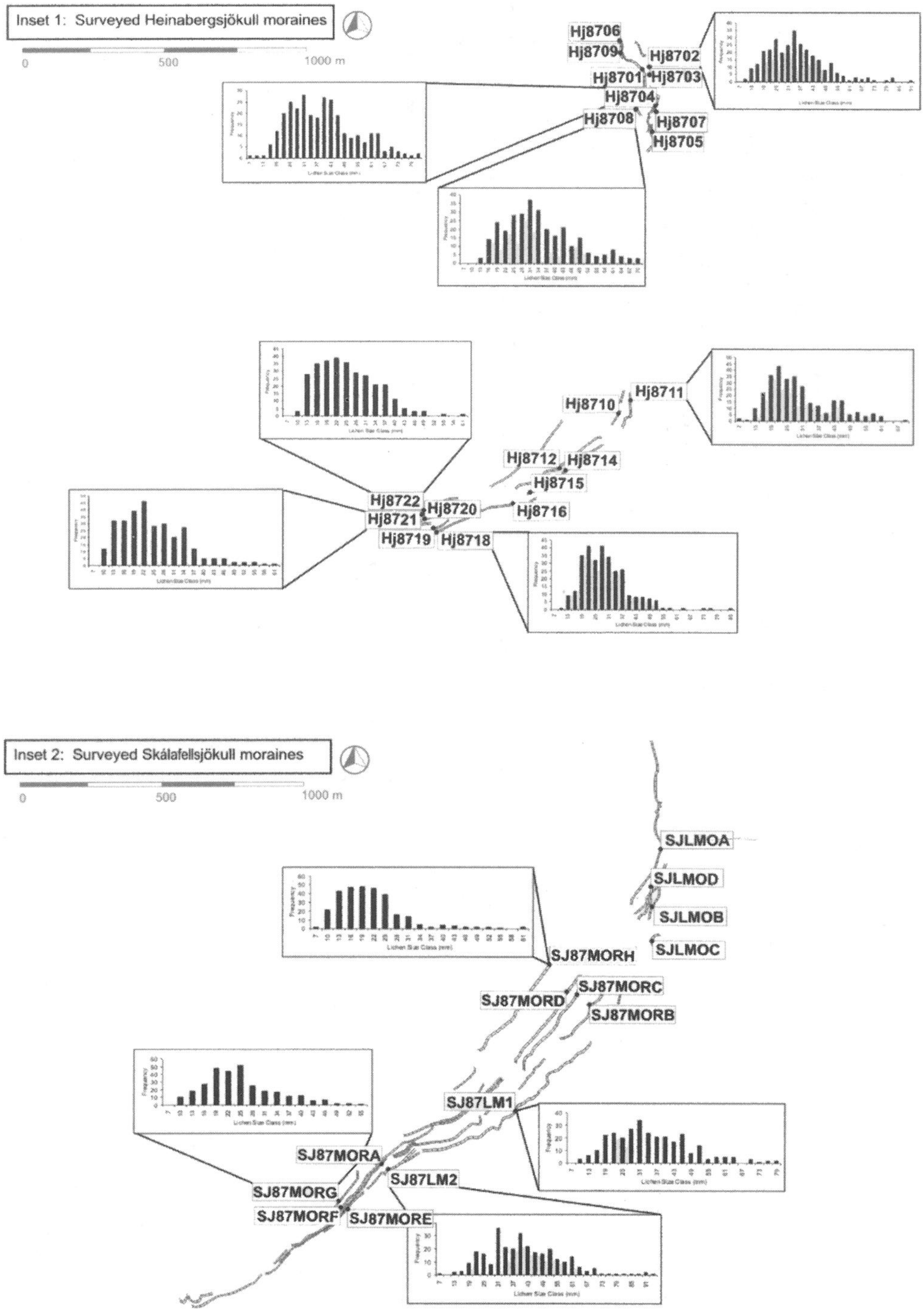


Fig. 1. (A) Location map of southeast Iceland showing Vatnajökull and some of its outlets mentioned in the text: Skálafellsjökull (64°16'N, 15°40'W), Heinabergsjökull (64°17'N, 15°40'W), Fláajökull (64°19'N, 15°33'W) and Lambatungnajökull (64°29'N, 15°17'W). Also shown is the generalized surficial geomorphology of Skálafellsjökull and Heinabergsjökull. (B) Sultartungnajökull. Lichen size–frequency distributions for bracketing LIA moraines are shown (see A, insets 1 and 2, and B)



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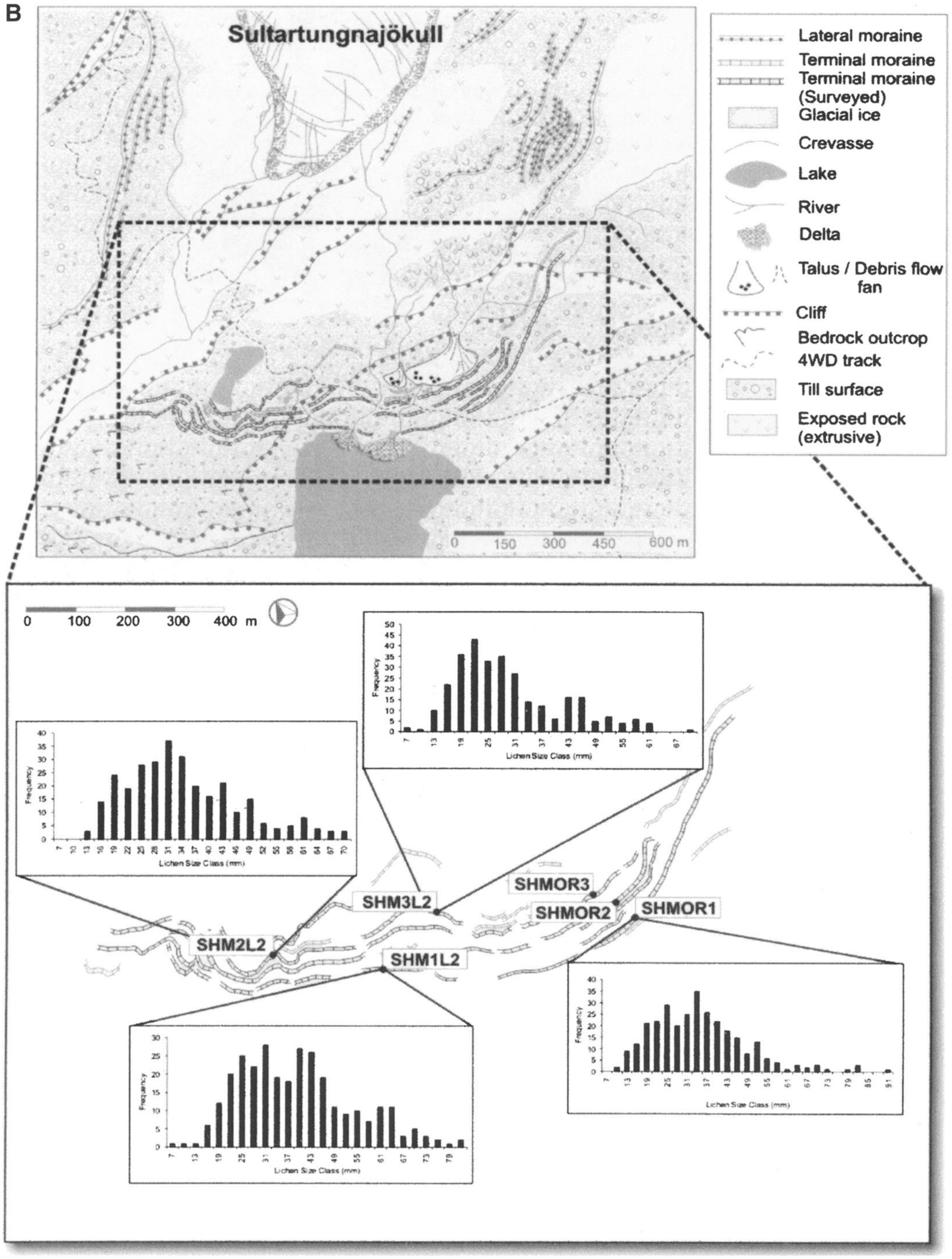


Fig. 1. Continued

Table 1. Summary of lichenometric methods previously used to calibrate lichen dating curves in southeast Iceland. After Bradwell (2001b), p. 139

Reference	Survey date	Location	Lichen species	Lichen parameter measured	Number of lichens measured*	Survey area (m^2)†	Calibration surfaces	Calibration method	Oldest surface (year AD)	Ecesis (years)‡	Growth rate (mm/yr)
Gordon and Sharp (1983)	1980	Skálafells-jökull	*R. geog.*	Long axis	1	150	Moraines	Largest lichen	1887	15	0.769
Thompson and Jones (1986)	1984	Öræfi	*R. geog. agg.*	Short axis	5	Entire	Moraines	Average of 5 largest lichens	1870	–	0.585–0.725
Evans *et al.* (1999)	1993	South, southeast (including Heinabergsjökull) and eastern Iceland	*R. geog. s.l.*	Long axis	5	Entire	Moraines Lake shorelines Gravestones	Average of 5 5 largest lichens	*c.* 1870–1890	6.5	0.8
Bradwell (2001a,b)	1999	Southeast Iceland	*R.* Section *R.* (includes *R. geog.*)	Long axis	*c.* 300	30	Glacial bedrock Moraines Rockfall Lava flow Jökulhlaup deposit	Size–frequency population gradient Largest lichen	1727	 –	 –
Bradwell (2004)	1999	Southeast Iceland	*R.* Section *R.* (includes *R. geog.*)	Long axis	*c.* 300	30	Glacial bedrock Moraines Rockfall Lava flow Jökulhlaup deposit	Largest lichen Size–frequency population gradient	 1727	 –	 –

* Number of lichens used to derive surface age, e.g. 5 = the 5 largest lichens were averaged to determine surface age
† Size of the area where lichens were measured, e.g. entire = the entire surface was searched
‡ Time lag for a lichen spore to arrive on and successfully colonize a surface

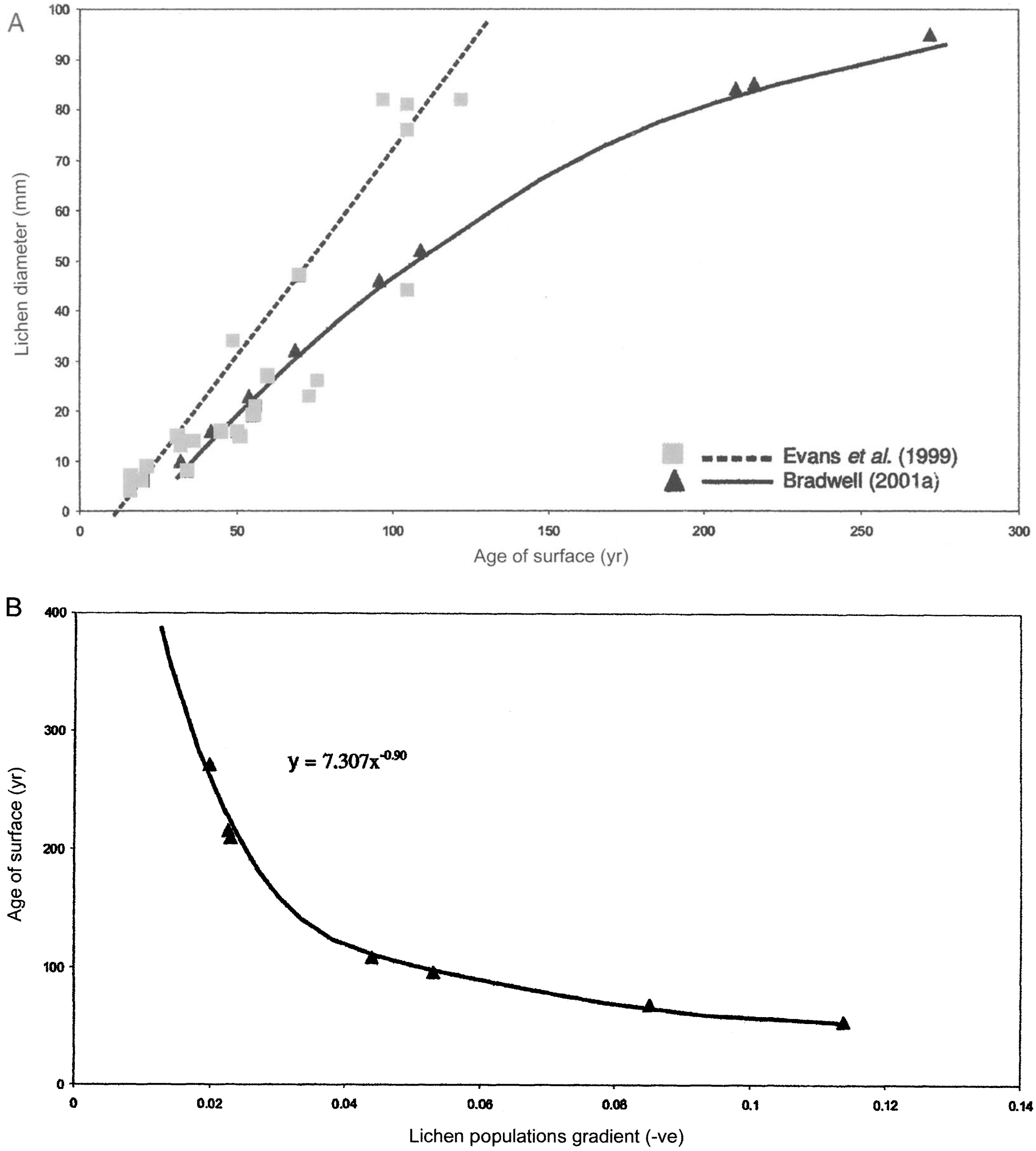


Fig. 2. Lichen dating curves for southeast Iceland including (A) 'age–size' curves (Evans *et al.* 1999; Bradwell 2001a), and (B) the 'age–gradient' curve (Bradwell 2004). The antiquity of dated surfaces used by Bradwell (2001a, 2004) is much greater than those used by Evans *et al.* (1999). Note also that both curves by Bradwell (2001a, 2004) are curvilinear, which suggests that growth of Section *Rhizocarpon* lichens decreases with time, rather than increasing at a consistent linear rate

in glacier mass balance and provide a means of establishing the timing of maximum terminus positions for different glaciers. The timing of these maxima may help elucidate effects of climate change in the North Atlantic during the LIA and aid in assessing potential future impacts of climate change on glacial systems in this region, such as contributions to global sea-level rise (Dowdeswell *et al.* 1997). However, this requires a reliable, and accurate, method for dating moraine surfaces.

Lichenometric dating of key Vatnajökull outlet glaciers

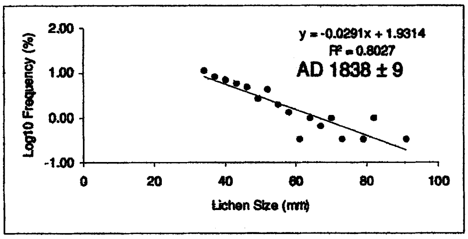
Lichenometric dating of moraine surfaces, using either lichen size or another index, such as lichen size–frequency distributions, as an indicator of surface age (Beschel 1950; Benedict 1967, 1985) is often the only dating tool available in glacial environments. Several different lichenometric methods have been applied to dating Icelandic LIA moraines, although the largest or average of the five largest lichen thalli growing on a surface has conventionally been used to estimate age based on locally calibrated lichen growth curves (e.g. Jaksch 1970, 1975; Gordon and Sharp 1983; Maizels and Dugmore 1985; Thompson and Jones 1986; Häberli 1991; Kugelmann 1991; Guðmundsson 1998; Evans *et al.* 1999). However, this approach relies upon finding the largest lichen(s) among potential multiple lichen populations and is limited by a small data set that is not statistically robust. Despite these concerns, several authors have constructed lichen calibration curves for southeast Iceland, particularly from locations surrounding Vatnajökull, using this approach (Fig. 1, Table 1).

For example, the linear 'age–size' curve calibrated by Evans *et al.* (1999; Fig. 2A) uses *Rhizocarpon geographicum s.l.* and is based on the average of the five largest lichens per surface from control points in the vicinity of Heinabergsjökull, Skálafellsjökull and Fláajökull (Fig. 1; lichens up to 80 mm diameter long axis from surfaces thought to be *c.* 120 years old). These include historically dated surfaces that suggest Heinabergsjökull reached its LIA maximum in AD 1887 (Thórarinsson 1943). However, the overall reliability of historical records has been questioned (e.g. Kugelmann 1991; Guðmundsson 1997; Bradwell 2001a; Sigurðsson in press), which indicates that historical control points should not be used to calibrate lichen growth curves unless they can be located and dated unequivocally. Subsequently, Evans *et al.* (1999) used their own lichen measurements throughout the forelands of Heinabergsjökull in conjunction with those collected by Gordon and Sharp (1983) from Skálafellsjökull, despite different field techniques (Table 1). They concluded that both glaciers reached their LIA maxima in AD 1887.

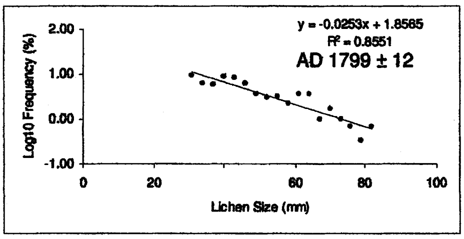
More recently, a lichen size–frequency approach has been advocated as a statistically more reliable dating method since it involves sample sizes of >200 individuals per site (e.g. Caseldine 1991; Kirkbride and Dugmore 2001; Bradwell 2001a, 2004). Furthermore, this alternative method uses the lichen size–frequency distribution at a site to calculate the population gradient, an intrinsic and non-biased characteristic of the lichen population, in order to estimate surface age. For instance, Bradwell (2001a) critically re-evaluated historically dated surfaces throughout southeast Iceland in order to calibrate a curvilinear 'age–size' dating curve that uses *Rhizocarpon* Section *Rhizocarpon* and is based on the largest lichen in a single population (Fig. 2A). This curve illustrates that the relationship between largest-lichen diameter and surface age is best described by a third-order polynomial function. Lichen data from nine tightly constrained historical control points were first examined using the size–frequency approach to ensure that lichens constituted a single coherent population (lichens up to 95 mm diameter long axis; surfaces up to 272 years old) before construction of the lichen dating curve. The apparent decline in growth rates of older lichens may reflect the impact of climate change on lichen growth in southeast Iceland during the past three centuries, or may represent an inherent phase of slower growth (Bradwell 2001a).

Using the gradient of the size–frequency distributions collected from his control points, Bradwell (2004) constructed a curvilinear 'age–gradient' curve, which plots the age of reliably dated surfaces (cf. Bradwell 2001a) against the slope of lichen population size–frequency distributions of *Rhizocarpon* Section *Rhizocarpon* (Fig. 2B). Overall, steep gradients indicate immature populations and hence younger surfaces, whilst shallow gradients reflect mature lichen populations growing on older surfaces. As a test, lichen data from moraines of known age at two Öræfajökull outlet glaciers (a separate ice-cap that merges with Vatnajökull; Fig. 1) were analysed using both of Bradwell's (2001a, 2004) 'age–size' and 'age–gradient' curves. Results from each method corroborated one another and closely reproduced reliable historical dates from these surfaces (i.e. late-19th century), thus highlighting their strength as an alternative approach for lichenometric dating in southeast Iceland. Subsequently, both curves were used to determine the ages of the outermost undated moraines at one of the Öræfajökull outlet glaciers (Bradwell 2004), as well as at Lambatungnajökull (Bradwell 2001b; Fig. 1). Dates derived using both approaches again corroborated one another and indicates late 18th century (*c.* AD 1770–1800) LIA glacier maxima at these sites.

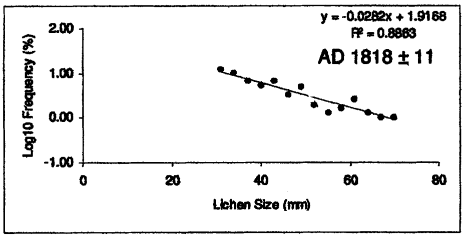
A



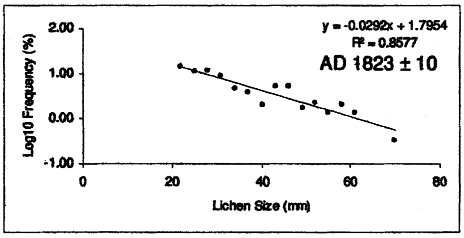
(ai). Outer LIA moraine at Sultartungnajökull – site 'SHMOR1'



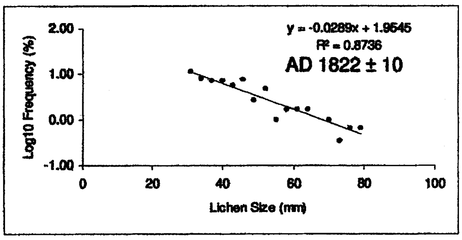
(aii). Outer LIA moraine at Sultartungnajökull – site 'SHM1L2'



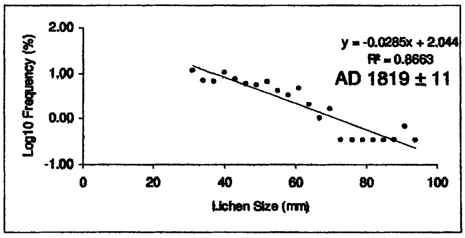
(aiii). Inner LIA moraine at Sultartungnajökull – site 'SHM2L2''



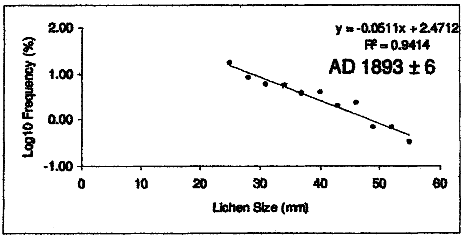
(aiv). Inner LIA moraine at Sultartungnajökull – site 'SHM3L2'



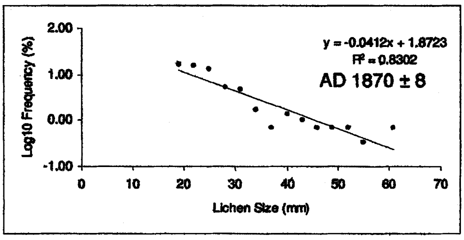
(av). Outer LIA moraine at Skálafellsjökull – site 'SJ87LM1'



(avi). Outer LIA moraine at Skálafellsjökull – site 'SJ87LM2'



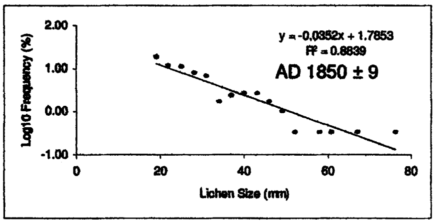
(avii). Inner LIA moraine at Skálafellsjökull – site 'SJMORG'



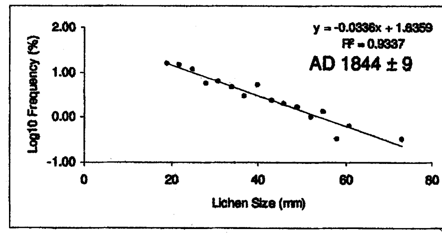
(aviii). Inner LIA moraine at Skálafellsjökul – site 'SJMORH'

Fig. 3. Lichen size–frequency plots for moraines used to date the outermost and innermost LIA moraines at (A) Skálafellsjökull (including Sultartungnajökull) and (B) Heinabergsjökull. Dates are derived using the 'age–gradient' curve (see Fig. 2B)

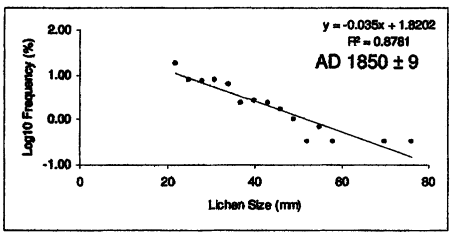
B



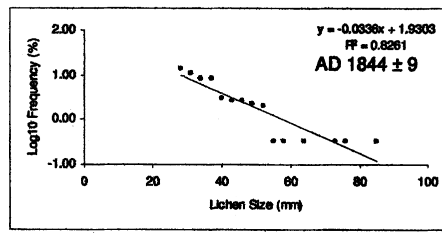
(bi). Outer LIA moraine at Heinabergsjökull – site 'HJ8702'



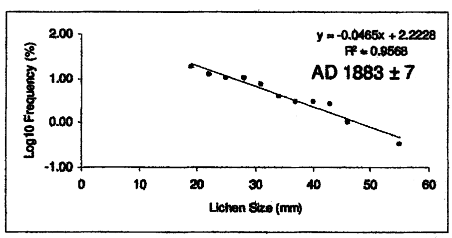
(bii). Outer LIA moraine at Heinabergsjökull – site 'HJ8704'



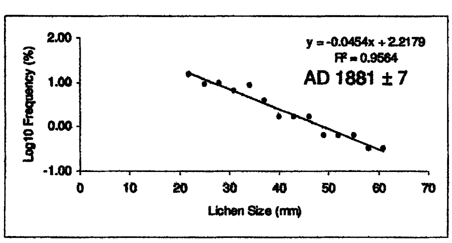
(biii). Outer LIA moraine at Heinabergsjökull – site 'HJ8711'



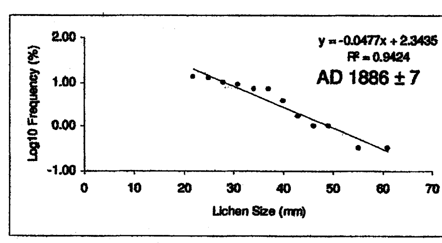
(biv). Outer LIA moraine at Heinabergsjökull – site 'HJ8718'



(bv). Inner LIA moraine at Heinabergsjökull – site 'HJ8708'



(bvi). Inner LIA moraine at Heinabergsjökull – site 'HJ8721'



(bvii). Innermost LIA moraine at Heinabergsjökull – site 'HJ8722'

Fig. 3. Continued

Table 2. Derived surface dates for all LIA moraine fragments at Sultartungnajökull, Skálafellsjökull and Heinabergsjökull using different lichen dating curves for SE Iceland

Moraine fragment (see Fig. 3 for location)	Population gradient (negative)	Modal size class	Year AD using 'age–gradient' curve (Bradwell 2004)	Largest lichen diameter – long axis (mm)	Year AD using 'age–size' curve (Bradwell 2001a)	Average of 5 largest lichen diameters – long axis (mm)	Year AD using 'age–size' curve (Evans *et al.* 1999)
Sultartungnajökull							
SHMOR1*	0.0291	34	1838 ± 9†	89	1753	83	1884
SHMOR2	0.0255	37	1800 ± 12	86	1769	80	1886
SHMOR3	0.0421	31	1873 ± 7	70	1842	62	1906
SHM1L2*	0.0253	31 and ~40, ~43	1799 ± 12	82	1790	78	1891
SHM2L2*	0.0282	31	1818 ± 11	70	1842	68	1906
SHM3L2*	0.0292	22	1823 ± 10	68	1849	62	1909
Skálafellsjökull							
SJ87LM1*	0.0289	31	1822 ± 10	78	1809	76	1897
SJ87LM2*	0.0285	31 and ~40	1819 ± 11†	92	1735	88	1877
SJ87MORA	0.0349	25 and ~28	1849 ± 9†	82	1790	73	1889
SJ87MORB	0.0441	25	1878 ± 7	66	1856	61	1910
SJ87MORC	0.047	22	1884 ± 7	64	1862	51	1912
SJ87MORD	0.0564	22	1902 ± 6	53	1894	48	1924
SJ87MORE	0.0313	25 and ~22 to 31	1834 ± 19	71	1838	69	1907
SJ87MORF	0.0402	25	1867 ± 8	70	1842	62	1906
SJ87MORG*	0.0511	25 and ~19	1893 ± 6	54	1891	50	1923
SJ87MORH*	0.0412	19 and ~13 to 22	1870 ± 8	61	1872	55	1914
SJLMOA	0.0457	19	1882 ± 7	51	1899	49	1927
SJLMOB	0.0363	19 and ~25	1855 ± 8	66	1856	56	1910
SJLMOC	0.0414	22 and 25	1871 ± 8	63	1866	58	1913
SJLMOD	0.0305	22	1830 ± 10	78	1809	74	1897
Heinabergsjökull							
HJ8701	0.0583	16 and ~22	1905 ± 6	47	1908	45	1931
HJ8702*	0.0352	19	1850 ± 9	74	1826	61	1901
HJ8703	0.0592	16	1906 ± 5	46	1910	43	1933
HJ8704*	0.0336	19 and ~40, ~43	1844 ± 9	71	1838	61	1903
HJ8705	0.0527	16	1896 ± 6	50	1901	47	1928
HJ8706	0.0454	19	1881 ± 7	61	1872	55	1914
HJ8707	0.0441	19	1878 ± 7	56	1886	51	1922
HJ8708*	0.0465	19	1883 ± 7	53	1894	46	1926
HJ8709	0.043	16 and ~19 to 22	1875 ± 7	52	1896	49	1927
HJ8710	0.0399	22	1866 ± 8	62	1869	56	1913
HJ8711*	0.035	22	1850 ± 9	76	1818	63	1898
HJ8712	0.0475	22 and ~13 to 16	1886 ± 7	56	1886	48	1922
HJ8714	0.0404	22	1868 ± 8	63	1866	60	1912
HJ8715	0.0483	19	1887 ± 7	60	1875	51	1915
HJ8716	0.0435	22	1876 ± 7	64	1862	57	1911
HJ8718*	0.0336	22 and ~28	1844 ± 9†	85	1775	71	1887
HJ8719	0.0404	25	1868 ± 8	55	1889	54	1923
HJ8720	0.0537	22 and ~16 to 19	1897 ± 6	55	1889	49	1923
HJ8721*	0.0454	22	1881 ± 7	61	1872	55	1914
HJ8722*	0.0477	22 and ~19 to 25	1886 ± 7	60	1875	52	1915

* Indicates bracketing LIA moraine fragment (i.e. spatially and temporally)
† Indicates discrepancies >50 years in derived dates based on Bradwell (2001a, 2004)

Study aim

The aim of this study is to test the reliability of different lichenometric approaches previously used to estimate the timing of LIA maxima in southeast Iceland, which has yielded a discrepancy of *c.* 100 years (i.e. late 18th to late 19th century). Specifically, this study attempts to: (1) re-date the moraines at Skálafellsjökull (including Sultartungnajökull, which has not previously been investigated) and Heinabergsjökull using the dating curves established by Evans *et al.* (1999) and Bradwell (2001a, 2004); (2) evaluate any disparities in LIA chronologies that may result from the different lichenometric techniques; (3) consider whether the reassessed LIA maxima accurately reflect the timing of glacier response to climate change, or whether they are an artefact of landscape disturbance or dating technique.

Study area

Vatnajökull, the largest European ice-cap (8100 km^2; Björnsson *et al.* 1998; Sigurðsson 1998), is situated in southeast Iceland (Fig. 1) and comprises different types of glaciers. In contrast to the large, lobate, surging outlets draining the north and west of Vatnajökull, the smaller and steeper outlet glaciers draining the southeast margin of the ice-cap, including Skálafellsjökull (*c.* 100 km^2) and Heinabergsjökull (*c.* 85 km^2), are non-surging, and their mass balance is directly affected by the direction and magnitude of climatic change. The firn-line in the south and east of Vatnajökull lies at *c.* 1100 m a.s.l. (Björnsson 1979). Both Skálafellsjökull and Heinabergsjökull are characterized by high-elevation nevés (*c.* 1500 m a.s.l.) and long tongues (*c.* 25 km) which terminate at *c.* 60 m a.s.l. on the sandur plain (Sigurðsson 1998). A response to climatic perturbations occurs at the termini 5 to 10 years after a change in temperature, although it may take up to 30 years for the overall mass balance of each glacier to respond fully to climate change (Sigurðsson and Jónsson 1995). However, Skálafellsjökull exhibits a steeper surface profile and greater ice thickness, which implies a slightly faster response to climatic perturbations. Heinabergsjökull currently calves into a proglacial lake, thus complicating the relationship between terminus fluctuations and climate. Sultartungnajökull (also called Eyvindstungnajökull) is a small lobe that diverges from the south margin of Skálafellsjökull and currently terminates *c.* 400 m a.s.l. above the Jöklasel road.

Although these glaciers are not strictly confined within valleys, prominent nested moraines are abundant in the forelands and ice-marginal locations (Fig. 1). Thus, the geomorphology in the area indicates that the outermost bands of nested LIA moraines at Skálafellsjökull and Heinabergsjökull are ideal locations to assess different lichenometric methods for dating moraine fragments in southeast Iceland.

Methods

During summer 2003, yellow-green *Rhizocarpon* Section *Rhizocarpon* were measured on each of 40 moraine fragments (12 000 lichens in total) along the margins of Skálafellsjökull, including Sultartungnajökull, and Heinabergsjökull. Due to the difficulties surrounding field identification to the species level, thalli were only identified to the section level as recommended by Innes (1982, 1985) using the criteria of Poelt (1988). *Rhizocarpon* Section *Rhizocarpon* includes the species *Rhizocarpon geographicum* (L.) DC. (Cernohorský 1977). A fixed area of 30 m^2 was delimited on the proximal side of each fragment, and a sample lichen population of 300 individuals was measured per designated site (Fig. 1). The longest axis per lichen thallus >5 mm was recorded to the nearest millimetre using a clear plastic ruler. Elongate and irregularly shaped thalli were included in the survey, although coalescent thalli were disregarded. Thalli were only measured on non-vesicular, basaltic rocks, which are abundant in the study area.

Following the method of Bradwell (2001a, 2004), size–frequency classes were produced using a class interval of 3 mm in order to examine the lichen population distribution, e.g. whether populations were singular or composite. Subsequent graphs were constructed using the logarithm (base 10) of the frequency (%) as the dependent variable, and lichen diameter as the independent variable. Lichens falling below the modal class on each moraine fragment were excluded. Regression lines fitted to the data using the least-squares method enabled size–frequency distributions to be described in the form $y = mx + c$ with the slope of the regression line indicating population age (Fig. 3).

For comparison, three different lichenometric dating curves previously constructed for southeast Iceland were used to derive possible surface ages in our study area (Table 2). These included both the

Table 3. Minimum estimates of LIA maxima obtained from different lichenometric methods. Derivations from sites of questionable reliability (see text) are included to produce a range of possible dates

Lichenometric method	Timing of LIA maximum* for Skálafellsjökull (including Sultartungnajökull)	Timing of LIA maximum* for Heinabergsjökull
'Age–gradient' curve (Bradwell 2004)	early-19th century (*c.* AD 1800 to 1820)	mid-19th century (*c.* AD 1840 to 1850)
'Age–size' curve (Bradwell 2001a)	mid-18th to early-19th century (*c.* AD 1740 to 1810)	late-18th to early-19th century (*c.* AD 1780 to 1820)
'Age–size' curve (Evans *et al.* 1999)	late-19th to early-20th century (*c.* AD 1880 to 1910)	late-19th to early-20th century (*c.* AD 1890 to 1900)

* Dates have been rounded to the nearest decade

linear and curvilinear 'age–size' curves produced by Evans *et al.* (1999) and Bradwell (2001a) respectively (Fig. 2A), and Bradwell's (2004) curvilinear 'age–gradient' curve (Fig. 2B).

Lichenometric analyses

The 'age–gradient' approach

All lichen populations show strong correlations between size and $\log_{10}$ frequency (r^2 = 0.8027 to 0.9467). Regression analyses also show that, the shallower the gradient, the older the lichen population (Fig. 3), which corroborates previous research throughout Iceland (Caseldine 1991; Bradwell 2001a, 2004). However, inspection of size–frequency histograms and related modal size classes also reveals the complexity of lichen distributions (Fig. 1, Table 2). For example, lichen populations are apparently bimodal at site HJ8718 (possibly also site SJ87LM2), and multi-modal at several others (e.g. SJ87MORH, SHM1L2, HJ8704, HJ8722).

If sites where composite populations exist are omitted to provide conservative estimates, then the 'age–gradient' curve predicts a minimum date of *c.* AD 1820 (site SJ87LM1) and *c.* AD 1850 (sites HJ8702 and HJ8711) for the LIA maximum of Skálafellsjökull and Heinabergsjökull respectively (Fig. 1a, Table 2). Modal class values should increase as lichen populations mature (Gellatly 1982), hence the older the modal size class, the older the surface. Thus, a relative comparison between modal class values from the outermost moraines of Skálafellsjökull (31 mm) and Heinabergsjökull (19 to 21 mm) imply the occurrence of an older LIA glacier maximum at Skálafellsjökull (Table 2).

The 'age–gradient' curve predicts a minimum estimate of *c.* AD 1800 and *c.* AD 1840 for both outermost moraine fragments, SHM1L2 and SHMOR1 respectively at the marginal lobe Sultartungnajökull (Fig. 1B, Table 2). However, using the older date to infer the timing of the LIA maximum may not be reliable, as site SHM1L2 contained a multi-modal lichen population (modal class of 31 and *c.* 40, *c.* 43 mm). Furthermore, the subdued appearance of moraine fragment SHMOR1 suggests that post-depositional disturbance may have affected lichen growth, thus yielding a younger surface age. However, the lichen population at site SHM2L2 (Fig. 1b) is unimodal (31 mm) and dates to AD 1818 ± 11 (gradient of 0.0282). Although a LIA maximum of *c.* AD 1800 at Sultartungnajökull may be equivocal, the 'age–gradient' approach suggests that this lobe was in an advanced position (*c.* 50 m inside the outermost moraine) in *c.* AD 1820, which corresponds to the timing of the maximum advance at the Skálafellsjökull terminus.

The 'age–size' approach

The choice of 'age–size' dating curve used to derive moraine age estimates has a significant impact on the inferred timing of LIA maxima for Skálafellsjökull (including Sultartungnajökull) and Heinabergsjökull (Table 2). Using Bradwell's (2001a) dating curve, Skálafellsjökull's LIA maximum extent was reached by AD 1735 (AD 1753 for the Sultartungnajökull lobe), whereas Heinabergsjökull's maximum did not occur until AD 1775. However, these dates are based on the largest lichens found in bimodal lichen populations (e.g. sites SJ87LM2 and HJ8718; Fig. 1A), as shown in the size–frequency distributions. At Sultartungnajökull, lichens growing at SHMOR1 consist of a single population, which seemingly provides support for an AD 1753 LIA maximum, although the subdued appearance of the moraine fragment implies that post-depositional disturbance has affected the site. If site SHM2L2 is used instead as a conservative estimate, then Sultartungnajökull's maximum limit occurred by AD 1842 (Table 2).

Overall, when composite lichen populations are excluded, Bradwell's (2001a) 'age–size' dating curve predicts an early 19th century LIA maxima for Skálafellsjökull and Heinabergsjökull (i.e. AD 1809 and AD 1818 respectively; Fig. 1A, Table 2). In contrast, Evans *et al.* (1999) dating curve predicts a late-19th century LIA maximum (i.e. AD 1897 and AD 1898 respectively) that corresponds to their previous estimate. Evans *et al.* (1999) dating curve also predicts that Sultartungnajökull was just inside the LIA maximum limit during the early-20th century (i.e. AD 1906; Fig. 1B, Table 2). Thus, discrepancies in the timing of LIA maxima between 'age–size' dating curves are at least *c.* 60 to 90 years.

Discussion

Results from this study show that the choice of lichen calibration curve used to date moraines in the study area has a significant impact on the interpretation of the timing of LIA maxima (Table 3). Dates obtained using both of Bradwell's (2001a, 2004) curves appear to corroborate one another and suggest that Skálafellsjökull's LIA maximum occurred by the early 19th century, while Heinabergsjökull advanced to its LIA maximum extent slightly later. Most dates derived using Bradwell's (2001a) 'age–size' method are close to or within the range of error resulting from the 'age–gradient' method, except when composite lichen populations or landform disturbance appears at a site. This supports Bradwell's (2004) conclusion that both curves can be used in tandem in order to test the reliability of lichenometric dating in southeast Iceland. However, dates derived from Evans *et al.* (1999) dating curve are consistently younger and place the timing of LIA maxima for both glaciers at the end of the 19th century (Table 3), although this accords well with the historically purported late 19th century glacier maxima along southeastern Vatnajökull. Following the LIA maxima, all three lichenometric methods used to re-date the LIA moraines in this study yield evidence of overall glacial retreat that was generally sustained throughout the early 20th century.

Discrepancies between lichenometric methods may partially be explained by the shape of dating curves produced by different authors. Bradwell's (2001a, 2004) 'age–size' and 'age–gradient' curves imply that both the lichen growth rate and lichen population gradient decrease with time. This corroborates Benedict's (1967) assertion that lichens do not grow at a constant rate throughout their lifespan. Although the portion of the 'age–size' curve younger than *c.* AD 1890 also approximates to a linear function, it does not conform to the rapidity of lichen growth that is suggested by Evans *et al.* (1999). Lichen growth varies across the Icelandic landscape (Guðmundsson 1997), with development more rapid in the temperate, maritime south/southeast and slower in the colder, more arid north. It is also possible that lichen growth in the southeast was reduced during the LIA relative to the 20th century (Bradwell 2001a). Such a potential growth history sheds doubt on the pattern of constant linear lichen growth derived by Evans *et al.* (1999).

Anomalously young dates within the LIA moraines at both glacier forelands may be the result of landscape disturbance (Table 2). Relaxation in ice-cored moraines, a common feature around the present-day Skálafellsjökull margin, is modified over time as the ice-core eventually melts away and the ice-proximal slope readjusts (Sharp 1984). This can delay ecesis, as lichens will not successfully colonize a surface until it has become stable (Benedict 1967). Furthermore, periglacial modification of surfaces is apparent at sites HJ8701, 03, 07 and 15. Evidence for this modification includes frost-shattered boulders and moraines partially veneered by small (<10 cm diameter long axis), angular shards. Individual lichens growing on these boulders prior to shattering are subsequently fragmented, thus arresting growth (cf. Maizels and Dugmore 1985; Thompson and Jones 1986), and shard recolonization by second generation lichens will cause age misinterpretation. Additionally, sorted stone-banked terraces were observed among sites SJ87MORD and SJLMOA-D, which indicate downslope movement by freeze–thaw action (French 1996). Other authors have also found evidence of periglacial activity inhibiting lichen growth on moraines at Fláajökull (Jaksch 1975; Dąbski 2002). All of these processes may lead to substantial underestimation of surface age estimates using lichenometry.

Ice dynamics may also help explain the existence of composite lichen populations. Nested moraines in the forelands of Skálafellsjökull and Heinabergsjökull are closely spaced (<30 m apart), and many are double-crested in places where overriding has occurred during successive glacier re-advances. The Icelandic LIA climate was characterized by frequent variability (Ogilvie 1986, 1992; Guðmundsson 1997; Jonsson and Garðarsson 2001), and each period conducive to glacier growth allowed termini to advance to positions of similar extent (Kirkbride and Dugmore 2001). Thus, the closer the moraine spacing, the more likely that remnants of older lichen populations growing on reworked sediments may have been incorporated into younger LIA moraine deposits. Inheritance can only be revealed by examining lichen size–frequency distributions and is an issue that is not addressed using conventional lichenometric techniques.

Landform censoring may also have impacted lichen populations growing on the outermost moraine fragments (Kirkbride and Brazier 1998). Orientation of terminal moraines at both Skálafellsjökull and Heinabergsjökull demarcates a coalesced ice-front during the LIA. On one hand, the discrepancy between lichen modal size classes at the outermost Skálafellsjökull moraine (31 mm) and the corresponding Heinabergsjökull moraine (22 mm) implies that despite coalescence, the Skálafellsjökull margin reached its LIA maximum and began subsequent retreat earlier than the Heinabergsjökull margin. Different glaciological characteristics between sites presage varying rates of frontal movement. Thus, the apparent disparity in timing between neighbouring glaciers may reflect a true glaciological response to LIA climate change. However, moraine preservation beyond the Heinabergsjökull limit is questionable due to the existence of a heavily eroded sandur plain. Preceding a switch during the mid-20th century to the dominant north–south drainage, meltwater was directed through various palaeochannels and likely destroyed any moraines in its path. Bimodal lichen size classes on the perceived outermost Heinabergsjökull moraines may then be interpreted as a remnant inherited from a censored outermost moraine. The northern extension of LIA moraines at Heinabergsjökull has also been lost due to emptying of a former ice-dammed lake, Dalvatn, which significantly modified the sandur surface during the 1920s (Evans *et al.* 1999). Overall, the appearance of the Skálafellsjökull and Heinabergsjökull proglacial areas indicates a dynamic glacio-fluvial landscape. This suggests that the lichenometric dates reassessed in this study may also be an artefact of landscape disturbance.

Implications for the timing of LIA glacier maxima

Despite these potential problems, it is suggested that all three dating curves provide at least a minimum estimate of the timing of glacier fluctuations in southeast Iceland. In this context, evidence from sources such as historical documents, sea-ice reconstructions and the instrumental record may help resolve disparities regarding the exact timing of LIA maxima for Skálafellsjökull and Heinabergsjökull.

Summarizing available historical documents, Sigurðsson (in press) reports that the dominant local opinion by the early 20th century was that the southeast Vatnajökull outlets from Heinabergsjökull (at that time coalesced with Skálafellsjökull) to Lambatungnajökull had reached their LIA maxima *c.* AD 1890. The lichenometric dates derived in the present study utilizing the Evans *et al.* (1999) dating curve support this observation. Björnsson (1979) also concludes that outlet glaciers attained their LIA maxima during the mid- to late 19th century, while limits for smaller and steeper glaciers were reached during the mid-18th century. Thórarinsson (1943) implies that the spatial extent of these two episodes was similar, thus raising the question whether or not the true LIA maximum limit in many areas of southeast Iceland is identifiable.

Results from the present study incorporating Bradwell's (2001a, 2004) tandem lichenometric method provide increasing support for an earlier LIA maximum (late 18th to mid-19th century) in southeast Iceland. Accordingly, at least the Skálafellsjökull lobe (and Sultartungnajökull) of the coalesced Heinabergsjökull piedmont glacier may have attained its LIA maximum during this period, as did Lambatungnajökull and one of the Öræfajökull outlets (Bradwell 2001b, 2004). More widely, this evidence also supports conclusions by Kirkbride and Dugmore (2001) and Casely and Dugmore (2004) regarding revised late 18th century LIA maxima at outlet glaciers draining Eyjafjallajökull and Mýrdalsjökull (southern Iceland) using the lichen population gradient approach constrained by a well-established regional tephrochronology. Overall, Kirkbride and Dugmore (2001) conclude that conventional lichenometry-based chronologies unconstrained by independent dating methods may underestimate actual landform age by >100 years and misleadingly cluster LIA maxima in the mid- to late 19th century.

Climatic conditions favourable for glacier

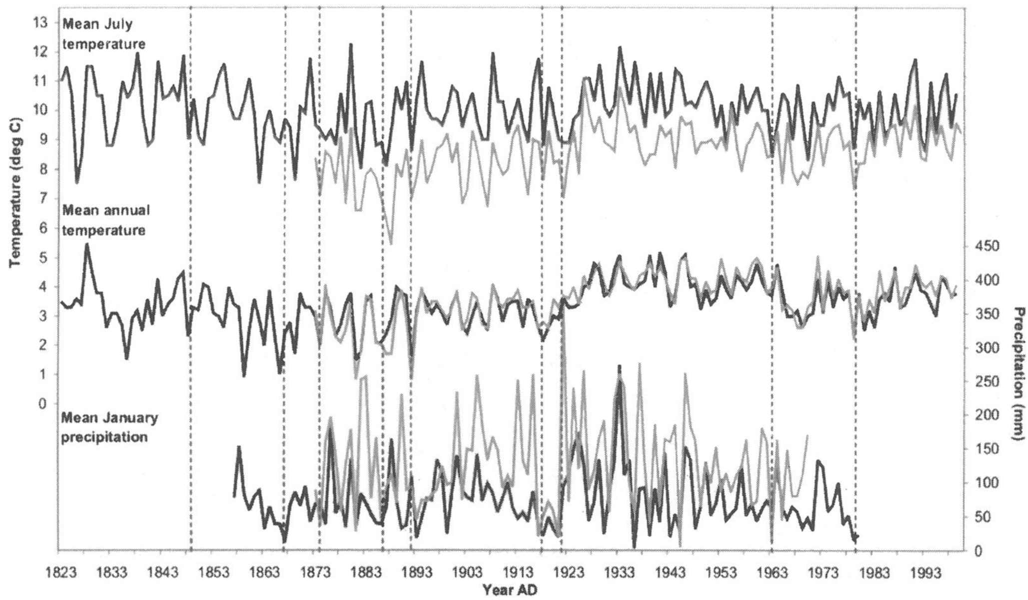


Fig. 4. Instrumental climate data recorded from Stykkisholmur (black lines) and Teigarhorn (grey lines) during the 19th and 20th century (from the Icelandic Meteorological Office). Dashed vertical lines indicate general periods of known glacier advance (including results from this study) from locations throughout Iceland

growth in Iceland occurred several times during recent centuries, including the late 17th century, mid-18th century, 1780s, mid- and late 19th century, during the 1920s, and in some locations after 1960. Southeast Iceland's glaciers are most sensitive to variations in summer temperature (Jóhannesson and Sigurðsson 1998). A strong correlation between sea-ice incidence and land temperature has previously been demonstrated (Bergthórsson 1969; Ogilvie 1984), and the greatest extent (surrounding all coasts) and duration (persisting from winter through summer) of sea-ice occurred during the 1780s (Ogilvie 1992). Although instrumental data do not extend back into the late 18th century, information derived from the sea-ice record implies a considerable reduction in summer temperature during this time, thereby reducing ablation at glacier termini and allowing more precipitation to fall as snow. Recent reconstructions of glacier equilibrium line altitude (ELA) at Sólheimajökull (an outlet of the Mýrdalsjökull ice-cap) indicate that the overall cold peak between the 1780s and 1790s corresponded to a temperature decrease of 1.6°C compared to the 1960–1990 mean (Mackinstosh *et al.* 2002).

Furthermore, 19th and 20th century instrumental temperature and precipitation records from Stykkisholmur (western Iceland) and Teigarhorn (eastern Iceland) reveal that episodes of known glacier expansion (including results from this study) often corresponded to cold years with shortened summers and drier winters (Fig. 4), a scenario characteristic of the negative mode of the North Atlantic Oscillation (NAO). By contrast, elsewhere in the North Atlantic, such as southern Norway, a prevailing positive NAO mode results in positive glacier mass balance primarily due to increased precipitation (Nesje and Dahl 2003; Winkler 2003). Precipitation may be less important to Icelandic glacier mass balance and consequent terminus fluctuations on a sub-decadal time scale (Bradwell 2001b; Mackintosh *et al.* 2002). Thus, allowing for an appropriate terminus response time (cf. Sigurðsson and Jónsson 1995), it is conceivable that eventual widespread advance of Icelandic glaciers occurred during the late 18th to mid-19th century in response primarily to temperature variability as indicated by the sea-ice record and changes in the NAO.

Conclusions

LIA moraines along the margins of Skálafellsjökull and Heinabergsjökull, two neighbouring outlet glaciers flowing from the Vatnajökull ice-cap, have been re-dated to test the reliability of different lichenometric approaches. Our findings are summarized as follows:

1. The choice of lichen dating curve has a significant impact on the estimated timing of LIA maxima at Skálafellsjökull (including Sultartungnajökull) and Heinabergsjökull. Possible discrepancies between methods span the entire 19th century.
2. A comparison of limitations involved in the various lichenometric methods tested suggests that Bradwell's (2001a, 2004) tandem approach using both 'age–size' and 'age–gradient' curves together yield reliable dates.
3. An early to mid-19th century LIA maximum at Skálafellsjökull and Heinabergsjökull respectively as determined in this study accords well with other emerging evidence (e.g. Icelandic geochronology reconstructions, sea-ice and NAO records). This indicates that the often-cited late 19th century LIA glacier maximum requires further revision. Additional refinement to these chronologies using independent dating constraints, such as tephrochronology, will elucidate the precise timing of the Icelandic LIA glacier maximum and shed further light on glacier–climate interactions in the North Atlantic.

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