Lichenometry in Iceland, results and application

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Lichénométrie en Islande, application et résultats

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1. Introduction

Lichenometry is an inexpensive well-established calibrated-dating technique using lichen size to determine the relative or absolute age of exposed surfaces (Beschel, 1950, 1973). The technique takes advantage of the radial development of the thallus on the rock, specifically the species within the Rhizocarpon subgenus, and has been applied in Iceland as well as in other cold environments (Golledge et al., 2010; Wiles et al, 2010; Hansen, 2010; Trenbirth and Matthews, 2010; Roberts et al., 2010). The field method remained quite similar over the last four decades, but the statistical techniques to analyse the collected data sets evolved considerably in the last several years, leading to some debate in the scientific literature.

The use of lichenometry in Iceland raises the issue of absolute vs. relative dating, and short term vs. long term accuracy of the proposed ages. Results are better for short periods of time, when sources of errors are minimal (less lichen species on the surface, less mortality within the first generation that colonised the surface), starting to become much relative over about hundred years, a period of time beyond which very few control points are available. This leads to the second issue, regarding the suitability of control points/surfaces as Icelandic environmental conditions can change drastically in very short distances, particularly in glacier surroundings. Through
examples, the validity of lichenometry as an absolute dating method is questioned.

2. Aims of lichenometric studies in Iceland

A common aim of many applied lichenometric studies is dating various geomorphological processes or related landforms with closely limiting numerical ages. In Iceland, most lichenometric studies have been performed in proglacial environments to date moraine sequences (e.g. Jaksch, 1970, 1975; Caseldine 1983). Some studies have used these dated moraine records to make climatic inferences spanning the last three centuries (e.g. Thompson, 1988; Casely and Dugmore, 2004; Bradwell et al., 2006). Researchers have generally focussed on the timing of “Little Ice Age” and 20th-century glacier fluctuations (e.g. Caseldine, 1987; Kugelmann, 1990, 1991; Bradwell, 2004a,b; Chenet et al., 2010). Some studies have used lichenometry to date glacial outwash deposits (Maizels and Dugmore, 1985) and proglacial river incision (Thompson and Jones, 1986; Roussel et al., 2008). Whilst far less numerous studies have applied lichenometry to soil erosion quantification (Buckland, 1994), debris-flow dating (Caseldine, 1991; Decaulne and Sæmundsson, 2003; Decaulne et al., 2005) and to extreme snow-avalanche frequency (Decaulne and Sæmundsson, 2010), investigations in glacier forelands remain prevalent (tab. 1).

Several authors also used their geomorphic studies to test new approaches to lichenometry dating (e.g. Bradwell and Armstrong, 2007; Orwin et al., 2008), or to test techniques against the findings of other dating methods, such as validating the age estimates by comparing lichenometric ages against tephrochronological ages (e.g. Kirkbride and Dugmore, 2001, 2008).

Because of the aim of most lichenometric studies in Iceland is to date proglacial landforms, notably moraines, the spatial distribution of investigated sites is uneven. The number of studies conducted adjacent to glaciers represents almost 80 % of all lichenometric studies conducted in Iceland (fig. 1), most of these have been conducted around the southern margins of Vatnajökull (50 %); followed by Mýrdalsjökull (22 %), then the Tröllaskagi glaciers in Northern Iceland (21 %), and finally one or two studies around Eiríksjökull in West Iceland, and adjacent to Drangajökull (Principato, 2008) in Northwestern Iceland (Buckland, 1994). More isolated investigations regarding debris-flow and snow-avalanche frequency have been carried out in Northwestern and North Iceland (Decaulne et al., 2005, 2010), and a single soil erosion study has been carried out in Northwestern Iceland. The contrasted environment (temperature and precipitation, wind and snow cover, …) of Iceland offers another possible aim that would test latitudinal and altitudinal comparisons of lichen growth to attempt getting answers on the influence of climate on lichen growth in Iceland.

Fig. 1 – Location of studies using lichenometry in Iceland.
Numbers refer to Table 1 as well as Figure 2.

Fig. 1 – Localisation des sites d’étude où la lichénométrie est utilisée en Islande.
Les nombres se réfèrent au Tableau 1 et à la Figure 2.
Tab. 1 – Main studies using lichenometry in Iceland since 1970.

1 Number referring to the study location on the map in Figure 1. 2 Principal dating technique(s) used: LL (largest lichen); SLL (five largest lichens); SF (size-frequency distribution); LC (lichen cover); U (goodness-of-fit); GEV (generalised extreme value).

(*) Recapulated with supplement measurements made in 2009 (0.403 according to the growth curve published in 2005). In bold: studies conducted in North Iceland – all other studies were conducted in South Iceland.

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<th>Nbr</th>
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<th>Technique(s) used</th>
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<th>Lag time (years)</th>
<th>Reference</th>
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<td>01</td>
<td>a: Sólheimajökull &amp; b: Síðujökull</td>
<td>Glacier fluctuations</td>
<td>LL</td>
<td>moraine</td>
<td>0.73</td>
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<td>Jakusch (1970)</td>
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<td>moraine</td>
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<td>Glacier fluctuations</td>
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<td>LL</td>
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<td>gravestones</td>
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<td>Climate variation &amp; Method</td>
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<td>existing curve</td>
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<td>19</td>
<td>Guðmundsson (1992 &amp; 1998)</td>
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<td>LL</td>
<td>existing curve</td>
<td>0.85</td>
<td>20-25</td>
<td>Caseldine &amp; Baker (1998)</td>
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<td>a: Orðra area (Kvárajökull &amp; Hólarjökull), b: Hnæfargjökull, c: East Mýrdalsjökull area (Oldhóllisfelljökull &amp; Sandfellbíjökull) &amp; d: North Vatnajökull (Brúarájökull, Eyjafjallajökull and Snæfell)</td>
<td>Glacier fluctuation</td>
<td>SLL</td>
<td>existing curves, moraines, shoreline, bridge &amp; gravestones</td>
<td>0.85-0.5</td>
<td>20-25</td>
<td>Caseldine &amp; Baker (1998)</td>
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<td>Methods &amp; glacier fluctuations</td>
<td>LL, SLL, SF</td>
<td>moraines, flood deposit</td>
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<td>&gt;10</td>
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<td>South East Iceland</td>
<td>Glacier fluctuations</td>
<td>LL, SF</td>
<td>moraines, glacial bedrock &amp; rockfall</td>
<td>0.6-0.25</td>
<td>&gt;10</td>
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<td>0.23-0.8</td>
<td>0.23-0.8</td>
<td>Bradwell &amp; Armstrong (2007)</td>
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<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>Casely &amp; Dugmore (2004)</td>
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<td>SF, LL</td>
<td>moraines, glacier bedrock, rockfall, lava flow &amp; flood deposit</td>
<td>0.59</td>
<td>15</td>
<td>Bradwell (2004)</td>
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<td>LL, SF</td>
<td>moraines, glacier bedrock</td>
<td>0.59</td>
<td>15</td>
<td>Bradwell (2004)</td>
</tr>
<tr>
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<td>Little Ice Age timing</td>
<td>LL, SF</td>
<td>moraines, rockfall, lava flow &amp; flood deposit</td>
<td>0.59</td>
<td>15</td>
<td>Bradwell (2004)</td>
</tr>
<tr>
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<td>Methods</td>
<td>SF</td>
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<td>n/a</td>
<td>n/a</td>
<td>Bradwell &amp; Armstrong (2007)</td>
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<td>Little Ice Age timing &amp; Method</td>
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<td>n/a</td>
<td>n/a</td>
<td>Casely &amp; Dugmore (2004)</td>
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<td>n/a</td>
<td>n/a</td>
<td>Chenet (2008)</td>
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<td>Little Ice Age timing</td>
<td>GEV</td>
<td>moraines, rockfall, lava flow, flood deposits, dams</td>
<td>n/a</td>
<td>n/a</td>
<td>Chenet &amp; Roussell (2008)</td>
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<tr>
<td>31</td>
<td>a: Sólheimajökull, b: Morsárjökull &amp; c: Flãajökull, Fljafljökull &amp; Hoffelljökull</td>
<td>Outwash deposit incision</td>
<td>SF</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>Roussell et al. (2008)</td>
</tr>
<tr>
<td>32</td>
<td>Gígjökull &amp; Steinshólsjökull</td>
<td>Glacier fluctuations &amp; Methods</td>
<td>SF</td>
<td>0.23-0.8</td>
<td>0.23-0.8</td>
<td>0.23-0.8</td>
<td>Kirkbride &amp; Dugmore (2008)</td>
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<td>moraines, rockfall, lava flow, flood deposits, dams</td>
<td>0.33</td>
<td>n/a</td>
<td>Chenet et al. (2009)</td>
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<td>35</td>
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<td>Extreme snow avalanche frequency</td>
<td>LC</td>
<td>existing curve</td>
<td>n/a</td>
<td>n/a</td>
<td>Decauline &amp; Sæmundsson (2010)</td>
</tr>
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</table>
3. Lichenometric techniques used in Iceland and their overall assessment

Several lichenometric methods have been applied in Iceland to date a range of different surfaces (tab. 1). The simplest one, consisting of measuring diameters of large lichens and selecting only the single largest lichen thallus, growing on a surface, follows Beschel’s pioneer work (1950); this method has been commonly used in Iceland since 1970 (see Table 1). Also commonly applied is the five largest lichens approach, where researchers take into account either the long axes (most authors) or the short axes of the five largest lichens on a surface or within a subsample of the surface (e.g. Gordon and Sharp, 1983; Guðmundsson, 1992, 1998). Both approaches were retaining only a limited amount of lichens measured on each surface, proposing an average result that limits the weight of the potential anomalous largest lichen. Relying on few data sets only, the method is considered weak from a statistical point of view (McKinsey et al., 2004, 2005; Rosenwinkel et al., 2015). The bases for these two simplest approaches are grounded, according to Beschel (1950), on: (i) the lichen cannot be older that the surface it grows on, (ii) the radial development of a single thallus is uniform when averaged over the long-term, (iii) the largest thallus grows under optimal conditions and therefore indicates the minimum age of a surface that is closest to the actual age. However, the second of these basic statements is an assumption unsupported by ecological properties and population dynamics of lichens (Joachimsen, 1973; McCarthy, 1999).

From the late 1980s the size-frequency approach was introduced in Iceland, first by Caseldine (1990, 1991) in Þrøllaskagi. In this approach, all thalli of a certain species (typically R. geographicum agg.) growing on a single surface are measured and mathematically describe the structure of multiple lichen populations (Bradwell, 2009). This novel approach has gained popularity since the last 20 years and has been applied by several authors in southern Iceland (e.g. Bradwell 2001a,b and 2004a,b; Kirkbride and Dugmore 2001; McKinsey et al., 2004a,b and 2005; Orwin et al., 2008). It has been widely used as it is thought to be a statistically more robust and reliable dating technique, as it considers a whole lichen population and includes a large number of measurements (200-5000, 1000 being recommended in Bradwell, 2009), which enables identifying anomalous growth/large lichens. Furthermore, the size-frequency approach avoids the potential problems surrounding the unreliability and insignificance of a small number of lichens (single largest lichen or five largest lichen approaches) on surfaces where several lichen populations might coexist.

More recently, two other lichenometric approaches have been introduced in Iceland; both are based on complex statistical treatments of lichenometric data: (i) the \( U^2 \) statistic (Orwin et al., 2008), built on the size-frequency technique, enables the user to identify multiple lichen populations growing on complex multi-event landforms; the \( U^2 \) statistic is a relative dating technique with a strong spatial component, recognizing the surfaces with similar lichen cover, i.e. of potentially similar age, therefore clustering lichen populations according to their ages; and (ii) the Generalised Extreme Value (GEV) approach which measures the diameter of the largest thallus of a specific lichen species on each boulder per geomorphic unit and compares this with a Bayesian model distribution of lichen sizes on the whole surface (Roussel et al., 2008; Chenet et al., 2010). This method also relies on a large number of measurements, and integrates confidence intervals for the computed ages.

For reviews of the different lichenometric methods applied worldwide, the reader should refer to Innes (1983a,b and 1985b), Matthews (1994), Jomelli et al. (2007), Bradwell (2009), Benedict (2009), McCarthy (2013) and Osborn et al. (2015).

4. Lichenometric dating ‘curves’ in Iceland

As in other areas, many of the authors who have published their results from studies conducted in Iceland have presented age-time scatterplots that they called lichen ‘growth curves’ (e.g. Jaksch, 1975; Maizels and Dugmore, 1985; Evans et al., 1999; Decaulne et al., 2005). Such ‘curves’ are in fact built from the measure of several individual lichens of various sizes growing on rock surfaces that have been exposed for different periods of time, at a given time. Such ‘curves’ are therefore not truly representing the growth of lichens as it doesn’t follow the development of one individual thallus through time, ignoring population dynamics on the rock surface, as pointed out by e.g. Joachimsen (1973) and Osborn et al. (2015). These scatterplots should thus be described as lichen dating ‘curves’. A range of lichen dating ‘curves’, most using the yellow-green Rhizocarpon lichen, have been published in connection with Icelandic geomorphologic studies (most of these refer to the lichen at species level viz. Rhizocarpon geographicum, whilst others identify only to section level viz. R. section Rhizocarpon). Here I propose to group these ‘curves’ in two geographical areas, one referring to North Iceland, and the other referring to South Iceland, to highlight their clear differences. Most of the ‘curves’ are based on linear regression plots, although some are polynomial (Thompson and Jones, 1986) or logarithmic (Bradwell, 2001a,b and 2004a,b), taking into account the different phases of lichen growth (establishment, juvenile, maturation, maturity; Bradwell and Armstrong, 2007). The latter two ‘curves’ are also amongst the longest constructed, going back over 130 years.

Interestingly, all published lichen dating ‘curves’ (fig. 2-3) propose different ages for the same lichen diameter, for different reasons: they were built in different environments, from the measure of different thalli, from the measure of different axes (longest or shortest), with different operators with various rigor regarding the measure precision, etc. Directly comparing landform ages resulting from these ‘curves’ is not easy, as it requires deciphering the robust ‘curves’ from the possible wrong ones, as the quality of the data is hardly evaluated from the literature. Table 2 provides a review of some of the criteria regarding the data robustness, such as lichen identification, proximity of control points and reproducibility of measurements; the proposed ranking is arbitrary, based on these sole criteria, but help extracting the most thorough work that has been carried out in Iceland on lichens. It’s helps at explaining the wide range of results. Let’s arbitrary take the example of the age range offered from all ‘curves’ for a 10 mm large thallus: in South Iceland, a 10 mm thallus results in a predicted ‘age’ range of 23 (Maizels and Dugmore, 1985) to 36 years (Bradwell, 2001a); this difference is far larger in North Iceland, with ‘ages’ ranging from 9 (Häberle, 1991) to 41 years (Caseldine, 1983); in this latter instance, the minimal age of 9 years for lichens with a 10 mm long-axis presents two problems: (i) a growth rate of the thallus of almost 1 mm.a\(^{-1}\), disagrees with the average 0.41 mm.a\(^{-1}\) growth rate presented by the author (Häberle, 1991) and (ii) neglects the lag time necessary from the building of the landform and the visible thallus on the newly exposed rockface, which is highly variable, from 7 (Decaulne et al., 2005) to over 20 years (Caseldine, 1983; Maizels and Dugmore, 1985; see Table 1); the variability in lag time necessary for lichen colonisation of newly exposed bedrock is also an indicator of differential environments that condition lichen growth in North vs. South Iceland (tab. 1). Overall, the slope of ‘curves’ built in southern Iceland is steeper during the first decades of lichen growth, suggesting a faster growth of the lichen. Regarding the wide range of lichen size at oldest ages, difference may be mostly due to the scarcity of available (i) large lichens on rock surfaces, (ii) old reference surfaces for long term control of lichen growth, and (iii) to the mortality of a lichen population that is subject to rapid turnover.
Fig. 2 – Lichen growth ‘curves’ published from measures carried out in North and South Iceland.
Numbers refer to Table 1 and Figure 1. The light grey shades correspond to 95% interval calculated by the respective authors.

Fig. 2 – ‘Courbes’ de croissance des lichens mesurés en Islande septentrionale et méridionale.
Les nombres se réfèrent au Tableau 1 et à la Figure 1. Les intervalles de confiance calculés par les auteurs apparaissent en gris.

Fig. 3 – Differences in lichenometric dating results on moraines from outlets of the Vatnajökull ice-cap, south-east Iceland, according to different authors using different measuring techniques and data processing.
1. GEV – Chenet et al. (2010); 2. SF – Bradwell (2001); 3. SF – McKinsey et al. (2004); 4. 5LL – Evans et al. (1999); 5. SF – Dąbski (2002).

Fig. 3 – Différences des résultats de datations lichénométriques des moraines de plusieurs émissaires glaciaires de la calotte du Vatnajökull, dans le sud-est islandais, selon différents auteurs utilisant différentes techniques de mesure et de traitement de la donnée.
1. GEV – Chenet et al. (2009); 2. SF – Bradwell (2001); 3. SF – McKinsey et al. (2004); 4. 5LL – Evans et al. (1999); 5. SF – Dąbski (2002).
Tab. 2 – An evaluation of the robustness of lichen identification and measures in Iceland.

* ranks on data robustness extracted from the scientific papers, as sum of the following parameters arbitrary weighted: lichen identification by a lichenologist (L) = 2; key identification (K) = 1; none = 0; point; control point within the valley = 2, within the region 1, no reference surface = 0; Repetitive measurements of the very same thalli (RT) = 2, repetitive measurements on the same surface (R) = 1, unique measurement (U) = 0; other information such as lichen used in the study, number of control points and number of lichen measured, and the production of a lichen growth curve (Yes or No) are just informative, as extracted from the references cited.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Lichen used</th>
<th>Lichen identification by a lichenologist (L) or keys (K)</th>
<th>Number of control surfaces and distance from the measures</th>
<th>Number of lichens measured (out of control points)</th>
<th>Measure accuracy (mm)</th>
<th>Unique measurement season (U) or repetitive measurement seasons (R) of the same thalli (T)</th>
<th>Dating curve</th>
<th>Score*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jaksch (1970)</td>
<td>Rhizocarpon geographicum</td>
<td>NONE</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>U</td>
<td>N</td>
<td>0</td>
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<tr>
<td>Jaksch (1975)</td>
<td>Rhizocarpon geographicum</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>U</td>
<td>N</td>
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<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
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<td>-</td>
<td>U</td>
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<td>19 (ruins, memorial stones, bridges, mudflow) - valley</td>
<td>-</td>
<td>-</td>
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<td>Y</td>
<td>2</td>
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<td>N</td>
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<td>K (Poelt, 1988)</td>
<td>9 (roche moutonnée, moraines, bedrock steps, rockfall, lava flow, outwash deposits) – SE Iceland</td>
<td>&lt; 2700</td>
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<td>3725</td>
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<td>U</td>
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<td></td>
<td>K (Poelt, 1988)</td>
<td>9 – SE Iceland</td>
<td>&gt; 5000</td>
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<td>Y</td>
</tr>
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<td>Bradwell &amp; Armstrong (2007)</td>
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<td>K (Poelt, 1988)</td>
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<td>8 (outwash deposits, lava flow, rockfall, moraines, dams) – SE Iceland</td>
<td>1400</td>
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<td>Chenet et al. (2010)</td>
<td>Rhizocarpon geographicum</td>
<td>NONE</td>
<td>8 (outwash deposits, lava flow, rockfall, moraines, dams) – SE Iceland</td>
<td>50/surface, total 1450</td>
<td>1</td>
<td>U</td>
<td>Y</td>
<td>1</td>
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<tr>
<td>Decaultine &amp; Samundsson (2010)</td>
<td>Rhizocarpon geographicum</td>
<td>NONE</td>
<td>Existing curve (Decaultine et al. 2005)</td>
<td>&gt; 300</td>
<td>0.5</td>
<td>U</td>
<td>N</td>
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impeding the initial cohort to survive while the rock-surface gets older (Loso and Doak, 2006).

5. Reliability of lichenometric application in Iceland

Lichenometry is a simple technique, easily applied in the field, and with results thought to be simple to interpret. This is the main reason it took off so quickly amongst the geomorphological community, along with the fact that R. geographicum agg. is one of the few species that is found in most sub-polar environments. However, lichenometric results are often simplistically interpreted in Iceland: there, contrasting environments are found over very short distances, and a wide range of geomorphic processes impede rock surface stability; in addition, and as seen previously, the validity of many measurements can be questioned as lichenometric ages do not always accord with tephrachronologic ages. It is worth considering whether lichenometry is best considered a relative or absolute dating tool.

5.1. Rhizocarpon

The consistent recognition of lichen species in the field is always problematic. Although this is not a limitation specific to Iceland, the thalli of Rhizocarpon geographicum (section Rhizocarpon) and Rhizocarpon inerance (section Alplica) on the same boulder are very difficult to recognize for non-lichenologists without closer examination in the laboratory, although different identification keys exist, either in open access (internet) or in the high latitude literature (Hansen, 1995; Thomson, 1984, 1997). Both are crustose thalli, yellow-green in color, and can hardly be distinguished in the field. Such identification problems were noticed first by Innes (1982, 1983a,b and 1985a,b), then by Benedict (1988) and Poel (1988) who all recommend working at Rhizocarpon Section Rhizocarpon or Subgenus Rhizocarpon level, in order to include Rhizocarpon geographicum and other closely related species. Hansen (2008) presents photographs of thalli of Rhizocarpon geographicum (section Rhizocarpon) and Rhizocarpon inerance (section Alplica) on the same boulder; they look very similar; the author states that microscopic observation is required, in addition to different chemical methods in the lab for proper identification. This lichen recognition issue may result in lichenometric ‘curves’ that encompass a number of species all with differing growth rates (Innes, 1985b), and to the illusion that lichenometry is a handy technique easily usable in the field, leading several generations of geomorphologists to apply a technique without mastering the craft, ignoring its prerequisite, i.e. recognizing the correct species to be measured and how it should be measured. Most papers dealing with lichenometry in Iceland do not describe the lichen(s) that had been used (e.g. Maizels and Dugmore, 1985; Thompson and Jones, 1986; Evans et al., 1999), and some do not even name it (e.g. Casely and Dugmore, 2004; Orwin et al., 2008), most authors basing their own research on the previous publication of lichenometric work without questioning the validity of earlier work (tab. 2). Very few authors used keys to help lichen identification (e.g. Bradwell, 2001a,b and 2004a,b; McKinsey et al., 2004, 2005; tab. 2).

5.2. Investigated and reference surfaces

Lichenometry is most suitable for decoding non-complex terrains, with well identified coherent suites of landforms. A complex suite of landforms, reworked to varying degrees over time, is more difficult to decipher. Time scale is therefore crucial. For instance in Töllaskagi, North Iceland, lichenometric studies date frontal moraines deposits (e.g. Háberle, 1991, 1994; Kugelmann, 1991) that were in part built by surging glaciers, as shown by recent investigations (Brynjólfsson and Ingólfsson, 2010 and personal communication). As a result, some of the lichen-bearing material has been much reworked, and several lichen populations may have been mixed. A single moraine may be composed of blocks of different ages, and a single block may have been reworked several times. In southern Iceland, 75 % of glaciers from the Vatnajökull ice cap also experience surging behaviours (Björnsson et al., 2003).

Interpretation of lichen growth is also compromised by human interference. Tens of scientists and students in field courses, in addition to hundreds of tourists, trample on numerous moraines each year in South Iceland, on the southern marginals of both Mýrdalsjökull and Vatnajökull.

The reliability and number of adequate reference surfaces for dating calibration is essential (Innes, 1984, 1985a). In Iceland, few accurately dated surfaces exist and most of them are quite young (>100 years); several authors have already pointed out both in the south (e.g. Kirkbride and Dugmore, 2001) and in the north (e.g. Caseldine and Baker, 1998). Gravestones have been regarded to be the most reliable dated surfaces, if it is assumed that their surfaces have never been cleaned, because they are dated. Innes (1983a,b and 1985b) pointed out that several lichen species, with not necessarily the fastest growth rate and the large variability of size/age relationship make gravestone data inconsistent and not necessarily reliable. Furthermore, gravestones are small and do not compare well in size to the geomorphic features being dated. Farm ruins are similarly difficult for calibration purposes, as the lag time for lichen colonisation also requires an additional period for the ruination of the roof in order to expose the inside walls of the building; lichen colonisation on the outside of the building is undated in most instances. Gravestones and farm ruins that have been used in Iceland are moreover located several kilometres away from the geomorphic landforms that are investigated, and most often located at lower altitude, implying a different environment that do impact the lichen growth. Flood deposits (Thompson and Jones, 1986), rockfalls (Bradwell, 2001, 2004; Decaulne and Sæmundsson, 2003; Chenet et al., 2010) and debris flows (Decaulne et al., 2005) are potentially the most reliable surfaces, if they were witnessed or recorded and their outline clearly identified in the field. However, it must be assumed that the deposits do not incorporate older lichens, and that the 'original' landforms have not been buried by a subsequent event of larger magnitude. In addition to the above mentioned limitations of transferring of a reference growth of Rhizocarpon directly to other geomorphic features is the significance of the reference 'growth curve'. In fact, the 'growth curve' that is developed from direct measurements of a lichen population on the oldest reference surface (anthropic or natural) cannot be taken for an age-size scatterplot as it figures out the growth of survivors only, i.e. a growth and life expectancy that are influenced by death and replacement rates within the lichen population (Tulajpurkar and Horvitz, 2006). As for other measurements, a lichen growth curve should be built by measuring again and again the very same thalli on the same reference surface to take into account the establishment of the lichen in a new habitat, as Bradwell et Armstrong (2007) started. And that does not agree with the acquisition of quick results during short and scarce, far and costly field seasons.

Other aspects of the Icelandic environment are restrictive. The Icelandic volcanic (basaltic) parent material can be unsuitable for lichen development, particularly if highly vesicular; therefore, sometimes only part of any geomorphic feature can be dateable using lichenometry. Caseldine (1991), Caseldine and Baker (1998) and Kugelmann (1991) mentioned the lack of large lichens in Northern Iceland, and related it to the production of fine-grained volatile and acid material from the Laki eruptions in 1783-84; this might also
be valid for Southern Iceland, where the Laki eruption delivered the thickest fallout. Indeed, the effect of volcanic fallouts is unknown on the development of lichens; so far, no study has highlighted the reactions of lichens to burial by ash after volcanic eruptions, or to acid rains due to silicic tephra dispersion in the Icelandic atmosphere.

However, recent history is rich in eruptions that severely affected the Icelandic environment (e.g. Thordarson and Larsen, 2007; Larsen, 2010). Since the 14th century, major volcanic eruptions resulting in heavy ash production and consecutive tephra deposition are numerous in Iceland. Figure 5 shows the distribution of fallouts thicker than 0.5 mm (0.1 mm at the furthest distances), superimposed to sites where lichenometry has been used. Most sites from SE Iceland have been affected by repetitive tephra fallouts, suggesting that volcanic activity might have had a significant disruptive ecological effect on lichen growth and survival. Therefore, lichenometric ages provided in areas subject to recurrent fallouts are suspect. Caseldine and Baker (1998) therefore are probably too optimistic by stating that lichenometry in Iceland provides a good opportunity to examine size-frequency distribution since the Laki eruption of 1783, as only the western- and north-westernmost parts of Iceland have not encounter tephra fallouts, as well as some parts of north and east Iceland (fig. 4).

The distance between reference surfaces is also a major issue. For instance, Bradwell (2001a,b) proposes a reference growth curve based on nine reference surfaces ranging from Southern Myrdalsjökull to Eastern Vatnajökull, i.e. along a line over 200 km long. This curve is built on accurately dated surfaces, both natural (historically dated moraines or rockfall) and man-made (bridge piers); providing a growth-curve for the whole area. But over such a long distance, lichens are exposed to different microenvironments, even though the global climate of SE Iceland can be considered as homogeneous. The Icelandic volcanic parent material varies through this transect, with intrusive, extrusive acid, basic and vesicular characteristics; all of which affect lichen growth, but first of all the lichen colonisation rate. Deflation in the sandar areas reduces lichen growth more than in the mossy SW Mýrdalsjökull areas; katabatic winds below the glaciers impede glacier facing lichen growth more than south facing ones; jökulhlaup occurrence sparsely redistributes debris; etc. Even if the selected control points are the only ones available in the area studied, it calls into question the significance of combining such measurements to propose (i) dates, which, even though combined, are (ii) relatively poor for such a large area, and (iii) do not produce a reference document as no age-lichen size scatterplots reflect true growth rates of lichens at a site as lichen vital rates (natality, mortality and growth) are not known (Osborn et al., 2015). With this much environmental variability such a curve cannot be used as a reference for the entire area.

Chenet et al. (2010) built a curve that is much more spatially constrained, with 6 reference points located within a 20 km long line, with two additional points located about 30 and 70 km away providing reference ages thought valid for the late 18th century. Even in this smaller area the variability of landscapes on which the reference curve was built does not account for variable environmental conditions.

Iceland is also a country where frost-shattering, shedding, wind erosion and snow cover are active geomorphic agents (Etienne and Dupont, 2002; Etienne, 2002). These factors all prevent the development of large lichens; Jakusch acknowledged these limitations already in 1975. For all these reasons, lichen growth will be highly dependent on the ecological characteristics of its local habitat. Even lichens measured in close proximity with the same technique show significant differences in lichen growth, as shown by the ‘curves’ developed by Caseldine (1983), Hæberle (1991) and Kugelmann (1991) in the vicinity of the Skóbadalur valley in North Iceland. Therefore, it is proposed that lichen dating ‘curves’ should ideally be limited to studies at valley-scale or even smaller, owing to numerous micro-climate differences (e.g. up and down valley winds, thermal effects, altitudinal effects, snowcover, etc). As a consequence it is proposed that transfer or adaptation of existing ‘curves’ out of its original area should be avoided. This minimizes the risk of under- or overestimating the age of analysed surfaces due to the misinterpretation of a lichen-dating curve constructed in a different environment. The case study of Principato (2008) around Drangajökull, in Northwestern Iceland clearly shows that the ages of landforms derived from Kugelmann’s Tröllaskagi curve, Northern Iceland (1991) do not match historical observations. This study also shows that environmental conditions, hence lichen growth rates, vary markedly over a distance of ~50 km.

5.3. Post-field processing

Recently, a controversy arose in the literature, focussing on lichenometric dating of the Little Ice Age maximum in Southern Iceland. This polemic was initiated by Bradwell (2009), concentrating on the use of the size-frequency approach vs. the hierarchical Bayesian model based on Generalized Extreme Value distribution. Size-frequency approach is mainly defended in Iceland by Bradwell (2001a,b; 2004a,b; 2009), while the GEV approach is defended by Cooley et al. (2006), Naveau et al. (2007) and Jomelli et al. (2007), and represented in Iceland by Chenet et al. (2010, 2011). Chenet et al. (2010) compared Bayesian results with the largest one and the five largest ones; they obtained the same trends and conclusions, except the dates were different: lichenometry is an effective relative dating tool, not an absolute one, which is also the conclusion of Rosenwinkel et al. (2015) reached. Dabski (2010) found in a criticism of the GEV approach that size-frequency results are very close from those obtained by Evans et al. (1999) who used the five largest lichens, while the GEV results are older. The difference between size-frequency and GEV approaches is mainly in the type of statistics, as both require a large amount of data, and the need for an assistant to run the statistics, i.e. the simplicity or complexity of both statistical approaches.

The five largest lichens, or the largest lichen, are approaches that are not statistically robust, as it does not follow a normal distribution, being based on the distribution of maxima; thus the calculation of the mean is biased. To my view, this debate is pointless as looking for more or less complex statistics is not improving the quality of the raw data, i.e. the lichen that has been measured; none of the methods are integrating the lichen growth variability, very few being thorough on the lichen identification and measure (tab. 2). This point is also made by Osborn et al. (2015). However the data are processed, if variations in size-age relationship over an area are not accounted for, the results will not be robust. The direct use of any existing dating ‘curve’, derived from whatever statistics, leads to very different derived surface dates, as shown by McKinsey et al. (2004, 2005), with over 100 years differences. The inconsistency of results and methods has led some authors to ignore lichenometric dating in Iceland in the study of the Little Ice Age (for instance Grove, 2003).

5.4. Lichenometry versus tephrachronology

Kirkbride and Dugmore (2001, 2008) and Kirkbride (2009) investigated in detail glacier front fluctuations in southern Iceland. On a site north of Mýrdalsjökull, joint observations of lichens and tephras enabled testing the validity of absolute lichenometric dating for the moraine formation. While the age of two contiguous moraines is well constrained between 1721 and 1755 through the identification of an aeolian layer that (i) shows the absence of tephra
Fig. 4 – Tephra fallouts over 0.5 cm thick from the main eruptions since the 17th century.

The Öræfí fallout (1362) is also shown as it concerns an area where many lichenometric studies have been carried out (compiled from Gronvold et al., 1983; Thorarinson and Self, 1993; Larsen et al., 1999; Hafldason et al., 2000; Thorarinson and Self, 2003; Thorarinson and Larsen, 2007; Thorarinson et Höskuldsson, 2008; Oddsson, 2007; Larsen, 2010).

Fig. 4 – Retombées de cendres de plus de 0.5 mm d’épaisseur dues aux principales éruptions volcaniques depuis le XVIIème siècle.

Les retombées de l’éruption de l’Öræfí (1362) sont également montrées car elles concernent une zone où les études lichenométriques ont été nombreuses (compilé de Gronvold et al., 1983 ; Thorarinson and Self, 1993 ; Larsen et al., 1999 ; Hafldason et al., 2000 ; Thorarinson and Self, 2003 ; Thorarinson et Larsen, 2007 ; Oddsson, 2007 ; Thorarinson et Höskuldsson, 2008 ; Larsen, 2010).
K 1721 (deposited after the Katla volcano eruption between May and August 1721) and (ii) shows the presence of tephra layer K 1755 (idem, eruption active between October 1755 and February 1756); the lichenometric analysis of 550 thalli on one moraine and 717 thalli on the other indicates a date of 1854 in one case and 1831 in the other, using several methods (largest lichen, five largest lichens, size-frequency). Thus, lichenometric analysis proposes an age 100 to 150 years younger that the date imposed by tephrochronology. Such a disparity, unquestionable due to tephrochronological evidence, arises even though the lichenometric techniques are apparently robust: lichens grow on stable surfaces, and show coherent populations according to the size-frequency relationship, and the regional growth curve is well constrained. The reason for the disparity is probably that lichens measured on boulders constituting the moraine are not the first generation ones. The fallacy of the assumption that the largest lichens on a surface have been there since the surface was exposed was pointed out by Joachimsen (1973) and Osborn et al. (2015), and the older the surface the most source of error exists.

In other cases, disparities in dating can reach several hundreds of years. In the case of Kvíárjökull proglacial area, in the south-eastern part of Óræfí, south of Vatnajökull ice cap, tephra Ö 1362 (corresponding to the Óraefi eruption in 1362) is observed on the proximal flank of the external moraine (Kirkbride, 2009).

However, the lichenometrical analysis proposes that the moraine dates from 1871 (Evans et al., 1999). The same tephra has been observed on a Fláajökull moraine with a lichenometric date of 1871.
Concluding remarks

Starting as an easy-to-use field technique, lichenometry evolved into a more complex method seeking higher accuracy. However, work in Iceland shows that the ecological and environmental aspects of lichens impede the quality of the results, with researchers seeking different geomorphologic processes. Most authors having worked in Iceland were aware of the rough Icelandic nature, and aimed at finding a proxy that could date landforms they observed, lacking all source of accurate dating. They all attempted to limit the potential source of lichen growth rate variations that led to dating errors, for example by forcing thresholds in size measurements (Thompson and Jones, 1986), or selecting the face of boulders they sample (Evans et al., 1999). The recent shift of the debate toward methods did not improve lichen use for dating landforms, and occulted the biology of lichens. Confronting the results from several studies conducted in common places (SE Iceland for instance) show that lichenometry is a relevant relative dating technique, but not that an efficient absolute dating tool.

Adoption of any existing curve for new dating assessments should only be performed with caution, as the lichen habitat and growth conditions can change drastically across short distances (<1 km). Furthermore, lichen growth ‘curves’ should be living, meaning that the dataset of control points should be measured again and again with time, especially when short time periods are considered in a specific area. This point is made especially important when the different developmental stages of lichen growth and the different growth
rates are properly considered (i.e., juvenile, maturation, mortality, senescence; see Bradwell and Armstrong, 2007). A further serious issue is the recognition and discrimination of certain lichen species in the field.

However, this review has shown that lichenometry is a relative dating technique that can be used, when caution is taken, as an absolute dating technique, with some uncertainty, for recent periods less than about 100 years well documented by a large number of reference surfaces. Due to the overlap with more accurate historical data during these years, lichenometry loses interest for the most recent years. However, the well-documented recent times in Iceland might help building up lichen population monitoring that would give light on population dynamics on features built by geomorphic processes, helping at better understand the influence of mortality on the building of lichen growth ‘curves’ and its potential toward dating curves.

Some suggestions for improving future lichenometric work can be made, as (i) associating one lichenologist is required to ensure the correct identification of lichen species on the studied landforms, leading to (ii) detail the identification key for Rhizocarpon in different Icelandic environments; (iii) to create a repository gathering Rhizocarpon specimens that (iv) will be used to teach non-lichenologists to recognize the lichens in the field, especially to the party members who will be measuring lichens on selected landforms in the field; (v) revisiting the same sites and repeating the measure of the exact same individual thalli to better capture their true growth and to take into account their mortality, on the reference surface and on the geomorphic surfaces to be dated; (vi) to reduce the scale of investigation at small areas where environmental conditions do not vary and were control points are available; (vii) to avoid growth ‘curve’ transfer from one area to another several kilometres away, with latitudinal and altitudinal changes; reference growth curves should be built at local scales, not regional ones.

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References


**Version française abrégée**

La lichénométrie est une méthode de datation calibrée qui utilise la taille du thalle du lichen pour déterminer l’âge des surfaces rocheuses exposées sur lesquelles il se développe (Bescul 1950, 1973). En Islande, les chercheurs se sont concentrés sur la temporalité du Petit Âge Glaciaire (PAG) et des fluctuations glaciaires du 20ème siècle (Bradwell, 2004a; Chenet et al., 2010), des dépôts des débâcles glaciaires (Maizels et Dugmore, 1985) et des incisions fluviales proglaciaires (Roussel et al., 2008), de l’ablation des sols (Buckland, 1994), des coulées de débris (Decaulne et Sæmundsson, 2003).

Plusieurs techniques ont été appliquées selon les principes exprimés par Bescul (1950) : (i) le lichen ne peut être plus vieux que la surface qui le porte, (ii) le développement radial, incrémentiel d’un thalle unique est uniforme lorsqu’il est moyenné à long terme, (iii) le thalle du lichen le plus large croît dans des conditions optimales, indiquant l’âge minimum de la surface considérée la plus proche de son âge réel. Or, le deuxième principe est hypothétique, non démontré par les propriétés écologiques des lichens et la dynamique de leur population (McCarthy, 1999). Plusieurs ‘couleurs de datation’ ont été élaborées en Islande, proposant des âges différents pour des diamètres de lichen identiques du fait de la faiblesse de l’échantillon disponible des (i) lichens larges, et (ii) des rares surfaces de référence anciennes pour un contrôle à long-terme de la croissance.
La lichénométrie est une méthode facilement applicable sur le terrain, ne requérant aucun équipement lourd ou coûteux, et offrant des résultats qui sont affichés comme simples à interpréter. Cependant, les résultats islandais sont présentés de manière simpliste : les terrains, ne requérant aucun équipement lourd ou coûteux, et offrant environnements sont contrastés, plusieurs processus géomorphologiques menacent la stabilité des surfaces rocheuses, et les âges lichénométriques sont en désaccord avec les âges téphrochronologiques. Reconnaître l’espèce correcte de lichen sur le terrain a toujours été problématique ; les 'cours de croissance' lichénométriques englobent un nombre d'espèces indifférenciées, avec des taux de croissance différents (Innes, 1985a), donnant l'illusion d'une technique accessible facilement applicable sur le terrain, menant des générations de géomorphologues à l'utiliser sans en maîtriser la reconnaissance, la mesure et ses implications. Beaucoup des articles fondant leurs résultats sur la lichénométrie en Islande ne décrivent pas le lichen, certains ne le nomment pas. Les auteurs basent leur recherche sur des publications antérieures faisant état de résultats lichénométriques ; très peu d'auteurs ont utilisé des clés d'identification lichénique (Bradwell, 2001a,b).

La fiabilité et le nombre de surfaces adéquates pour offrir une datation calibrée sont essentiels (Innes, 1985a). En Islande, peu de surfaces correctement datées existent, et elles sont jeunes (<100 ans). Sur des surfaces anciennes, la mesure des lichens et la courbe dérivée ne constitue pas une courbe de référence car seuls les individus survivants sont mesurés : la croissance et l'espérance de vie de ces individus est influencée par la mortalité et le taux de remplacement de la population (Tuljapurkar et Horvitz, 2006). La seule manière de créer une 'courbe de croissance' fiable prenant en compte l'établissement du lichen dans son nouvel habitat serait de mesurer de façon répétée les mêmes thalles sur la même surface rocheuse pendant des années, comme Bradwell et Armstrong (2007) ont commencé à le faire.

D'autres paramètres sont restrictifs pour la croissance lichénique. Jusqu'ici, aucune étude ne fait la lumière sur les réactions des lichens face à des éruptions volcaniques ayant produit une grande quantité de cendres qui se sont déposées jusque dans le nord et l'est de l'Islande. La distance entre les surfaces de contrôle est une difficulté majeure pour construire une courbe de référence. Même si les points de contrôle sélectionnés sont les seuls disponibles, cela questionne la signification de la combinaison de telles mesures pour proposer (i) des dates, qui sont (ii) relativement pauvres pour une zone d'étude à grande échelle, et (iii) ne produisent pas un document de référence car aucun nuage de point représentant la taille et l'âge ne reflète les véritables taux de croissance des lichens sur un site lorsque les indices vitaux (naissance, mortalité, croissance) demeurent inconnus (Osborn et al., 2015).

Récemment, une controverse est apparue, se focalisant sur la datation par lichénométrie des moraines construites pendant le PAG dans le sud-est de l'Islande. La polémique, initiée par Bradwell (2009), défenseur de l'approche taille-fréquence, s'est concentrée sur l'approche GEV représentée en Islande par Chenet et al. (2010). Selon moi, le débat est sans fin, puisque la recherche d'un traitement statistique simple ou complexe n'améliore rien la qualité de la donnée brute, soit le lichen qui a été mesuré, son identification, la finesse de la mesure : quel que soit le traitement utilisé, si les variations de relation âge-taille ne sont pas prises en compte, le résultat ne sera pas robuste (Osborn et al., 2015). Kirkbride et Dagmore (2001, 2008) ont observé conjointement des lichens et des téphras pour tester la validation des datations lichénométriques absolues proposées pour la construction morainique. Les analyses lichénométriques proposent un âge 100 à 150 ans inférieur aux âges téphrochronologiques, alors que les techniques lichénométriques employées sont apparentemment robustes. L'idée fausse que les plus gros lichens ont été présents depuis que la surface rocheuse a été mise à nu a été démontrée par Joachimsen (1973) et Osborn et al. (2015) : plus la surface est ancienne, plus les sources d'erreurs sont nombreuses.

D'abord une technique de terrain simple, la lichénométrie a évolué vers une méthode plus complexe recherchant une meilleure résolution. Or, les travaux en Islande montrent que l'on ne peut minimiser les composantes écologiques du lichen lui-même, spécialement lorsque l'on sollicite une datation absolue fiable. Les auteurs étaient conscients de la nature islandaise rude, et recherchaient un indicateur qui daterais les modèles observés, sans autre source de datation disponible. Ils ont tous tenté de limiter les sources de variations des taux de croissance du lichen. Pour les années les plus récentes, la lichénométrie ne présente que peu d'intérêt puisque d'autres moyens de datation sont disponibles. Mais justement, la possibilité de croiser plusieurs sources de datation différentes pourrait permettre de construire des courbes de croissance lichénométriques plus fiables, pouvant éventuellement évoluer vers des courbes de datation lichénométrique dans différents environnements islandais.

Plusieurs suggestions peuvent être formulées pour améliorer les travaux futurs utilisant la lichénométrie : (i) associer un lichénologue pour assurer la reconnaissance des espèces lichéniques sur les modèles géomorphologiques pour (ii) détailler les clés d'identification de Rhizocarpon ; (iii) créer un fonds rassemblant des spécimens pour (iv) illustrer l'enseignement des espèces à reconnaître aux non-lichénologues ; (v) revisiter les mêmes sites en répétant les mesures sur les mêmes thalles pour mieux appréhender leur croissance véritable et prendre en compte leur mortalité, sur les surfaces de référence et sur les surfaces à dater ; (vii) éviter l'emprunt ou le transfert de 'courbes de croissance' d'un site à un autre, avec des changements latitudinaux et altitudinaux ; une courbe de référence devrait être construite au plus près des zones d'intérêt, à une échelle locale, non régionale.