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A multi-proxy approach to Late Holocene fluctuations of Tungnahryggsjökull glaciers in the Tröllaskagi peninsula (northern Iceland).

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1 Abstract

2 The Tröllaskagi Peninsula in northern Iceland hosts more than a hundred small glaciers
3 that have left a rich terrestrial record of Holocene climatic fluctuations in their
4 forelands. Traditionally, it has been assumed that most of the Tröllaskagi glaciers
5 reached their Late Holocene maximum extent during the Little Ice Age (LIA). However,
6 there is evidence of slightly more advanced pre-LIA positions. LIA moraines from
7 Iceland have been primary dated mostly through lichenometric dating, but the limitations
8 of this technique do not allow dating of glacial advances prior to the 18th or 19th
9 centuries. The application of ³⁶Cl Cosmic-Ray Exposure (CRE) dating to
10 Tungnahryggsjökull moraine sequences in Vesturdalur and Austurdalur (central
11 Tröllaskagi) has revealed a number of pre-LIA glacial advances at ~400 and ~700 CE,
12 and a number of LIA advances in the 15th and 17th centuries, the earliest LIA advances
13 dated so far in Tröllaskagi. This technique hence shows that the LIA chronology in
14 Tröllaskagi agrees with that of other European areas such as the Alps or the
15 Mediterranean mountains. The combined use of lichenometric dating, aerial
16 photographs, satellite images and fieldwork shows that the regional colonization lag of
17 the commonly used lichen species *Rhizocarpon geographicum* is longer than previously
18 assumed. For exploratory purposes, an alternative lichen species (*Porpidia soredizodes*)
19 has been tested for lichenometric dating, estimating a tentative growth rate of 0.737 mm
20 yr⁻¹.

21 1. Introduction

22 The Tröllaskagi Peninsula (northern Iceland) hosts over 160 small alpine cirque glaciers
23 (Björnsson, 1978; see synthesis in Andrés et al., 2016). Only a few of these small
24 glaciers do not have supraglacial debris cover that allows them to react quickly to small
25 climatic fluctuations (Caseldine, 1985b; Häberle, 1991; Kugelmann, 1991), compared to

26 the reduced dynamism of the predominant rock glaciers and debris-covered glaciers
27 ([Martin et al., 1991](#); [Andrés et al., 2016](#); [Tanarro et al., 2019](#)). As a result of their high
28 sensitivity to climatic changes, the few debris-free glaciers in Tröllaskagi fluctuated
29 repeatedly in the past, forming a large number of moraines in front of their termini (see
30 [Caseldine, 1983, 1985b, 1987](#); [Kugelmann, 1991](#) amongst others). However, the
31 relation between glacier fluctuations and the climate is complicated due to: (i) the well-
32 known surging potential activity in Tröllaskagi ([Brynjólfsson et al., 2012](#); [Ingólfsson et](#)
33 [al., 2016](#)); (ii) the possibility of glaciers being debris-covered in the past, with the
34 subsequent change of their climate sensitivity over time; (iii) the intense and dynamic
35 slope geomorphological activity, paraglacial to a great extent ([Jónsson, 1976](#); [Whalley](#)
36 [et al., 1983](#); [Mercier et al., 2013](#); [Cossart et al., 2014](#); [Feuillet et al., 2014](#); [Decaulne and](#)
37 [Sæmundsson, 2006](#); [Sæmundsson et al., 2018](#)) that hides and erases the previous glacial
38 features.

39 In Iceland, a great part of the research on glacial fluctuations during the late Holocene,
40 LIA ([Grove, 1988](#); 1250-1850 CE, see [Solomina et al., 2016](#)) and later stages has been
41 approached through application of radiocarbon dating of organic material, analyzing
42 lake sediment varves ([Larsen et al., 2011](#); [Striberger et al., 2012](#)), dead vegetation
43 remnants ([Harning et al., 2018](#)) and threshold lake sediment records ([Harning et al.,](#)
44 [2016b](#); [Schomacker et al., 2016](#)). These provide high-resolution records of glacier
45 variability. In Tröllaskagi, very few reliable dates exist at present, obtained from
46 radiocarbon and tephrochronology ([Häberle, 1991, 1994](#); [Stötter, 1991](#); [Stötter et al.,](#)
47 [1999](#); [Wastl and Stötter, 2005](#)). They suggest that late Holocene glaciers were slightly
48 more advanced than during the LIA maximum in Tröllaskagi. However, these
49 techniques only provide minimum or maximum ages for Holocene glacier history in
50 northern Iceland ([Wastl and Stötter, 2005](#)). In addition, at Tröllaskagi most of the

51 moraines are at 600-1000 m a.s.l., where the applicability of tephrochronology is very
52 limited (Caseldine, 1990) due to the great intensity of slope geomorphological
53 processes.

54 In any case, most of the moraine datings of Tröllaskagi –especially those of the last
55 millenium– comes from lichenometry (see synthesis in Decaulne, 2016). However, the
56 ages derived from this technique tend to be younger if they are compared to those
57 estimated from tephra layers (Kirkbride and Dugmore, 2001). Generally, there is
58 disagreement about the validity of the results provided by lichenometry, due to the
59 difficulty of the lichen species identification in the field, the complexity and reliability
60 of the sampling and measurement strategies, the uncertainty estimates, the nature of the
61 ages provided as relative, as well as the relative reliability at producing lichen growth
62 curves of the different species, with an extreme dependence on local environmental
63 factors (see Osborn et al., 2015).

64 In fact, these problems had already been detected in northern Iceland, where in spite of
65 the time elapsed since the first applications of this technique (Jaksch, 1970, 1975, 1984;
66 Gordon and Sharp, 1983; Maizels and Dugmore, 1985) and contrasting with its
67 widespread use in the south and southeast of the island (Thompson and Jones, 1986;
68 Evans et al., 1999; Russell et al., 2001; Kirkbride and Dugmore, 2001; Bradwell, 2001,
69 2004a; Harris et al., 2004; Bradwell and Armstrong, 2006; Orwin et al., 2008; Chenet et
70 al., 2010 and others), there are still very few established growth rates for the lichen
71 group *Rhizocarpon geographicum* (Roca-Valiente et al., 2016) from Tröllaskagi
72 (Caseldine, 1983; Häberle, 1991; Kugelmann, 1991; Caseldine and Stötter, 1993; see
73 synthesis in Decaulne, 2016). In general, the growth curves from Tröllaskagi suffer
74 from a few control points (i.e. surfaces of known age) for calibration. This leads to
75 considerable underestimation when lichen thalli sizes are beyond the calibration growth

76 curve (Caseldine, 1990; see e.g. Caseldine, 1985b; Caseldine and Stötter, 1993;
77 Kugelmann, 1991). That is to say, the extrapolation does not account for the decreasing
78 growth rate with increasing age (i.e. non-linear growth). Kugelmann's (1991) growth
79 curve has the highest number of control points to date (19 in total). In addition, the
80 colonization lag in Tröllaskagi is poorly defined, although 10-15 years have been
81 assumed for the *Rhizocarpon geographicum* (Caseldine, 1983; Kugelmann, 1991).
82 Other issues, such as the absence of large thalli (Maizels and Dugmore, 1985), lichen
83 saturation (e.g. Wiles et al., 2010), and other environmental factors (Innes, 1985 and
84 references included; Hamilton and Whalley, 1995) contribute to appreciable age
85 underestimations when dating surfaces using this approach. Snow is also a major
86 environmental factor for lichenometry in Iceland due to its long residence time on the
87 ground (Dietz et al., 2012) and the avalanching frequency –especially in Tröllaskagi–,
88 whose effect restricts the growth rate of lichens, and even destroys them (Sancho et al.,
89 2017). These problems considerably limit the quality (reliability) of the lichenometric
90 dating range of utility for applying lichenometric dating in Iceland, where the oldest
91 ages estimated so far are between 160 and 220 years (Maizels and Dugmore, 1985;
92 Thompson and Jones, 1986; Evans et al., 1999), thus preventing the dating of glacial
93 advances prior to the 18th century.

94 In spite of the high uncertainty of the lichenometric dating, many authors working in
95 Tröllaskagi have treated their lichenometric results as absolute ages (see Caseldine,
96 1983, 1985b, 1987; Kugelmann, 1991; Häberle, 1991; Caseldine and Stötter, 1993,
97 amongst others). In fact, previously considered dates of LIA maximum glacier
98 culmination are restricted to the very late 18th and early 19th centuries (Caseldine, 1983,
99 1985b, 1987; Kugelmann, 1991; Caseldine and Stötter, 1993; Caseldine, 1991; Martin
100 et al., 1991), very close to the applicability threshold of this method. Consequently, no

101 evidence of previous advances during phases of the LIA that were more conducive to
102 glacier expansion (probably colder; see e.g. [Ogilvie, 1984, 1996](#); [Ogilvie and Jónsdóttir,](#)
103 [2000](#); [Ogilvie and Jónsson, 2001](#)) has been found ([Kirkbride and Dugmore, 2001](#)).

104 In the recent years, dating methods based on the Exposure to the Cosmic-Rays (CRE)
105 have been introduced successfully to date moraines of the last millennium, and even
106 formed during the LIA ([Schimmelpfennig et al., 2012, 2014](#); [Le Roy et al., 2017](#);
107 [Young et al., 2015](#); [Jomelli et al., 2016](#); [Li et al., 2016](#); [Dong et al., 2017](#); [Palacios et](#)
108 [al., 2018](#)). The cosmogenic nuclides ^{36}Cl and ^3He have been applied previously in
109 northern Iceland to date the Pleistocene deglaciation. [Principato et al. \(2006\)](#) studied the
110 deglaciation of Vestfirðir combining ^{36}Cl CRE dating of moraine boulders and bedrock
111 surfaces with marine records and tephra marker beds. [Andrés et al. \(2018\)](#) reconstructed
112 the deglaciation at the Late Pleistocene to Holocene transition at Skagafjörður through
113 ^{36}Cl CRE dating applied to polished surfaces along a transect from the highlands to the
114 mouth of the fjord. [Brynjólfsson et al. \(2015b\)](#) applied the same isotope to samples
115 coming from the highlands and the fjords to reconstruct the glacial history of the
116 Drangajökull region. The other cosmogenic isotope used is ^3He , applied to helium-
117 retentive olivine phenocrysts by [Licciardi et al. \(2007\)](#) to determine eruption ages of
118 Icelandic table mountains and to reconstruct the volcanic history and the thickness
119 evolution of the Icelandic Ice Sheet during the last glacial cycle. However, CRE dating
120 has not yet been applied to the late Holocene glacial landforms both in Iceland as a
121 whole and the Tröllaskagi Peninsula. CRE dating is an alternative to the use of high-
122 resolution continuous lacustrine records in northern Iceland, given the rarity of lakes in
123 this peninsula, which limits the application of radiocarbon to date the deglaciation
124 processes ([Striberger et al., 2012](#); [Harning et al., 2016b](#)).

125 Nevertheless, CRE dating methods approach the nuclides' detection limit when applied
126 to very recent moraines (Marrero et al., 2016; Jomelli et al., 2016). This issue precludes
127 the application of CRE dating to the abundant post-LIA moraines existing in some of
128 the Tröllaskagi valleys whose headwalls are occupied by climate-sensitive debris-free
129 glaciers (Caseldine and Cullingford, 1981; Caseldine, 1983,1985b; Kugelmann, 1991;
130 Fernández-Fernández et al., 2017). Dating these post-LIA moraines allows to
131 reconstruct recent climate evolution, and even to match and assess the climate
132 reconstructions with the instrumental climate records (see Dahl and Nesje, 1992;
133 Caseldine and Stötter, 1993; Fernández-Fernández et al., 2017). Furthermore, improving
134 the knowledge of the recent evolution of alpine mountain glaciers, such as those of
135 Tröllaskagi, is fundamental in the assessment of present global warming (Marzeion et
136 al., 2014)

137 The use of aerial photographs from different dates is a reliable approach to the glacier
138 evolution during the last decades (Fernández-Fernández et al., 2017; Tanarro et al.,
139 2019). The main advantage of this technique is the possibility of studying the evolution
140 of glacier snouts in recent dates with high accuracy. In fact, there is no dependence on
141 the glacial features (i.e. moraines), which circumvents moraine deterioration issues
142 derived by the geomorphological activity of the slopes. However, the main shortcoming
143 of the aerial photo imagery is the availability only on few dates, at least in Tröllaskagi.
144 This circumstance makes it impossible to obtain the glacier fluctuations with a high
145 time resolution (i.e. only the periods between the available aerial photos; Fernández-
146 Fernández et al., 2017; Tanarro et al., 2019), and hence to match them to short-term
147 (decadal scale) climate fluctuations that are known to exert a major control especially
148 on small mountain glaciers with short time responses (see Caseldine, 1985b;
149 Sigurðsson, 1998; Sigurðsson et al., 2007; Fernández-Fernández et al., 2017). The only

150 way to fill the gap between two dates with available aerial photos is through applying
151 lichenometric dating (Sancho et al., 2011), as there is no tree species suitable to apply
152 dendrochronology. In addition, the information provided by the aerial photo imagery
153 (i.e. glacier snout position) constrains the period when the lichens appear and begin to
154 grow, which circumvents many of the criticisms made on lichenometry (see Osborn et
155 al., 2015).

156 Moreover, a detailed geomorphological mapping allows for identification of stable
157 moraines, not remobilized or destroyed by glacier advances or slope processes
158 (avalanches, slope deformations, debris-flows, etc.) and also to reconstruct the glacier
159 snout geometry throughout different phases (see Caseldine, 1981; Bradwel, 2004b;
160 Principato et al., 2006 amongst others). The analysis of the moraine morphology and the
161 glacial features on the forelands is a key tool to confirm whether the glaciers were
162 debris-free or debris-covered in the past (Kirkbride, 2011; Janke et al., 2015; Knight, et
163 al., 2018, amongst others) as this issue determines their climate sensitivity (see
164 Fernández-Fernández et al., 2017; Tanarro et al., 2019).

165 The western and eastern Tungnahryggsjökull glaciers, in the Vesturdalur and
166 Austurdalur Valleys (central Tröllaskagi), respectively (Fig. 1), are two of the few
167 debris-free glaciers –or almost debris-free in the case of the western glacier– of the
168 peninsula that are both small and highly sensitive to climatic fluctuations (Fernández-
169 Fernández et al., 2017). This makes them ideal for studying glacial and climatic
170 evolution during last last millennia.

171 The aim of our work was to apply the best methodology possible to analyze the glacial
172 evolution of western and eastern Tungnahryggsjökull glaciers during the last millennia
173 to the present. Applying for the first time a number of dating techniques to study the
174 Late Holocene evolution of the two glaciers, the objectives of this paper are:

175 (i) To carry out a detailed geomorphological survey of the glacier forelands in order to
176 map accurately well-preserved glacial features. This mapping is used both to devise the
177 sampling strategy for dating, and also to reconstruct the palaeoglaciers in 3D in order to
178 obtain glaciologic climate indicators such as the Equilibrium-Line Altitudes (ELAs).
179 These can be used as a proxy to infer palaeoclimatic information (see [Dahl and Nesje,](#)
180 [1992](#); [Caseldine and Stötter, 1993](#); [Brugger, 2006](#); [Hughes et al., 2010](#); [Fernández-](#)
181 [Fernández et al., 2017](#) amongst others).

182 (ii) To use aerial photographs / satellite imagery post-dating 1946 to map the glacier
183 extent in each available date in order to improve the information of ELA evolution in
184 the recent decades. Aerial photographs will be used to constrain the possible periods of
185 lichen colonization and growth over stable boulders, and will be useful to identify
186 phases of advance, stagnation or retreat of the glacier snouts. By this way we will
187 complete the glacier evolution from pre-instrumental glacial stages (identified from
188 geomorphological evidence, i.e. moraines) to their current situation.

189 (iii) To apply CRE dating when possible depending on the preservation degree of the
190 glacial features, and when moraines were too old to be dated by lichenometry.

191 (iv) To apply lichenometric relative dating to recent moraines or those where CRE
192 dating might not be suitable (i.e. limit of applicability) and provided that: 1) the
193 geomorphological criteria evidence a good preservation of glacial features; and 2) aerial
194 photographs constrain the earliest and oldest possible lichen ages. This approach will
195 also allow to check the growth rates and colonization lags of the lichen species usually
196 used in Iceland for lichenometric dating purposes.

197 The experimentation and validation of this methodological purpose will help to improve
198 the knowledge of the recent climate evolution of northern Iceland. This is of maximum

199 interest if we consider its location within the current atmospheric and oceanic setting,
200 strongly linked to the evolution of the Meridional Overturning Circulation ([Andrews](#)
201 [and Giraudeau, 2003](#); [Xiao et al., 2017](#)), a key factor in the studies for the assessment of
202 the global climate change effects ([Barker et al., 2010](#); [Chen et al., 2015](#) amongst others).
203 Moreover, if this proposal is valid, it could be applied to the research on the recent
204 evolution of other mountain glaciers similar to those of Tröllaskagi. This aspect is a
205 main research objective at present, as these glaciers represent the greatest contribution
206 to the current sea-level rise ([Jacob et al., 2012](#); [Gardner et al., 2013](#) amongst others).

207 **2. Regional setting**

208 The Tröllaskagi Peninsula extends into the Atlantic Ocean at 66°12' N from the central
209 highland plateau (65°23' N) of Iceland ([Fig. 1](#)). The fjords of Skagafjörður (19°30' W)
210 and Eyjafjörður (18°10' W) separate it from the Skagi and Flateyjarskagi peninsulas,
211 respectively. Tröllaskagi is an accumulation of successive Miocene basalt flows,
212 interspersed with reddish sedimentary strata ([Sæmundsson et al., 1980](#); [Jóhannesson](#)
213 [and Sæmundsson, 1989](#)). The plateau culminates at altitudes of 1000-1500 m a.s.l. (with
214 the highest peak Kerling at 1536 m a.s.l.) and is dissected by deep valleys with steep
215 slopes whose headwaters are currently glacial cirques. These cirques host more than 160
216 small glaciers, mostly north-facing, resulting from the leeward accumulation of snow
217 from the plateau ([Caseldine and Stötter, 1993](#)) and reduced exposure to solar radiation.
218 In fact, deposits caused by rock-slope failure are common in Tröllaskagi valley slopes
219 and have been considered a result of the final deglaciation during the early Holocene
220 ([Jónsson, 1976](#); [Feuillet et al., 2014](#); [Cossart et al., 2014](#); [Coquin et al., 2015](#)). Most of
221 the glaciers are rock or debris-covered glaciers, due to the intense paraglacial activity
222 affecting the walls that minimizes cosmogenic nuclide concentrations from earlier
223 exposure periods on the cirque headwalls ([Andrés et al, 2018](#)).

224 The climate in Tröllaskagi is characterized by a mean annual air temperature (MAAT;
225 1901-1990 series) of 2 to 4 °C at sea level, dropping to between -2 and -4 °C at the
226 summits (Etzelmüller et al., 2007). At the town of Akureyri, located in the east of the
227 peninsula at the mouth of Eyjafjarðardalur (Fig. 1), the MAAT is 3.4 °C and the average
228 temperature in the three summer months is about 9 to 10 °C (Einarsson, 1991). Annual
229 precipitation (1971-2000) ranges from 400 mm at lower altitudes to 2500 mm at the
230 summits (Crochet et al., 2007).

231 The frontier location of Icelandic glaciers in relation to atmosphere and ocean systems
232 (warm/moist Subtropical and cold/dry Arctic air masses; and the warm Irminger and
233 cold East Greenland sea currents) makes them exceptionally sensitive to climate
234 oscillations (Bergþórsson, 1969; Flowers et al., 2008; Geirsdóttir et al., 2009), and these
235 debris-free glaciers are thus reliable indicators of climatic evolution and the impact of
236 climate change on the cryosphere (see Jóhannesson and Sigurðsson, 1998; Bradwell,
237 2004b; Sigurðsson, 2005; Geirsdóttir et al., 2009; Fernández-Fernández et al., 2017).

238 The glaciers studied here are the western (6.5 km²) and eastern (3.9 km²)
239 Tungnahryggsjökull, located in the Vesturdalur and Austurdalur valleys respectively,
240 separated from each other by the crest of Tungnaryggur, and tributaries of the
241 Kolbeinsdalur Valley (Fig. 1).

242 **3. Methodology**

243 *3.1 Geomorphological mapping and glacier geometry mapping*

244 Four summer field campaigns (2012, 2013, 2014 and 2015) were conducted in
245 Vesturdalur and Austurdalur, with the objective of identifying moraines that clearly
246 provided evidence of various glacial culminations of the western and eastern
247 Tungnahryggsjökull glaciers. We identified the palaeo-positions of the glacier snouts,

248 the glacier geometry and extent through photo interpretation of stereoscopic pairs and
249 previous fieldwork. Mapping of glacial and non-glacial landforms was conducted on
250 two enlarged 50-cm-resolution aerial orthophotos ([National Land Survey of Iceland,](#)
251 [2015](#)) plotted at scale $\approx 1:7000$. These maps were imported into an ArcGIS 1.4.1
252 database after geo-referencing. Finally, all the glacial linear landforms were digitized,
253 and where the moraines were prominent, continuous, or well-preserved, they were
254 assumed to represent major culminations, and hence, glacial stages. In addition to the
255 geomorphological evidence, glacier variations in recent years were mapped, based on
256 the photo interpretation of four historical aerial photographs from 1946, 1985, 1994 and
257 2000 ([National Land Survey of Iceland, 2015](#)), and also one SPOT satellite image
258 (2005), previously geo-referenced in ArcGIS. For more details of the aerial photograph
259 processing, see [Fernández-Fernández and Andrés \(2018\)](#). As the glacier headwalls are
260 ice diffluences in both cases, it was assumed that: (i) the ice divides are the upper
261 boundaries of the glaciers for the different stages, and (ii) the ice divide is invariant for
262 the different stages/dates, following [Koblet et al. \(2010\)](#) as changes in the extent of the
263 accumulation zone are smaller than the outlining differences derived from the operator
264 mapping. Likewise, in the case of the upper glacier edge constrained by the cirque wall,
265 the glacier geometry was also assumed to be invariant from stage to stage unless the
266 aerial photographs showed otherwise.

267 *3.2 Glacier reconstruction and equilibrium-line altitude (ELA) calculation*

268 [Benn and Hulton's \(2010\)](#) glacier reconstruction approach using a physical-based model
269 describing ice rheology and glacier flow ([Van der Veen, 1999](#)) was preferred to
270 arbitrary hand-drawn contouring (e.g. [Sissons, 1974](#)) in order to achieve more robust
271 reconstructions ([Fernández-Fernández and Andrés, 2018](#)). This model operates on
272 deglaciated areas with non-extant glaciers. As this is not the case in our study area, we

273 approached the glacier bedrock by tentatively estimating the ice thickness' spatial
274 distribution on the two glaciers studied. The "VOLTA" ("Volume and Topography
275 Automation") ArcGIS toolbox (James and Carrivick, 2016) was applied with the default
276 parameters. It only requires the glacier outline and its digital elevation model (DEM). In
277 the first step, the tool "volta_1_2_centrelines" creates the glacier centrelines, and then
278 the tool "volta_1_2_thickness" estimates ice thickness at points along them, assuming
279 perfect-plasticity rheology, and interpolates the values using a glaciologically correct
280 routine. The final result is an ice-free DEM in which we reconstructed the glacier. The
281 former glacier surface topographies at the different stages/dates were reconstructed
282 applying the semi-automatic "GLaRe" ArcGIS toolbox designed by Pellitero et al.
283 (2016), which implements the Benn and Hulton (2010) numerical model and estimates
284 ice-thickness along glacier flowlines. To simplify the glacier surface modelling, shear-
285 stress was assumed to be constant along the glacier flowline and over time. Using the
286 value 110 kPa for the shear-stress resembles best the current longitudinal profile of the
287 glaciers in the Benn and Hulton (2010) spreadsheet. This value can be considered
288 appropriate as it falls within the normal shear-stress range of 50-150 kPa observed in
289 current glaciers and is very close to the standard value of 100 kPa (Paterson, 1994). The
290 glacier contours were manually adjusted to the ice surface elevation values of the ice-
291 thickness points estimated by "GLaRe" instead of using an interpolation routine, to
292 obtain a more realistic surface (concave and convex contours above and below the
293 ELA).

294 Finally, we calculated the ELAs automatically by using the "ELA calculation" ArcGIS
295 toolbox (Pellitero et al., 2015). The methods comprised: (i) AABR (Area Altitude
296 Balance Ratio; Osmaston, 2005) with the ratio 1.5 ± 0.4 proposed for Norwegian glaciers
297 by Rea (2009) and successfully tested on Tröllaskagi debris-free glaciers in Fernández-

298 [Fernández et al. \(2017\)](#); and (ii) the AAR (Accumulation Area Ratio) with the ratio 0.67
299 previously used by [Stötter \(1990\)](#) and [Caseldine and Stötter \(1993\)](#) for Tröllaskagi
300 glaciers. Alternative approaches for ELA calculation in northern Iceland have been
301 carried out by considering morphometric parameters of glacial cirques (altitude ratio,
302 cirque floor, minimum point; [Ipsen et al., 2018](#)). However, we preferred the methods
303 considering the glacier hypsometry as they reflect more evident changes from stage to
304 stage ([Fernández-Fernández et al., 2017](#); [Fernández-Fernández and Andrés, 2018](#)), if
305 compared to morphometric parameters of the cirques. In this sense, the cirque floor
306 elevation is derived from the last erosion period, and it is impossible to know the values
307 corresponding to previous glacial stages.

308 *3.3 Lichenometric dating procedures*

309 Lichenometry was used as a relative dating tool, assuming that the lichens increase in
310 diameter with respect to age. The results aim to complete the age control (of recent
311 landforms non suitable for CRE dating) on the periods between aerial photos of known
312 date as it has been applied successfully to control lichen ([Sancho et al., 2011](#)) and
313 bryophyte ([Arróniz-Crespo et al., 2014](#)) growth during primary succession in recently
314 deglaciaded surfaces. First, we surveyed the moraines thoroughly, starting from the
315 current glacier snouts downwards, looking for large stable boulders (i.e. well embedded
316 in the moraine, not likely of having been overturned or remobilized by slope processes
317 which could have affected lichen growth, e.g. snow avalanches, debris-flows, rockfall,
318 landslides or debris-flows) with surfaces valid for dating (not weathered or resulting
319 from block break). Lichenometry was applied to date moraine ridge boulders with the
320 following criteria and assumptions: (i) boulders must clearly belong to the moraine
321 ridge; (ii) lichen species should be abundant enough to allow measurements of a number
322 of thalli at each location and hence enable surfaces to be dated under favourable

323 environmental conditions such as basaltic rocks in subpolar mountains; (iii) only the
324 largest lichen (circular or ellipsoidal thalli) of species *Rhizocarpon geographicum*,
325 located on smooth horizontal boulder surfaces, was measured; (iv) the lichenometric
326 procedures should not be applied when the lichen thalli coalesce on the boulder surface
327 and individual thalli cannot be identified. We preferred the geomorphological criterion
328 (stability vs. slope processes) to the establishment of lichenometry plots of a fixed area
329 (e.g. [Bickerton and Matthews, 1992](#)) to ensure that lichens were measured on reliable
330 boulders. This measurement strategy tries to circumvent or at least to minimize the
331 specific problems of Tröllaskagi when dating glacial features so that: (i) snow
332 accumulation should be lower in the moraine crest; (ii) lichen ages will be estimated
333 only for the boulders located on the crests used to map and reconstruct the glaciers; and
334 (iii) and lichens subjected to thalli saturation (coalescence) or high competition are not
335 measured.

336 First, *Rhizocarpon geographicum* lichens were measured with a Bernier calibrator.
337 Then, digital photographs for high-precision measurements were taken of the most
338 representative of the largest thallus located in each selected boulder ([Suppl. figure SF1](#)),
339 using an Icelandic króna coin (21 mm diameter) parallel to the surface of the lichen as a
340 graphic scale. We preferred the single largest lichen approach as previously has been
341 done in Tröllaskagi for lichenometric dating of moraines ([Caseldine, 1983, 1985b,](#)
342 [1987; Kugelmann, 1991](#)). The photos were scaled in ArcGIS to real size and lichen
343 thalli were outlined manually through visual inspection of the photos and measured
344 automatically with high accuracy according to the diameter of the smallest circle which
345 can circumscribe the lichen outline ([Suppl. figure SF1](#)). We preferred the simple
346 geometrical shape of the circle and its diameter to identify the largest axis to circumvent

347 the problem of complex-shaped lichens. Similar procedures for lichen thalli
348 measurement from photographs are outlined in [Hooker and Brown \(1977\)](#).

349 Then, we initially applied a 0.44 mm yr^{-1} constant growth rate and a 10-year
350 colonization lag ([Kugelmann, 1991](#)) to the measurement of the largest *Rhizocarpon*
351 *geographicum* lichen (longest axis). This growth rate is derived from the lichen growth
352 curve with the highest number of control points so far in Tröllaskagi ([Kugelmann,](#)
353 [1991](#)), and it is very similar to that reported from the near Hörgárdalur valley ([Häberle,](#)
354 [1991](#)). However, the authors are aware that using a constant growth rate implies not
355 taking account the growth rate decline with increasing age. Other longer colonization
356 lags of 15, 20, 25 and 30 years were added to the age estimate from the growth rate in
357 order to test the colonization lag originally assumed by [Kugelmann \(1991\)](#), on the
358 suspicion of longer colonization lags reported elsewhere ([Caseldine, 1983](#); [Evans et al.,](#)
359 [1999, Table 1](#)). The resulting ages were compared to the dates of historical aerial
360 photographs where the glacier snout positions constrain the maximum and minimum
361 ages of the lichen stations.

362 In the case of *Porpidia cf. soredizodes*, since no growth rate value has been described so
363 far, a value will be tentatively estimated in this study. For this reason, we took
364 measurements of the two species in the same sampling locations wherever possible. It
365 should be noted that visual distinction between *Porpidia cf. soredizodes* and *Porpidia*
366 *tuberculosa* is not always conclusive based on morphological characteristics, but we
367 feel confident using the measurements of the *Porpidia cf. soredizodes* we identified in
368 the field.

369 3.4 ³⁶Cl Cosmic-Ray Exposure (CRE) dating

370 Where the thalli either coalesced and prevented identification of the largest thallus or
371 dating results indicated that a moraine was too old to be dated by this method, rock
372 samples were collected for CRE dating. The criteria for boulder and surface selection
373 where the same as for lichenometric purposes: stable boulders with no signs of being
374 affected by slope processes (landslides, debris-flows) or postglacial overturning, well
375 embedded in the moraine, and with no sign of surface weathering or previous boulder
376 break. The cosmogenic nuclide ^{36}Cl was chosen because of the basalt lithology
377 ubiquitous in Iceland, which lacks quartz, which is needed for standard ^{10}Be CRE
378 methods. Using a hammer and chisel, samples were collected from flat-topped surfaces
379 of moraine boulders. In order to obtain a maximum time constraint for the deglaciation
380 of both surveyed valleys, two samples were taken from Elliði (Fig. 1), a glacially
381 polished ridge downstream from the Tungnahryggsjökull forelands separating
382 Kolbeinsdalur to the north and Viðinesdalur to the south. The laboratory procedures
383 applied for ^{36}Cl extraction from silicate whole rock samples were those described in
384 Schimmelpfennig et al. (2011). Note that the samples had not enough minerals to
385 perform the ^{36}Cl extraction on mineral separates, which is generally the preferred
386 approach to minimize the uncertainties in age exposure estimates, as in mineral
387 separates ^{36}Cl is often produced by less and better known production pathways than in
388 whole rock samples (Schimmelpfennig et al., 2009). The samples were crushed and
389 sieved to 0.25-1 mm in the Physical Geography Laboratory in the Complutense
390 University, Madrid. Chemical processing leading to ^{36}Cl extraction from the whole rock
391 was carried out at the Laboratoire National des Nucléides Cosmogéniques (LN₂C) at the
392 Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement
393 (CEREGE), Aix-en-Provence (France). Initial weights of about 120 g per sample were
394 used. A chemically untreated split of each sample was set aside for analyses of the

395 chemical composition of the bulk rocks at CRPG-SARM. First, the samples were rinsed
396 to remove dust and fines. Then, 25-30% of the mass was dissolved to remove
397 atmospheric ^{36}Cl and potentially Cl-rich groundmass by leaching with a mixture of
398 ultra-pure dilute nitric (10% HNO_3) and concentrated hydrofluoric (HF) acids. In the
399 next step, 2 g aliquots were taken to determine the major element concentrations; these
400 were analysed by ICP-OES at CRPG-SARM. Then, before total dissolution, $\sim 260 \mu\text{L}$ of
401 a ^{35}Cl carrier solution (spike) manufactured in-house (concentration: 6.92 mg g^{-1} ;
402 $^{35}\text{Cl}/^{37}\text{Cl}$ ratio: 917) were added to the sample for isotope dilution (Ivy-Ochs et al.,
403 2004). Total dissolution was achieved with excess quantities of the above mentioned
404 acid mixture. Following total dissolution, the samples were centrifuged to remove the
405 undissolved residues and gel (fluoride complexes such as CaF_2). Next, chlorine was
406 precipitated to silver chloride (AgCl) by adding 2 ml of silver nitrate (AgNO_3) solution
407 at 10%. After storing the samples for two days in a dark place to allow the AgCl to
408 settle on the bottom, the supernatant acid solution was extracted by a peristaltic pump.
409 To reduce the isobaric interferences of ^{36}S during the ^{36}Cl AMS measurements, the first
410 precipitate was re-dissolved in 2 ml of ammonia ($\text{NH}_3+\text{H}_2\text{O}$ 1:1 vol \rightarrow NH_4OH), and 1
411 ml of a saturated solution of barium nitrate ($\text{Ba}(\text{NO}_3)_2$) was added to the samples to
412 precipitate barium sulphate (BaSO_4). It was removed by centrifuging and filtering the
413 supernatant with a syringe through acrodisc filters. AgCl was precipitated again with 3-
414 4 ml of diluted HNO_3 (1:1 vol). The precipitate was collected by centrifuging, rinsed,
415 and dried in an oven at $80 \text{ }^\circ\text{C}$ for 2 days.

416 The final AgCl targets were analysed by accelerator mass spectrometry (AMS) to
417 measure the $^{35}\text{Cl}/^{37}\text{Cl}$ and $^{36}\text{Cl}/^{35}\text{Cl}$ ratios, from which the Cl and ^{36}Cl concentration
418 were inferred. The measurements were carried out at the Accélérateur pour les Sciences
419 de la Terre, Environnement et Risques (ASTER) at CEREGE in March 2017 using

420 inhouse standard SM-CL-12 with an assigned value of $1.428 (\pm 0.021) \times 10^{-12}$ for the
421 $^{36}\text{Cl}/^{35}\text{Cl}$ ratio (Merchel et al., 2011) and assuming a natural ratio of 3.127 for the stable
422 ratio $^{35}\text{Cl}/^{37}\text{Cl}$.

423 When calculating exposure ages, the ExcelTM spreadsheet for in situ ^{36}Cl exposure age
424 calculations proposed by Schimmelpfennig et al. (2009) was preferred to other online
425 calculators (e.g. CRONUS Earth; Marrero et al., 2016) as it allows input of different
426 ^{36}Cl production rates from spallation, referenced to sea level and high latitude (SLHL).
427 Thus, three SLHL ^{36}Cl production rates from Ca spallation, i.e. the most dominant ^{36}Cl
428 production reaction in our samples, were applied to allow comparisons both with other
429 Icelandic areas (57.3 ± 5.2 atoms $^{36}\text{Cl} (\text{g Ca})^{-1} \text{yr}^{-1}$; Licciardi et al., 2008) and other areas
430 of the world (48.8 ± 3.4 atoms $^{36}\text{Cl} (\text{g Ca})^{-1} \text{yr}^{-1}$, Stone et al., 1996; 42.2 ± 4.8 atoms ^{36}Cl
431 $(\text{g Ca})^{-1} \text{yr}^{-1}$, Schimmelpfennig et al., 2011). For ^{36}Cl production reactions other than Ca
432 spallation, the following SLHL ^{36}Cl production parameters were applied: 148.1 ± 7.8
433 atoms $^{36}\text{Cl} (\text{g K})^{-1} \text{yr}^{-1}$ for K spallation (Schimmelpfennig et al., 2014b), 13 ± 3 atoms
434 $^{36}\text{Cl} (\text{g Ti})^{-1} \text{yr}^{-1}$ for Ti spallation (Fink et al., 2000), 1.9 ± 0.2 atoms $^{36}\text{Cl} (\text{g Fe})^{-1} \text{yr}^{-1}$ for
435 Fe spallation (Stone et al., 2005) and 696 ± 185 neutrons $(\text{g air})^{-1} \text{yr}^{-1}$ for the production
436 rate of epithermal neutrons for fast neutrons in the atmosphere at the land/atmosphere
437 interface (Marrero et al., 2016). Elevation-latitude scaling factors were based on the
438 time invariant “St” scheme (Stone et al., 2000). The high-energy neutron attenuation
439 length value applied was 160 g cm^{-2} .

440 All production rates from spallation of Ca mentioned above are based on calibration
441 samples with a predominant Ca composition. Iceland is permanently affected by a low-
442 pressure cell, the Icelandic Low (Einarsson, 1984). As the atmospheric pressure
443 modifies the cosmic-ray particle flux, and thus has an impact on the local cosmogenic
444 nuclide production rate, the atmospheric pressure anomaly has to be taken into account

445 when scaling the SLHL production rates to the study site. Only [Licciardi et al.'s \(2008\)](#)
446 production rate already accounts for this anomaly, as the calibration sites of study are
447 located in south western Iceland (see also [Licciardi et al., 2006](#)). On the other hand,
448 [Stone et al.'s \(1996\)](#) and [Schimmelfennig et al.'s \(2011\)](#) production rates were
449 calibrated in Tabernacle Hill (Utah, western U.S.A.) and Etna volcano (Italy),
450 respectively, hence they need to be corrected for the atmospheric pressure anomaly
451 when applied in Iceland. [Dunai \(2010\)](#) advises including any long-term atmospheric
452 pressure anomaly at least for Holocene exposure periods. Therefore, the local
453 atmospheric pressure at the sample locations was applied in the scaling factor
454 calculations when using the [Stone et al. \(1996\)](#) and [Schimmelfennig et al. \(2011\)](#)
455 production rates. Instead of the standard value of 1013.25 hPa at sea level, a sea level
456 value of 1006.9 hPa (Akureyri meteorological station; [Icelandic Meteorological Office,](#)
457 [2018](#)) was used. The atmospheric pressure correction assumed a linear variation of
458 temperature with altitude. The results presented and discussed below are based on the
459 ^{36}Cl production rate for Ca spallation of [Licciardi et al. \(2008\)](#) as it is calibrated for
460 Iceland and considers the atmospheric pressure anomaly. The exposure ages presented
461 throughout the text and figures include analytical and production rate errors unless
462 stated otherwise. Our <2000 yr CRE ages have also been rounded to the nearest decade,
463 and then converted to CE dates through their subtraction from the year 2015 (i.e.
464 fieldwork and sampling campaign). In order to achieve robust comparisons of our
465 results with those obtained by radiocarbon or tephrochronology, we have calibrated the
466 ^{14}C ages previously published in the literature through the OxCal 4.3 online calculator
467 (<https://c14.arch.ox.ac.uk/oxcal/OxCal.html>) implementing the IntCal13 calibration
468 curve ([Reimer et al., 2013](#)).

469 **4. Results**

470 *4.1 Geomorphological mapping, aerial photos and identified glacial stages*

471 Based on photo-interpretation of aerial photographs and fieldwork, two
472 geomorphological maps were generated at ~1:7000 scale, in which well preserved
473 moraine segments, current glacier margins and stream network were also mapped (Figs.
474 2 and 3). In Vesturdalur, over 1000 moraine ridge fragments (including terminal and
475 lateral moraine segments) were identified and mapped, with increased presence from
476 1.7 km upwards to the current glacier terminus. In the analysis, we retained only ridge
477 fragments if they are at least 50 m long, protruding 2 m above the valley bottom and the
478 alignment of glacial boulders embedded in the moraine crest is preserved, as indicators
479 of major glacial culminations and well preservation state. Otherwise we considered
480 either they represented insignificant glacial stages or were most probably affected by
481 post-glacial slope reworking.

482 Following these criteria, we retained 12 glacial stages based on the geomorphological
483 mapping of the Vesturdalur foreland (Fig. 2). We were able to verify in the field that the
484 selected sections had not been affected by postglacial slope processes as none of these
485 moraines was cut by debris-flows or deformed/covered by landslides. The palaeo-
486 position of the glacier terminus was clearly defined by pairs of latero-frontal moraines
487 in stages 1, 4 and 6. In stages 2, 3, 5, 9, 10, 11 and 12, it was poorly defined by short
488 latero-frontal moraines on one side of the valley, very close to the river, with their
489 prolongation and intersection with the river assumed to be the former apex, and so a
490 tentative terminus geometry was drawn. The lateral geometry of the tongue was
491 accurately reconstructed in stages 6, 8 and 9 based on long and aligned, ridge fragments,
492 and in the other stages an approximate geometry was drawn from the terminus to the
493 headwall. The greatest retreat between consecutive stages (1 km) occurred in the

494 transition from the stage 1 to the stage 2. No intermediate frontal moraines were
495 observed in the transect between the stages 1 and 2.

496 In Austurdalur, over 1600 moraine ridge fragments were identified and mapped.
497 Following the same criteria as in Vesturdalur, 13 stages were identified based on the
498 geomorphological evidence (Fig. 3). The furthest moraines marking the maximum
499 extent of the eastern Tungnahryggsjökull appear at 1.3 km from the current terminus. In
500 contrast to the other valley, moraines populate the glacier foreland more densely and
501 regularly on both sides of the valley. Most of them are <50 m long with a few exceeding
502 100-200 m. The frontal moraine ridge fragments in Austurdalur clearly represent the
503 geometry of the terminus in all the stages, as they are well-preserved and are only
504 bisected by the glacier meltwater, with the counterparts easily identifiable. The most
505 prominent (over 2 m protruding over the bottom of the valley) and well preserved
506 moraines are those marking the terminus position at stages 1 to 8, with lengths ranging
507 from 170 to 380 m.

508 Both glaciers were also outlined on aerial photos of 1946, 1985, 1994 (only for western
509 Tungnahryggsjökull), and 2000, and on a SPOT satellite image (2005), and hence new
510 recent stages from the past century were studied for the Tungnahryggsjökull, five for the
511 western glacier (stages 13, 14, 15, 16 and 17) and four for the eastern glacier (stages 11,
512 15, 16 and 17) (Suppl. figure SF2; Suppl. table ST1). The stages identified on the basis
513 of the geomorphological mapping and those obtained from glacier outlining over
514 historical aerial photos sum up to a total of 17 stages for each glacier.

515 *4.2. Glacier length, extent and volume*

516 The reconstructed glacier surfaces corresponding to the different glacial stages is shown
517 in Suppl. figure SF3. The length of the glaciers during their reconstructed maximum ice

518 extent was unequal, with the western Tungnahryggsjökull being 6.5 km long, and the
519 eastern glacier being 3.8 km long (Suppl. table ST2). The same occurred with the area,
520 9.4 and 5.3 km², respectively (Suppl. table ST3). Over the different stages, the western
521 glacier lost 31% of its area and retreated 51% of its total length (Suppl. tables ST2 and
522 ST3) while there was less shrinkage of the eastern glacier both in area loss (26%) and
523 length (34%). Figs. 2B and 3B and Suppl. table ST2 show only one reversal during the
524 general retreating trend, in the stage 15 of the western and the stage 16 of the eastern
525 Tungnahryggsjökull. The greatest area losses occurred in the transition to the stages 2,
526 4, 7, 9 and 14 (>3%) on the western glacier while losses between stages in the eastern
527 glacier were lower except for the transition between the stages 14 and 17, where a
528 noticeable reduction of the accumulation area was observed in the aerial photos of 1946
529 and 1985, and the satellite image of 2005 (Fig. 3B). The volumes calculated from the
530 reconstructed glacier DEM and the corrected bed DEM show that the glaciers reached
531 ~1.10 km³ (western) and ~0.47 km³ (eastern) at their recorded maximum extent
532 corresponding to their outmost moraines. From the oldest to the most recent stage they
533 lost 30% and 23% of their ice volume, respectively. The losses between consecutive
534 stages of the glaciers were in general lower than 3% with the exception of the stages 2,
535 4, 7, 9 (western) and stage 14 (eastern), where the values ranged from 3% to 10%
536 (Suppl. table ST3). Only one slight inversion of the volume trend is seen in the stages
537 15 of the western glacier and in 16 of the eastern glacier.

538 4.3. Equilibrium-Line Altitudes (ELAs)

539 The application of the AAR (0.67) method showed ELAs ranging from 1021 to 1099 m
540 a.s.l. (western glacier) and from 1032 to 1065 m a.s.l. (eastern glacier) for the different
541 reconstructed stages. This means an overall rise of 78 and 33 m respectively (Table 1)
542 from the maximum to the minimum extent recorded. The results from applying the

543 AABR (1.5) show the same trend and similar ELAs, with differences of up to ± 15 m
544 compared with those obtained from the AAR. The AABR-ELAs tend to be higher than
545 the AAR-ELAs, especially in the second half of the reconstructed stages with the most
546 remarkable differences occurring in the eastern Tungnahryggsjökull (Table 1).
547 However, the error derived from the uncertainties associated to the applied balance ratio
548 (BR, ± 0.4) tends to decrease as the glaciers get smaller. The greatest change in the ELA
549 between consecutive stages is found between the stages 1 and 2 in the western glacier
550 (+26 m), fully coincident with the largest retreat measured, about 1 km. An interesting
551 result is that the ELA rise is attenuated in both glaciers from stage 10 onwards, with
552 stage-to-stage variations close to zero predominating, and with only one inversion (-3
553 m) occurring in the western glacier between the stages 14 and 15 (Table 1).

554 4.4. Lichenometric dating

555 Altogether 17 lichenometry stations (8 in Vesturdalur and 9 in Austurdalur) were set up
556 during fieldwork in the two glacier forelands. Their spatial distribution and
557 correspondence with the different glacial stages are given in Figs. 2 and 3 and Suppl.
558 table ST4. The table also shows the measurements of the largest *Rhizocarpon*
559 *geographicum* thalli found during fieldwork in the moraines (stages) to which the
560 stations correspond. TUE-0 was the only station where no lichen of either species was
561 found in 2015. Unlike *Porpidia* cf. *soredizodes* thalli, which are present in all the
562 remaining lichenometry stations, *Rhizocarpon geographicum* thalli suitable for
563 measuring (ellipsoidal, not coalescent) were only found in stations TUV-2 to TUV-7 in
564 Vesturdalur, and in TUE-2 to TUE-7 in Austurdalur.

565 The measurements considered the diameter of the smallest circle bounding the thallus
566 outline as representative of the longest axis (Suppl. figure SF1). The obtained values
567 ranged from 19.3 to 71.5 mm in Vesturdalur, and from 19.0 to 47.7 mm in Austurdalur

568 (Suppl. table ST4). Only one size inversion (decreasing size with increasing distance to
569 the current terminus) was detected in Austurdalur in the station TUE-6 (Fig. 3).
570 *Rhizocarpon geographicum* thalli were absent in the nearest stations (TUW-1 and TUE-
571 1) and were coalescent in the most distant stations (TUW-8 and TUE-8) in both glacier
572 forelands. On the other hand, *Porpidia cf. soredizodes* thalli measurements ranged from
573 18.3 to 148.4 mm in Vesturdalur, and from 16.8 to 141.8 mm in Austurdalur (Suppl.
574 table ST4). A size inversion of *Porpidia cf. soredizodes* thalli is also observed in TUE-6
575 and in TUE-7.

576 When the ages of *Rhizocarpon geographicum* lichens are calculated applying a 0.44
577 mm yr⁻¹ growth rate and a 10-year colonization lag following Kugelmann (1991), they
578 range from 54 to 173 years in Vesturdalur, and from 53 to 119 years in Austurdalur. If
579 longer colonization lags of 15, 20, 25 and 30 years (see Methods section) are applied
580 tentatively, the oldest ages obtained are ~170-190 years, and the youngest ~40-70 years
581 (Table 2). In general, the further away the lichenometry stations are, the older are the
582 ages (Figs. 2 and 3), with the inversions mentioned above. Apparently the lichenometry-
583 dated moraines are younger than the CRE-dated distal moraines.

584 The absence of *Rhizocarpon geographicum* lichens in 2015 at lichenometry station
585 TUW-1 (uncovered by the glacier at some time between 1994 and 2000; Suppl. figure
586 SF2) suggests a colonization lag of at least 15-21 years. In addition, it is only when the
587 colonization lag is assumed to be longer than 10 years and shorter than 30 years that the
588 ages obtained at stations TUW-3 and TUE-2 are in good agreement with the ages
589 deduced from the aerial photos (Table 2).

590 During the 2015 field campaign, the species *Porpidia cf. soredizodes* was absent in
591 station TUE-0, located on a glacially polished threshold uncovered by the glacier after
592 2005 (post-stage 17). However, it was found in stations TUW-1 and TUE-1, dated to

593 1994-2000 and 1946-1985 respectively, based on the position of the snouts in the aerial
594 photos ([Suppl. figure SF2](#)). These observations suggest a colonization lag from 10 to
595 15-21 years, thus shorter than for *Rhizocarpon geographicum*.

596 4.5. ³⁶Cl CRE dating

597 The detailed geomorphological analysis carried out on the numerous moraine ridges of
598 both valleys has greatly limited the number of boulders reliable for successfully
599 applying ³⁶Cl CRE and lichenometry dating methods. Due to the great intensity of the
600 slope processes (especially snow avalanches and debris-flows), only a few boulders are
601 well-preserved, sometimes only one in each moraine ridge that retains its original
602 glacier location. Thus, it should be highlighted that this issue prevented performing a
603 statistically valid sampling for both methods (see e.g. [Schaefer et al., 2009](#); [Heymann
604 et al., 2011](#)).

605 During the fieldwork campaigns in the forelands of the western and eastern
606 Tungnahryggsjökull glaciers, 12 samples from stable and very protrusive moraine
607 boulders ([Suppl. figure SF4](#)) were collected in areas where lichenometric dating was not
608 suitable because of lichen thalli coalescence, and also 2 samples from a polished ridge
609 downwards the confluence of Vesturdalur and Austurdalur ([Suppl. figure SF5](#)). The
610 input data for exposure age calculations, namely sample thickness, topographic
611 shielding factor, major element concentrations of bulk/target fractions, are summarized
612 in the [Suppl. tables ST5, ST6, ST7 and ST8](#) includes the ³⁶Cl CRE ages calculated
613 according to different Ca spallation production rates and the distance to the most recent
614 glacier terminus position mapped. [Table 3](#) includes the ³⁶Cl CRE ages converted to CE
615 dates format presented throughout the text. The dates presented below are based on the
616 [Licciardi et al. \(2008\)](#) Ca spallation production rate.

617 Aiming to obtain a maximum (oldest) age for the onset of the deglaciation in the valleys
618 studied, two samples (ELLID-1 and ELLID-2) were extracted from the western sector
619 of Elliði, a 660-m-high glacially polished crest separating Viðinesdalur and
620 Kolbeinsdalur valleys (Suppl. figure SF5), and located at 11 km downstream from the
621 confluence of Vesturdalur and Austurdalur valleys. Both samples yielded dates of
622 14300 ± 1700 BCE and 14200 ± 1700 BCE.

623 In Vesturdalur, 8 samples were collected from 5 moraines corresponding to 5 of the
624 stages identified on the geomorphological map (Fig. 2). Samples TUW-9 and TUW-10
625 were taken from two boulders in the moraine that correspond to the left latero-frontal
626 edge of the glacier during the stage 7, ~1 km from the 2005 CE (stage 17) glacier
627 terminus (measured along the flowline from the reconstructed terminus apex); they
628 yielded consistent dates of 1590 ± 100 CE and 1640 ± 90 CE. Samples TUW-11 and
629 TUW-12 were extracted from the moraines corresponding to the glacial stages 6 and 5,
630 at 185 m and 465 m downstream respectively (~1.2 km and ~1.5 km respectively from
631 the 2005 CE snout), and gave consistent dates 1480 ± 120 CE and 1450 ± 100 CE. The
632 next ^{36}Cl samples (TUW-13 and TUW-14) were taken from two adjacent moraine
633 boulders on the left latero-frontal moraine ridge corresponding to the stage 3, at 264 m
634 downstream (1.8 km from the 2005 CE snout); they yielded dates of 1470 ± 130 CE and
635 670 ± 210 CE, which are significantly different from each other. The most distant
636 samples (TUW-15 and TUW-16) were extracted from the stage 2 moraine, ~400 m
637 downstream from the moraine ridge corresponding to stage 3 (2.2 km from the 2005 CE
638 terminus). They yielded dates of 1460 ± 110 CE and 1220 ± 190 CE, respectively, that are
639 consistent with each other and in chronological order with sample TUW-13 from the
640 stage 3. However, these ages are not in agreement with the oldest date of TUW-14
641 (670 ± 210 CE) from the stage 3.

642 Four ^{36}Cl samples were taken from two prominent moraines in the Austurdalur valley
643 (Fig. 3). Samples TUE-9 and TUE-10 were collected on the frontal moraine
644 corresponding to stage 4 (1 km from the 2005 CE glacier terminus) and yield
645 significantly different dates of 740 ± 170 CE and 1460 ± 100 CE. Samples TUE-11 and
646 TUE-12 were taken from two moraine boulders located on the ridge of the left lateral
647 moraine that records the maximum ice extent (Fig. 3). Their calculated ^{36}Cl dates,
648 380 ± 200 CE and 400 ± 200 CE, are consistent with each other and in stratigraphic order
649 with the ages from stage 4.

650 The dates derived from Stone et al. (1996) Ca spallation production rate are similar to
651 those presented above, only 4% older. Those derived from the Schimmelpfennig et al.
652 (2011) production rate yielded dates older by 15% on average (Suppl. table ST8). These
653 small differences do not represent statistical difference given the calculated age
654 uncertainties.

655 5. Discussion

656

657 5.1. ^{36}Cl CRE dating

658 The dates obtained in both valleys range from 380 ± 200 CE to 1640 ± 90 CE and are
659 significantly younger than the ages from Elliði polished ridge (Suppl. table ST8). T UW-
660 14 (670 ± 210 CE) could be the only outlier as it is significantly older than the other
661 sample obtained from the same moraine of the stage 3 (T UW-13; 1470 ± 130 CE) and
662 also older than the samples T UW-15 (1460 ± 110 CE) and T UW-16 (1220 ± 190 CE),
663 from the moraine of the previous stage 2 (Fig. 2). This would imply assuming nuclide
664 inheritance for sample T UW-14 due to either remobilization of an earlier exposed
665 moraine boulder (see Matthews et al., 2017) or to previous exposure periods, but the

666 high geomorphological dynamism of the slopes limits this possibility (Andres et al.,
667 2019). Another possible interpretation is that the samples T UW-15 and T UW-16 (stage
668 2) would be the outliers since they may have experienced incomplete exposure due to
669 post-depositional shielding (Heymann, 2011). The possibility of both samples being
670 affected by proglacial processes can be ruled out given the distance to the meltwaters
671 channel or the absence of glacial burst features (see Caseldine, 1985a) in the
672 surroundings of the sampled boulders. Thus, the ages of samples T UW-14 and T UW-13
673 would indicate that the moraine of stage 3 was built during two overlapped glacial
674 advances at 670 ± 210 CE and 1470 ± 130 CE. In Austurdalur, the interpretation of the
675 ages is also complex. Samples T UE-9 (740 ± 170 CE) and T UE-10 (1460 ± 100 CE) from
676 the same moraine are significantly different, but it is difficult to decide whether or not
677 one of these two samples is an outlier. It is also possible that the younger age indicates
678 the timing of a further readvance with the snout reaching the same moraine. It would be
679 necessary to take more samples, but it will be difficult to find other sectors of these
680 moraines that are not affected by slope processes, especially debris-flows. The
681 hypothesis of supraglacial debris dumping can be rejected due to the lack of supraglacial
682 debris or other features indicative of a palaeo debris-covered glacier. Other possibility
683 to be consider is that older boulders may be incorporated in the formation of push
684 moraines as has been shown in maritime Scandinavia, and identified to give
685 overestimated ages for LIA-moraines (Matthews et al., 2017). The asynchronicity of
686 glacial advances and retreat in both valleys should not be surprising as glaciers can
687 retreat or advance differently in adjacent valleys due to a number of factors such as
688 hypsometry, aspect, gradient, etc. Caseldine (1985b) suggested a high climate
689 sensitivity of the glacier in Vesturdalur due to its steeper wally floor and thinness”,
690 which could explain a different behaviour of the glacier compared to the eastern glacier.

691 *5.1.1. Pre-LIA glacial advances*

692 ^{36}Cl CRE dating results from glacially polished surfaces on the Elliði crest show an age
693 of 14250 ± 1700 yr (mean) for the Kolbeinsdalur deglaciation ([Suppl. figure SF5](#)).
694 However, this should be considered as a minimum age since this probably indicates
695 when the retreating and thinning glacier uncovered the ridge, and thus the start of the
696 final deglaciation of the main valley. From this point to the outmost frontal moraines
697 surveyed in this paper, no glacially polished outcrops or erratic boulders suitable for
698 ^{36}Cl sampling were found, impeding us to provide further chronological constraints for
699 the deglaciation pattern of these valleys.

700 Our ^{36}Cl CRE dating results suggest late Holocene glacial advances prior to the LIA, at
701 around ~ 400 and ~ 700 CE, in Vesturdalur and Austurdalur, respectively, coinciding
702 with the Dark Ages Cold Period (DACP) (between 400 and 765 CE) in central Europe,
703 according to [Helama et al. \(2017\)](#). In fact, recent synthesis about Icelandic lake records
704 indicate a strong decline in temperature at 500 CE ([Geirsdóttir et al., 2018](#)).

705 The presence of Late Holocene moraines outside the outermost LIA moraines in other
706 valleys of Tröllaskagi has been suggested through radiocarbon dating and
707 tephrochronology in the Vatnsdalur (first, between 4880 ± 325 cal. BCE (tephra Hekla 5)
708 and 3430 ± 510 cal. BCE, and another after 1850 ± 425 cal. BCE; [Stötter, 1991](#)),
709 Lambárdalur (before 3915 ± 135 cal. BCE; [Wastl and Stötter, 2005](#)), Þverárdalur (before
710 3500 ± 130 cal. BCE; [Wastl and Stötter, 2005](#)), Kóngsstaðadalur (after 1945 ± 170 cal.
711 BCE; [Wastl and Stötter, 2005](#)), Barkárdalur (between 375 ± 375 cal. BCE and 190 ± 340
712 cal. CE and before 460 ± 200 cal. CE; [Häberle, 1991](#)) and Bægisárdalur (2280 ± 205 cal.
713 BCE and 1050 ± 160 cal. CE; [Häberle, 1991](#)) valleys. Specifically, our oldest ^{36}Cl dates
714 (~ 400 and ~ 700 CE) coincide with glacial advances that are radiocarbon dated from

715 intra-morainic peat bogs in other valleys in Tröllaskagi and southern Iceland, e.g. the
716 Barkárdalur II stage (ca. 460 CE) in Subatlantic times (Häberle, 1991, 1994), and given
717 the uncertainties of our dates (200 yr), also with Drangajökull (NW Iceland) advancing
718 at the same time (~300 CE; Harning et al., 2018). On the other hand, Meyer and Venzke
719 (1985) had already suggested the presence of pre-LIA moraines at Klængshóll (eastern
720 cirque, tributary of Skíðadalur). Caseldine (1987, 1991) proposed a date of 5310±345
721 cal. BCE as the youngest for a moraine in that cirque, based on tephrochronology
722 (tephra layer Hekla 5 dated in a similar ground in Gljúfurárdalur) and rock weathering
723 measurements using the Schmidt hammer technique. Based on the big size of some
724 moraines in Skíðadalur and Holárdalur, Caseldine (1987, 1991) also supports the
725 hypothesis of pre-LIA moraines formed during several advances. All this information is
726 not in agreement with the hypothesis that all the glaciers in Tröllaskagi reached their
727 maximum ice extent since the Early Holocene during the LIA (Hjort et al., 1985;
728 Caseldine, 1987, 1991; Caseldine and Hatton, 1994).

729 In south and central and northwest Iceland, the ice caps reached their Late Holocene
730 maximum advance during the LIA (Brynjólfsson, et al. 2015a; Larsen et al. 2015;
731 Harning et al., 2016a; Anderson et al., 2018; Geirsdóttir et al., 2018). But also pre-LIA
732 advances have been identified and dated through radiocarbon and tephrochronology in a
733 moraine sequence of Kvíárjökull (south-east Vatnajökull), the first of which occurred at
734 Subatlantic times (before 110±240 cal. BCE) and the second at 720±395 CE (Black,
735 1990; cited in Guðmundsson, 1997). Considering the uncertainty of our ~400 and ~700
736 CE dates, these advances likely were coetaneous with other advances reported from
737 southern Iceland in Kötlujökull (after 450±100 cal. CE, radiocarbon dated and
738 supported by tephrochronology; Schomaker et al., 2003) and Sólheimajökull (southern
739 Mýrkdalsjökull, “Ystagil stage”; Dugmore, 1989). In fact, the 669±211 CE advance of

740 western Tungnahryggsjökull (stage 3) also overlaps with the Drangajökull and
741 Langjökull advances at ~560 CE and 550 CE, respectively (Larsen et al., 2011; Harning
742 et al., 2016a) during DACP, in response to the summer cooling between ~250 CE and
743 ~750 CE (Harning et al., 2016a). These advances would correspond to the general
744 atmospheric cooling in the North Atlantic reflected by widespread glacier advances
745 (Solomina et al., 2016).

746 The timing of the stage 2 in Vesturdalur is difficult to define because the sample TUW-
747 16 (1220±190 CE) has almost 200-year uncertainty, and thus overlaps with both the
748 LIA and the higher temperatures of the Medieval Warm Period (MWP, Lamb, 1965; 950-
749 1250 CE, see Solomina et al., 2016) not conducive to glacier development as it has been
750 observed in northwest and central Iceland (Larsen et al., 2011; Harning et al., 2016a).
751 On the other hand, moraines in Greenland Arctic environments date within the MWP,
752 based on cosmogenic nuclide dating (Young et al., 2015; Jomelli et al., 2016),
753 suggesting a cooling in the western North Atlantic while the eastern sector remained
754 warm. Iceland is located in the middle of this dipole “see-saw” pattern (Rogers and van
755 Loon, 1979). Thus, the correlations with the glacier fluctuations Greenland or Norway,
756 are complicated as the climate anomalies in both regions show opposing signs in the
757 different see-saw modes. To increase the difficulty of interpretation, glaciers of
758 Tröllaskagi are known to surge occasionally (Brynjólfsson et al., 2012; Ingólfsson et al.,
759 2016), which could explain additional complexity in the glacial advances pattern, as it
760 would not be driven by climatic variability. Brynjólfsson et al. (2012) pointed out that
761 only four surges from three glaciers (Teigarjökull, Búrfellsjökull, Bægisárjökull) have
762 been reported in the Tröllaskagi peninsula, where over 160 cirque glaciers exist.

763 *5.1.2. LIA glacial advances (15th-17th centuries)*

764 The remaining ^{36}Cl ages obtained from Vesturdalur and Austurdalur are within the
765 1450-1640 CE range (Suppl. table ST8; Table 3) and so correspond to different glacial
766 advances or standstills during the second third of the LIA during the 15th, 16th and 17th
767 centuries. According to our results, one of the largest glacier extents of the LIA
768 culminated in both valleys at the latest around the mid-15th century (samples: TUW-12:
769 1450±100 CE / stage 6; TUE-10: 1460±100 CE / stage 4). This is a very early date
770 compared to the LIA advances previously dated in Tröllaskagi. Earlier lichenometric
771 research carried out in nearby valleys report more recent dates for the LIA maximum:
772 mid-18th century in Barkárdalur (Häberle, 1991); early 19th century in Bægisárjökull and
773 Skríðudalur (Häberle, 1991), and in Búrfellsdalur and Vatnsdalur (Kugelmann, 1991,
774 Fig. 7); mid-19th century (1845-1875 CE) in Myrkárjökull, Vindheimajökull (Häberle,
775 1991), Þverárdalur, Teigardalur, Grýtudalur, Vesturárdalur (Kugelmann, 1991, Fig. 7),
776 Heiðinnamannadalur and Kvarnárdalur (Caseldine, 1991); and late 19th century (1880s-
777 1890s CE) in Gljúfurárdalur (Caseldine, 1985b, 1991). Caseldine (1991) proposed
778 1810-1820 CE as the date of the “outer” moraine of Vesturdalur based on a minimum
779 lichenometric age. According to our ^{36}Cl moraine ages, the LIA maximum of
780 Tungnahryggsjökull glaciers occurred ~400 years earlier than these dates. This should
781 not be surprising as Kirkbride and Dugmore (2001) reported lichenometric ages >100
782 years younger than those derived from tephrochronology in the same landforms. Our
783 results also give the earliest LIA dates based on moraine dating obtained so far in
784 Iceland, compared to the previously published dates all obtained through lichenometric
785 dating: 1740-1760 CE in south-east Iceland (Chenet et al., 2010). In northwestern
786 Iceland, glaciolacustrine sediments recorded a contemporary expansion of Drangajökull
787 at ~1400 CE (Harning et al., 2016a). Likewise a first major advance of Langjökull
788 (western central Iceland; Fig. 1A) between 1450 and 1550 CE has been reported (Larsen

789 [et al., 2011](#)), as well as advances in central Iceland between 1690 and 1740 CE
790 ([Kirkbride and Dugmore, 2006](#)), based on varve thickness variance together with annual
791 layer counting and C:N mass ratio, and tephrochronology (geochemical analysis),
792 respectively.

793 The dates of samples TUV-13, TUV-12 and TUV-11 in Vesturdalur (average date
794 1470 ± 120 CE; stages 3, 5 and 6) cannot be distinguished statistically if their internal
795 uncertainty is considered ([Fig. 4](#); [Suppl. table ST8](#)). The spatial scatter of these
796 sampling sites ([Fig. 2](#)) may indicate frequent and intense terminus fluctuations in a short
797 time interval. Different ages obtained from the moraines of the stages 3 and 4 in
798 Vesturdalur and Austurdalur, respectively, may indicate that in the 15th century the
799 glacier termini reached the moraines deposited at ~ 700 CE ([Figs. 2 and 3](#)) and rebuilt
800 them, which may explain the large size of these moraines. [Caseldine \(1987\)](#) argued that
801 other moraines in Skíðadalur were formed during more than one advance. Based on the
802 size of the largest moraines, he also pointed out that many glaciers must have advanced
803 to positions similar to those of the late 19th century earlier in the Neoglacial.

804 The glacier advances in the 15th century in Vesturdalur and Austurdalur may have been
805 the result of different climate forcings during that century: negative radiative forcing
806 and summer cooling were linked to intense volcanic activity ([Miller et al., 2012](#)), the
807 low solar activity of the Spörer Minimum (1460-1550 CE; [Eddy, 1976](#)), the sea-
808 ice/ocean feedback with increased sea ice ([Miller et al., 2012](#)) and the weakening of the
809 Atlantic Meridional Overturning Circulation (AMOC) ([Zhong et al., 2011](#)). Solar
810 activity may have played a major role in these glacial advances if we consider that the
811 climate in the North Atlantic is highly influenced by solar activity variability ([Jiang et al.,](#)
812 [2015](#)). On the contrary, historical records, although not determinant, suggest a mild
813 climate for 1430-1550 CE ([Ogilvie and Jonsdóttir, 2000](#)), and especially for 1412-1470

814 CE (Ogilvie, 1984). This would also be compatible with increased precipitation and
815 hence more winter snow in warm periods (Caseldine and Stötter, 1993; Stötter et al.,
816 1999; Fernández-Fernández et al., 2017), and also with potential surge activity with
817 glacial advances not directly linked to specific climate periods (e.g. Brynjólfsson et al.,
818 2012; Ingólfsson et al., 2016).

819 In Vesturdalur, the dates of samples TUW-9 (1590±100 CE) and TUW-10 (1640±90
820 CE) are compatible with a cold period from the late 1500s to 1630 CE (Ogilvie and
821 Jónsson, 2001). Nevertheless, considering the uncertainties of these samples, their dates
822 also overlap with the Maunder Minimum (1645-1715 CE) (Eddy, 1976), when the LIA
823 maximum glacial advance occurred in the Alps (Holzhauser et al., 2005).

824 5.2. Lichenometric dating.

825 5.2.1. ³⁶Cl CRE dating vs. lichenometric dating. Multiple lichen species dating 826 approach.

827 The contrast between our CRE dating results and earlier lichenometry-based results
828 published elsewhere evidences the clear underestimation of the latter. This could be
829 explained either by lichen growth inhibition due to saturation of the rock surface and
830 competition of other thalli (Wiles et al., 2010; Le Roy et al., 2017) or a colonization lag
831 longer than assumed up to now, from 10 to 15 years in Tröllaskagi (Kugelmann, 1991;
832 Caseldine, 1985b, respectively). However, other factors affect the reliability of the
833 lichen-derived ages, and may explain the differences with CRE dates. One of them is
834 the reliability of the growth rates and lichenometric calibration curves that are
835 commonly assumed to be linear (constant) growth in northern Iceland (e.g. Caseldine,
836 1983, 1985b; Häberle, 1991; Kugelmann, 1991), although it has been demonstrated that
837 the lichen diameter growth declines with age (see e.g. Winkler, 2003, Fig. 4). This

838 might lead to significant age underestimations for the oldest dates, putting potentially
839 earlier dates in the 19th century. Most of the fixed control points from which lichen
840 growth rates have been derived in northern Iceland comprise abandoned gravestones,
841 memorial stones, old bridges and mostly abandoned farmsteads ([Caseldine, 1983](#);
842 [Kugelmann, 1991](#)). Time of death is commonly assumed for gravestones, and
843 abandonment date for farmsteads. Although the latter is well known on the basis of
844 historical documentation, the colonization lag sometimes relies on the “the likely
845 duration” of the deterioration of the buildings after abandonment that depends on the
846 quality and stability of the constructions (see [Kugelmann, 1991](#)), and hence affect the
847 results. However, it should be highlighted that our approach circumvents this last issue
848 by combining field observations with historical aerial photographs. In addition, given
849 that lichen growth of *Rhizocarpon* subgenus depends mostly on available humidity, the
850 location of the measured lichens has also a potential effect on the results, i.e. to micro-
851 climatic changes (see [Innes, 1985](#); [Hamilton and Whalley, 1995](#)) between the location
852 of the fixed points and the location on the moraine (crest: dryer and more exposed;
853 green zone on the proximal slope, etc.). In the literature cited above about lichenometry-
854 dated LIA advances no detailed information is provided about the location of the lichen
855 measured for dating purposes, so potential error derived from this issue can not be
856 assessed. Nevertheless, given that we measured lichens on horizontal flat surfaces
857 where there is no restriction to the moisture receipt of the lichens, we can consider our
858 results presented throughout the next sections valid. In any case, such a great difference
859 of our CRE dates and the previous lichen-derived is more likely to be explained by the
860 technical limitations of the technique rather than environmental factors.

861 Our field observations and historical aerial photos of known age restricted the dates of
862 the moraines colonized by *Rhizocarpon geographicum* lichens. This approach would

863 support the dates obtained from the 0.44 mm yr⁻¹ growth rate of Kugelmann (1991) and
864 the 20-year colonization lag. This rate is slightly higher than those reported from the
865 Antarctic Peninsula (0.31 mm yr⁻¹; Sancho et al., 2017), but lower than in Tierra del
866 Fuego (0.63 mm yr⁻¹; Sancho et al., 2011). The correlation between the sizes of largest
867 *Rhizocarpon geographicum* and *Porpidia* cf. *soredizodes* thalli at the same stations
868 showed a proportionality between the largest thalli of both species: thalli of *Porpidia* cf.
869 *soredizodes* species grow faster than those of *Rhizocarpon geographicum*. The sizes of
870 the largest *Rhizocarpon geographicum* thalli were plotted against the sizes of the largest
871 *Rhizocarpon geographicum* lichens (Fig. 5). The slope of the best-fit linear curve
872 obtained was around 1.675 (r²=0.82) that suggests that *Porpidia* cf. *soredizodes* lichens
873 grow 1.675 times faster than those of *Rhizocarpon geographicum*. So if we assume 0.44
874 mm yr⁻¹ growth rate for *Rhizocarpon geographicum* lichens, a tentative growth rate of
875 *Porpidia* cf. *soredizodes* would be 0.737 mm yr⁻¹. However, this approach should be
876 taken with caution due to the limited number of lichens (n=7) used of each species.
877 Aiming to obtain a tentative date (Table 2), this growth rate was applied to the largest
878 *Porpidia* cf. *soredizodes* lichens found in those stations where no *Rhizocarpon*
879 *geographicum* lichens could be measured (TUW-1, TUW-8, TUE-1 and TUE-8).

880 Assuming colonization lags of 20 and 15 years for *Rhizocarpon geographicum* and
881 *Porpidia* cf. *soredizodes* lichens, respectively, and the above-mentioned growth rates,
882 several glacial advances or standstills are tentatively placed in the 19th and 20th
883 centuries, in the context of a general retreat from the most advanced LIA positions, as
884 discussed in the next section.

885 5.2.2. LIA glacial advances/standstills: 19th century

886 Despite the low number of lichenometry stations surveyed and the limitations of this
887 dating approach discussed in the previous sections, our results are in accordance with

888 the geomorphological logic and with the chronological frame obtained from historical
889 aerial photos. The ages derived from *Rhizocarpon geographicum* thalli measurements at
890 lichenometry stations pre-dating 1946 suggest that the western and eastern
891 Tungnahryggsjökull culminated successive advances/standstills around the 1830s,
892 1840s, 1860s and 1890s CE (Figs. 2 and 3, Table 2). Ages tentatively estimated from
893 *Porpidia* cf. *soredizodes* thalli considering its apparently higher growth rate suggest
894 glacial advances/standstills around the 1800s (Figs. 2 and 3, Table 2). No inconsistency
895 (age inversions) is detected in the lichenometry-dated moraine sequence, but we
896 recognise that some age underestimation may occur since: (i) we assume linear growth
897 when applying a growth rate; and (ii) our 19th dates were derived from >40-45 mm-
898 diameter lichens (Table 2 and Suppl. table ST4), which exceed the size of the biggest
899 control point from which Kugelmann's growth rate was estimated (Kugelmann, 1991,
900 Fig. 3). This problem reinforces the need of taking lichen-derived ages as relative. The
901 interpretation of the chronology in Austurdalur is more complicated: the lichen sizes
902 measured at the stations TUE-6 (1890s CE, stage 9) and TUE-7 (1880s CE; stage 7)
903 yield more recent dates than at station TUE-5 (1860s CE; stage 10) despite being
904 representative of earlier stages (Fig. 3). Given that this anomaly occurs in both lichen
905 species, it is reasonable to conclude that an environmental factor could have affected the
906 lichen populations at both stations. It could even indicate a date when the boulders may
907 have been remobilized by postglacial processes.

908 Our chronology of the 19th century glacial advances in both valleys (Table 2) does not
909 coincide exactly with the phases identified by Kugelmann (1991) in Svarfaðardalur-
910 Skíðadalur (1810, 1850, 1870-1880, 1890-1900 CE). It also differs appreciably from the
911 chronology proposed by Caseldine (1985b) in Vesturdalur (moraines of 1868, 1878,
912 1887, 1898 CE). Nevertheless, it should be borne in mind that we are considering only

913 two glaciers with their own glaciological properties. Moreover, we have estimated the
914 ages from the growth rate (instead of a specific calibration growth curve), longer
915 colonization lag based on field observations, and applied to the longest axis
916 measurements ([Kugelmann, 1991](#)). On the other hand, micro-climatic differences
917 between the location of fixed points and our lichen measured may occur. However, we
918 recognise that the comparisons with [Caseldine's \(1985b\)](#) results are quite difficult since:
919 (i) the moraines dated by Caseldine are poorly located in his mapping (and hard to
920 identify over aerial photos and our moraine mapping); (ii) we are not able to apply the
921 same parameters to his measurements, as he used the mean longest axis of the five
922 largest lichen is not provided (only the average value); and (iii) he recognised the lichen
923 growth slowdown when dating the outermost moraine, which probably is one of those
924 dated with ^{36}Cl in this work.

925 Our results, despite the limitations of the applied method, largely due to the low number
926 of moraine boulders suitable for its application can be considered compatible and in
927 good agreement with glacial advances and cold periods during the first third of the 19th
928 century as we show below. [Martin et al. \(1991\)](#) pointed out the existence of a moraine
929 dated to ca. 1810-1820 CE in “Western Tröllaskagi Tungnahryggsjökull” (ambiguously,
930 without providing any detail of its location), as well as others of this period in
931 Svarfaðardalur, Búrfellisdalur and Vatnsdalur. Other dates obtained from more
932 sophisticated statistical techniques applied to lichenometry dating procedures also
933 evidenced a glacial advance phase 1810-1820 CE ([Chenet et al., 2010](#)). These advance
934 phases were coetaneous with significant sea ice persistence in the early 1800s ([Ogilvie
935 and Jónsson, 2001](#)), decreased solar activity, and strong volcanic eruptions (Dalton
936 Minimum, 1790-1830 CE; [Wagner et al., 2005](#)). The moraines dated in Vesturdalur to
937 around 1830 CE (TUW-7: 1830s CE, stage 10) and the early 1890s CE (TUW-5: 1890s

938 CE, stage 12) are in good agreement with the glacial advances in Svarfaðardalur-
939 Skíðadalur during the 1830s and early 1890s CE (Kugelmann, 1991, Fig. 8), as well as
940 with the low temperatures and presence of sea ice at these dates (Koch, 1945; Ogilvie,
941 1996; Ogilvie and Jonsdóttir, 2000; Ogilvie and Jónsson, 2001; Kirkbride, 2002).

942 5.2.3. Post-LIA glacial advances/standstills.

943 Lichen-derived ages from *Rhizocarpon geographicum* thalli suggest the occurrence of
944 glacial advances or standstills at the first half of the 20th century, culminating in 1910s,
945 1930s, 1940s and 1950s CE, although the 1930s CE date (TUE-3; stage 12) disagrees
946 with the date inferred from the aerial photos, at some point between 1946 and 1985 CE
947 (Suppl. figure SF2; Table 2). However, the 1910s CE date in both valleys is in good
948 agreement with the moraine abandonment during the first two decades of the 20th
949 century; it would be the result of the accumulated effect of the temperature rise since the
950 latter half of the 19th century (Caseldine, 1987; Wanner et al., 2008). Thus, the
951 subsequent advances would be the response to specific relative thermal minima within a
952 warmer climate (Stötter et al., 1999). The date of TUW-3 (stage 13) representing the
953 moraine abandonment in ~1940 CE is in agreement with the overall context of general
954 glacier retreat as a result of the warmest decades of the 1930s and 1940s CE, which
955 triggered an intense retreat of the glaciers (Einarsson, 1991; Martin et al., 1991;
956 Kirkbride, 2002). The advances/standstills dated to the early 1950s CE in both
957 Tungnahryggsjökull glaciers are likely to be synchronous given the similarity of the
958 dates obtained (Table 2). They could represent glacial advances in consonance with the
959 late 1940s – early/mid-1950s CE cooling (Einarsson, 1991; Fernández-Fernández et al.,
960 2017), recorded both in Akureyri and many other weather stations throughout Iceland.
961 Caseldine (1983) found a similar chronology in Gljúfurárdalur (Skíðadalur headwater,

962 10 km to the east), with moraine deposition between mid-1910s and 1930, around mid-
963 1930s and late 1940s-1950 CE.

964 The subsequent trend of the Tungnahryggsjökull glaciers, inferred from aerial
965 photographs, a satellite image, geomorphological mapping, and glacier reconstruction,
966 was characterized by continuous retreat and volume loss, in line with the increasing
967 temperature trend since the end of the LIA. This trend was only reversed between the
968 mid-1960s and mid-1980s CE by a major cooling event (Einarsson, 1991; Sigurðsson,
969 2005; Fernández-Fernández et al., 2017). Two moraines have been dated after the 1950s
970 CE. The date obtained in station TUE-1 (1970s CE; stage 14) agrees with the date
971 deduced from the 1946 and 1985 aerial photographs (Suppl. figure SF2). However, the
972 date estimated in station TUW-1 (1970s CE; between stages 15 and 16) is prior to that
973 obtained from the 1994 and 2000 aerial photographs. The reason for this mismatch may
974 be a non-linear growth phase of the *Porpidia cf. soledizodes* thalli measured (i.e. its real
975 growth rate may have been lower than the estimated). Nevertheless, more research on
976 this species is required to use it successfully in lichenometric dating.

977 The aerial photographs from 1994 (stage 15 western Tungnahryggsjökull) and 2000
978 (stage 16) show a reversal in the trend of both Tungnahryggsjökull glaciers (Suppl.
979 figure SF2), as the positions of their termini are more advanced than in 1985 (stages 14
980 and 15; see Fernández-Fernández et al., 2017). These advances in Vesturdalur and
981 Austurdalur, culminating after 1985 in a period non-conducive to glacier expansion,
982 may have been linked to above average precipitation for 1988-1995, which prevented a
983 negative mass balance of the glaciers (Sigurðsson, 2005). The 2000 aerial photo (stage
984 16) and 2005 SPOT satellite image (stage 17) display the retreat of both glaciers. This
985 trend was reinforced by the sudden warming initiated in 1995, which triggered
986 decreased snowfall, negative mass balances for 1996-2000, and retreat of the non-

987 surging glaciers after 2000 (Sigurðsson, 2005). In spite of these glacial fluctuations in
988 response to the intense climatic fluctuations of the last century, the ELAs estimated in
989 this paper only show a general rise of 5-10 m (Table 1). This small ELA increase may
990 be derived from some artifacts of the glacier reconstruction or the attenuating effect of
991 the increase in winter precipitation suggested by glacier-climate models (Caseldine and
992 Stötter, 1993; Fernández-Fernández et al., 2017).

993 *5.3. Final remarks: Can the occurrence of pre-LIA glacial advances be confirmed? Was*
994 *the LIA in northern Iceland the Holocene glacial maximum? Was it a single maximum*
995 *advance?*

996 Our results demonstrate that Tungnahryggsjökull advanced during Late Holocene glacial
997 stages prior to the LIA and reached considerably more advanced positions, even though
998 the Iceland large ice caps reached generally their Late Holocene maximum advance
999 during the LIA (Larsen et al. 2015, Harning et al., 2016a; Anderson et al., 2018,
1000 Geirsdóttir et al., 2018). The chronological data presented in the previous sections
1001 suggests that during the LIA the glaciers overlapped moraines deposited in pre-LIA
1002 glacial stages. Our results also show LIA advances since the 15th century and are thus
1003 contrary to the traditional proposal of a single maximum LIA advance occurring during
1004 either mid-18th or late-19th centuries in Tröllaskagi peninsula, followed by subsequent
1005 minor readvances in an overall retreating trend (see Caseldine, 1983, 1985b, 1987;
1006 Kugelmann, 1991; Martin et al., 1991). The use of the ³⁶Cl production rates from Ca
1007 spallation reported by Stone et al. (1996) does not lead to major changes in the
1008 interpretation and conclusions as the changes in the nominal dates (up to 90 yr earlier;
1009 Table 3) are within the external uncertainty and also overlap with the results presented
1010 above based on the Licciardi et al. (2008) production rate. Similarly, if we consider the
1011 results derived by the Schimmelpfennig et al. (2011) production rate, we obtain even

1012 earlier ages, which still overlap with the results derived by the other production rates
1013 due to a higher external uncertainty (see [Table 3](#)). Although the snow cover duration is
1014 known to be high in northern Iceland (see [Dietz et al., 2012](#)), quantifying the effect of
1015 snow cover on sub-surface ^{36}Cl production is a complex issue: on the one side, snow
1016 lowers the isotopic production rates related to spallation reactions due to the shielding
1017 effect on high-energy neutrons ([Benson et al., 2004](#); [Schildgen et al., 2005](#)), and on the
1018 other side it increases the ^{36}Cl production rate from thermal neutrons below the rock
1019 surface, due to the enhancing effect of hydrogen on these low-energy neutrons ([Dunai et](#)
1020 [al., 2014](#)). Both effects might cancel out depending on the composition of the samples,
1021 and their quantification is still debated and affected by high uncertainties ([Zweck et al.,](#)
1022 [2013](#); [Dunai et al., 2014](#); [Delunel et al., 2014](#)). Given this complexity, snow shielding
1023 was not applied. In any case its effect is unlikely to be higher than the uncertainty
1024 derived from extracting ^{36}Cl from whole rock instead of minerals.

1025 Our results are in concordance with several valleys in northern Iceland, but also with the
1026 results that are being obtained in other sectors of Arctic and North Atlantic region in the
1027 last years, such as: in Baffin Island (northern Canada), where glaciers reached Late
1028 Holocene maximum positions prior to the LIA ([Young et al., 2015](#); ^{10}Be dating), or
1029 West Greenland, with several advances or stabilizations at 1450 ± 90 CE and 1720 ± 60
1030 CE ([Jomelli et al., 2016](#); ^{36}Cl dating). However, it is striking that the early LIA
1031 advances of northern Iceland reported in the present paper do not agree with maritime
1032 Norway with later maximum culminations (see [Nesje et al., 2008](#)) despite being the
1033 glaciated region most comparable with Iceland in terms of climate and glaciology. Our
1034 results also agree with farther and southern areas such as the Alps, with maximum
1035 advances at around 1430 CE ([Schimmelpfennig et al., 2012, 2014a](#)); ^{10}Be dates; and
1036 Sierra Nevada (Iberian Peninsula), where LIA advances have been reported between the

1037 14th and 17th centuries (Palacios et al., 2019; ¹⁰Be dates). Our detailed moraine
1038 mapping, combined with CRE dating in the surveyed valleys, clearly shows a number of
1039 advances throughout the LIA, in response to the great climatic variability of the region
1040 with alternating cold and mild/warm periods (Ogilvie, 1984, 1996; Ogilvie and
1041 Jónsdóttir, 2000; Ogilvie and Jónsson, 2001; Geirsdóttir et al., 2009) as occurred in the
1042 Alps (e.g. Schimmelpfennig et al., 2014a) or the Iberian mountains (e.g. Oliva et al.,
1043 2018). The ELA calculations show that the major long-lasting rise of the glacier ELA
1044 (24-50 m depending on the calculation method) took place prior to 1900s/1910s.

1045 According to the results, the evolution pattern described by Fernández-Fernández et al.
1046 (2017) for the Tungnahryggsjökull glaciers should be revised as the ³⁶Cl CRE dates
1047 from the 15th and 17th centuries indicate that LIA maximum was reached earlier than
1048 previously thought. Thus, if we consider the ELA of the earliest LIA dates obtained
1049 with ³⁶Cl CRE (i.e. stages 5 and 4 of western and eastern Tungnahryggsjökull), these
1050 imply ELA depressions (with reference to the 2005 date) of 24-50 m (depending on the
1051 ELA calculation method), occurring for at least 560 years (Table 1) and not 150 years as
1052 had been previously assumed (Caseldine and Stötter, 1993; Fernández-Fernández et al.,
1053 2017).

1054 **Conclusions**

1055 (i) This paper highlights the detailed geomorphological analysis of the glacial landforms
1056 as an essential pre-requisite prior to the application of dating methods on them.
1057 Nevertheless, this has greatly limited the number of valid moraine boulders to be dated,
1058 since the vast majority of those were affected by post-glacial processes. This issue which
1059 has prevented a statistically acceptable sampling and the validation or invalidation of
1060 the “inconsistent” ages yielded by several boulders, so a conclusive explanation cannot
1061 be given.

1062 (ii) Applying ^{36}Cl CRE dating for the first time in the Tröllaskagi peninsula enabled us
1063 to identify pre-LIA glacial advances in Vesturdalur and Austurdalur. Thus, the western
1064 and eastern Tungnahryggsjökull glaciers did not reach their Late Holocene maximum
1065 extent during the LIA. The maximum extent for the eastern glacier was dated to ~400
1066 CE. For the western glacier a latest date of ~700 CE and an earliest of 16300 years ago
1067 (when the Elliði crest was deglaciated) have been obtained.

1068 (iii) The LIA maximum in Vesturdalur and Austurdalur was reached by the 15th century
1069 at the latest. A combination of detailed moraine mapping and ^{36}Cl CRE dating confirm a
1070 number of glacial advances between the 15th and 17th centuries, the earliest LIA
1071 advances dated in Tröllaskagi at present.

1072 (iv) For the recent dates, the complementary use of aerial photographs, a satellite image
1073 and fieldwork has aided to obtain lichenometry-derived ages tentatively in good
1074 agreement with the morpho-stratigraphic order of the glacial landforms. It has also
1075 compensated some of the limitations and error sources of lichenometric dating. Thus, it
1076 has proved to be a useful tool to assess the colonization lags and the validity of the
1077 lichenometry-derived ages.

1078 (v) Fieldwork on recently deglaciated surfaces and historical aerial photographs have
1079 shown clearly that the colonization lag of *Rhizocarpon geographicum* lichen species is
1080 from 15-21 to 30 years, considerably longer than previously assumed in Tröllaskagi.
1081 Colonization of the *Porpidia* cf. *soredizodes* species is shorter, between 10 and 21
1082 years.

1083 (vi) From the measurements carried out in different lichenometry stations, growth of
1084 *Porpidia* cf. *soredizodes* lichen appeared to be higher than in the case of *Rhizocarpon*
1085 *geographicum*, and also proportional to that. Its growth rate has been tentatively

1086 estimated for the first time, at around 0.737 mm yr⁻¹. However, further research on the
1087 growth rates of this species is required for its potential use in lichenometric dating as a
1088 complementary species, since it also shows a shorter colonisation lag than *Rhizocarpon*
1089 *geographicum*.

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- 1634

1635 **Figure captions.**

1636 Figure 1. Location of the Tungnahryggsjökull glaciers and their forelands (C)
1637 (Vesturdalur and Austurdalur) in the context of Iceland (A) and the Tröllaskagi
1638 peninsula (B). The red boxes in panels A and B are panels B and C, respectively. The
1639 figure also includes the location of the place names mentioned throughout the paper.
1640 This figure is available in colour in the online version.

1641 Figure 2. Geomorphological map of the Vesturdalur foreland. (A) General view of the
1642 Western Tungnahryggsjökull foreland. (B) Detailed moraine mapping and glacier
1643 margin geometry reconstructed throughout the different glacial stages identified, and
1644 ^{36}Cl CRE and lichenometric dating results (both are expressed in ages and calendar
1645 years). Note that stages 13, 14, 15 and 16 correspond to the years 1946, 1985, 1994 and
1646 2000. The surface-contoured glacier (white) corresponds to the year 2005 (stage 17).
1647 The abbreviations “Rg” and “Ps” in lichenometry stations indicate that the estimated
1648 dates are derived from the *Rhizocarpon geographicum* and *Porpidia sorelizodes*
1649 lichens, respectively, and the number correspond to the longest axis of the largest lichen
1650 measured. This figure is available in colour in the online version.

1651 Figure 3. Geomorphological map of the Austurdalur foreland. (A) General view of the
1652 Eastern Tungnahryggsjökull foreland. (B) Detailed moraine mapping and glacier margin
1653 geometry reconstructed throughout the different glacial stages identified, and ^{36}Cl CRE
1654 and lichenometric dating results (both are expressed in ages and calendar years). Note
1655 that stages 11, 15 and 16 correspond to the years 1946, 1985 and 2000. The surface-
1656 contoured glacier (white) corresponds to the year 2005 (stage 17). The abbreviations
1657 “Rg” and “Ps” in lichenometry stations indicate that the estimated dates are derived
1658 from the *Rhizocarpon geographicum* and *Porpidia sorelizodes* lichens, respectively,

1659 and the number correspond to the longest axis of the largest lichen measured. This
1660 figure is available in colour in the online version.

1661 Figure 4. ^{36}Cl CRE ages and internal (analytical) uncertainty at 1σ level of the samples
1662 from Vesturdalur and Austurdalur. Note that the samples clustering around 500 yr (15th
1663 century) in Austurdalur are indistinguishable. Distance to the terminus (year 2005) is
1664 measured along the flowline from the reconstructed snout apex of the phase where the
1665 samples were collected. This figure is available in colour in the online version.

1666 Figure 5. Correlation between largest thalli (longest axis) of species *Rhizocarpon*
1667 *geographicum* and *Porpidia* cf. *soredizodes* in several lichenometry stations. With the
1668 aim of avoiding those lichens potentially affected for any environmental factor
1669 disturbing their normal growth, the largest lichens used come from those lichenometry
1670 stations where no lichen size decrease with increasing distance to the terminus was
1671 observed (i.e., TUV-2, TUV-4, TUV-5, TUV-6, TUV-2, TUE-4 and TUE-5). From
1672 the measurements, it appears that *Porpidia* cf. *soredizodes* lichens grow faster than
1673 those of *Rhizocarpon geographicum*.

1674

1675 **Table captions**

1676 Table 1. Glacial Equilibrium-Line Altitudes (ELAs) calculated over
1677 Tungnahryggsjökull glaciers through the application of the AAR and AABR methods
1678 over the 3D glacier reconstructions.

1679 Table 2. Surface ages estimated from *Kugelmann's (1991)* 0.44 mm yr^{-1} growth rate for
1680 different colonization lags. The ages obtained from *Rhizocarpon geographicum* lichens
1681 discussed throughout the text are those derived from a 20-yr colonization lag. The
1682 figures in italics correspond to ages tentatively inferred from the largest *Porpidia*
1683 *soredizodes* lichen, assuming a 0.737 mm yr^{-1} growth rate and a 15-year colonization
1684 lag (see section 5.2.1).

1685 Table 3. ^{36}Cl CRE ages converted to CE/BCE dates according to the different ^{36}Cl
1686 production rates from Ca spallation. Uncertainties include the analytical and production
1687 rate error.

1688 **Supplementary figures captions**

1689 **SF1.** Examples of *Rhizocarpon geographicum* group and *Porpidia soredizodes* thalli
1690 measured over scaled field photos from the lichenometric station TUW-3. The lines
1691 refer to the minimum circle (white) bounding the thalli outlines (yellow) and the
1692 diameter of the circle (black). Note the contrasted size of the largest thalli in the
1693 different species.

1694 **SF2.** Location of the lichenometry stations in relation to the glacier snout position
1695 shown in the different aerial photographs and the satellite image. The lines refer to the
1696 glacier margin outlined over the aerial photo at a specific date (red) and at the previous
1697 date with aerial photo available (green dashed line). The points display the location of
1698 the lichenometry stations. The aerial photos provide the dating control for the validation
1699 of the lichenometric dates.

1700 **SF3.** Glacier surface reconstruction for the CRE- and lichenometry-dated glacial stages.

1701 **SF4.** Examples of moraine boulders sampled for ^{36}Cl CRE dating in Vesturdalur
1702 (“TUW” samples) and Austurdalur (“TUE” samples) and their dates derived from the
1703 [Licciardi et al. \(2008\)](#) ^{36}Cl production rate from Ca spallation.

1704 **SF5.** Location and BCE dates of the ^{36}Cl samples from the Elliði crest.

1705 **Supplementary tables captions.**

1706 ST1. Correspondence between glacial stages mapped over historical aerial photos and
1707 the dates.

1708 ST2. Glacier length and snout position variations measured along the flowline.

1709 ST3. Glacier extent and volume variations calculated from 2D and 3D glacier
1710 reconstructions.

1711 ST4. Size of the largest lichen at the lichenometry stations in the forelands of the
1712 western and eastern Tungnahryggsjökull glaciers.

1713 ST5. Geographic sample locations, topographic shielding factor, sample thickness and
1714 distance from terminus.

1715 ST6. Chemical composition of the bulk rock samples before chemical treatment. The
1716 figures in italic correspond to the average values of the bulk samples analysed and were
1717 those used for the age-exposure calculations of the samples without bulk chemical
1718 composition analysis.

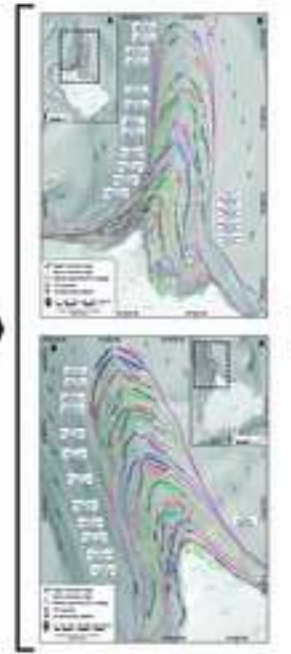
1719 ST7. Concentrations of the ^{36}Cl target elements Ca, K, Ti and Fe, determined in splits
1720 taken after the chemical pre-treatment (acid etching).

1721 ST8. ^{36}Cl analytical data and CRE dating results according to different ^{36}Cl production
1722 rates from Ca spallation. $^{36}\text{Cl}/^{35}\text{Cl}$ and $^{35}\text{Cl}/^{37}\text{Cl}$ ratios were inferred from measurements
1723 at the ASTER AMS facility. The numbers in italic correspond to the internal
1724 (analytical) uncertainty at 1σ level.

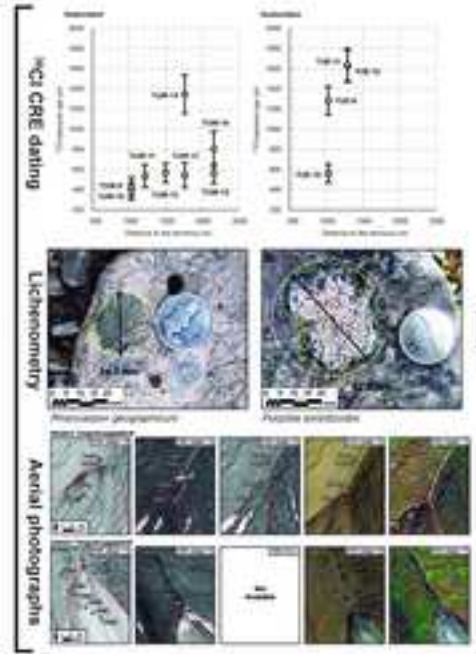
Tröllaskagi Peninsula (Northern Iceland) and the Tungnahryggsjökull glaciers



Glacial landforms and geomorphological mapping



Dating of glacial stages and study of the recent evolution



Reconstruction of the Late Holocene glacier fluctuations



Highlights

- A multi-disciplinary approach reconstructs Late Holocene glacial evolution.
- High-detail moraine mapping was done for two glacier forelands.
- Late Holocene glacial maximum occurred prior to the Little Ice Age.
- Maximum Little Ice Age glacial culminations were prior to the 19th century.
- *Porpidia soledizodes* species is tested for lichenometric dating.

1 **Abstract**

2 The Tröllaskagi Peninsula in northern Iceland hosts more than a hundred small glaciers
3 that have left a rich terrestrial record of Holocene climatic fluctuations in their
4 forelands. Traditionally, it has been assumed that most of the Tröllaskagi glaciers
5 reached their Late Holocene maximum extent during the Little Ice Age (LIA). However,
6 there is evidence of slightly more advanced pre-LIA positions. LIA moraines from
7 Iceland have been primarily dated mostly through lichenometric dating, but the limitations
8 of this technique do not allow dating of glacial advances prior to the 18th or 19th
9 centuries. The application of ³⁶Cl Cosmic-Ray Exposure (CRE) dating to
10 Tungnahryggsjökull moraine sequences in Vesturdalur and Austurdalur (central
11 Tröllaskagi) has revealed a number of pre-LIA glacial advances at ~400 and ~700 CE,
12 and a number of LIA advances in the 15th and 17th centuries, the earliest LIA advances
13 dated so far in Tröllaskagi. This technique hence shows that the LIA chronology in
14 Tröllaskagi agrees with that of other European areas such as the Alps or the
15 Mediterranean mountains. The combined use of lichenometric dating, aerial
16 photographs, satellite images and fieldwork shows that the regional colonization lag of
17 the commonly used lichen species *Rhizocarpon geographicum* is longer than previously
18 assumed. For exploratory purposes, an alternative lichen species (*Porpidia soredizodes*)
19 has been tested for lichenometric dating, estimating a tentative growth rate of 0.737 mm
20 yr⁻¹.

21 **1. Introduction**

22 The Tröllaskagi Peninsula (northern Iceland) hosts over 160 small alpine cirque glaciers
23 ([Björnsson, 1978](#); see synthesis in [Andrés et al., 2016](#)). Only a few of these small
24 glaciers do not have supraglacial debris cover that allows them to react quickly to small
25 climatic fluctuations ([Caseldine, 1985b](#); [Häberle, 1991](#); [Kugelmann, 1991](#)), compared to

26 the reduced dynamism of the predominant rock glaciers and debris-covered glaciers
27 ([Martin et al., 1991](#); [Andrés et al., 2016](#); [Tanarro et al., 2019](#)). As a result of their high
28 sensitivity to climatic changes, the few debris-free glaciers in Tröllaskagi fluctuated
29 repeatedly in the past, forming a large number of moraines in front of their termini (see
30 [Caseldine, 1983, 1985b, 1987](#); [Kugelmann, 1991](#) amongst others). However, the
31 relation between glacier fluctuations and the climate is complicated due to: (i) the well-
32 known surging potential activity in Tröllaskagi ([Brynjólfsson et al., 2012](#); [Ingólfsson et](#)
33 [al., 2016](#)); (ii) the possibility of glaciers being debris-covered in the past, with the
34 subsequent change of their climate sensitivity over time; (iii) the intense and dynamic
35 slope geomorphological activity, paraglacial to a great extent ([Jónsson, 1976](#); [Whalley](#)
36 [et al., 1983](#); [Mercier et al., 2013](#); [Cossart et al., 2014](#); [Feuillet et al., 2014](#); [Decaulne and](#)
37 [Sæmundsson, 2006](#); [Sæmundsson et al., 2018](#)) that hides and erases the previous glacial
38 features.

39 In Iceland, a great part of the research on glacial fluctuations during the late Holocene,
40 LIA ([Grove, 1988](#); 1250-1850 CE, see [Solomina et al., 2016](#)) and later stages has been
41 approached through application of radiocarbon dating of organic material, analyzing
42 lake sediment varves ([Larsen et al., 2011](#); [Striberger et al., 2012](#)), dead vegetation
43 remnants ([Harning et al., 2018](#)) and threshold lake sediment records ([Harning et al.,](#)
44 [2016b](#); [Schomacker et al., 2016](#)). These provide high-resolution records of glacier
45 variability. In Tröllaskagi, very few reliable dates exist at present, obtained from
46 radiocarbon and tephrochronology ([Häberle, 1991, 1994](#); [Stötter, 1991](#); [Stötter et al.,](#)
47 [1999](#); [Wastl and Stötter, 2005](#)). They suggest that late Holocene glaciers were slightly
48 more advanced than during the LIA maximum in Tröllaskagi. However, these
49 techniques only provide minimum or maximum ages for Holocene glacier history in
50 northern Iceland ([Wastl and Stötter, 2005](#)). In addition, at Tröllaskagi most of the

51 moraines are at 600-1000 m a.s.l., where the applicability of tephrochronology is very
52 limited (Caseldine, 1990) due to the great intensity of slope geomorphological
53 processes.

54 In any case, most of the moraine datings of Tröllaskagi –especially those of the last
55 millenium– comes from lichenometry (see synthesis in Decaulne, 2016). However, the
56 ages derived from this technique tend to be younger if they are compared to those
57 estimated from tephra layers (Kirkbride and Dugmore, 2001). Generally, there is
58 disagreement about the validity of the results provided by lichenometry, due to the
59 difficulty of the lichen species identification in the field, the complexity and reliability
60 of the sampling and measurement strategies, the uncertainty estimates, the nature of the
61 ages provided as relative, as well as the relative reliability at producing lichen growth
62 curves of the different species, with an extreme dependence on local environmental
63 factors (see Osborn et al., 2015).

64 In fact, these problems had already been detected in northern Iceland, where in spite of
65 the time elapsed since the first applications of this technique (Jaksch, 1970, 1975, 1984;
66 Gordon and Sharp, 1983; Maizels and Dugmore, 1985) and contrasting with its
67 widespread use in the south and southeast of the island (Thompson and Jones, 1986;
68 Evans et al., 1999; Russell et al., 2001; Kirkbride and Dugmore, 2001; Bradwell, 2001,
69 2004a; Harris et al., 2004; Bradwell and Armstrong, 2006; Orwin et al., 2008; Chenet et
70 al., 2010 and others), there are still very few established growth rates for the lichen
71 group *Rhizocarpon geographicum* (Roca-Valiente et al., 2016) from Tröllaskagi
72 (Caseldine, 1983; Häberle, 1991; Kugelmann, 1991; Caseldine and Stötter, 1993; see
73 synthesis in Decaulne, 2016). In general, the growth curves from Tröllaskagi suffer
74 from a few control points (i.e. surfaces of known age) for calibration. This leads to
75 considerable underestimation when lichen thalli sizes are beyond the calibration growth

76 curve (Caseldine, 1990; see e.g. Caseldine, 1985b; Caseldine and Stötter, 1993;
77 Kugelmann, 1991). That is to say, the extrapolation does not account for the decreasing
78 growth rate with increasing age (i.e. non-linear growth). Kugelmann's (1991) growth
79 curve has the highest number of control points to date (19 in total). In addition, the
80 colonization lag in Tröllaskagi is poorly defined, although 10-15 years have been
81 assumed for the *Rhizocarpon geographicum* (Caseldine, 1983; Kugelmann, 1991).
82 Other issues, such as the absence of large thalli (Maizels and Dugmore, 1985), lichen
83 saturation (e.g. Wiles et al., 2010), and other environmental factors (Innes, 1985 and
84 references included; Hamilton and Whalley, 1995) contribute to appreciable age
85 underestimations when dating surfaces using this approach. Snow is also a major
86 environmental factor for lichenometry in Iceland due to its long residence time on the
87 ground (Dietz et al., 2012) and the avalanching frequency –especially in Tröllaskagi–,
88 whose effect restricts the growth rate of lichens, and even destroys them (Sancho et al.,
89 2017). These problems considerably limit the quality (reliability) of the lichenometric
90 dating range of utility for applying lichenometric dating in Iceland, where the oldest
91 ages estimated so far are between 160 and 220 years (Maizels and Dugmore, 1985;
92 Thompson and Jones, 1986; Evans et al., 1999), thus preventing the dating of glacial
93 advances prior to the 18th century.

94 In spite of the high uncertainty of the lichenometric dating, many authors working in
95 Tröllaskagi have treated their lichenometric results as absolute ages (see Caseldine,
96 1983, 1985b, 1987; Kugelmann, 1991; Häberle, 1991; Caseldine and Stötter, 1993,
97 amongst others). In fact, previously considered dates of LIA maximum glacier
98 culmination are restricted to the very late 18th and early 19th centuries (Caseldine, 1983,
99 1985b, 1987; Kugelmann, 1991; Caseldine and Stötter, 1993; Caseldine, 1991; Martin
100 et al., 1991), very close to the applicability threshold of this method. Consequently, no

101 evidence of previous advances during phases of the LIA that were more conducive to
102 glacier expansion (probably colder; see e.g. [Ogilvie, 1984, 1996](#); [Ogilvie and Jónsdóttir,](#)
103 [2000](#); [Ogilvie and Jónsson, 2001](#)) has been found ([Kirkbride and Dugmore, 2001](#)).

104 In the recent years, dating methods based on the Exposure to the Cosmic-Rays (CRE)
105 have been introduced successfully to date moraines of the last millennium, and even
106 formed during the LIA ([Schimmelpfennig et al., 2012, 2014](#); [Le Roy et al., 2017](#);
107 [Young et al., 2015](#); [Jomelli et al., 2016](#); [Li et al., 2016](#); [Dong et al., 2017](#); [Palacios et](#)
108 [al., 2018](#)). The cosmogenic nuclides ^{36}Cl and ^3He have been applied previously in
109 northern Iceland to date the Pleistocene deglaciation. [Principato et al. \(2006\)](#) studied the
110 deglaciation of Vestfirðir combining ^{36}Cl CRE dating of moraine boulders and bedrock
111 surfaces with marine records and tephra marker beds. [Andrés et al. \(2018\)](#) reconstructed
112 the deglaciation at the Late Pleistocene to Holocene transition at Skagafjörður through
113 ^{36}Cl CRE dating applied to polished surfaces along a transect from the highlands to the
114 mouth of the fjord. [Brynjólfsson et al. \(2015b\)](#) applied the same isotope to samples
115 coming from the highlands and the fjords to reconstruct the glacial history of the
116 Drangajökull region. The other cosmogenic isotope used is ^3He , applied to helium-
117 retentive olivine phenocrysts by [Licciardi et al. \(2007\)](#) to determine eruption ages of
118 Icelandic table mountains and to reconstruct the volcanic history and the thickness
119 evolution of the Icelandic Ice Sheet during the last glacial cycle. However, CRE dating
120 has not yet been applied to the late Holocene glacial landforms both in Iceland as a
121 whole and the Tröllaskagi Peninsula. CRE dating is an alternative to the use of high-
122 resolution continuous lacustrine records in northern Iceland, given the rarity of lakes in
123 this peninsula, which limits the application of radiocarbon to date the deglaciation
124 processes ([Striberger et al., 2012](#); [Harning et al., 2016b](#)).

125 Nevertheless, CRE dating methods approach the nuclides' detection limit when applied
126 to very recent moraines (Marrero et al., 2016; Jomelli et al., 2016). This issue precludes
127 the application of CRE dating to the abundant post-LIA moraines existing in some of
128 the Tröllaskagi valleys whose headwalls are occupied by climate-sensitive debris-free
129 glaciers (Caseldine and Cullingford, 1981; Caseldine, 1983,1985b; Kugelmann, 1991;
130 Fernández-Fernández et al., 2017). Dating these post-LIA moraines allows to
131 reconstruct recent climate evolution, and even to match and assess the climate
132 reconstructions with the instrumental climate records (see Dahl and Nesje, 1992;
133 Caseldine and Stötter, 1993; Fernández-Fernández et al., 2017). Furthermore, improving
134 the knowledge of the recent evolution of alpine mountain glaciers, such as those of
135 Tröllaskagi, is fundamental in the assessment of present global warming (Marzeion et
136 al., 2014)

137 The use of aerial photographs from different dates is a reliable approach to the glacier
138 evolution during the last decades (Fernández-Fernández et al., 2017; Tanarro et al.,
139 2019). The main advantage of this technique is the possibility of studying the evolution
140 of glacier snouts in recent dates with high accuracy. In fact, there is no dependence on
141 the glacial features (i.e. moraines), which circumvents moraine deterioration issues
142 derived by the geomorphological activity of the slopes. However, the main shortcoming
143 of the aerial photo imagery is the availability only on few dates, at least in Tröllaskagi.
144 This circumstance makes it impossible to obtain the glacier fluctuations with a high
145 time resolution (i.e. only the periods between the available aerial photos; Fernández-
146 Fernández et al., 2017; Tanarro et al., 2019), and hence to match them to short-term
147 (decadal scale) climate fluctuations that are known to exert a major control especially
148 on small mountain glaciers with short time responses (see Caseldine, 1985b;
149 Sigurðsson, 1998; Sigurðsson et al., 2007; Fernández-Fernández et al., 2017). The only

150 way to fill the gap between two dates with available aerial photos is through applying
151 lichenometric dating (Sancho et al., 2011), as there is no tree species suitable to apply
152 dendrochronology. In addition, the information provided by the aerial photo imagery
153 (i.e. glacier snout position) constrains the period when the lichens appear and begin to
154 grow, which circumvents many of the criticisms made on lichenometry (see Osborn et
155 al., 2015).

156 Moreover, a detailed geomorphological mapping allows for identification of stable
157 moraines, not remobilized or destroyed by glacier advances or slope processes
158 (avalanches, slope deformations, debris-flows, etc.) and also to reconstruct the glacier
159 snout geometry throughout different phases (see Caseldine, 1981; Bradwel, 2004b;
160 Principato et al., 2006 amongst others). The analysis of the moraine morphology and the
161 glacial features on the forelands is a key tool to confirm whether the glaciers were
162 debris-free or debris-covered in the past (Kirkbride, 2011; Janke et al., 2015; Knight, et
163 al., 2018, amongst others) as this issue determines their climate sensitivity (see
164 Fernández-Fernández et al., 2017; Tanarro et al., 2019).

165 The western and eastern Tungnahryggsjökull glaciers, in the Vesturdalur and
166 Austurdalur Valleys (central Tröllaskagi), respectively (Fig. 1), are two of the few
167 debris-free glaciers –or almost debris-free in the case of the western glacier– of the
168 peninsula that are both small and highly sensitive to climatic fluctuations (Fernández-
169 Fernández et al., 2017). This makes them ideal for studying glacial and climatic
170 evolution during last last millennia.

171 The aim of our work was to apply the best methodology possible to analyze the glacial
172 evolution of western and eastern Tungnahryggsjökull glaciers during the last millennia
173 to the present. Applying for the first time a number of dating techniques to study the
174 Late Holocene evolution of the two glaciers, the objectives of this paper are:

175 (i) To carry out a detailed geomorphological survey of the glacier forelands in order to
176 map accurately well-preserved glacial features. This mapping is used both to devise the
177 sampling strategy for dating, and also to reconstruct the palaeoglaciers in 3D in order to
178 obtain glaciologic climate indicators such as the Equilibrium-Line Altitudes (ELAs).
179 These can be used as a proxy to infer palaeoclimatic information (see [Dahl and Nesje,](#)
180 [1992](#); [Caseldine and Stötter, 1993](#); [Brugger, 2006](#); [Hughes et al., 2010](#); [Fernández-](#)
181 [Fernández et al., 2017](#) amongst others).

182 (ii) To use aerial photographs / satellite imagery post-dating 1946 to map the glacier
183 extent in each available date in order to improve the information of ELA evolution in
184 the recent decades. Aerial photographs will be used to constrain the possible periods of
185 lichen colonization and growth over stable boulders, and will be useful to identify
186 phases of advance, stagnation or retreat of the glacier snouts. By this way we will
187 complete the glacier evolution from pre-instrumental glacial stages (identified from
188 geomorphological evidence, i.e. moraines) to their current situation.

189 (iii) To apply CRE dating when possible depending on the preservation degree of the
190 glacial features, and when moraines were too old to be dated by lichenometry.

191 (iv) To apply lichenometric relative dating to recent moraines or those where CRE
192 dating might not be suitable (i.e. limit of applicability) and provided that: 1) the
193 geomorphological criteria evidence a good preservation of glacial features; and 2) aerial
194 photographs constrain the earliest and oldest possible lichen ages. This approach will
195 also allow to check the growth rates and colonization lags of the lichen species usually
196 used in Iceland for lichenometric dating purposes.

197 The experimentation and validation of this methodological purpose will help to improve
198 the knowledge of the recent climate evolution of northern Iceland. This is of maximum

199 interest if we consider its location within the current atmospheric and oceanic setting,
200 strongly linked to the evolution of the Meridional Overturning Circulation ([Andrews](#)
201 [and Giraudeau, 2003](#); [Xiao et al., 2017](#)), a key factor in the studies for the assessment of
202 the global climate change effects ([Barker et al., 2010](#); [Chen et al., 2015](#) amongst others).
203 Moreover, if this proposal is valid, it could be applied to the research on the recent
204 evolution of other mountain glaciers similar to those of Tröllaskagi. This aspect is a
205 main research objective at present, as these glaciers represent the greatest contribution
206 to the current sea-level rise ([Jacob et al., 2012](#); [Gardner et al., 2013](#) amongst others).

207 **2. Regional setting**

208 The Tröllaskagi Peninsula extends into the Atlantic Ocean at 66°12' N from the central
209 highland plateau (65°23' N) of Iceland ([Fig. 1](#)). The fjords of Skagafjörður (19°30' W)
210 and Eyjafjörður (18°10' W) separate it from the Skagi and Flateyjarskagi peninsulas,
211 respectively. Tröllaskagi is an accumulation of successive Miocene basalt flows,
212 interspersed with reddish sedimentary strata ([Sæmundsson et al., 1980](#); [Jóhannesson](#)
213 [and Sæmundsson, 1989](#)). The plateau culminates at altitudes of 1000-1500 m a.s.l. (with
214 the highest peak Kerling at 1536 m a.s.l.) and is dissected by deep valleys with steep
215 slopes whose headwaters are currently glacial cirques. These cirques host more than 160
216 small glaciers, mostly north-facing, resulting from the leeward accumulation of snow
217 from the plateau ([Caseldine and Stötter, 1993](#)) and reduced exposure to solar radiation.
218 In fact, deposits caused by rock-slope failure are common in Tröllaskagi valley slopes
219 and have been considered a result of the final deglaciation during the early Holocene
220 ([Jónsson, 1976](#); [Feuillet et al., 2014](#); [Cossart et al., 2014](#); [Coquin et al., 2015](#)). Most of
221 the glaciers are rock or debris-covered glaciers, due to the intense paraglacial activity
222 affecting the walls that minimizes cosmogenic nuclide concentrations from earlier
223 exposure periods on the cirque headwalls ([Andrés et al, 2018](#)).

224 The climate in Tröllaskagi is characterized by a mean annual air temperature (MAAT;
225 1901-1990 series) of 2 to 4 °C at sea level, dropping to between -2 and -4 °C at the
226 summits (Etzelmüller et al., 2007). At the town of Akureyri, located in the east of the
227 peninsula at the mouth of Eyjafjarðardalur (Fig. 1), the MAAT is 3.4 °C and the average
228 temperature in the three summer months is about 9 to 10 °C (Einarsson, 1991). Annual
229 precipitation (1971-2000) ranges from 400 mm at lower altitudes to 2500 mm at the
230 summits (Crochet et al., 2007).

231 The frontier location of Icelandic glaciers in relation to atmosphere and ocean systems
232 (warm/moist Subtropical and cold/dry Arctic air masses; and the warm Irminger and
233 cold East Greenland sea currents) makes them exceptionally sensitive to climate
234 oscillations (Bergþórsson, 1969; Flowers et al., 2008; Geirsdóttir et al., 2009), and these
235 debris-free glaciers are thus reliable indicators of climatic evolution and the impact of
236 climate change on the cryosphere (see Jóhannesson and Sigurðsson, 1998; Bradwell,
237 2004b; Sigurðsson, 2005; Geirsdóttir et al., 2009; Fernández-Fernández et al., 2017).

238 The glaciers studied here are the western (6.5 km²) and eastern (3.9 km²)
239 Tungnahryggsjökull, located in the Vesturdalur and Austurdalur valleys respectively,
240 separated from each other by the crest of Tungnaryggur, and tributaries of the
241 Kolbeinsdalur Valley (Fig. 1).

242 **3. Methodology**

243 *3.1 Geomorphological mapping and glacier geometry mapping*

244 Four summer field campaigns (2012, 2013, 2014 and 2015) were conducted in
245 Vesturdalur and Austurdalur, with the objective of identifying moraines that clearly
246 provided evidence of various glacial culminations of the western and eastern
247 Tungnahryggsjökull glaciers. We identified the palaeo-positions of the glacier snouts,

248 the glacier geometry and extent through photo interpretation of stereoscopic pairs and
249 previous fieldwork. Mapping of glacial and non-glacial landforms was conducted on
250 two enlarged 50-cm-resolution aerial orthophotos ([National Land Survey of Iceland,](#)
251 [2015](#)) plotted at scale $\approx 1:7000$. These maps were imported into an ArcGIS 1.4.1
252 database after geo-referencing. Finally, all the glacial linear landforms were digitized,
253 and where the moraines were prominent, continuous, or well-preserved, they were
254 assumed to represent major culminations, and hence, glacial stages. In addition to the
255 geomorphological evidence, glacier variations in recent years were mapped, based on
256 the photo interpretation of four historical aerial photographs from 1946, 1985, 1994 and
257 2000 ([National Land Survey of Iceland, 2015](#)), and also one SPOT satellite image
258 (2005), previously geo-referenced in ArcGIS. For more details of the aerial photograph
259 processing, see [Fernández-Fernández and Andrés \(2018\)](#). As the glacier headwalls are
260 ice diffluences in both cases, it was assumed that: (i) the ice divides are the upper
261 boundaries of the glaciers for the different stages, and (ii) the ice divide is invariant for
262 the different stages/dates, following [Koblet et al. \(2010\)](#) as changes in the extent of the
263 accumulation zone are smaller than the outlining differences derived from the operator
264 mapping. Likewise, in the case of the upper glacier edge constrained by the cirque wall,
265 the glacier geometry was also assumed to be invariant from stage to stage unless the
266 aerial photographs showed otherwise.

267 *3.2 Glacier reconstruction and equilibrium-line altitude (ELA) calculation*

268 [Benn and Hulton's \(2010\)](#) glacier reconstruction approach using a physical-based model
269 describing ice rheology and glacier flow ([Van der Veen, 1999](#)) was preferred to
270 arbitrary hand-drawn contouring (e.g. [Sissons, 1974](#)) in order to achieve more robust
271 reconstructions ([Fernández-Fernández and Andrés, 2018](#)). This model operates on
272 deglaciated areas with non-extant glaciers. As this is not the case in our study area, we

273 approached the glacier bedrock by tentatively estimating the ice thickness' spatial
274 distribution on the two glaciers studied. The "VOLTA" ("Volume and Topography
275 Automation") ArcGIS toolbox (James and Carrivick, 2016) was applied with the default
276 parameters. It only requires the glacier outline and its digital elevation model (DEM). In
277 the first step, the tool "volta_1_2_centrelines" creates the glacier centrelines, and then
278 the tool "volta_1_2_thickness" estimates ice thickness at points along them, assuming
279 perfect-plasticity rheology, and interpolates the values using a glaciologically correct
280 routine. The final result is an ice-free DEM in which we reconstructed the glacier. The
281 former glacier surface topographies at the different stages/dates were reconstructed
282 applying the semi-automatic "GLaRe" ArcGIS toolbox designed by Pellitero et al.
283 (2016), which implements the Benn and Hulton (2010) numerical model and estimates
284 ice-thickness along glacier flowlines. To simplify the glacier surface modelling, shear-
285 stress was assumed to be constant along the glacier flowline and over time. Using the
286 value 110 kPa for the shear-stress resembles best the current longitudinal profile of the
287 glaciers in the Benn and Hulton (2010) spreadsheet. This value can be considered
288 appropriate as it falls within the normal shear-stress range of 50-150 kPa observed in
289 current glaciers and is very close to the standard value of 100 kPa (Paterson, 1994). The
290 glacier contours were manually adjusted to the ice surface elevation values of the ice-
291 thickness points estimated by "GLaRe" instead of using an interpolation routine, to
292 obtain a more realistic surface (concave and convex contours above and below the
293 ELA).

294 Finally, we calculated the ELAs automatically by using the "ELA calculation" ArcGIS
295 toolbox (Pellitero et al., 2015). The methods comprised: (i) AABR (Area Altitude
296 Balance Ratio; Osmaston, 2005) with the ratio 1.5 ± 0.4 proposed for Norwegian glaciers
297 by Rea (2009) and successfully tested on Tröllaskagi debris-free glaciers in Fernández-

298 [Fernández et al. \(2017\)](#); and (ii) the AAR (Accumulation Area Ratio) with the ratio 0.67
299 previously used by [Stötter \(1990\)](#) and [Caseldine and Stötter \(1993\)](#) for Tröllaskagi
300 glaciers. Alternative approaches for ELA calculation in northern Iceland have been
301 carried out by considering morphometric parameters of glacial cirques (altitude ratio,
302 cirque floor, minimum point; [Ipsen et al., 2018](#)). However, we preferred the methods
303 considering the glacier hypsometry as they reflect more evident changes from stage to
304 stage ([Fernández-Fernández et al., 2017](#); [Fernández-Fernández and Andrés, 2018](#)), if
305 compared to morphometric parameters of the cirques. In this sense, the cirque floor
306 elevation is derived from the last erosion period, and it is impossible to know the values
307 corresponding to previous glacial stages.

308 *3.3 Lichenometric dating procedures*

309 Lichenometry was used as a relative dating tool, assuming that the lichens increase in
310 diameter with respect to age. The results aim to complete the age control (of recent
311 landforms non suitable for CRE dating) on the periods between aerial photos of known
312 date as it has been applied successfully to control lichen ([Sancho et al., 2011](#)) and
313 bryophyte ([Arróniz-Crespo et al., 2014](#)) growth during primary succession in recently
314 deglaciaded surfaces. First, we surveyed the moraines thoroughly, starting from the
315 current glacier snouts downwards, looking for large stable boulders (i.e. well embedded
316 in the moraine, not likely of having been overturned or remobilized by slope processes
317 which could have affected lichen growth, e.g. snow avalanches, debris-flows, rockfall,
318 landslides or debris-flows) with surfaces valid for dating (not weathered or resulting
319 from block break). Lichenometry was applied to date moraine ridge boulders with the
320 following criteria and assumptions: (i) boulders must clearly belong to the moraine
321 ridge; (ii) lichen species should be abundant enough to allow measurements of a number
322 of thalli at each location and hence enable surfaces to be dated under favourable

323 environmental conditions such as basaltic rocks in subpolar mountains; (iii) only the
324 largest lichen (circular or ellipsoidal thalli) of species *Rhizocarpon geographicum*,
325 located on smooth horizontal boulder surfaces, was measured; (iv) the lichenometric
326 procedures should not be applied when the lichen thalli coalesce on the boulder surface
327 and individual thalli cannot be identified. We preferred the geomorphological criterion
328 (stability vs. slope processes) to the establishment of lichenometry plots of a fixed area
329 (e.g. [Bickerton and Matthews, 1992](#)) to ensure that lichens were measured on reliable
330 boulders. This measurement strategy tries to circumvent or at least to minimize the
331 specific problems of Tröllaskagi when dating glacial features so that: (i) snow
332 accumulation should be lower in the moraine crest; (ii) lichen ages will be estimated
333 only for the boulders located on the crests used to map and reconstruct the glaciers; and
334 (iii) and lichens subjected to thalli saturation (coalescence) or high competition are not
335 measured.

336 First, *Rhizocarpon geographicum* lichens were measured with a Bernier calibrator.
337 Then, digital photographs for high-precision measurements were taken of the most
338 representative of the largest thallus located in each selected boulder ([Suppl. figure SF1](#)),
339 using an Icelandic króna coin (21 mm diameter) parallel to the surface of the lichen as a
340 graphic scale. We preferred the single largest lichen approach as previously has been
341 done in Tröllaskagi for lichenometric dating of moraines ([Caseldine, 1983, 1985b,](#)
342 [1987; Kugelmann, 1991](#)). The photos were scaled in ArcGIS to real size and lichen
343 thalli were outlined manually through visual inspection of the photos and measured
344 automatically with high accuracy according to the diameter of the smallest circle which
345 can circumscribe the lichen outline ([Suppl. figure SF1](#)). We preferred the simple
346 geometrical shape of the circle and its diameter to identify the largest axis to circumvent

347 the problem of complex-shaped lichens. Similar procedures for lichen thalli
348 measurement from photographs are outlined in [Hooker and Brown \(1977\)](#).

349 Then, we initially applied a 0.44 mm yr^{-1} constant growth rate and a 10-year
350 colonization lag ([Kugelmann, 1991](#)) to the measurement of the largest *Rhizocarpon*
351 *geographicum* lichen (longest axis). This growth rate is derived from the lichen growth
352 curve with the highest number of control points so far in Tröllaskagi ([Kugelmann,](#)
353 [1991](#)), and it is very similar to that reported from the near Hörgárdalur valley ([Häberle,](#)
354 [1991](#)). However, the authors are aware that using a constant growth rate implies not
355 taking account the growth rate decline with increasing age. Other longer colonization
356 lags of 15, 20, 25 and 30 years were added to the age estimate from the growth rate in
357 order to test the colonization lag originally assumed by [Kugelmann \(1991\)](#), on the
358 suspicion of longer colonization lags reported elsewhere ([Caseldine, 1983](#); [Evans et al.,](#)
359 [1999, Table 1](#)). The resulting ages were compared to the dates of historical aerial
360 photographs where the glacier snout positions constrain the maximum and minimum
361 ages of the lichen stations.

362 In the case of *Porpidia cf. soredizodes*, since no growth rate value has been described so
363 far, a value will be tentatively estimated in this study. For this reason, we took
364 measurements of the two species in the same sampling locations wherever possible. It
365 should be noted that visual distinction between *Porpidia cf. soredizodes* and *Porpidia*
366 *tuberculosa* is not always conclusive based on morphological characteristics, but we
367 feel confident using the measurements of the *Porpidia cf. soredizodes* we identified in
368 the field.

369 *3.4 ³⁶Cl Cosmic-Ray Exposure (CRE) dating*

370 Where the thalli either coalesced and prevented identification of the largest thallus or
371 dating results indicated that a moraine was too old to be dated by this method, rock
372 samples were collected for CRE dating. The criteria for boulder and surface selection
373 where the same as for lichenometric purposes: stable boulders with no signs of being
374 affected by slope processes (landslides, debris-flows) or postglacial overturning, well
375 embedded in the moraine, and with no sign of surface weathering or previous boulder
376 break. The cosmogenic nuclide ^{36}Cl was chosen because of the basalt lithology
377 ubiquitous in Iceland, which lacks quartz, which is needed for standard ^{10}Be CRE
378 methods. Using a hammer and chisel, samples were collected from flat-topped surfaces
379 of moraine boulders. In order to obtain a maximum time constraint for the deglaciation
380 of both surveyed valleys, two samples were taken from Elliði (Fig. 1), a glacially
381 polished ridge downstream from the Tungnahryggsjökull forelands separating
382 Kolbeinsdalur to the north and Viðinesdalur to the south. The laboratory procedures
383 applied for ^{36}Cl extraction from silicate whole rock samples were those described in
384 Schimmelpfennig et al. (2011). Note that the samples had not enough minerals to
385 perform the ^{36}Cl extraction on mineral separates, which is generally the preferred
386 approach to minimize the uncertainties in age exposure estimates, as in mineral
387 separates ^{36}Cl is often produced by less and better known production pathways than in
388 whole rock samples (Schimmelpfennig et al., 2009). The samples were crushed and
389 sieved to 0.25-1 mm in the Physical Geography Laboratory in the Complutense
390 University, Madrid. Chemical processing leading to ^{36}Cl extraction from the whole rock
391 was carried out at the Laboratoire National des Nucléides Cosmogéniques (LN₂C) at the
392 Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement
393 (CEREGE), Aix-en-Provence (France). Initial weights of about 120 g per sample were
394 used. A chemically untreated split of each sample was set aside for analyses of the

395 chemical composition of the bulk rocks at CRPG-SARM. First, the samples were rinsed
396 to remove dust and fines. Then, 25-30% of the mass was dissolved to remove
397 atmospheric ^{36}Cl and potentially Cl-rich groundmass by leaching with a mixture of
398 ultra-pure dilute nitric (10% HNO_3) and concentrated hydrofluoric (HF) acids. In the
399 next step, 2 g aliquots were taken to determine the major element concentrations; these
400 were analysed by ICP-OES at CRPG-SARM. Then, before total dissolution, $\sim 260 \mu\text{L}$ of
401 a ^{35}Cl carrier solution (spike) manufactured in-house (concentration: 6.92 mg g^{-1} ;
402 $^{35}\text{Cl}/^{37}\text{Cl}$ ratio: 917) were added to the sample for isotope dilution (Ivy-Ochs et al.,
403 2004). Total dissolution was achieved with excess quantities of the above mentioned
404 acid mixture. Following total dissolution, the samples were centrifuged to remove the
405 undissolved residues and gel (fluoride complexes such as CaF_2). Next, chlorine was
406 precipitated to silver chloride (AgCl) by adding 2 ml of silver nitrate (AgNO_3) solution
407 at 10%. After storing the samples for two days in a dark place to allow the AgCl to
408 settle on the bottom, the supernatant acid solution was extracted by a peristaltic pump.
409 To reduce the isobaric interferences of ^{36}S during the ^{36}Cl AMS measurements, the first
410 precipitate was re-dissolved in 2 ml of ammonia ($\text{NH}_3 + \text{H}_2\text{O}$ 1:1 vol \rightarrow NH_4OH), and 1
411 ml of a saturated solution of barium nitrate ($\text{Ba}(\text{NO}_3)_2$) was added to the samples to
412 precipitate barium sulphate (BaSO_4). It was removed by centrifuging and filtering the
413 supernatant with a syringe through acrodisc filters. AgCl was precipitated again with 3-
414 4 ml of diluted HNO_3 (1:1 vol). The precipitate was collected by centrifuging, rinsed,
415 and dried in an oven at $80 \text{ }^\circ\text{C}$ for 2 days.

416 The final AgCl targets were analysed by accelerator mass spectrometry (AMS) to
417 measure the $^{35}\text{Cl}/^{37}\text{Cl}$ and $^{36}\text{Cl}/^{35}\text{Cl}$ ratios, from which the Cl and ^{36}Cl concentration
418 were inferred. The measurements were carried out at the Accélérateur pour les Sciences
419 de la Terre, Environnement et Risques (ASTER) at CEREGE in March 2017 using

420 inhouse standard SM-CL-12 with an assigned value of $1.428 (\pm 0.021) \times 10^{-12}$ for the
421 $^{36}\text{Cl}/^{35}\text{Cl}$ ratio (Merchel et al., 2011) and assuming a natural ratio of 3.127 for the stable
422 ratio $^{35}\text{Cl}/^{37}\text{Cl}$.

423 When calculating exposure ages, the ExcelTM spreadsheet for in situ ^{36}Cl exposure age
424 calculations proposed by Schimmelpfennig et al. (2009) was preferred to other online
425 calculators (e.g. CRONUS Earth; Marrero et al., 2016) as it allows input of different
426 ^{36}Cl production rates from spallation, referenced to sea level and high latitude (SLHL).
427 Thus, three SLHL ^{36}Cl production rates from Ca spallation, i.e. the most dominant ^{36}Cl
428 production reaction in our samples, were applied to allow comparisons both with other
429 Icelandic areas (57.3 ± 5.2 atoms $^{36}\text{Cl} (\text{g Ca})^{-1} \text{yr}^{-1}$; Licciardi et al., 2008) and other areas
430 of the world (48.8 ± 3.4 atoms $^{36}\text{Cl} (\text{g Ca})^{-1} \text{yr}^{-1}$, Stone et al., 1996; 42.2 ± 4.8 atoms ^{36}Cl
431 $(\text{g Ca})^{-1} \text{yr}^{-1}$, Schimmelpfennig et al., 2011). For ^{36}Cl production reactions other than Ca
432 spallation, the following SLHL ^{36}Cl production parameters were applied: 148.1 ± 7.8
433 atoms $^{36}\text{Cl} (\text{g K})^{-1} \text{yr}^{-1}$ for K spallation (Schimmelpfennig et al., 2014b), 13 ± 3 atoms
434 $^{36}\text{Cl} (\text{g Ti})^{-1} \text{yr}^{-1}$ for Ti spallation (Fink et al., 2000), 1.9 ± 0.2 atoms $^{36}\text{Cl} (\text{g Fe})^{-1} \text{yr}^{-1}$ for
435 Fe spallation (Stone et al., 2005) and 696 ± 185 neutrons $(\text{g air})^{-1} \text{yr}^{-1}$ for the production
436 rate of epithermal neutrons for fast neutrons in the atmosphere at the land/atmosphere
437 interface (Marrero et al., 2016). Elevation-latitude scaling factors were based on the
438 time invariant “St” scheme (Stone et al., 2000). The high-energy neutron attenuation
439 length value applied was 160 g cm^{-2} .

440 All production rates from spallation of Ca mentioned above are based on calibration
441 samples with a predominant Ca composition. Iceland is permanently affected by a low-
442 pressure cell, the Icelandic Low (Einarsson, 1984). As the atmospheric pressure
443 modifies the cosmic-ray particle flux, and thus has an impact on the local cosmogenic
444 nuclide production rate, the atmospheric pressure anomaly has to be taken into account

445 when scaling the SLHL production rates to the study site. Only [Licciardi et al.'s \(2008\)](#)
446 production rate already accounts for this anomaly, as the calibration sites of study are
447 located in south western Iceland (see also [Licciardi et al., 2006](#)). On the other hand,
448 [Stone et al.'s \(1996\)](#) and [Schimmelfennig et al.'s \(2011\)](#) production rates were
449 calibrated in Tabernacle Hill (Utah, western U.S.A.) and Etna volcano (Italy),
450 respectively, hence they need to be corrected for the atmospheric pressure anomaly
451 when applied in Iceland. [Dunai \(2010\)](#) advises including any long-term atmospheric
452 pressure anomaly at least for Holocene exposure periods. Therefore, the local
453 atmospheric pressure at the sample locations was applied in the scaling factor
454 calculations when using the [Stone et al. \(1996\)](#) and [Schimmelfennig et al. \(2011\)](#)
455 production rates. Instead of the standard value of 1013.25 hPa at sea level, a sea level
456 value of 1006.9 hPa (Akureyri meteorological station; [Icelandic Meteorological Office,](#)
457 [2018](#)) was used. The atmospheric pressure correction assumed a linear variation of
458 temperature with altitude. The results presented and discussed below are based on the
459 ^{36}Cl production rate for Ca spallation of [Licciardi et al. \(2008\)](#) as it is calibrated for
460 Iceland and considers the atmospheric pressure anomaly. The exposure ages presented
461 throughout the text and figures include analytical and production rate errors unless
462 stated otherwise. Our <2000 yr CRE ages have also been rounded to the nearest decade,
463 and then converted to CE dates through their subtraction from the year 2015 (i.e.
464 fieldwork and sampling campaign). In order to achieve robust comparisons of our
465 results with those obtained by radiocarbon or tephrochronology, we have calibrated the
466 ^{14}C ages previously published in the literature through the OxCal 4.3 online calculator
467 (<https://c14.arch.ox.ac.uk/oxcal/OxCal.html>) implementing the IntCal13 calibration
468 curve ([Reimer et al., 2013](#)).

469 **4. Results**

470 *4.1 Geomorphological mapping, aerial photos and identified glacial stages*

471 Based on photo-interpretation of aerial photographs and fieldwork, two
472 geomorphological maps were generated at ~1:7000 scale, in which well preserved
473 moraine segments, current glacier margins and stream network were also mapped (Figs.
474 2 and 3). In Vesturdalur, over 1000 moraine ridge fragments (including terminal and
475 lateral moraine segments) were identified and mapped, with increased presence from
476 1.7 km upwards to the current glacier terminus. In the analysis, we retained only ridge
477 fragments if they are at least 50 m long, protruding 2 m above the valley bottom and the
478 alignment of glacial boulders embedded in the moraine crest is preserved, as indicators
479 of major glacial culminations and well preservation state. Otherwise we considered
480 either they represented insignificant glacial stages or were most probably affected by
481 post-glacial slope reworking.

482 Following these criteria, we retained 12 glacial stages based on the geomorphological
483 mapping of the Vesturdalur foreland (Fig. 2). We were able to verify in the field that the
484 selected sections had not been affected by postglacial slope processes as none of these
485 moraines was cut by debris-flows or deformed/covered by landslides. The palaeo-
486 position of the glacier terminus was clearly defined by pairs of latero-frontal moraines
487 in stages 1, 4 and 6. In stages 2, 3, 5, 9, 10, 11 and 12, it was poorly defined by short
488 latero-frontal moraines on one side of the valley, very close to the river, with their
489 prolongation and intersection with the river assumed to be the former apex, and so a
490 tentative terminus geometry was drawn. The lateral geometry of the tongue was
491 accurately reconstructed in stages 6, 8 and 9 based on long and aligned, ridge fragments,
492 and in the other stages an approximate geometry was drawn from the terminus to the
493 headwall. The greatest retreat between consecutive stages (1 km) occurred in the

494 transition from the stage 1 to the stage 2. No intermediate frontal moraines were
495 observed in the transect between the stages 1 and 2.

496 In Austurdalur, over 1600 moraine ridge fragments were identified and mapped.
497 Following the same criteria as in Vesturdalur, 13 stages were identified based on the
498 geomorphological evidence (Fig. 3). The furthest moraines marking the maximum
499 extent of the eastern Tungnahryggsjökull appear at 1.3 km from the current terminus. In
500 contrast to the other valley, moraines populate the glacier foreland more densely and
501 regularly on both sides of the valley. Most of them are <50 m long with a few exceeding
502 100-200 m. The frontal moraine ridge fragments in Austurdalur clearly represent the
503 geometry of the terminus in all the stages, as they are well-preserved and are only
504 bisected by the glacier meltwater, with the counterparts easily identifiable. The most
505 prominent (over 2 m protruding over the bottom of the valley) and well preserved
506 moraines are those marking the terminus position at stages 1 to 8, with lengths ranging
507 from 170 to 380 m.

508 Both glaciers were also outlined on aerial photos of 1946, 1985, 1994 (only for western
509 Tungnahryggsjökull), and 2000, and on a SPOT satellite image (2005), and hence new
510 recent stages from the past century were studied for the Tungnahryggsjökull, five for the
511 western glacier (stages 13, 14, 15, 16 and 17) and four for the eastern glacier (stages 11,
512 15, 16 and 17) (Suppl. figure SF2; Suppl. table ST1). The stages identified on the basis
513 of the geomorphological mapping and those obtained from glacier outlining over
514 historical aerial photos sum up to a total of 17 stages for each glacier.

515 *4.2. Glacier length, extent and volume*

516 The reconstructed glacier surfaces corresponding to the different glacial stages is shown
517 in Suppl. figure SF3. The length of the glaciers during their reconstructed maximum ice

518 extent was unequal, with the western Tungnahryggsjökull being 6.5 km long, and the
519 eastern glacier being 3.8 km long (Suppl. table ST2). The same occurred with the area,
520 9.4 and 5.3 km², respectively (Suppl. table ST3). Over the different stages, the western
521 glacier lost 31% of its area and retreated 51% of its total length (Suppl. tables ST2 and
522 ST3) while there was less shrinkage of the eastern glacier both in area loss (26%) and
523 length (34%). Figs. 2B and 3B and Suppl. table ST2 show only one reversal during the
524 general retreating trend, in the stage 15 of the western and the stage 16 of the eastern
525 Tungnahryggsjökull. The greatest area losses occurred in the transition to the stages 2,
526 4, 7, 9 and 14 (>3%) on the western glacier while losses between stages in the eastern
527 glacier were lower except for the transition between the stages 14 and 17, where a
528 noticeable reduction of the accumulation area was observed in the aerial photos of 1946
529 and 1985, and the satellite image of 2005 (Fig. 3B). The volumes calculated from the
530 reconstructed glacier DEM and the corrected bed DEM show that the glaciers reached
531 ~1.10 km³ (western) and ~0.47 km³ (eastern) at their recorded maximum extent
532 corresponding to their outmost moraines. From the oldest to the most recent stage they
533 lost 30% and 23% of their ice volume, respectively. The losses between consecutive
534 stages of the glaciers were in general lower than 3% with the exception of the stages 2,
535 4, 7, 9 (western) and stage 14 (eastern), where the values ranged from 3% to 10%
536 (Suppl. table ST3). Only one slight inversion of the volume trend is seen in the stages
537 15 of the western glacier and in 16 of the eastern glacier.

538 4.3. Equilibrium-Line Altitudes (ELAs)

539 The application of the AAR (0.67) method showed ELAs ranging from 1021 to 1099 m
540 a.s.l. (western glacier) and from 1032 to 1065 m a.s.l. (eastern glacier) for the different
541 reconstructed stages. This means an overall rise of 78 and 33 m respectively (Table 1)
542 from the maximum to the minimum extent recorded. The results from applying the

543 AABR (1.5) show the same trend and similar ELAs, with differences of up to ± 15 m
544 compared with those obtained from the AAR. The AABR-ELAs tend to be higher than
545 the AAR-ELAs, especially in the second half of the reconstructed stages with the most
546 remarkable differences occurring in the eastern Tungnahryggsjökull (Table 1).
547 However, the error derived from the uncertainties associated to the applied balance ratio
548 (BR, ± 0.4) tends to decrease as the glaciers get smaller. The greatest change in the ELA
549 between consecutive stages is found between the stages 1 and 2 in the western glacier
550 (+26 m), fully coincident with the largest retreat measured, about 1 km. An interesting
551 result is that the ELA rise is attenuated in both glaciers from stage 10 onwards, with
552 stage-to-stage variations close to zero predominating, and with only one inversion (-3
553 m) occurring in the western glacier between the stages 14 and 15 (Table 1).

554 4.4. Lichenometric dating

555 Altogether 17 lichenometry stations (8 in Vesturdalur and 9 in Austurdalur) were set up
556 during fieldwork in the two glacier forelands. Their spatial distribution and
557 correspondence with the different glacial stages are given in Figs. 2 and 3 and Suppl.
558 table ST4. The table also shows the measurements of the largest *Rhizocarpon*
559 *geographicum* thalli found during fieldwork in the moraines (stages) to which the
560 stations correspond. TUE-0 was the only station where no lichen of either species was
561 found in 2015. Unlike *Porpidia* cf. *soredizodes* thalli, which are present in all the
562 remaining lichenometry stations, *Rhizocarpon geographicum* thalli suitable for
563 measuring (ellipsoidal, not coalescent) were only found in stations TUW-2 to TUW-7 in
564 Vesturdalur, and in TUE-2 to TUE-7 in Austurdalur.

565 The measurements considered the diameter of the smallest circle bounding the thallus
566 outline as representative of the longest axis (Suppl. figure SF1). The obtained values
567 ranged from 19.3 to 71.5 mm in Vesturdalur, and from 19.0 to 47.7 mm in Austurdalur

568 (Suppl. table ST4). Only one size inversion (decreasing size with increasing distance to
569 the current terminus) was detected in Austurdalur in the station TUE-6 (Fig. 3).
570 *Rhizocarpon geographicum* thalli were absent in the nearest stations (TUW-1 and TUE-
571 1) and were coalescent in the most distant stations (TUW-8 and TUE-8) in both glacier
572 forelands. On the other hand, *Porpidia cf. soredizodes* thalli measurements ranged from
573 18.3 to 148.4 mm in Vesturdalur, and from 16.8 to 141.8 mm in Austurdalur (Suppl.
574 table ST4). A size inversion of *Porpidia cf. soredizodes* thalli is also observed in TUE-6
575 and in TUE-7.

576 When the ages of *Rhizocarpon geographicum* lichens are calculated applying a 0.44
577 mm yr⁻¹ growth rate and a 10-year colonization lag following Kugelmann (1991), they
578 range from 54 to 173 years in Vesturdalur, and from 53 to 119 years in Austurdalur. If
579 longer colonization lags of 15, 20, 25 and 30 years (see Methods section) are applied
580 tentatively, the oldest ages obtained are ~170-190 years, and the youngest ~40-70 years
581 (Table 2). In general, the further away the lichenometry stations are, the older are the
582 ages (Figs. 2 and 3), with the inversions mentioned above. Apparently the lichenometry-
583 dated moraines are younger than the CRE-dated distal moraines.

584 The absence of *Rhizocarpon geographicum* lichens in 2015 at lichenometry station
585 TUW-1 (uncovered by the glacier at some time between 1994 and 2000; Suppl. figure
586 SF2) suggests a colonization lag of at least 15-21 years. In addition, it is only when the
587 colonization lag is assumed to be longer than 10 years and shorter than 30 years that the
588 ages obtained at stations TUW-3 and TUE-2 are in good agreement with the ages
589 deduced from the aerial photos (Table 2).

590 During the 2015 field campaign, the species *Porpidia cf. soredizodes* was absent in
591 station TUE-0, located on a glacially polished threshold uncovered by the glacier after
592 2005 (post-stage 17). However, it was found in stations TUW-1 and TUE-1, dated to

593 1994-2000 and 1946-1985 respectively, based on the position of the snouts in the aerial
594 photos (Suppl. figure SF2). These observations suggest a colonization lag from 10 to
595 15-21 years, thus shorter than for *Rhizocarpon geographicum*.

596 4.5. ^{36}Cl CRE dating

597 The detailed geomorphological analysis carried out on the numerous moraine ridges of
598 both valleys has greatly limited the number of boulders reliable for successfully
599 applying ^{36}Cl CRE and lichenometry dating methods. Due to the great intensity of the
600 slope processes (especially snow avalanches and debris-flows), only a few boulders are
601 well-preserved, sometimes only one in each moraine ridge that retains its original
602 glacier location. Thus, it should be highlighted that this issue prevented performing a
603 statistically valid sampling for both methods (see e.g. Schaefer et al., 2009; Heymann
604 et al., 2011).

605 During the fieldwork campaigns in the forelands of the western and eastern
606 Tungnahryggsjökull glaciers, 12 samples from stable and very protrusive moraine
607 boulders (Suppl. figure SF4) were collected in areas where lichenometric dating was not
608 suitable because of lichen thalli coalescence, and also 2 samples from a polished ridge
609 downwards the confluence of Vesturdalur and Austurdalur (Suppl. figure SF5). The
610 input data for exposure age calculations, namely sample thickness, topographic
611 shielding factor, major element concentrations of bulk/target fractions, are summarized
612 in the Suppl. tables ST5, ST6, ST7 and ST8 includes the ^{36}Cl CRE ages calculated
613 according to different Ca spallation production rates and the distance to the most recent
614 glacier terminus position mapped. Table 3 includes the ^{36}Cl CRE ages converted to CE
615 dates format presented throughout the text. The dates presented below are based on the
616 Licciardi et al. (2008) Ca spallation production rate.

617 Aiming to obtain a maximum (oldest) age for the onset of the deglaciation in the valleys
618 studied, two samples (ELLID-1 and ELLID-2) were extracted from the western sector
619 of Elliði, a 660-m-high glacially polished crest separating Viðinesdalur and
620 Kolbeinsdalur valleys (Suppl. figure SF5), and located at 11 km downstream from the
621 confluence of Vesturdalur and Austurdalur valleys. Both samples yielded dates of
622 14300 ± 1700 BCE and 14200 ± 1700 BCE.

623 In Vesturdalur, 8 samples were collected from 5 moraines corresponding to 5 of the
624 stages identified on the geomorphological map (Fig. 2). Samples TUW-9 and TUW-10
625 were taken from two boulders in the moraine that correspond to the left latero-frontal
626 edge of the glacier during the stage 7, ~1 km from the 2005 CE (stage 17) glacier
627 terminus (measured along the flowline from the reconstructed terminus apex); they
628 yielded consistent dates of 1590 ± 100 CE and 1640 ± 90 CE. Samples TUW-11 and
629 TUW-12 were extracted from the moraines corresponding to the glacial stages 6 and 5,
630 at 185 m and 465 m downstream respectively (~1.2 km and ~1.5 km respectively from
631 the 2005 CE snout), and gave consistent dates 1480 ± 120 CE and 1450 ± 100 CE. The
632 next ^{36}Cl samples (TUW-13 and TUW-14) were taken from two adjacent moraine
633 boulders on the left latero-frontal moraine ridge corresponding to the stage 3, at 264 m
634 downstream (1.8 km from the 2005 CE snout); they yielded dates of 1470 ± 130 CE and
635 670 ± 210 CE, which are significantly different from each other. The most distant
636 samples (TUW-15 and TUW-16) were extracted from the stage 2 moraine, ~400 m
637 downstream from the moraine ridge corresponding to stage 3 (2.2 km from the 2005 CE
638 terminus). They yielded dates of 1460 ± 110 CE and 1220 ± 190 CE, respectively, that are
639 consistent with each other and in chronological order with sample TUW-13 from the
640 stage 3. However, these ages are not in agreement with the oldest date of TUW-14
641 (670 ± 210 CE) from the stage 3.

642 Four ^{36}Cl samples were taken from two prominent moraines in the Austurdalur valley
643 (Fig. 3). Samples TUE-9 and TUE-10 were collected on the frontal moraine
644 corresponding to stage 4 (1 km from the 2005 CE glacier terminus) and yield
645 significantly different dates of 740 ± 170 CE and 1460 ± 100 CE. Samples TUE-11 and
646 TUE-12 were taken from two moraine boulders located on the ridge of the left lateral
647 moraine that records the maximum ice extent (Fig. 3). Their calculated ^{36}Cl dates,
648 380 ± 200 CE and 400 ± 200 CE, are consistent with each other and in stratigraphic order
649 with the ages from stage 4.

650 The dates derived from Stone et al. (1996) Ca spallation production rate are similar to
651 those presented above, only 4% older. Those derived from the Schimmelpfennig et al.
652 (2011) production rate yielded dates older by 15% on average (Suppl. table ST8). These
653 small differences do not represent statistical difference given the calculated age
654 uncertainties.

655 5. Discussion

656

657 5.1. ^{36}Cl CRE dating

658 The dates obtained in both valleys range from 380 ± 200 CE to 1640 ± 90 CE and are
659 significantly younger than the ages from Elliði polished ridge (Suppl. table ST8). T UW-
660 14 (670 ± 210 CE) could be the only outlier as it is significantly older than the other
661 sample obtained from the same moraine of the stage 3 (T UW-13; 1470 ± 130 CE) and
662 also older than the samples T UW-15 (1460 ± 110 CE) and T UW-16 (1220 ± 190 CE),
663 from the moraine of the previous stage 2 (Fig. 2). This would imply assuming nuclide
664 inheritance for sample T UW-14 due to either remobilization of an earlier exposed
665 moraine boulder (see Matthews et al., 2017) or to previous exposure periods, but the

666 high geomorphological dynamism of the slopes limits this possibility (Andres et al.,
667 2019). Another possible interpretation is that the samples T UW-15 and T UW-16 (stage
668 2) would be the outliers since they may have experienced incomplete exposure due to
669 post-depositional shielding (Heymann, 2011). The possibility of both samples being
670 affected by proglacial processes can be ruled out given the distance to the meltwaters
671 channel or the absence of glacial burst features (see Caseldine, 1985a) in the
672 surroundings of the sampled boulders. Thus, the ages of samples T UW-14 and T UW-13
673 would indicate that the moraine of stage 3 was built during two overlapped glacial
674 advances at 670 ± 210 CE and 1470 ± 130 CE. In Austurdalur, the interpretation of the
675 ages is also complex. Samples T UE-9 (740 ± 170 CE) and T UE-10 (1460 ± 100 CE) from
676 the same moraine are significantly different, but it is difficult to decide whether or not
677 one of these two samples is an outlier. It is also possible that the younger age indicates
678 the timing of a further readvance with the snout reaching the same moraine. It would be
679 necessary to take more samples, but it will be difficult to find other sectors of these
680 moraines that are not affected by slope processes, especially debris-flows. The
681 hypothesis of supraglacial debris dumping can be rejected due to the lack of supraglacial
682 debris or other features indicative of a palaeo debris-covered glacier. Other possibility
683 to be consider is that older boulders may be incorporated in the formation of push
684 moraines as has been shown in maritime Scandinavia, and identified to give
685 overestimated ages for LIA-moraines (Matthews et al., 2017). The asynchronicity of
686 glacial advances and retreat in both valleys should not be surprising as glaciers can
687 retreat or advance differently in adjacent valleys due to a number of factors such as
688 hypsometry, aspect, gradient, etc. Caseldine (1985b) suggested a high climate
689 sensitivity of the glacier in Vesturdalur due to its steeper wally floor and thinness”,
690 which could explain a different behaviour of the glacier compared to the eastern glacier.

691 *5.1.1. Pre-LIA glacial advances*

692 ^{36}Cl CRE dating results from glacially polished surfaces on the Elliði crest show an age
693 of 14250 ± 1700 yr (mean) for the Kolbeinsdalur deglaciation ([Suppl. figure SF5](#)).
694 However, this should be considered as a minimum age since this probably indicates
695 when the retreating and thinning glacier uncovered the ridge, and thus the start of the
696 final deglaciation of the main valley. From this point to the outmost frontal moraines
697 surveyed in this paper, no glacially polished outcrops or erratic boulders suitable for
698 ^{36}Cl sampling were found, impeding us to provide further chronological constraints for
699 the deglaciation pattern of these valleys.

700 Our ^{36}Cl CRE dating results suggest late Holocene glacial advances prior to the LIA, at
701 around ~ 400 and ~ 700 CE, in Vesturdalur and Austurdalur, respectively, coinciding
702 with the Dark Ages Cold Period (DACP) (between 400 and 765 CE) in central Europe,
703 according to [Helama et al. \(2017\)](#). In fact, recent synthesis about Icelandic lake records
704 indicate a strong decline in temperature at 500 CE ([Geirsdóttir et al., 2018](#)).

705 The presence of Late Holocene moraines outside the outermost LIA moraines in other
706 valleys of Tröllaskagi has been suggested through radiocarbon dating and
707 tephrochronology in the Vatnsdalur (first, between 4880 ± 325 cal. BCE (tephra Hekla 5)
708 and 3430 ± 510 cal. BCE, and another after 1850 ± 425 cal. BCE; [Stötter, 1991](#)),
709 Lambárdalur (before 3915 ± 135 cal. BCE; [Wastl and Stötter, 2005](#)), Þverárdalur (before
710 3500 ± 130 cal. BCE; [Wastl and Stötter, 2005](#)), Kóngsstaðadalur (after 1945 ± 170 cal.
711 BCE; [Wastl and Stötter, 2005](#)), Barkárdalur (between 375 ± 375 cal. BCE and 190 ± 340
712 cal. CE and before 460 ± 200 cal. CE; [Häberle, 1991](#)) and Bægisárdalur (2280 ± 205 cal.
713 BCE and 1050 ± 160 cal. CE; [Häberle, 1991](#)) valleys. Specifically, our oldest ^{36}Cl dates
714 (~ 400 and ~ 700 CE) coincide with glacial advances that are radiocarbon dated from

715 intra-morainic peat bogs in other valleys in Tröllaskagi and southern Iceland, e.g. the
716 Barkárdalur II stage (ca. 460 CE) in Subatlantic times (Häberle, 1991, 1994), and given
717 the uncertainties of our dates (200 yr), also with Drangajökull (NW Iceland) advancing
718 at the same time (~300 CE; Harning et al., 2018). On the other hand, Meyer and Venzke
719 (1985) had already suggested the presence of pre-LIA moraines at Klængshóll (eastern
720 cirque, tributary of Skíðadalur). Caseldine (1987, 1991) proposed a date of 5310±345
721 cal. BCE as the youngest for a moraine in that cirque, based on tephrochronology
722 (tephra layer Hekla 5 dated in a similar ground in Gljúfurárdalur) and rock weathering
723 measurements using the Schmidt hammer technique. Based on the big size of some
724 moraines in Skíðadalur and Holárdalur, Caseldine (1987, 1991) also supports the
725 hypothesis of pre-LIA moraines formed during several advances. All this information is
726 not in agreement with the hypothesis that all the glaciers in Tröllaskagi reached their
727 maximum ice extent since the Early Holocene during the LIA (Hjort et al., 1985;
728 Caseldine, 1987, 1991; Caseldine and Hatton, 1994).

729 In south and central and northwest Iceland, the ice caps reached their Late Holocene
730 maximum advance during the LIA (Brynjólfsson, et al. 2015a; Larsen et al. 2015;
731 Harning et al., 2016a; Anderson et al., 2018; Geirsdóttir et al., 2018). But also pre-LIA
732 advances have been identified and dated through radiocarbon and tephrochronology in a
733 moraine sequence of Kvíárjökull (south-east Vatnajökull), the first of which occurred at
734 Subatlantic times (before 110±240 cal. BCE) and the second at 720±395 CE (Black,
735 1990; cited in Guðmundsson, 1997). Considering the uncertainty of our ~400 and ~700
736 CE dates, these advances likely were coetaneous with other advances reported from
737 southern Iceland in Kötlujökull (after 450±100 cal. CE, radiocarbon dated and
738 supported by tephrochronology; Schomaker et al., 2003) and Sólheimajökull (southern
739 Mýrkdalsjökull, “Ystagil stage”; Dugmore, 1989). In fact, the 669±211 CE advance of

740 western Tungnahryggsjökull (stage 3) also overlaps with the Drangajökull and
741 Langjökull advances at ~560 CE and 550 CE, respectively (Larsen et al., 2011; Harning
742 et al., 2016a) during DACP, in response to the summer cooling between ~250 CE and
743 ~750 CE (Harning et al., 2016a). These advances would correspond to the general
744 atmospheric cooling in the North Atlantic reflected by widespread glacier advances
745 (Solomina et al., 2016).

746 The timing of the stage 2 in Vesturdalur is difficult to define because the sample TUW-
747 16 (1220±190 CE) has almost 200-year uncertainty, and thus overlaps with both the
748 LIA and the higher temperatures of the Medieval Warm Period (MWP, Lamb, 1965; 950-
749 1250 CE, see Solomina et al., 2016) not conducive to glacier development as it has been
750 observed in northwest and central Iceland (Larsen et al., 2011; Harning et al., 2016a).
751 On the other hand, moraines in Greenland Arctic environments date within the MWP,
752 based on cosmogenic nuclide dating (Young et al., 2015; Jomelli et al., 2016),
753 suggesting a cooling in the western North Atlantic while the eastern sector remained
754 warm. Iceland is located in the middle of this dipole “see-saw” pattern (Rogers and van
755 Loon, 1979). Thus, the correlations with the glacier fluctuations Greenland or Norway,
756 are complicated as the climate anomalies in both regions show opposing signs in the
757 different see-saw modes. To increase the difficulty of interpretation, glaciers of
758 Tröllaskagi are known to surge occasionally (Brynjólfsson et al., 2012; Ingólfsson et al.,
759 2016), which could explain additional complexity in the glacial advances pattern, as it
760 would not be driven by climatic variability. Brynjólfsson et al. (2012) pointed out that
761 only four surges from three glaciers (Teigarjökull, Búrfellsjökull, Bægisárjökull) have
762 been reported in the Tröllaskagi peninsula, where over 160 cirque glaciers exist.

763 *5.1.2. LIA glacial advances (15th-17th centuries)*

764 The remaining ^{36}Cl ages obtained from Vesturdalur and Austurdalur are within the
765 1450-1640 CE range (Suppl. table ST8; Table 3) and so correspond to different glacial
766 advances or standstills during the second third of the LIA during the 15th, 16th and 17th
767 centuries. According to our results, one of the largest glacier extents of the LIA
768 culminated in both valleys at the latest around the mid-15th century (samples: TUW-12:
769 1450±100 CE / stage 6; TUE-10: 1460±100 CE / stage 4). This is a very early date
770 compared to the LIA advances previously dated in Tröllaskagi. Earlier lichenometric
771 research carried out in nearby valleys report more recent dates for the LIA maximum:
772 mid-18th century in Barkárdalur (Häberle, 1991); early 19th century in Bægisárjökull and
773 Skríðudalur (Häberle, 1991), and in Búrfellsdalur and Vatnsdalur (Kugelmann, 1991,
774 Fig. 7); mid-19th century (1845-1875 CE) in Myrkárjökull, Vindheimajökull (Häberle,
775 1991), Þverárdalur, Teigardalur, Grýtudalur, Vesturárdalur (Kugelmann, 1991, Fig. 7),
776 Heiðinnamannadalur and Kvarnárdalur (Caseldine, 1991); and late 19th century (1880s-
777 1890s CE) in Gljúfurárdalur (Caseldine, 1985b, 1991). Caseldine (1991) proposed
778 1810-1820 CE as the date of the “outer” moraine of Vesturdalur based on a minimum
779 lichenometric age. According to our ^{36}Cl moraine ages, the LIA maximum of
780 Tungnahryggsjökull glaciers occurred ~400 years earlier than these dates. This should
781 not be surprising as Kirkbride and Dugmore (2001) reported lichenometric ages >100
782 years younger than those derived from tephrochronology in the same landforms. Our
783 results also give the earliest LIA dates based on moraine dating obtained so far in
784 Iceland, compared to the previously published dates all obtained through lichenometric
785 dating: 1740-1760 CE in south-east Iceland (Chenet et al., 2010). In northwestern
786 Iceland, glaciolacustrine sediments recorded a contemporary expansion of Drangajökull
787 at ~1400 CE (Harning et al., 2016a). Likewise a first major advance of Langjökull
788 (western central Iceland; Fig. 1A) between 1450 and 1550 CE has been reported (Larsen

789 [et al., 2011](#)), as well as advances in central Iceland between 1690 and 1740 CE
790 ([Kirkbride and Dugmore, 2006](#)), based on varve thickness variance together with annual
791 layer counting and C:N mass ratio, and tephrochronology (geochemical analysis),
792 respectively.

793 The dates of samples TUW-13, TUW-12 and TUW-11 in Vesturdalur (average date
794 1470 ± 120 CE; stages 3, 5 and 6) cannot be distinguished statistically if their internal
795 uncertainty is considered ([Fig. 4](#); [Suppl. table ST8](#)). The spatial scatter of these
796 sampling sites ([Fig. 2](#)) may indicate frequent and intense terminus fluctuations in a short
797 time interval. Different ages obtained from the moraines of the stages 3 and 4 in
798 Vesturdalur and Austurdalur, respectively, may indicate that in the 15th century the
799 glacier termini reached the moraines deposited at ~ 700 CE ([Figs. 2 and 3](#)) and rebuilt
800 them, which may explain the large size of these moraines. [Caseldine \(1987\)](#) argued that
801 other moraines in Skíðadalur were formed during more than one advance. Based on the
802 size of the largest moraines, he also pointed out that many glaciers must have advanced
803 to positions similar to those of the late 19th century earlier in the Neoglacial.

804 The glacier advances in the 15th century in Vesturdalur and Austurdalur may have been
805 the result of different climate forcings during that century: negative radiative forcing
806 and summer cooling were linked to intense volcanic activity ([Miller et al., 2012](#)), the
807 low solar activity of the Spörer Minimum (1460-1550 CE; [Eddy, 1976](#)), the sea-
808 ice/ocean feedback with increased sea ice ([Miller et al., 2012](#)) and the weakening of the
809 Atlantic Meridional Overturning Circulation (AMOC) ([Zhong et al., 2011](#)). Solar
810 activity may have played a major role in these glacial advances if we consider that the
811 climate in the North Atlantic is highly influenced by solar activity variability ([Jiang et al.,](#)
812 [2015](#)). On the contrary, historical records, although not determinant, suggest a mild
813 climate for 1430-1550 CE ([Ogilvie and Jonsdóttir, 2000](#)), and especially for 1412-1470

814 CE (Ogilvie, 1984). This would also be compatible with increased precipitation and
815 hence more winter snow in warm periods (Caseldine and Stötter, 1993; Stötter et al.,
816 1999; Fernández-Fernández et al., 2017), and also with potential surge activity with
817 glacial advances not directly linked to specific climate periods (e.g. Brynjólfsson et al.,
818 2012; Ingólfsson et al., 2016).

819 In Vesturdalur, the dates of samples TUW-9 (1590±100 CE) and TUW-10 (1640±90
820 CE) are compatible with a cold period from the late 1500s to 1630 CE (Ogilvie and
821 Jónsson, 2001). Nevertheless, considering the uncertainties of these samples, their dates
822 also overlap with the Maunder Minimum (1645-1715 CE) (Eddy, 1976), when the LIA
823 maximum glacial advance occurred in the Alps (Holzhauser et al., 2005).

824 *5.2. Lichenometric dating.*

825 *5.2.1. ³⁶Cl CRE dating vs. lichenometric dating. Multiple lichen species dating* 826 *approach.*

827 The contrast between our CRE dating results and earlier lichenometry-based results
828 published elsewhere evidences the clear underestimation of the latter. This could be
829 explained either by lichen growth inhibition due to saturation of the rock surface and
830 competition of other thalli (Wiles et al., 2010; Le Roy et al., 2017) or a colonization lag
831 longer than assumed up to now, from 10 to 15 years in Tröllaskagi (Kugelmann, 1991;
832 Caseldine, 1985b, respectively). However, other factors affect the reliability of the
833 lichen-derived ages, and may explain the differences with CRE dates. One of them is
834 the reliability of the growth rates and lichenometric calibration curves that are
835 commonly assumed to be linear (constant) growth in northern Iceland (e.g. Caseldine,
836 1983, 1985b; Häberle, 1991; Kugelmann, 1991), although it has been demonstrated that
837 the lichen diameter growth declines with age (see e.g. Winkler, 2003, Fig. 4). This

838 might lead to significant age underestimations for the oldest dates, putting potentially
839 earlier dates in the 19th century. Most of the fixed control points from which lichen
840 growth rates have been derived in northern Iceland comprise abandoned gravestones,
841 memorial stones, old bridges and mostly abandoned farmsteads ([Caseldine, 1983](#);
842 [Kugelmann, 1991](#)). Time of death is commonly assumed for gravestones, and
843 abandonment date for farmsteads. Although the latter is well known on the basis of
844 historical documentation, the colonization lag sometimes relies on the “the likely
845 duration” of the deterioration of the buildings after abandonment that depends on the
846 quality and stability of the constructions (see [Kugelmann, 1991](#)), and hence affect the
847 results. However, it should be highlighted that our approach circumvents this last issue
848 by combining field observations with historical aerial photographs. In addition, given
849 that lichen growth of *Rhizocarpon* subgenus depends mostly on available humidity, the
850 location of the measured lichens has also a potential effect on the results, i.e. to micro-
851 climatic changes (see [Innes, 1985](#); [Hamilton and Whalley, 1995](#)) between the location
852 of the fixed points and the location on the moraine (crest: dryer and more exposed;
853 green zone on the proximal slope, etc.). In the literature cited above about lichenometry-
854 dated LIA advances no detailed information is provided about the location of the lichen
855 measured for dating purposes, so potential error derived from this issue can not be
856 assessed. Nevertheless, given that we measured lichens on horizontal flat surfaces
857 where there is no restriction to the moisture receipt of the lichens, we can consider our
858 results presented throughout the next sections valid. In any case, such a great difference
859 of our CRE dates and the previous lichen-derived is more likely to be explained by the
860 technical limitations of the technique rather than environmental factors.

861 Our field observations and historical aerial photos of known age restricted the dates of
862 the moraines colonized by *Rhizocarpon geographicum* lichens. This approach would

863 support the dates obtained from the 0.44 mm yr⁻¹ growth rate of [Kugelmann \(1991\)](#) and
864 the 20-year colonization lag. This rate is slightly higher than those reported from the
865 Antarctic Peninsula (0.31 mm yr⁻¹; [Sancho et al., 2017](#)), but lower than in Tierra del
866 Fuego (0.63 mm yr⁻¹; [Sancho et al., 2011](#)). The correlation between the sizes of largest
867 *Rhizocarpon geographicum* and *Porpidia cf. soledizodes* thalli at the same stations
868 showed a proportionality between the largest thalli of both species: thalli of *Porpidia cf.*
869 *soledizodes* species grow faster than those of *Rhizocarpon geographicum*. The sizes of
870 the largest *Rhizocarpon geographicum* thalli were plotted against the sizes of the largest
871 *Rhizocarpon geographicum* lichens ([Fig. 5](#)). The slope of the best-fit linear curve
872 obtained was around 1.675 ($r^2=0.82$) that suggests that *Porpidia cf. soledizodes* lichens
873 grow 1.675 times faster than those of *Rhizocarpon geographicum*. So if we assume 0.44
874 mm yr⁻¹ growth rate for *Rhizocarpon geographicum* lichens, a tentative growth rate of
875 *Porpidia cf. soledizodes* would be 0.737 mm yr⁻¹. However, this approach should be
876 taken with caution due to the limited number of lichens (n=7) used of each species.
877 Aiming to obtain a tentative date ([Table 2](#)), this growth rate was applied to the largest
878 *Porpidia cf. soledizodes* lichens found in those stations where no *Rhizocarpon*
879 *geographicum* lichens could be measured (TUV-1, TUV-8, TUE-1 and TUE-8).

880 Assuming colonization lags of 20 and 15 years for *Rhizocarpon geographicum* and
881 *Porpidia cf. soledizodes* lichens, respectively, and the above-mentioned growth rates,
882 several glacial advances or standstills are tentatively placed in the 19th and 20th
883 centuries, in the context of a general retreat from the most advanced LIA positions, as
884 discussed in the next section.

885 5.2.2. LIA glacial advances/standstills: 19th century

886 Despite the low number of lichenometry stations surveyed and the limitations of this
887 dating approach discussed in the previous sections, our results are in accordance with

888 the geomorphological logic and with the chronological frame obtained from historical
889 aerial photos. The ages derived from *Rhizocarpon geographicum* thalli measurements at
890 lichenometry stations pre-dating 1946 suggest that the western and eastern
891 Tungnahryggsjökull culminated successive advances/standstills around the 1830s,
892 1840s, 1860s and 1890s CE (Figs. 2 and 3, Table 2). Ages tentatively estimated from
893 *Porpidia* cf. *soredizodes* thalli considering its apparently higher growth rate suggest
894 glacial advances/standstills around the 1800s (Figs. 2 and 3, Table 2). No inconsistency
895 (age inversions) is detected in the lichenometry-dated moraine sequence, but we
896 recognise that some age underestimation may occur since: (i) we assume linear growth
897 when applying a growth rate; and (ii) our 19th dates were derived from >40-45 mm-
898 diameter lichens (Table 2 and Suppl. table ST4), which exceed the size of the biggest
899 control point from which Kugelmann's growth rate was estimated (Kugelmann, 1991,
900 Fig. 3). This problem reinforces the need of taking lichen-derived ages as relative. The
901 interpretation of the chronology in Austurdalur is more complicated: the lichen sizes
902 measured at the stations TUE-6 (1890s CE, stage 9) and TUE-7 (1880s CE; stage 7)
903 yield more recent dates than at station TUE-5 (1860s CE; stage 10) despite being
904 representative of earlier stages (Fig. 3). Given that this anomaly occurs in both lichen
905 species, it is reasonable to conclude that an environmental factor could have affected the
906 lichen populations at both stations. It could even indicate a date when the boulders may
907 have been remobilized by postglacial processes.

908 Our chronology of the 19th century glacial advances in both valleys (Table 2) does not
909 coincide exactly with the phases identified by Kugelmann (1991) in Svarfaðardalur-
910 Skíðadalur (1810, 1850, 1870-1880, 1890-1900 CE). It also differs appreciably from the
911 chronology proposed by Caseldine (1985b) in Vesturdalur (moraines of 1868, 1878,
912 1887, 1898 CE). Nevertheless, it should be borne in mind that we are considering only

913 two glaciers with their own glaciological properties. Moreover, we have estimated the
914 ages from the growth rate (instead of a specific calibration growth curve), longer
915 colonization lag based on field observations, and applied to the longest axis
916 measurements ([Kugelmann, 1991](#)). On the other hand, micro-climatic differences
917 between the location of fixed points and our lichen measured may occur. However, we
918 recognise that the comparisons with [Caseldine's \(1985b\)](#) results are quite difficult since:
919 (i) the moraines dated by Caseldine are poorly located in his mapping (and hard to
920 identify over aerial photos and our moraine mapping); (ii) we are not able to apply the
921 same parameters to his measurements, as he used the mean longest axis of the five
922 largest lichen is not provided (only the average value); and (iii) he recognised the lichen
923 growth slowdown when dating the outermost moraine, which probably is one of those
924 dated with ^{36}Cl in this work.

925 Our results, despite the limitations of the applied method, largely due to the low number
926 of moraine boulders suitable for its application can be considered compatible and in
927 good agreement with glacial advances and cold periods during the first third of the 19th
928 century as we show below. [Martin et al. \(1991\)](#) pointed out the existence of a moraine
929 dated to ca. 1810-1820 CE in “Western Tröllaskagi Tungnahryggsjökull” (ambiguously,
930 without providing any detail of its location), as well as others of this period in
931 Svarfaðardalur, Búrfellsdalur and Vatnsdalur. Other dates obtained from more
932 sophisticated statistical techniques applied to lichenometry dating procedures also
933 evidenced a glacial advance phase 1810-1820 CE ([Chenet et al., 2010](#)). These advance
934 phases were coetaneous with significant sea ice persistence in the early 1800s ([Ogilvie
935 and Jónsson, 2001](#)), decreased solar activity, and strong volcanic eruptions (Dalton
936 Minimum, 1790-1830 CE; [Wagner et al., 2005](#)). The moraines dated in Vesturdalur to
937 around 1830 CE (TUW-7: 1830s CE, stage 10) and the early 1890s CE (TUW-5: 1890s

938 CE, stage 12) are in good agreement with the glacial advances in Svarfaðardalur-
939 Skíðadalur during the 1830s and early 1890s CE (Kugelmann, 1991, Fig. 8), as well as
940 with the low temperatures and presence of sea ice at these dates (Koch, 1945; Ogilvie,
941 1996; Ogilvie and Jonsdóttir, 2000; Ogilvie and Jónsson, 2001; Kirkbride, 2002).

942 5.2.3. Post-LIA glacial advances/standstills.

943 Lichen-derived ages from *Rhizocarpon geographicum* thalli suggest the occurrence of
944 glacial advances or standstills at the first half of the 20th century, culminating in 1910s,
945 1930s, 1940s and 1950s CE, although the 1930s CE date (TUE-3; stage 12) disagrees
946 with the date inferred from the aerial photos, at some point between 1946 and 1985 CE
947 (Suppl. figure SF2; Table 2). However, the 1910s CE date in both valleys is in good
948 agreement with the moraine abandonment during the first two decades of the 20th
949 century; it would be the result of the accumulated effect of the temperature rise since the
950 latter half of the 19th century (Caseldine, 1987; Wanner et al., 2008). Thus, the
951 subsequent advances would be the response to specific relative thermal minima within a
952 warmer climate (Stötter et al., 1999). The date of TUW-3 (stage 13) representing the
953 moraine abandonment in ~1940 CE is in agreement with the overall context of general
954 glacier retreat as a result of the warmest decades of the 1930s and 1940s CE, which
955 triggered an intense retreat of the glaciers (Einarsson, 1991; Martin et al., 1991;
956 Kirkbride, 2002). The advances/standstills dated to the early 1950s CE in both
957 Tungnahryggsjökull glaciers are likely to be synchronous given the similarity of the
958 dates obtained (Table 2). They could represent glacial advances in consonance with the
959 late 1940s – early/mid-1950s CE cooling (Einarsson, 1991; Fernández-Fernández et al.,
960 2017), recorded both in Akureyri and many other weather stations throughout Iceland.
961 Caseldine (1983) found a similar chronology in Gljúfurárdalur (Skíðadalur headwater,

962 10 km to the east), with moraine deposition between mid-1910s and 1930, around mid-
963 1930s and late 1940s-1950 CE.

964 The subsequent trend of the Tungnahryggsjökull glaciers, inferred from aerial
965 photographs, a satellite image, geomorphological mapping, and glacier reconstruction,
966 was characterized by continuous retreat and volume loss, in line with the increasing
967 temperature trend since the end of the LIA. This trend was only reversed between the
968 mid-1960s and mid-1980s CE by a major cooling event (Einarsson, 1991; Sigurðsson,
969 2005; Fernández-Fernández et al., 2017). Two moraines have been dated after the 1950s
970 CE. The date obtained in station TUE-1 (1970s CE; stage 14) agrees with the date
971 deduced from the 1946 and 1985 aerial photographs (Suppl. figure SF2). However, the
972 date estimated in station TUW-1 (1970s CE; between stages 15 and 16) is prior to that
973 obtained from the 1994 and 2000 aerial photographs. The reason for this mismatch may
974 be a non-linear growth phase of the *Porpidia* cf. *soredizodes* thalli measured (i.e. its real
975 growth rate may have been lower than the estimated). Nevertheless, more research on
976 this species is required to use it successfully in lichenometric dating.

977 The aerial photographs from 1994 (stage 15 western Tungnahryggsjökull) and 2000
978 (stage 16) show a reversal in the trend of both Tungnahryggsjökull glaciers (Suppl.
979 figure SF2), as the positions of their termini are more advanced than in 1985 (stages 14
980 and 15; see Fernández-Fernández et al., 2017). These advances in Vesturdalur and
981 Austurdalur, culminating after 1985 in a period non-conducive to glacier expansion,
982 may have been linked to above average precipitation for 1988-1995, which prevented a
983 negative mass balance of the glaciers (Sigurðsson, 2005). The 2000 aerial photo (stage
984 16) and 2005 SPOT satellite image (stage 17) display the retreat of both glaciers. This
985 trend was reinforced by the sudden warming initiated in 1995, which triggered
986 decreased snowfall, negative mass balances for 1996-2000, and retreat of the non-

987 surging glaciers after 2000 (Sigurðsson, 2005). In spite of these glacial fluctuations in
988 response to the intense climatic fluctuations of the last century, the ELAs estimated in
989 this paper only show a general rise of 5-10 m (Table 1). This small ELA increase may
990 be derived from some artifacts of the glacier reconstruction or the attenuating effect of
991 the increase in winter precipitation suggested by glacier-climate models (Caseldine and
992 Stötter, 1993; Fernández-Fernández et al., 2017).

993 *5.3. Final remarks: Can the occurrence of pre-LIA glacial advances be confirmed? Was*
994 *the LIA in northern Iceland the Holocene glacial maximum? Was it a single maximum*
995 *advance?*

996 Our results demonstrate that Tungnahryggsjökull advanced during Late Holocene glacial
997 stages prior to the LIA and reached considerably more advanced positions, even though
998 the Iceland large ice caps reached generally their Late Holocene maximum advance
999 during the LIA (Larsen et al. 2015, Harning et al., 2016a; Anderson et al., 2018,
1000 Geirsdóttir et al., 2018). The chronological data presented in the previous sections
1001 suggests that during the LIA the glaciers overlapped moraines deposited in pre-LIA
1002 glacial stages. Our results also show LIA advances since the 15th century and are thus
1003 contrary to the traditional proposal of a single maximum LIA advance occurring during
1004 either mid-18th or late-19th centuries in Tröllaskagi peninsula, followed by subsequent
1005 minor readvances in an overall retreating trend (see Caseldine, 1983, 1985b, 1987;
1006 Kugelmann, 1991; Martin et al., 1991). The use of the ³⁶Cl production rates from Ca
1007 spallation reported by Stone et al. (1996) does not lead to major changes in the
1008 interpretation and conclusions as the changes in the nominal dates (up to 90 yr earlier;
1009 Table 3) are within the external uncertainty and also overlap with the results presented
1010 above based on the Licciardi et al. (2008) production rate. Similarly, if we consider the
1011 results derived by the Schimmelpfennig et al. (2011) production rate, we obtain even

1012 earlier ages, which still overlap with the results derived by the other production rates
1013 due to a higher external uncertainty (see [Table 3](#)). Although the snow cover duration is
1014 known to be high in northern Iceland (see [Dietz et al., 2012](#)), quantifying the effect of
1015 snow cover on sub-surface ^{36}Cl production is a complex issue: on the one side, snow
1016 lowers the isotopic production rates related to spallation reactions due to the shielding
1017 effect on high-energy neutrons ([Benson et al., 2004](#); [Schildgen et al., 2005](#)), and on the
1018 other side it increases the ^{36}Cl production rate from thermal neutrons below the rock
1019 surface, due to the enhancing effect of hydrogen on these low-energy neutrons ([Dunai et](#)
1020 [al., 2014](#)). Both effects might cancel out depending on the composition of the samples,
1021 and their quantification is still debated and affected by high uncertainties ([Zweck et al.,](#)
1022 [2013](#); [Dunai et al., 2014](#); [Delunel et al., 2014](#)). Given this complexity, snow shielding
1023 was not applied. In any case its effect is unlikely to be higher than the uncertainty
1024 derived from extracting ^{36}Cl from whole rock instead of minerals.

1025 Our results are in concordance with several valleys in northern Iceland, but also with the
1026 results that are being obtained in other sectors of Arctic and North Atlantic region in the
1027 last years, such as: in Baffin Island (northern Canada), where glaciers reached Late
1028 Holocene maximum positions prior to the LIA ([Young et al., 2015](#); ^{10}Be dating), or
1029 West Greenland, with several advances or stabilizations at 1450 ± 90 CE and 1720 ± 60
1030 CE ([Jomelli et al., 2016](#); ^{36}Cl dating). However, it is striking that the early LIA
1031 advances of northern Iceland reported in the present paper do not agree with maritime
1032 Norway with later maximum culminations (see [Nesje et al., 2008](#)) despite being the
1033 glaciated region most comparable with Iceland in terms of climate and glaciology. Our
1034 results also agree with farther and southern areas such as the Alps, with maximum
1035 advances at around 1430 CE ([Schimmelpfennig et al., 2012, 2014a](#)); ^{10}Be dates; and
1036 Sierra Nevada (Iberian Peninsula), where LIA advances have been reported between the

1037 14th and 17th centuries (Palacios et al., 2019; ¹⁰Be dates). Our detailed moraine
1038 mapping, combined with CRE dating in the surveyed valleys, clearly shows a number of
1039 advances throughout the LIA, in response to the great climatic variability of the region
1040 with alternating cold and mild/warm periods (Ogilvie, 1984, 1996; Ogilvie and
1041 Jónsdóttir, 2000; Ogilvie and Jónsson, 2001; Geirsdóttir et al., 2009) as occurred in the
1042 Alps (e.g. Schimmelpfennig et al., 2014a) or the Iberian mountains (e.g. Oliva et al.,
1043 2018). The ELA calculations show that the major long-lasting rise of the glacier ELA
1044 (24-50 m depending on the calculation method) took place prior to 1900s/1910s.

1045 According to the results, the evolution pattern described by Fernández-Fernández et al.
1046 (2017) for the Tungnahryggsjökull glaciers should be revised as the ³⁶Cl CRE dates
1047 from the 15th and 17th centuries indicate that LIA maximum was reached earlier than
1048 previously thought. Thus, if we consider the ELA of the earliest LIA dates obtained
1049 with ³⁶Cl CRE (i.e. stages 5 and 4 of western and eastern Tungnahryggsjökull), these
1050 imply ELA depressions (with reference to the 2005 date) of 24-50 m (depending on the
1051 ELA calculation method), occurring for at least 560 years (Table 1) and not 150 years as
1052 had been previously assumed (Caseldine and Stötter, 1993; Fernández-Fernández et al.,
1053 2017).

1054 **Conclusions**

1055 (i) This paper highlights the detailed geomorphological analysis of the glacial landforms
1056 as an essential pre-requisite prior to the application of dating methods on them.
1057 Nevertheless, this has greatly limited the number of valid moraine boulders to be dated,
1058 since the vast majority of those were affected by post-glacial processes. This issue which
1059 has prevented a statistically acceptable sampling and the validation or invalidation of
1060 the “inconsistent” ages yielded by several boulders, so a conclusive explanation cannot
1061 be given.

1062 (ii) Applying ^{36}Cl CRE dating for the first time in the Tröllaskagi peninsula enabled us
1063 to identify pre-LIA glacial advances in Vesturdalur and Austurdalur. Thus, the western
1064 and eastern Tungnahryggsjökull glaciers did not reach their Late Holocene maximum
1065 extent during the LIA. The maximum extent for the eastern glacier was dated to ~400
1066 CE. For the western glacier a latest date of ~700 CE and an earliest of 16300 years ago
1067 (when the Elliði crest was deglaciated) have been obtained.

1068 (iii) The LIA maximum in Vesturdalur and Austurdalur was reached by the 15th century
1069 at the latest. A combination of detailed moraine mapping and ^{36}Cl CRE dating confirm a
1070 number of glacial advances between the 15th and 17th centuries, the earliest LIA
1071 advances dated in Tröllaskagi at present.

1072 (iv) For the recent dates, the complementary use of aerial photographs, a satellite image
1073 and fieldwork has aided to obtain lichenometry-derived ages tentatively in good
1074 agreement with the morpho-stratigraphic order of the glacial landforms. It has also
1075 compensated some of the limitations and error sources of lichenometric dating. Thus, it
1076 has proved to be a useful tool to assess the colonization lags and the validity of the
1077 lichenometry-derived ages.

1078 (v) Fieldwork on recently deglaciated surfaces and historical aerial photographs have
1079 shown clearly that the colonization lag of *Rhizocarpon geographicum* lichen species is
1080 from 15-21 to 30 years, considerably longer than previously assumed in Tröllaskagi.
1081 Colonization of the *Porpidia* cf. *soredizodes* species is shorter, between 10 and 21
1082 years.

1083 (vi) From the measurements carried out in different lichenometry stations, growth of
1084 *Porpidia* cf. *soredizodes* lichen appeared to be higher than in the case of *Rhizocarpon*
1085 *geographicum*, and also proportional to that. Its growth rate has been tentatively

1086 estimated for the first time, at around 0.737 mm yr⁻¹. However, further research on the
1087 growth rates of this species is required for its potential use in lichenometric dating as a
1088 complementary species, since it also shows a shorter colonisation lag than *Rhizocarpon*
1089 *geographicum*.

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- 1634

1635 **Figure captions.**

1636 Figure 1. Location of the Tungnahryggsjökull glaciers and their forelands (C)
1637 (Vesturdalur and Austurdalur) in the context of Iceland (A) and the Tröllaskagi
1638 peninsula (B). The red boxes in panels A and B are panels B and C, respectively. The
1639 figure also includes the location of the place names mentioned throughout the paper.
1640 This figure is available in colour in the online version.

1641 Figure 2. Geomorphological map of the Vesturdalur foreland. (A) General view of the
1642 Western Tungnahryggsjökull foreland. (B) Detailed moraine mapping and glacier
1643 margin geometry reconstructed throughout the different glacial stages identified, and
1644 ^{36}Cl CRE and lichenometric dating results (both are expressed in ages and calendar
1645 years). Note that stages 13, 14, 15 and 16 correspond to the years 1946, 1985, 1994 and
1646 2000. The surface-contoured glacier (white) corresponds to the year 2005 (stage 17).
1647 The abbreviations “Rg” and “Ps” in lichenometry stations indicate that the estimated
1648 dates are derived from the *Rhizocarpon geographicum* and *Porpidia sorelizodes*
1649 lichens, respectively, and the number correspond to the longest axis of the largest lichen
1650 measured. This figure is available in colour in the online version.

1651 Figure 3. Geomorphological map of the Austurdalur foreland. (A) General view of the
1652 Eastern Tungnahryggsjökull foreland. (B) Detailed moraine mapping and glacier margin
1653 geometry reconstructed throughout the different glacial stages identified, and ^{36}Cl CRE
1654 and lichenometric dating results (both are expressed in ages and calendar years). Note
1655 that stages 11, 15 and 16 correspond to the years 1946, 1985 and 2000. The surface-
1656 contoured glacier (white) corresponds to the year 2005 (stage 17). The abbreviations
1657 “Rg” and “Ps” in lichenometry stations indicate that the estimated dates are derived
1658 from the *Rhizocarpon geographicum* and *Porpidia sorelizodes* lichens, respectively,

1659 and the number correspond to the longest axis of the largest lichen measured. This
1660 figure is available in colour in the online version.

1661 Figure 4. ^{36}Cl CRE ages and internal (analytical) uncertainty at 1σ level of the samples
1662 from Vesturdalur and Austurdalur. Note that the samples clustering around 500 yr (15th
1663 century) in Austurdalur are indistinguishable. Distance to the terminus (year 2005) is
1664 measured along the flowline from the reconstructed snout apex of the phase where the
1665 samples were collected. This figure is available in colour in the online version.

1666 Figure 5. Correlation between largest thalli (longest axis) of species *Rhizocarpon*
1667 *geographicum* and *Porpidia* cf. *soredizodes* in several lichenometry stations. With the
1668 aim of avoiding those lichens potentially affected for any environmental factor
1669 disturbing their normal growth, the largest lichens used come from those lichenometry
1670 stations where no lichen size decrease with increasing distance to the terminus was
1671 observed (i.e., TUV-2, TUV-4, TUV-5, TUV-6, TUV-2, TUE-4 and TUE-5). From
1672 the measurements, it appears that *Porpidia* cf. *soredizodes* lichens grow faster than
1673 those of *Rhizocarpon geographicum*.

1674

1675 **Table captions**

1676 Table 1. Glacial Equilibrium-Line Altitudes (ELAs) calculated over
1677 Tungnahryggsjökull glaciers through the application of the AAR and AABR methods
1678 over the 3D glacier reconstructions.

1679 Table 2. Surface ages estimated from [Kugelmann's \(1991\)](#) 0.44 mm yr⁻¹ growth rate for
1680 different colonization lags. The ages obtained from *Rhizocarpon geographicum* lichens
1681 discussed throughout the text are those derived from a 20-yr colonization lag. The
1682 figures in italics correspond to ages tentatively inferred from the largest *Porpidia*
1683 *soredizodes* lichen, assuming a 0.737 mm yr⁻¹ growth rate and a 15-year colonization
1684 lag (see section 5.2.1).

1685 Table 3. ³⁶Cl CRE ages converted to CE/BCE dates according to the different ³⁶Cl
1686 production rates from Ca spallation. Uncertainties include the analytical and production
1687 rate error.

1688 **Supplementary figures captions**

1689 SF1. Examples of *Rhizocarpon geographicum* group and *Porpidia soredizodes* thalli
1690 measured over scaled field photos from the lichenometric station TUW-3. The lines
1691 refer to the minimum circle (white) bounding the thalli outlines (yellow) and the
1692 diameter of the circle (black). Note the contrasted size of the largest thalli in the
1693 different species.

1694 SF2. Location of the lichenometry stations in relation to the glacier snout position
1695 shown in the different aerial photographs and the satellite image. The lines refer to the
1696 glacier margin outlined over the aerial photo at a specific date (red) and at the previous
1697 date with aerial photo available (green dashed line). The points display the location of
1698 the lichenometry stations. The aerial photos provide the dating control for the validation
1699 of the lichenometric dates.

1700 SF3. Glacier surface reconstruction for the CRE- and lichenometry-dated glacial stages.

1701 SF4. Examples of moraine boulders sampled for ^{36}Cl CRE dating in Vesturdalur
1702 (“TUW” samples) and Austurdalur (“TUE” samples) and their dates derived from the
1703 [Licciardi et al. \(2008\)](#) ^{36}Cl production rate from Ca spallation.

1704 SF5. Location and BCE dates of the ^{36}Cl samples from the Elliði crest.

1705 **Supplementary tables captions.**

1706 ST1. Correspondence between glacial stages mapped over historical aerial photos and
1707 the dates.

1708 ST2. Glacier length and snout position variations measured along the flowline.

1709 ST3. Glacier extent and volume variations calculated from 2D and 3D glacier
1710 reconstructions.

1711 ST4. Size of the largest lichen at the lichenometry stations in the forelands of the
1712 western and eastern Tungnahryggsjökull glaciers.

1713 ST5. Geographic sample locations, topographic shielding factor, sample thickness and
1714 distance from terminus.

1715 ST6. Chemical composition of the bulk rock samples before chemical treatment. The
1716 figures in italic correspond to the average values of the bulk samples analysed and were
1717 those used for the age-exposure calculations of the samples without bulk chemical
1718 composition analysis.

1719 ST7. Concentrations of the ^{36}Cl target elements Ca, K, Ti and Fe, determined in splits
1720 taken after the chemical pre-treatment (acid etching).

1721 ST8. ^{36}Cl analytical data and CRE dating results according to different ^{36}Cl production
1722 rates from Ca spallation. $^{36}\text{Cl}/^{35}\text{Cl}$ and $^{35}\text{Cl}/^{37}\text{Cl}$ ratios were inferred from measurements
1723 at the ASTER AMS facility. The numbers in italic correspond to the internal
1724 (analytical) uncertainty at 1σ level.

Table 1[Click here to download Table: Table_1.docx](#)

Stage	W Tungnahryggsjökull				E Tungnahryggsjökull			
	<i>AAR (0.67)</i>	Δ	<i>AABR (1.5±0.4)</i>	Δ	<i>AAR (0.67)</i>	Δ	<i>AABR (1.5±0.4)</i>	Δ
1	1021	-	1006 +25/-20	-	1032	-	1027 ±20	-
2	1047	+26	1032 ±20	+26	1032	0	1032 ±15	+5
3	1052	+5	1037 +20/-15	+5	1034	+2	1034 ±15	+2
4	1054	+2	1049 +20/-15	+12	1037	+3	1037 ±15	+3
5	1059	+5	1059 ±15	+10	1041	+4	1041 ±15	+4
6	1067	+8	1062 +20/-10	+3	1042	+1	1042 ±15	+1
7	1072	+5	1072 +15/-10	+10	1046	+5	1046 ±15	+5
8	1076	+4	1081 ±15	+9	1047	+1	1052 ±15	+6
9	1082	+6	1087 +15/-10	+6	1054	+7	1054 +15/-10	+2
10	1086	+4	1091 +15/-10	+4	1055	+1	1060 +15/-10	+6
11	1094	+8	1099 +15/-10	+8	1061	+6	1071 ±10	+11
12	1094	0	1099 +15/-5	0	1060	-1	1070 ±10	-1
13	1094	0	1099 +15/-5	0	1061	+1	1071 +15/-10	+1
14	1100	+6	1110 ±10	+11	1060	-1	1075 ±10	+4
15	1102	+2	1107 +15/-5	-3	1061	+1	1076 +15/-10	+1
16	1098	-4	1108 +10/-5	+1	1061	0	1076 ±10	0
17	1099	+1	1109 +15/-5	+1	1065	+4	1080 ±10	+4

Table 1. Glacial Equilibrium-Line Altitudes (ELAs) calculated over Tungnahryggsjökull glaciers through the application of the AAR and AABR methods over the 3D glacier reconstructions. Delta (Δ) is referred to the change with respect to the previous stage.

Table 2

[Click here to download Table: Table_2.docx](#)

Glacier foreland	Lichen station	Glacial stage	Date deduced from photographic evidence	Surface date from growth rate				
				<i>10-yr col. lag</i>	<i>15-yr col. lag.</i>	<i>20-yr col. lag</i>	<i>25-yr col. lag.</i>	<i>30-yr col. lag</i>
W Tungnahryggsjökull	TUW-1	15-16	1994-2000	<i>1980*</i>	<i>1975*</i>	<i>1970*</i>	<i>1965*</i>	<i>1960*</i>
	TUW-2	13-15	1946-1994	1961	1956	1951	1946	1941*
	TUW-3	12-13	<1946	<i>1950*</i>	1945	1940	1935	1930
	TUW-4	12	<1946	1925	1920	1915	1910	1905
	TUW-5	11	<1946	1904	1899	1894	1889	1884
	TUW-6	10	<1946	1854	1849	1844	1839	1834
	TUW-7	9	<1946	1842	1837	1832	1827	1822
	TUW-8	8	<1946	<i>1804</i>	<i>1799</i>	<i>1794</i>	<i>1789</i>	<i>1784</i>
E Tungnahryggsjökull	TUE-0	post-17	2005<	-	-	-	-	-
	TUE-1	14	1946-1985	<i>1982</i>	<i>1977</i>	<i>1972</i>	<i>1967</i>	<i>1962</i>
	TUE-2	13	1946-1985	1962	1957	1952	1947	1942*
	TUE-3	12	1946-1985	1943*	1938*	1933*	1928*	1923*
	TUE-4	11	<1946	1925	1920	1915	1910	1905
	TUE-5	10	<1946	1879	1874	1869	1864	1859
	TUE-6	9	<1946	1901**	1896**	1891**	1886**	1881**
	TUE-7	7	<1946	1896**	1891**	1886**	1881**	1876**
	TUE-8	7	<1946	<i>1813</i>	<i>1808</i>	<i>1803</i>	<i>1798</i>	<i>1793</i>

Comment [JM1]: Asumiendo que el sector del frente en el que se encuentra el bloque, ha permanecido estático, estable desde 1946

Table 2. Surface exposure ages estimated from Kugelmann's (1991) 0.44 mm yr^{-1} growth rate for different colonization lags. The stars indicate that either the date does not agree with the date deduced from aerial photos (*) or the date is incoherent with the moraine chronostratigraphy (**). The figures in italics correspond to dates tentatively inferred from the largest *Porpidia soledizodes* lichen, assuming a 0.737 mm yr^{-1} growth rate and a 10-year colonization lag.

Table 3[Click here to download Table: Table_3.docx](#)**Table 3. ^{36}Cl CRE ages converted to CE/BCE dates according to the different ^{36}Cl production rates from Ca spallation. Uncertainties include the analytical and production rate error.**

Sample name	Dates (CE/BCE)		
	Licciardi et al. (2008) Ca spallation prod. rate	Stone et al. (1996) Ca spallation prod. rate	Schimmelpfennig et al. (2011) Ca spallation prod. rate
<i>Moraine boulders at Vesturdalur (W Tungnahryggsjökull foreland)</i>			
TUW-9	1590 ± 100	1570±100	1520±120
TUW-10	1640±90	1620±90	1580±110
TUW-11	1480±120	1470±120	1420±140
TUW-12	1450±100	1430±110	1370±120
TUW-13	1470±130	1450±130	1400±150
TUW-14	670±210	620±210	500±250
TUW-15	1460±110	1430±110	1370±120
TUW-16	1220±190	1200±190	1130±210
<i>Moraine boulders at Austurdalur (E Tungnahryggsjökull foreland)</i>			
TUE-9	740±170	660±170	510±210
TUE-10	1460±100	1430±100	1360±120
TUE-11	380±200	290±200	110±250
TUE-12	400±200	320±190	150±240
<i>Glacially polished ridge Elliði</i>			
ELLID-1	14300±1700	14900±1600	16600±2100
ELLID-2	14200±1700	14800±1700	16500±2100

Figure 1
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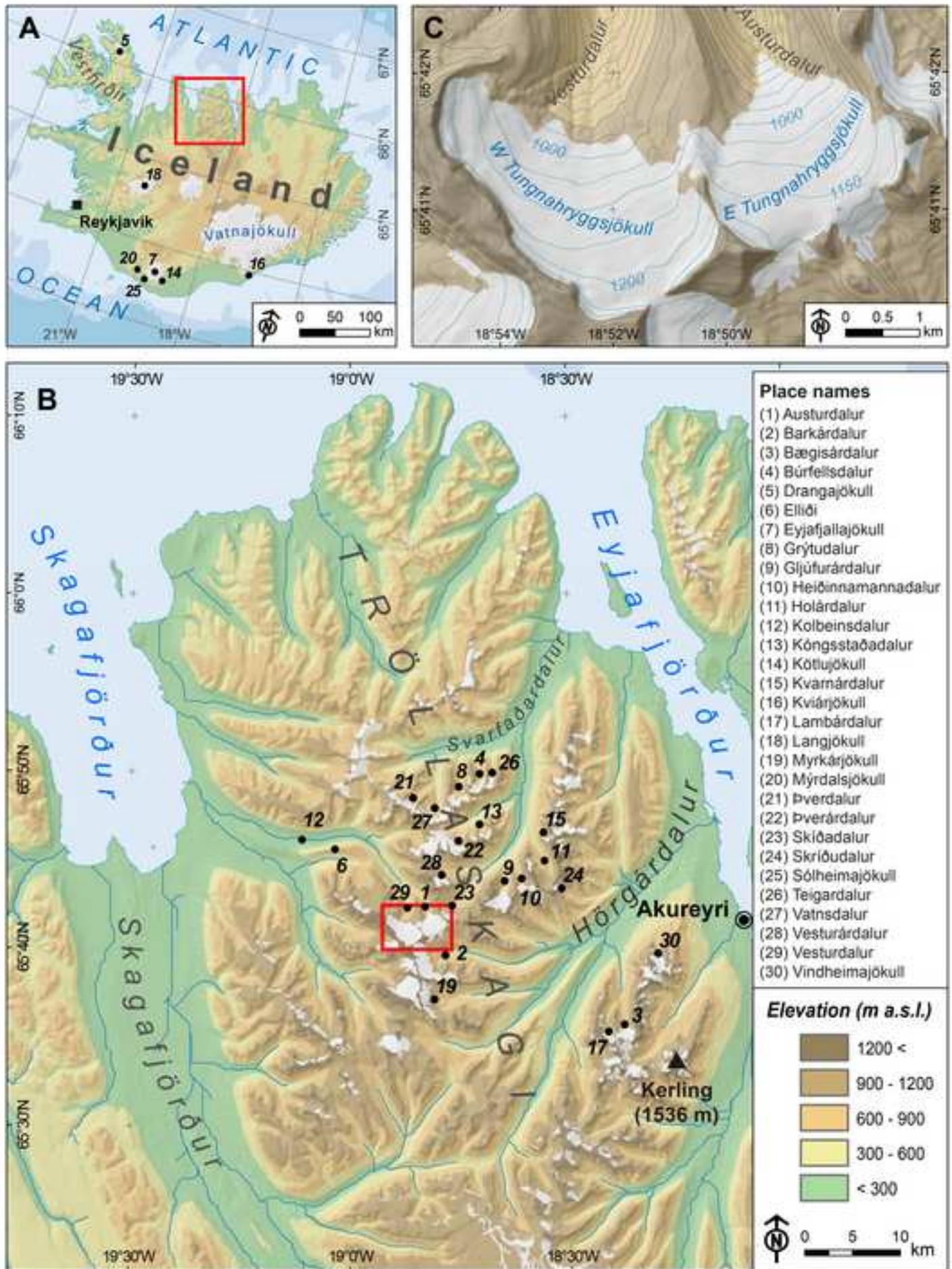


Figure 2

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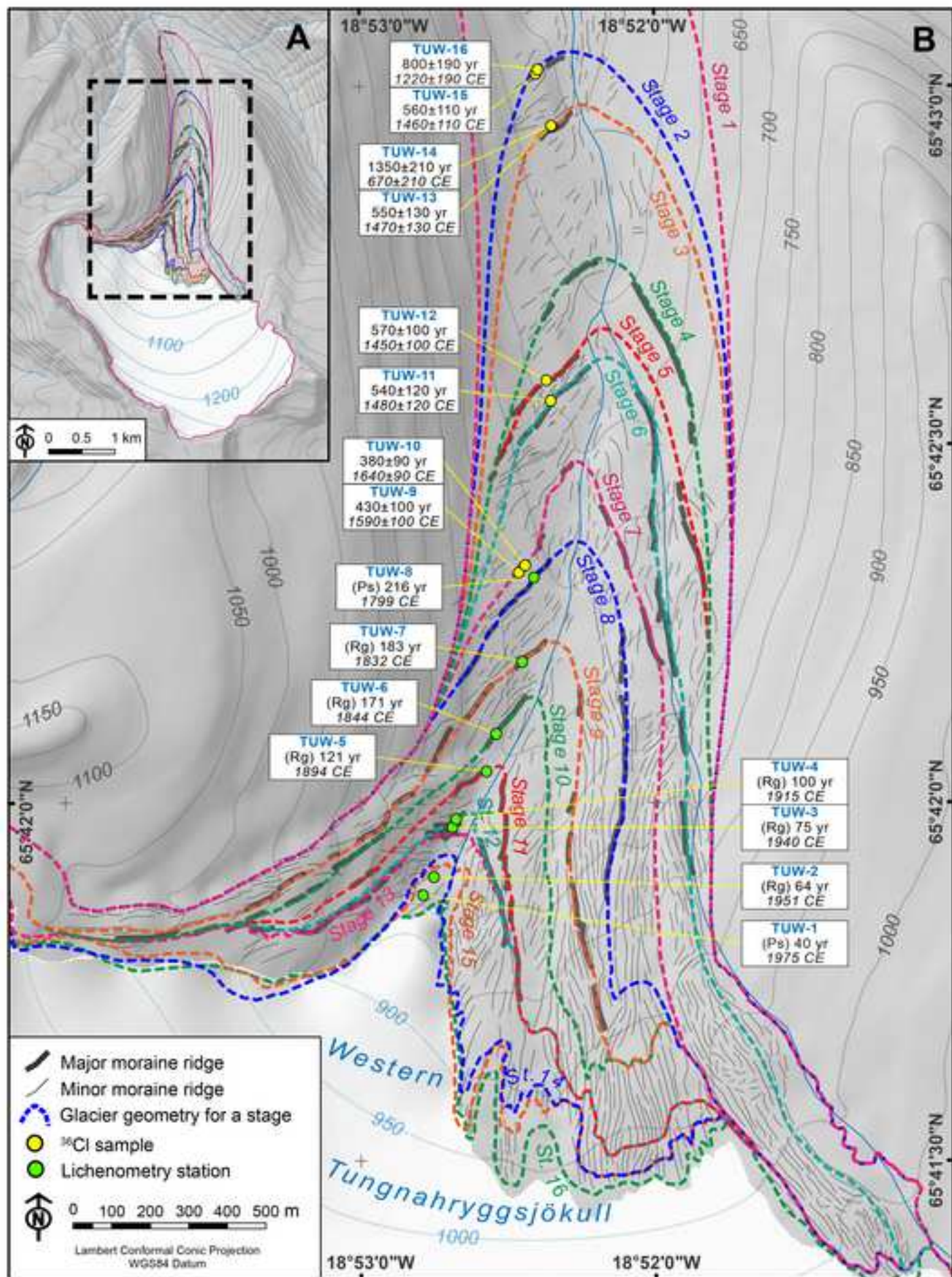


Figure 3
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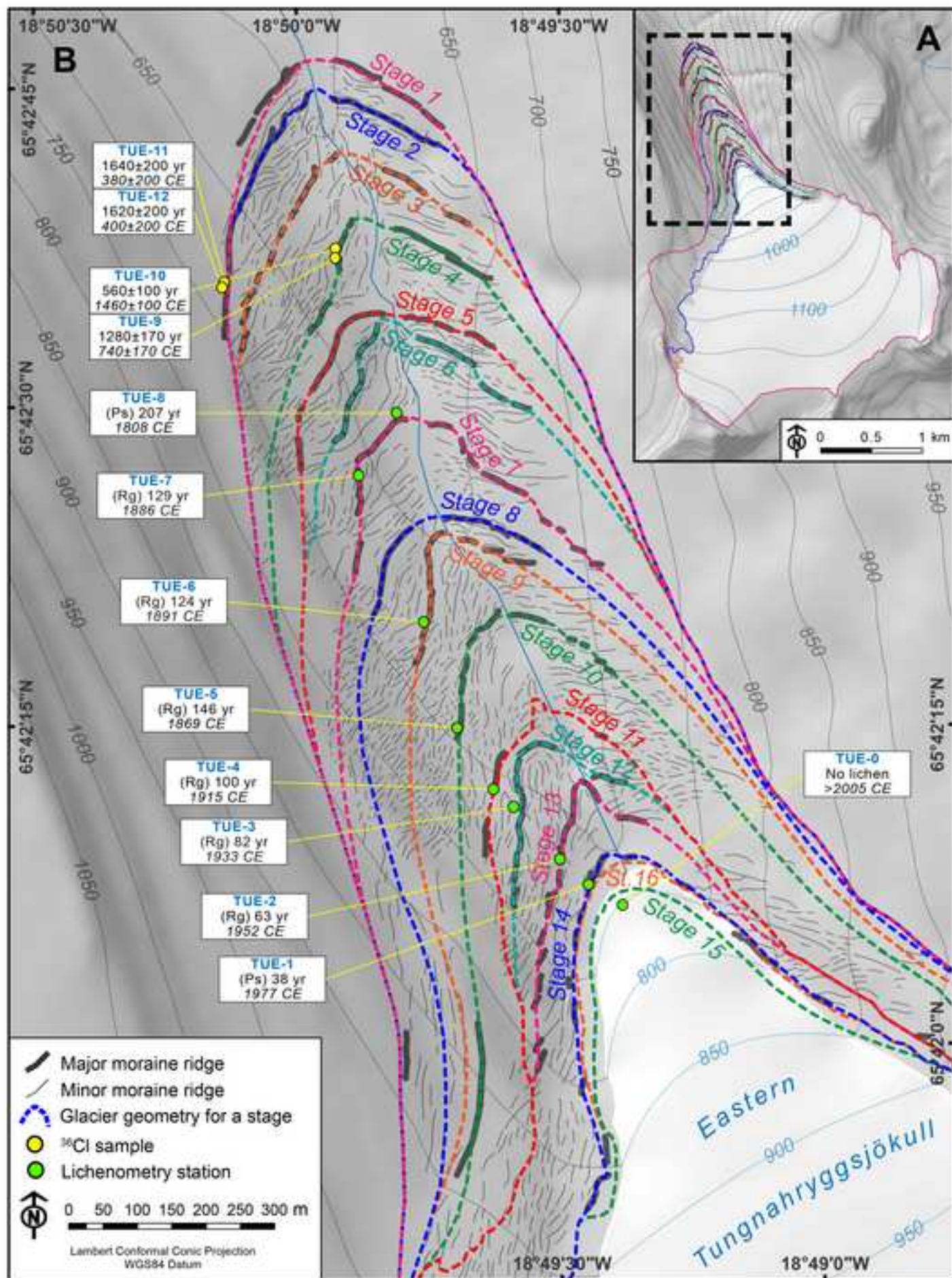


Figure 4
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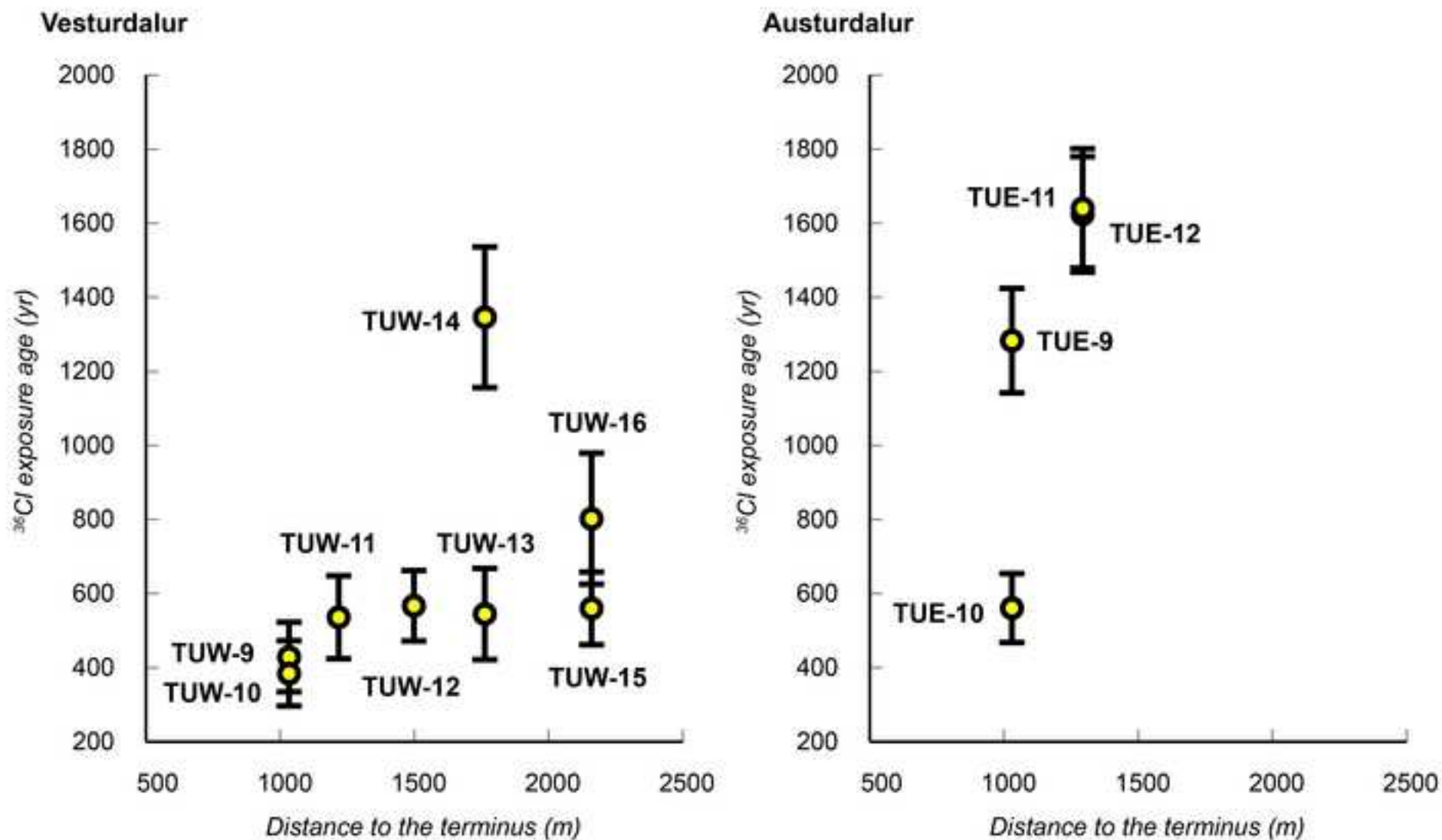
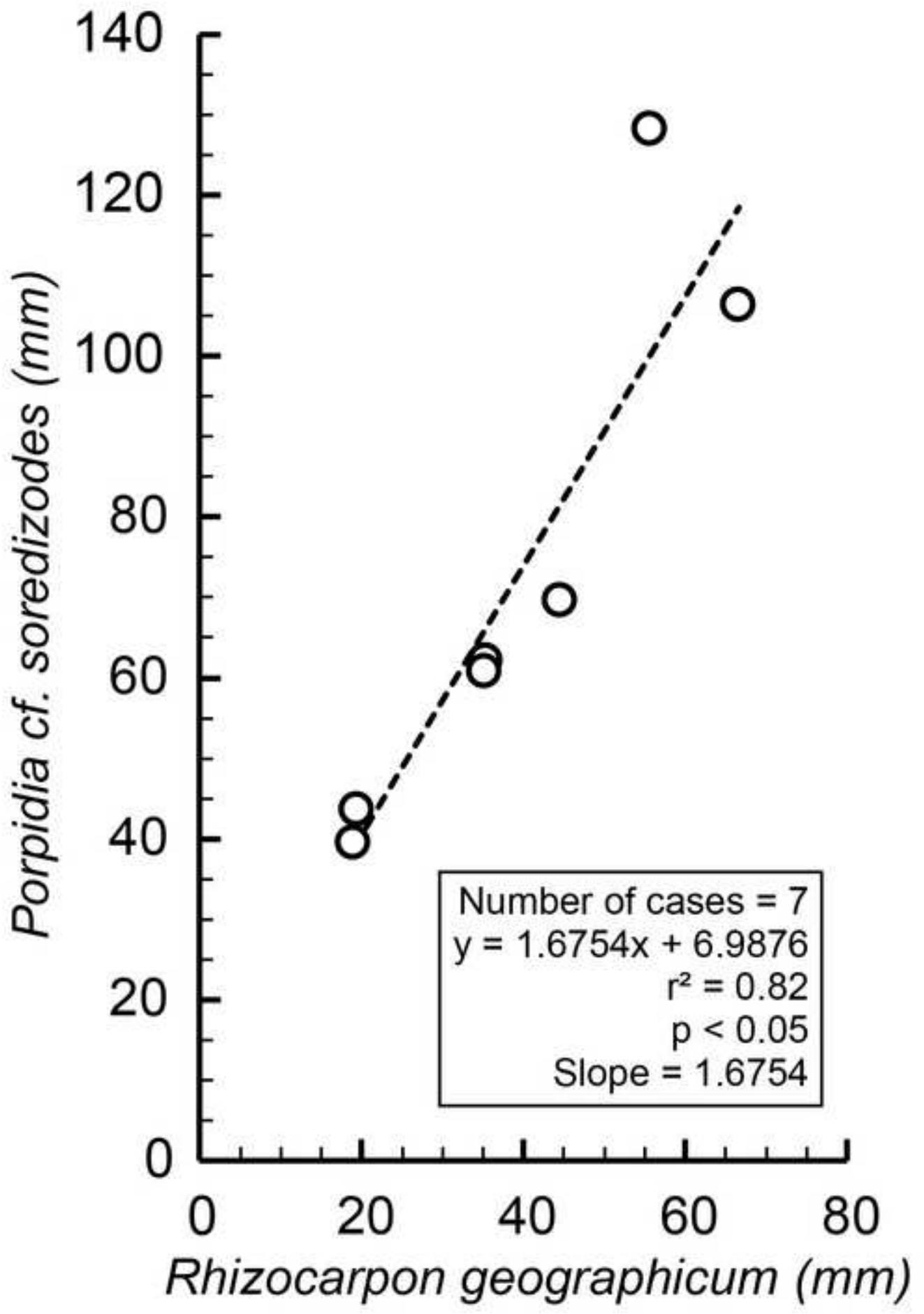


Figure 5
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