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# Mountain glacier fluctuations during the Lateglacial and Holocene on Clavering Island (northeastern Greenland) from $^{10}\text{Be}$ moraine dating

MELODY BIETTE, VINCENT JOMELLI, MARIE CHENET, RÉGIS BRAUCHER, VINCENT RINTERKNECHT, TIMOTHY LANE AND ASTER TEAM

Despite an increasing interest in Greenlandic mountain glaciers over the last decades, their evolution during the Lateglacial and Holocene still needs to be better constrained. Here we present 25  $^{10}\text{Be}$  cosmic-ray exposure (CRE) ages of boulders collected on moraines from three glaciers located on Clavering Island (northeastern Greenland). CRE ages span  $16.29 \pm 0.79$  ka to  $0.37 \pm 0.05$  ka and reveal three periods of moraine formation during the Lateglacial, the early and the late Holocene. Data show a multimodal distribution of the ages during the Lateglacial with exposure ages spanning from  $16.29 \pm 0.79$  ka to  $12.31 \pm 1.3$  ka. At least two glaciers experienced a greater expansion at the beginning of the Holocene than at the end of the Holocene, dated to  $11.3 \pm 0.3$  ka and  $10.8 \pm 0.6$  ka, respectively. At the end of the Holocene, glacial advances occurred during the Dark Ages Cold Period and the during the Little Ice Age (LIA), synchronous with glacial advances documented in nearby lake sediments. This new CRE chronology highlights that the LIA extent is not the largest glacier advance in the Late Holocene in Clavering Island. This broadly corresponds with other mountain glaciers of western and northern Greenland, and does not appear to reflect northern high latitude summer insolation that would suggest progressive temperature decrease, but instead mimics recent regional continental temperature reconstructions that show a long term warming driven by different forcing.

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From the Lateglacial to the end of the Holocene, Greenlandic ice core records (e.g. GRIP, NGRIP and GISP2 projects) reveal a period of fluctuating climate with strong centennial-scale variability in the order of 1-2 °C throughout the Holocene (Vinther *et al.* 2006, 2009; Kobashi *et al.* 2017). Due to their sensitivity to summer temperature and their short response time, the numerous mountain glaciers (or local glaciers as described by Kelly & Lowell (2009)) at the periphery of the Greenland Ice Sheet (GrIS) offer a unique opportunity to analyze glacier response to these periods of fluctuating palaeoclimate conditions (Masson-Delmotte *et al.* 2012). The application of the cosmic ray exposure (CRE) dating to moraine boulders is a pertinent method for obtaining direct evidence of the glacier history (Gosse & Klein 2015). However, despite some studies that focused on local glacier fluctuations over the last decades (Kelly & Lowell 2009; O'Hara *et al.* 2017; Schweinsberg *et al.* 2019), robust moraine chronologies based on CRE dating remain limited in Greenland. As a result, it is difficult to determine the chronology of the Holocene maximum extent, the possible regional asynchronies of this maximum extent in Greenland and the external/internal climate forcing responsible for this change of behavior.

At present, the most reliable CRE dating reconstructions of mountain glacier fluctuations since the Lateglacial Maximum (LGM) are in northwest and northeast Greenland. At Jensen Land, north Greenland,  $^{10}\text{Be}$  CRE dating evidences a Younger Dryas (YD) glacier advance (and subsequent

47 retreat) of three glaciers. The Sifs valley moraine, the Henson Bugt moraine, and the Moore glacier  
48 moraine are dated at  $12.1 \pm 0.6$ ,  $12.8 \pm 0.8$  and  $12.8 \pm 0.7$  ka, respectively (Möller *et al.* 2010; Larsen *et al.*  
49 2016; O'Hara *et al.* 2017). This is one of the only Greenlandic mountain glacier locations where a YD  
50 readvance has been documented. However, the Holocene trend of these glaciers behaviour remains  
51 unknown. Further south, on Disko Island, west Greenland, Jomelli *et al.* (2016) provided  $^{36}\text{Cl}$  CRE  
52 ages for four moraines from Lyngmarksbræen glacier dated to the Lateglacial/Holocene transition  
53 ( $11.9 \pm 1.7$  ka), and during the last millennium ( $0.82 \pm 0.13$ ,  $0.57 \pm 0.09$ , and  $0.3 \pm 0.06$  ka), with the  
54 largest glacier extent prior the Little Ice Age (LIA ~ AD 1450 to AD 1850). Close to Disko Island, a  
55 local glacier from Nakågajoq advanced at  $10.4 \pm 0.2$  ka (O'Hara *et al.* 2017), and at Uigordleq Lake  
56 Young *et al.* (2015) provided evidence of a glacial advance during the period of the Medieval Climate  
57 Anomaly (MCA ~ AD 950 to AD 1250) from a moraine dated to  $0.8 \pm 0.04$  ka. Finally, two glacial  
58 advances were dated from a local glacier on the Nuussuaq Peninsula, with the largest advance  
59 occurring at  $1.5 - 0.7$  ka, and a second less extensive advance occurring during the LIA (Schweinsberg  
60 *et al.* 2019).

61 In Scoresby Sund (northeast Greenland),  $^{10}\text{Be}$  CRE ages of bedrock and boulders down valley  
62 from moraines indicate that Bregne ice cap was within 250 m of its present-day limit by at least 10.7  
63 ka (Kelly *et al.* 2008; Levy *et al.* 2014). A second Late Holocene or LIA unweathered and unvegetated  
64 moraine was identified, but uncertainties associated with the  $^{10}\text{Be}$  CRE ages prevented precise dating.  
65 Nevertheless this glacier advance during Historical time was the most extensive since the Early  
66 Holocene. Results from Milne Land, Scoresby Sund, reveal that a local glacier retreated during the YD  
67 and deposited the inner Milne Stade moraines at  $\sim 11.4 \pm 0.6$  ka, in phase with fluctuations of the GrIS  
68 Fonfjord marine outlet glacier (Levy *et al.* 2016).

69  
70 Overall, our understanding of local mountain glacier fluctuations since the Lateglacial based  
71 on CRE ages remains elusive, due to: (i) the limited number of mountain glaciers studied, (ii) the  
72 uncertainties concerning the age of moraine deposition, and (iii) the difficulty of developing a  
73 continuous Lateglacial to Late Holocene glacial chronology at the same site, either because of field  
74 constraints or CRE dating uncertainties. To improve knowledge of glacier behaviour through the  
75 Lateglacial and Holocene, we present a new  $^{10}\text{Be}$  CRE dating based on moraine chronology from three  
76 mountain glaciers on Clavering Island, northeast Greenland. We then compare our local glacier  
77 chronology to independent lake sediment records close to our study area and with previously CRE  
78 dated local glacier advances in other parts of Greenland.

## 79 80 **Regional setting**

81  
82 Clavering Island is located in High Arctic northeast Greenland ( $74^\circ\text{N}$ ) in Gael Hamkes Bugt (Fig.1A).  
83 The island has a surface area of  $\sim 1500$  km<sup>2</sup> and is located  $\sim 8$  km south of the Zackenberg Research  
84 station. The basement rocks are primarily granite and gneiss combined with some mica-schist and  
85 basalt (Koch & Haller 1971). The island hosts two main ice caps; the Skillgletcher ice cap on northern  
86 Clavering Island is  $\sim 250$  km<sup>2</sup>, with a highest point at 1619 m a.s.l. and a depth  $< 200$  m and  
87 Taggletscher, a smaller ice cap ( $\sim 16$  km<sup>2</sup>) on the southern part of the island. Smaller valley glaciers are  
88 also present, mostly in the Northern part of the island. The region has a typical High Arctic climate  
89 (Kotttek *et al.* 2006), with mean annual air temperature of  $-9$  °C (annual range:  $\sim -24.5$  to  $6.6$  °C) based  
90 on 1996–2015 values measured at the Zackenberg Research station (Hobbie *et al.* 2017). Summer air  
91 temperature averages  $4.5$  °C (Hobbie *et al.* 2017) and average precipitation is  $200$  mm a<sup>-1</sup> (Hansen *et*  
92 *al.* 2008).

93 This study focuses on the Theodolit plateau (Fig.1B) and, more specifically, on three glaciers  
94 flowing to the northwest on the west side of the Skillgletcher ice cap, informally named TheoA,  
95 TheoB, and TheoC. TheoA glacier is the smallest glacier with a catchment area of  $\sim 3.5$  km<sup>2</sup> and with  
96 an elevation range between 1466 and 660 m a.s.l. TheoB glacier is the largest glacier with a catchment  
97 area of  $\sim 7$  km<sup>2</sup> and an elevation range of 1547 to 620 m a.s.l. A proglacial lake ( $\sim 0.3$  km<sup>2</sup>) has formed  
98 in front of TheoB, close to its current ice margin, present since at least 1980. TheoC glacier has a  
99 catchment area similar to TheoB ( $\sim 6.5$  km<sup>2</sup>) and its elevation ranges from 1436 to 760 m a.s.l.

100 In front of all three glaciers are successions of well-preserved, unvegetated or partly vegetated  
101 moraines (Fig. 2). In front of TheoA are three moraines, located 250 m, 630 m, and 1000 m from the  
102 current ice front, at elevations ranging from 650 to 520 m a.s.l. Four moraines were identified in front  
103 of TheoB, very close to each other, 1420 - 1220 m from the current ice margin. An additional moraine  
104 remnant was identified 2120 m from the current ice margin. Moraines and remnants have elevations  
105 ranging from  $\sim 620$  to  $\sim 530$  m a.s.l. Finally, two moraines were identified in front of TheoC 100 m  
106 and 250 m from the current ice front, with elevations from 760 to 720 m a.s.l., respectively.  
107 Downstream, two moraines remnants located at 860 m and 2000 m from the present ice margin have  
108 elevations ranging from  $\sim 690$  to  $\sim 600$  m a.s.l.

109

## 110 **Material and methods**

111

### 112 *Field sampling*

113

114 Large ( $>2$  m high and  $>20$  m long), accessible and easily identified moraines or moraine remnants  
115 without evidence of disturbance (river, possible rock fall) were sampled and mapped in the field with a  
116 Garmin GPS survey. These moraines were named from the furthest from the glacier front (M1) to the  
117 closest (Mx) (Fig. 2; Table 1). All moraines and moraine remnants identified in the forefield of the  
118 TheoB glacier were sampled. The moraines located proximal ( $<10$  m) to the current front position of  
119 TheoA and TheoC glaciers were not sampled. 30 granitic boulders ( $>60$  cm in height) were sampled  
120 from the crests of the selected moraines on broadly horizontal or sub-horizontal surfaces using a  
121 hammer and a chisel. Only sampled boulders with minimal signs of erosion were sampled.  
122 Topographic shielding was estimated in the field using a compass clinometer of the sample positions.  
123 Sample elevations were extracted from a handheld Garmin GPS (vertical uncertainty of 10 m). All  
124 boulders were photographed and their height from ground-to-sample measured.

### 125 *Analytical procedure*

126

127 The chemical procedure was conducted at CALM lab (Cosmonucléides Au Laboratoire de Meudon -  
128 France). Samples were crushed and sieved to retain 1 mm-710  $\mu$ m fractions then sieved again to retain  
129 the 250-500  $\mu$ m fractions. The 250-500  $\mu$ m grain size fractions were leached in a dilute HF/HNO<sub>3</sub> acid  
130 mixture to remove atmospheric <sup>10</sup>Be. Pure quartz was spiked with 500  $\mu$ L of a commercial standard  
131 solution from the Scharlau Company (1000 mg L<sup>-1</sup> of <sup>9</sup>Be) and then digested in 48% hydrofluoric acid.  
132 Beryllium was extracted using anion and cation exchange columns and alkaline precipitation. The  
133 obtained beryllium hydroxides were dried, and finally oxidized for one hour at 900 °C. The final BeO  
134 oxides were combined with Nb powder for AMS measurements at the French 5 MV AMS national  
135 facility ASTER (Aix-en-Provence) (Klein *et al.* 2008; Arnold *et al.* 2010). Measurements were  
136 calibrated against in-house standard STD-11 with an assigned <sup>10</sup>Be/<sup>9</sup>Be ratio of  $1.191 \pm 0.013 \times 10^{-11}$

137 (Braucher *et al.* 2015) using a  $^{10}\text{Be}$  half-life of  $1.387 \pm 0.0012 \times 10^6$  years (Chmeleff *et al.* 2010;  
138 Korschinek *et al.* 2010).

### 139 *Age calculation*

140

141 Surface cosmic ray exposure ages were calculated with the CREP online calculator (Martin *et al.*  
142 2017; <https://crep.otelo.univ-lorraine.fr/#/>) applying the Lal-Stone time corrected scaling scheme (Lal  
143 1991; Stone 2000), the ERA 40 atmosphere model and the atmospheric  $^{10}\text{Be}$  based VDM for  
144 geomagnetic data base. Given the location of the study, the “Arctic”  $^{10}\text{Be}$  production rate of  $3.93 \pm 0.15$   
145 atoms  $\text{g}^{-1} \text{a}^{-1}$  established by Young *et al.* (2013) was applied here.  $^{10}\text{Be}$  CRE ages are reported with  $1\sigma$   
146 “external” uncertainties, which include measurement, production rate and scaling uncertainties (e.g.  
147 Balco *et al.* 2008). For a given moraine, its age corresponds to the arithmetic mean of the sample ages  
148 from that moraine, which has successfully passed a  $\text{Chi}^2$  test (Ward & Wilson 1978) used to identify  
149 outliers. We also considered the stratigraphic relationships to identify outliers.

150

## 151 **Results**

152

### 153 *Glacial chronology in each valley*

154 We first analyze the three glaciers separately and focus on the  $^{10}\text{Be}$  CRE ages of the samples collected  
155 on the observed moraines (Table 1, Figs. 3-5). Fig. 6 reports ages with their associated internal  
156 uncertainties. Otherwise, in the main text and the other figures, we report individual ages with their  
157 associated external uncertainty and in Table 1 ages with both their associated internal and external  
158 uncertainties (including analytical and production rate uncertainties).

159 TheoA glacier. - Two moraines (M1 and M2) were dated from TheoA (Table 1, Fig. 3, 6A), in the  
160 northeast of Theodolit Plateau. A fresh moraine located few meters downslope of a small lake 50 m  
161 from the glacier front position was not sampled due to suspected instability. Two boulders were dated  
162 from lateral moraine on the left of the glacier (M1, ~1000 m from the glacier front) to  $11.07 \pm 0.82$  ka  
163 (Cla 48) and  $10.6 \pm 0.74$  ka (Cla 47), resulting in a mean age of  $10.8 \pm 0.6$  ka. Further upstream, two  
164 boulders were sampled from the moraine next closest to the glacier front (M2) yielding ages of  
165  $1.23 \pm 0.1$  ka (Zack 40) and  $1.41 \pm 0.28$  ka (Cla 54b), yielding a mean age of  $1.2 \pm 0.09$  ka.

166

167 TheoB glacier. - Five moraines and moraine remnants were identified and sampled in front of the  
168 TheoB glacier, downslope from the ice-contact proglacial lake (near the front position of the glacier)  
169 (Fig. 4). About 2 km from the glacier front, two moraine terminal remnants (M1 and M2a) on the left  
170 side of the main river, ~20 m above the river, were selected for sampling. Close to the front a large  
171 rampart ~60 m high is distinguishable, dissected by two rivers draining the lake. The largest river  
172 erodes the front of this rampart and flows northerly across the Theodolit plateau (Figs 1, 2, 4). Three  
173 distinct, sequential moraine segments that compose this rampart were sampled (M3, M4, M5) (Fig. 4).  
174 A single sample located on an external moraine remnant named here M1 (Zack 30) provided a  $^{10}\text{Be}$   
175 CRE age of  $14.79 \pm 1.9$  ka ( $n = 1$ ). Five boulders partly covered by lichens on the external side of the  
176 rampart at both sides of the glacier are from lateral remnants M2b; Cla 01, 02, 05 on the right side of  
177 the glacier and Cla 38, Cla 39b on the left side of the glacier. Cla 02 ( $0.68 \pm 0.08$  ka) was considered as  
178 an outlier based on the  $\text{Chi}^2$  test and not further considered for analyses (Fig. 6A). The other samples  
179 yielded a mean  $^{10}\text{Be}$  CRE age of  $11.3 \pm 0.4$  ka ( $n = 4$ ). The arcuate remain on the other side of the main  
180 river in front of the rampart. The location of this moraine segment makes it difficult to determine if  
181 this landform was formed by separate ice advance or if it corresponds to the front position of the

182 lateral moraine M2b. We thus consider these two hypotheses separately. Assuming this segment  
183 corresponds to a different glacier advance (named M2a here), this remnant would yield a mean CRE  
184 age of  $11.4 \pm 0.4$  ka based on three boulders Cla 24, Zack 31 and Zack 32. However, hypothesizing that  
185 this arcuate remnant corresponds to the frontal location of the lateral moraines M2b (thereby  
186 amalgamating ages from M2a and M2b), it yields a mean  $^{10}\text{Be}$  CRE age of  $11.3 \pm 0.3$  ka (M2a + M2b:  
187  $n = 7$ ). Three other boulders (Cla 03, 08 and Zack 35) were sampled on M3, the largest moraine. The  
188  $^{10}\text{Be}$  CRE ages of these three boulders range from  $3.5 \pm 0.29$  to  $2.46 \pm 0.2$  ka. Based on the  $\text{Chi}^2$  test, Cla  
189 03 ( $2.46 \pm 0.2$  ka) was considered as an outlier likely due to post-depositional modification and rejected  
190 from the mean calculation. Following this, M3 yielded a mean  $^{10}\text{Be}$  CRE age of  $3.3 \pm 0.2$  ka ( $n = 2$ ).  
191 Four boulders collected on moraine M4 (Cla 10, 14, 15 and Zack 34) yielded a mean  $^{10}\text{Be}$  CRE age of  
192  $1.2 \pm 0.1$  ka ( $n = 4$ ). Upstream of M4, two samples were taken from M5,  $\sim 10$  m above the current lake  
193 level (Cla 11, 13). Cla 13 ( $3.49 \pm 0.27$  ka) was considered as an outlier (possibly due to inheritance) and  
194 rejected from the analysis. The remaining sample (Cla 11), and therefore the age ascribed to M5,  
195 returned an age of  $0.37 \pm 0.05$  ka.

196

197 TheoC glacier. - On TheoC, three moraines were selected for dating (Figs 5, 6A, Table 1). The  
198 moraine closest to the current front position of the glacier was not sampled due to suspected  
199 instability. Three boulders (Cla 26:  $16.21 \pm 1.2$  ka, Cla 29:  $19.56 \pm 1.08$  ka and Cla 31:  $16.29 \pm 0.79$  ka)  
200 were sampled on a large and high moraine surface covered by few large boulders, interpreted as a  
201 medial moraine remnant (M1), possibly formed by the coalescence of west and southwest Skill  
202 glaciers. Cla 29 was considered as an outlier by the  $\text{Chi}^2$  test and rejected from the mean calculation.  
203 The other samples yielded a mean  $^{10}\text{Be}$  CRE age of  $16.2 \pm 0.6$  ( $n = 2$ ). About 1 km upstream of M1,  
204 two partly lichen- and moss-covered boulders were sampled from a lateral moraine (M2). These two  
205 boulders (Cla 36 and Cla 37) yielded a CRE age of  $14.53 \pm 0.73$  and  $10.5 \pm 1.12$  ka, respectively. These  
206 boulders may have been deposited during the Lateglacial/Early Holocene transition. However, because  
207 their ages are significantly different, it is not possible to provide an age for the moraine M2. On M3,  
208 three lichen-free boulders were sampled. Cla 32 yielded a  $^{10}\text{Be}$  CRE age of  $0.48 \pm 0.07$  ka, Cla 33 of  
209  $0.5 \pm 0.07$  ka, and Cla 34 of  $0.21 \pm 0.03$  ka. According to their  $\text{Chi}^2$  test, Cla 34 was considered as an  
210 outlier and not included in age calculation. Therefore, Cla 32 and 33 yielded a mean  $^{10}\text{Be}$  CRE age of  
211  $0.49 \pm 0.05$  ka for M3.

#### 212 *Glacier pattern at Theodolit plateau*

213 To provide an overview of the three glacier fluctuations and develop a regional chronology, we  
214 combined  $^{10}\text{Be}$  ages from all three glaciers, except previously rejected samples (Fig. 6B). This allowed  
215 our dataset to be divided into three periods: the Lateglacial, the early and the Late Holocene. A  
216 probability density function of the ages reveals a multimodal distribution of the ages during the  
217 Lateglacial, with exposure ages spanning from  $16.29 \pm 0.79$  to  $12.31 \pm 1.3$  ka. During the Early  
218 Holocene the distribution is modal, with a mean age of  $11.11 \pm 0.82$  ka ( $n = 9$ ). The Late Holocene  
219 samples span from  $3.5 \pm 0.29$  to  $0.37 \pm 0.05$  ka ( $n = 11$ ). Two major modes then appear: one centered on  
220 the DACP with a mean CRE age of  $1.25 \pm 0.18$  ka ( $n = 6$ ) and the other one during the LIA with a mean  
221 age of  $0.45 \pm 0.07$  ka ( $n = 3$ ). This dataset reveals two important points about the investigated glaciers:  
222 (i) these glaciers were larger during the Early Holocene than the Late Holocene and (ii) larger during  
223 the Late Holocene than during the LIA.

#### 224 **Discussion**

225

226 The  $^{10}\text{Be}$  CRE ages of boulders collected on moraines and remains of three mountain glaciers located  
227 on Clavering Island made it possible to interpret the timing of deglaciation during the Lateglacial and  
228 Holocene near Zackenberg. The TheoB site displays the highest number of moraines preserved in the  
229 field. Based on the competing hypotheses of M2 (see above), we favor the association of M2a and  
230 M2b as a single moraine for preserving a high number of samples to date this landform. Furthermore  
231 M2a and M2b are both within their uncertainties and completely overlapping. We thus assumed that  
232 the moraine remnant M2a is geomorphologically linked to the lateral moraines of M2. These  $^{10}\text{Be}$  ages  
233 indicate that the glacier recorded at least one advance during the Early Holocene. The M1 moraine  
234 remnant reveals that the glacier reached an extensive position at the end of Lateglacial period close to  
235 the maximum extent reached by the glacier during the Early Holocene. Following this Early Holocene  
236 maximum position, the glacier retreated, before re-advancing at least three times during the Late  
237 Holocene at  $\sim 3$  ka, 1 ka and the LIA. This long-term Holocene pattern of change is broadly consistent  
238 with the glacier advances of TheoA, which shows at least one moraine formed during the Early  
239 Holocene and one moraine formed during the last millennium. In front of TheoC glacier, we identified  
240 moraines formation during the Lateglacial (M1) and during the LIA (M3). However, regarding M2,  
241 the scattering of the ages of the samples prevents any conclusion about the moraine's age, which may  
242 have been formed during the Lateglacial or the Early Holocene. Because we did not document  
243 moraine formation during the Middle Holocene, we suspect that these glaciers were smaller during  
244 this time than in the Late Holocene.

245 Lake sediment records close to the glaciers investigated in this paper provide independent  
246 indirect high-resolution evidence of glacier advances and retreats. At Zackenberg, northeast  
247 Greenland, lake sediment record from Madsen Lake suggests that three glacier advances occurred over  
248 the last 2000 years (Adamson *et al.* 2018). The first two advances (1.3 – 0.8 ka) occurred prior to the  
249 LIA, corresponding to the Dark Ages Cold Period (DACP  $\sim 1.75$  – 1.25 ka) and the MCA respectively.  
250 Our moraine record suggests that the advance during the DACP was larger than the advance during the  
251 LIA at least for two glaciers, consistent with Madsen Lake record. In Kulusuk,  $\sim 1000$  km south of  
252 Zackenberg, sediment core analyses document glacier advances since 9.5 ka (Balascio *et al.* 2015).  
253 Interestingly, DACP and LIA glacier advances were also identified from Kulusuk lake sediment  
254 record. However, the reconstruction of Kulusuk glacier activity from XRF PC1 data over the last 9.5  
255 ka indicated that the most extensive glacier advances occurred at the end of the LIA (Fig.7D) and not  
256 during the DACP (Balascio *et al.* 2015).

257 Despite the development of this new glacial chronology in Clavering Island, the limited  
258 number of absolute  $^{10}\text{Be}$  moraine chronologies of local mountain glaciers across Greenland makes our  
259 knowledge of their overall trends during the Holocene still incomplete. In particular, the understanding  
260 of the chronology of the maximum Holocene extent remains unclear, potentially occurring during the  
261 Early Holocene or the last millennium. At Clavering Island, two of the three investigated glaciers  
262 recorded their maximum during the Early Holocene. These data can be correlated with other moraine  
263 records in West Greenland where mountain glaciers displayed their maximum Holocene advance in  
264 the Early Holocene (Larsen *et al.* 2016; O'Hara *et al.* 2017). At Scoresby Sund,  $\sim 400$  km south of  
265 Zackenberg, Kelly *et al.* (2008) and Levy *et al.* (2016) dated the inner Milne Land Stage moraines to  
266 the Early Holocene, broadly synchronous with our Clavering glacier advances. However, at Istorvet  
267 ice cap near Scoresby Sund, the glacier reached its maximum Holocene extent by  $\sim 0.87$  ka and  
268 retreated from this limit ever since (Lowell *et al.* 2013). Similarly, mountain glaciers in the Stauning  
269 Alper appear to have reached their maximum Holocene extents during the Late Holocene (Hall *et al.*  
270 2008; Kelly *et al.* 2008). Moreover, as mentioned above, at Kulusuk, glaciers reached their largest

271 extent in the past 9.5 ka during the LIA. Consequently, these studies suggest possible regional  
272 differences in the chronology of the Holocene maximum glacier extent in Greenland.

273 The contrast and variability in glacier behaviour across Greenland throughout the Holocene  
274 suggests complex interactions between glacier and regional climate conditions constrained by various  
275 forcings. During the Holocene, two contrasting trends in temperature change may be considered.  
276 Declining summer insolation through the Holocene (Solomina *et al.* 2015) leads to the warmest  
277 temperature occurring in the Early Holocene (Buizert *et al.* 2018; Lesnek *et al.* 2020), followed by  
278 long-term cooling (Fig.7A). This cooling trend would suggest a progressive increase of mountain  
279 glacier size during the Holocene with the maximum Holocene extent during the LIA (Pendleton *et al.*  
280 2019). Mountain glaciers at Clavering do not reflect this overall pattern. In contrast, recent summer  
281 temperature reconstructions from pollen records suggest cooler temperature in the Early Holocene  
282 than in the Late Holocene (Fig. 7B), consistent with ice core records (Marsicek *et al.* 2018). The  
283 combination of large ice cover and meltwater forcing (McKay *et al.* 2018) could have favored cooler  
284 temperatures during the Early Holocene than during the Late Holocene. This Holocene temperature  
285 evolution is consistent with our moraine record at Clavering and some other glacier chronologies  
286 documented in other regions of Greenland.

287 Superimposed on long-term temperature changes are episodes of glacier expansion and retreat  
288 on multi-decadal to centennial timescales. These are likely to be caused by forcings that include sea  
289 ice change variation (Fig.7E) (Bond *et al.* 1997), volcanic eruption, short-term solar variability or  
290 internal climate variability (e.g. Kelly & Lowell 2009; Levy *et al.* 2014; Jomelli *et al.* 2016; van der  
291 Bilt *et al.* 2019). Ice rafting events in the North Atlantic were invoked by Balascio *et al.* (2015) to  
292 explain these ice advance periods during the Late Holocene documented from Kulusuk lake sediment  
293 record. In addition, Moffa-Sanchez & Hall (2017) revealed three periods of enhanced cold and fresh  
294 polar waters from the east Greenland current around 3 ka, 1 ka and the LIA, which would explain the  
295 synchronicity of glacier advances at Clavering and Kulusuk. However, further data are needed from  
296 both moraine dating and lake sediment records before a robust understanding of the impacts of such  
297 forcing on glacier changes can be established, especially because of the specific character of moraine  
298 records (Gibbon *et al.* 1984). The respective influence of the geomorphic context (for instance slope,  
299 size of the catchment) (Chenet *et al.* 2010; Brun *et al.* 2019) and the local-regional climatic conditions  
300 responsible for variation in glacier behaviour could then be established. Interestingly, we showed that  
301 during the Late Holocene some episodes of glacier changes were synchronous from 74°N to 65°N on  
302 the eastern side of Greenland suggesting a regional climate change rather than a local glacier pattern  
303 driven by specific geomorphological conditions or ice dynamic. However, causes of these glacier  
304 advances are also still unclear. Gathering additional data from cosmic ray exposure dating on moraine  
305 will help our understanding of mountain glacier volume loss that has increased over the last centuries  
306 in NE Greenland (Carrivick *et al.* 2019).

## 307 **Conclusions**

308

309 Cosmic ray exposure dating of moraines from three adjacent mountain glaciers on western Clavering  
310 Island provide a new chronology of the glacial history in northeast Greenland from the Lateglacial to  
311 present. Only one glacier with a moraine dated at  $16.2 \pm 0.6$  ka allows identifying the extent of glaciers  
312 during the Lateglacial. During the Holocene, several glacial advances are well constrained. TheoA and  
313 TheoB glaciers exhibit a maximum Holocene glacial extent during the Early Holocene at  $10.8 \pm 0.6$  and  
314  $11.3 \pm 0.3$  ka, respectively. This maximum Holocene extent on Clavering Island is broadly synchronous  
315 with some glacier advances recorded across Greenland. We suggest that this larger Early Holocene  
316 glacier expansion may have been caused by cooler temperature during the Early Holocene in the



317 Arctic compared to the Late Holocene. The absence of Middle-Holocene moraines in the study area  
318 suggests that these glaciers were smaller during this period than during their Late Holocene extension  
319 that occurred at ~3 ka. Advances at ~3 ka, during DACP and the LIA are synchronous with glacial  
320 advances documented from lake sediments in the northeast Greenland.

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323 Sorbonne University. The  $^{10}\text{Be}$  measurements were performed at the ASTER AMS national facility  
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325 thématiques d'excellence" program for the "Equipements d'excellence" ASTER-CEREGE action and  
326 IRD. Finally, the authors would like to thank the anonymous reviewers whose suggestions helped  
327 improve and clarify this manuscript.

328

329 **Table caption:**

330

331 *Table 1.* Detailed cosmogenic nuclide sample concentrations and calculated exposure durations from  
332 the three glaciers in the Clavering Island. Measurements were calibrated against in-house standard  
333 STD-11 with an assigned  $^{10}\text{Be}/^9\text{Be}$  ratio of  $1.191 \pm 0.013 \times 10^{-11}$  (Braucher *et al.* 2015) using a  $^{10}\text{Be}$   
334 half-life of  $1.387 \pm 0.0012 \times 10^6$  years (Chmeleff *et al.* 2010; Korschinek *et al.* 2010). In samples Cla  
335 02, 29, 32, 33, 34, 38, 47, 48, 54b,  $^{10}\text{Be}/^9\text{Be}$  ratios were corrected for a process blank value of  
336  $(5.31 \pm 0.50) \times 10^{-15}$ . In samples Cla 05, 13, 14, 15, 36, Zack 35, 40,  $^{10}\text{Be}/^9\text{Be}$  ratios were corrected for a  
337 process blank value of  $(2.5 \pm 0.42) \times 10^{-15}$ . In samples Cla 03, 08, 11, Zack 32,  $^{10}\text{Be}/^9\text{Be}$  ratios were  
338 corrected for a process blank value of  $(4.26 \pm 0.46) \times 10^{-15}$ . In samples Cla 01, 31, 37, Zack 34,  
339  $^{10}\text{Be}/^9\text{Be}$  ratios were corrected for a process blank value of  $(4.59 \pm 0.48) \times 10^{-15}$ . In samples Cla 10, 24,  
340 Zack 30, 31,  $^{10}\text{Be}/^9\text{Be}$  ratios were corrected for a process blank value of  $(5.49 \pm 0.46) \times 10^{-15}$ . In  
341 samples Cla 26, 39b,  $^{10}\text{Be}/^9\text{Be}$  ratios were corrected for a process blank value of  $(9.11 \pm 0.82) \times 10^{-15}$ .  
342 Samples rejected by the  $\chi^2$  test or for stratigraphic reasons are highlighted in italics. See text for  
343 more explanation.

344

345 **Figures caption:**

346

347 *Fig. 1.* A. Map of Clavering Island region in northeast Greenland with the location of the study area  
348 (red box). B. Location of the three investigated glaciers and moraines (yellow lines) on Theodolit  
349 plateau. Sampling areas on studied moraines in this paper are indicated with white circles. Source  
350 photography: Earthstar Geographics.

351

352 *Fig. 2.* View of TheoB glacier from the Theodolit plateau with the two rivers cutting the rampart  
353 composed of several moraines in July 2017. A lake not visible on this picture is located behind the  
354 frontal moraine M5.

355

356 *Fig. 3.* Chronology of glacial advances dated from two moraines of TheoA glacier on Clavering  
357 Island. Source imagery: KMS.

358

359 *Fig. 4.* Chronology of glacial advances dated from five moraines of TheoB glacier on Clavering  
360 Island. Source imagery: KMS.

361

362 Fig. 5. Chronology of glacial advances dated from three moraines of TheoC glacier on Clavering  
363 Island. Source imagery: KMS.

364

365 Fig. 6. A. Camel plot of the individual (thin lines) and summed (thick lines)  $^{10}\text{Be}$  CRE ages (with their  
366 internal uncertainties) collected on the investigated glaciers on the Clavering Island. Distributions  
367 were calculated with free-MATLAB code from Greg Balco at the University at Washington  
368 Cosmogenic Isotope Lab available from

369 [http://depts.washington.edu/cosmolab/pubs/gb\\_pubs/camelplot.m](http://depts.washington.edu/cosmolab/pubs/gb_pubs/camelplot.m).

370 B. Combination of the all individual  $^{10}\text{Be}$  CRE ages (with their internal uncertainties) from the three  
371 glaciers on Clavering Island. Specific climatic periods/events: YD = Younger Dryas; DACP = Dark  
372 Age Cold Period; LIA = Little Ice Age (after Kolling *et al.* 2017). Realized with the KDX application  
373 (Spencer *et al.* 2017).

374

375 Fig. 7. Clavering moraine record compared with forcing. A. GRIP temperature,  $\text{CO}_2$  from Shakun *et al.*  
376 *al.* (2012) and summer insolation in the Northern Hemisphere. B. Temperature reconstruction of  
377 Northern marine margins, North America and Europe from Marsicek *et al.* (2018). C. Moraine record  
378 from TheoB glacier. TheoB chronology is the most complete in this study (dashed line = hypothetic  
379 glacier evolution). D. XRF PC1 Kulusuk proglacial lake representing glacier size from changes in the  
380 relative amount and grain size of minerogenic sediment (Balascio *et al.* 2015). E. Hematite-stained  
381 grains (HSG) identified in core MC52-VM29-191 interpreted to indicate ice-rafting events (Bond *et al.*  
382 1997).

383

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## 385 References

386

387 Adamson, K., Lane, T., Carney, M., Bishop, T. & Delaney, C. 2018: High-resolution proglacial lake  
388 records of pre-Little Ice Age glacier advance, Northeast Greenland. *Boreas* 48, 535– 550.

389

390 Arnold, M., Merchel, S., Bourlès, D.L., Braucher, R., Benedetti, L., Finkel, R.C., Aumaître, G.,  
391 Gottdang, A. & Klein, M. 2010: The French accelerator mass spectrometry facility ASTER: Improved  
392 performance and developments. *Nuclear Instruments and Methods in Physics Research Section B:  
393 Beam Interactions with Materials and Atoms* 268, 1954–1959.

394

395 Balascio, N. L., Andrea, W. J. & Bradley, R. S. 2015: Glacier response to North Atlantic climate  
396 variability during the Holocene. *Climate of the Past* 11, 1587–1598. [https://doi.org/10.5194/cp-11-  
397 1587-2015](https://doi.org/10.5194/cp-11-1587-2015)

398

399 Balco, G., Stone, J. O., Lifton, N. A. & Dunai, T. J. 2008: A complete and easily accessible means of  
400 calculating surface exposure ages or erosion rates from  $^{10}\text{Be}$  and  $^{26}\text{Al}$  measurements. *Quaternary  
401 Geochronology* 3, 174–195.

402

403 Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H.,  
404 Hajdas, I. & Bonani G. 1997: A Pervasive Millennial-Scale Cycle in North Atlantic Holocene and  
405 Glacial Climates. *Science* 278, 1257–1266. <https://doi.org/10.1126/science.278.5341.1257>

406

407 Braucher, R., Guillou, V., Bourlès, D. L., Arnold, M., Aumaître, G., Keddadouche, K. & Nottoli, E.,  
408 2015: Preparation of ASTER in-house  $^{10}\text{Be}/9\text{Be}$  standard solutions. *Nuclear Instruments and Methods  
409 in Physics Research Section B: Beam Interactions with Materials and Atoms* 361, 335–340.

410

411 Brun, F., Wagnon, P., Berthier, E., Jomelli, V., Maharjan, S. B., Shrestha, F. & Kraaijenbrink, P. D. A.  
412 2019: Heterogeneous influence of glacier morphology on the mass balance variability in high  
413 mountain Asia. *Journal of Geophysical Research: Earth Surface* 124, 1331– 1345.

414

415 Buizert, C., Keisling, B. A., Box, J. E., He, F., Carlson, A. E., Sinclair, G. & DeConto, R. M. 2018:  
416 Greenland-wide seasonal temperatures during the last deglaciation. *Geophysical Research Letters*, 45,  
417 4, 1905-1914.  
418

419 Carrivick, J. L., Boston, C. M., King, O., James, W. H. M., Quincey, D. J., Smith, M. W., Grimes, M.  
420 & Evans, J. 2019: Accelerated volume loss in glacier ablation zones of NE Greenland, Little Ice Age  
421 to present. *Geophysical Research Letters* 46, 1476- 1484.  
422

423 Chenet, M., Roussel, E., Jomelli, V., Grancher, D., 2010: Asynchronous Little Ice Age glacial  
424 maximum extent in southeast Iceland. *Geomorphology* 114, 253–260.  
425 <https://doi.org/10.1016/j.geomorph.2009.07.012>  
426

427 Chmeleff, J., von Blanckenburg, F., Kossert, K. & Jakob, D. 2010: Determination of the <sup>10</sup>Be half-life  
428 by multicollector ICP-MS and liquid scintillation counting. *Nuclear Instruments and Methods in*  
429 *Physics Research Section B: Beam Interactions with Materials and Atoms* 268, 192–199.  
430

431 Gibbons, A. B., Megeath, J. D. & Pierce, K. L. 1984: Probability of moraine survival in a succession  
432 of glacial advances. *Geology* 12, 327–330.  
433

434 Gosse J. & Klein J. 2015: Terrestrial cosmogenic dating. In Rink, W., Thompson, J. & Jeroen W.  
435 (eds.): *Encyclopedia of Scientific Dating Methods*, 799–812, Springer, Dordrecht.  
436

437 Hall, D. K., Williams, R. S., Luthcke, S. B. & Digirolamo, N. E. 2008: Greenland ice sheet surface  
438 temperature, melt and mass loss: 2000–06. *Journal of Glaciology* 54, 81 - 93.  
439

440 Hansen, B. U., Sigsgaard, C., Rasmussen, L., Cappelen, J., Hinkler, J., Mernild, S. H., Petersen, D.,  
441 Tamstorf, M. P., Rasch, M. & Hasholt, B. 2008: Present-day climate at Zackenberg. *Advances in*  
442 *Ecological Research* 40, 111–149.  
443

444 Hobbie, J. E., Shaver, G. R., Rastetter, E. B., Cherry, J. E., Goetz, S. J., Guay, K. C., Gould, W. A. &  
445 Kling, G. W. 2017: Ecosystem responses to climate change at a Low Arctic and a High Arctic long-  
446 term research site. *Ambio* 46, 160–173.  
447

448 Jomelli, V., Lane, T., Favier, V., Masson-Delmotte, V., Swingedouw, D., Rinterknecht, V.,  
449 Schimmelpfennig, I., Brunstein, D., Verfaillie, D., Adamson, K., Leanni, L., Mokadem, F., Aumaître,  
450 G., Bourlès, D.L., Keddadouche, K. & ASTER Team. 2016: Paradoxical cold conditions during the  
451 medieval climate anomaly in the Western Arctic. *Scientific Reports* 6, 32984. DOI: 10.1038/srep32984

452 Kelly, M. A. & Lowell, T. V. 2009: Fluctuations of local glaciers in Greenland during latest  
453 Pleistocene and Holocene time. *Quaternary Science Reviews* 28, 2088–2106.  
454

455 Kelly, M. A., Lowell, T. V., Hall, B. L., Schaefer, J. M., Finkel, R. C., Goehring, B. M., Alley, R. B.  
456 & Denton, G. H. 2008: A <sup>10</sup>Be chronology of lateglacial and Holocene mountain glaciation in the  
457 Scoresby Sund region, east Greenland: implications for seasonality during Lateglacial time.  
458 *Quaternary Science Reviews* 27, 2273–2282.  
459

460 Klein, M. G., Gott dang, A., Mous, D. J. W., Bourlès, D. L., Arnold, M., Hamelin, B., Aumaître, G.,  
461 Braucher, R., Merchel, S. & Chauvet, F. 2008: Performance of the HVE 5MV AMS system at  
462 CEREGE using an absorber foil for isobar suppression. *Nuclear Instruments and Methods in Physics*  
463 *Research Section B: Beam Interactions with Materials and Atoms* 266, 1828–1832.  
464

465 Kobashi, T., Menviel, L., Jeltsch-Thömmes, A., Vinther, B. M., Box, J. E., Muscheler, R.,  
466 Nakaegawa, T., Pfister, P. L., Döring, M., Leuenberger, M., Wanner, H. & Ohmura, A. 2017:  
467 Volcanic influence on centennial to millennial Holocene Greenland temperature change. *Scientific*  
468 *Reports*, 8, 1, 4292.

469  
470 Kolling, H. M., Stein, R., Fahl, K., Perner, K., & Moros, M. 2017: Short-term variability in Late  
471 Holocene sea ice cover on the East Greenland Shelf and its driving mechanisms. *Palaeogeography,*  
472 *Palaeoclimatology, Palaeoecology*, 485, 336- 350.  
473  
474 Kottek M., Grieser J., Beck C., Rudolf B. & Rubel F. 2006: World map of the Köppen-Geiger climate  
475 classification updated. *Meteorologische Zeitschrift* 15, 259–263.  
476  
477 Koch, L. & Haller, J. 1971: Geological map of East Greenland 72°-76°N. *Meddelelser om Grønland*  
478 *183*, 1-26.  
479  
480 Korschinek, G., Bergmaier, A., Faestermann, T., Gerstmann, U.C., Knie, K., Rugel, G., Wallner, A.,  
481 Dillmann, I., Dollinger, G., von Gostomski, Ch. L., Kossert, K., Maiti, M., Poutivtsev, M. & Remmert,  
482 A. 2010: A new value for the half-life of <sup>10</sup>Be by Heavy-Ion Elastic Recoil Detection and liquid  
483 scintillation counting. *Nuclear Instruments and Methods in Physics Research Section B: Beam*  
484 *Interactions with Materials and Atoms* 268, 187–191.  
485  
486 Lal, D. 1991: Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion  
487 models. *Earth and Planetary Science Letters* 104, 424–439.  
488  
489 Larsen, N. K., Funder, S., Linge, H., Möller, P., Schomacker, A., Fabel, D., Xu, S. & Kjær, K.H.  
490 2016: A Younger Dryas re-advance of local glaciers in north Greenland. *Quaternary Science Reviews*  
491 *147*, 47–58.  
492  
493 Lesnek, A. J., Briner, J. P., Young, N. E., & Cuzzone, J. K. 2020: Maximum southwest Greenland Ice  
494 Sheet recession in the Early Holocene. *Geophysical Research Letters*, 47,1.  
495 DOI:10.1029/2019gl083164  
496  
497 Levy, L. B., Kelly, M. A., Lowell, T. V., Hall, B. L., Hempel, L. A., Honsaker, W. M., Lusas, A. R.,  
498 Howley, J. A. & Axford, Y. L. 2014: Holocene fluctuations of Bregne ice cap, Scoresby Sund, east  
499 Greenland: a proxy for climate along the Greenland Ice Sheet margin. *Quaternary Science Reviews* 92,  
500 357–368.  
501  
502 Levy, L. B., Kelly, M. A., Lowell, T. V., Hall, B. L., Howley, J. A. & Smith, C. A. 2016: Coeval  
503 fluctuations of the Greenland ice sheet and a local glacier, central East Greenland, during late glacial  
504 and Early Holocene time: Beryllium-10 ages of Late Glacial moraines. *Geophysical Research Letters*  
505 *43*, 1623–1631.  
506  
507 Lowell, T. V., Hall, B. L., Kelly, M. A., Bennike, O., Lusas, A. R., Honsaker, W., Smith, C. A., Levy,  
508 L. B., Travis, S. & Denton, G. H. 2013: Late Holocene expansion of Istorvet ice cap, Liverpool Land,  
509 east Greenland. *Quaternary Science Reviews*, 63, 128- 140.  
510  
511 Marsicek, J., Shuman, B. N., Bartlein, P. J., Shafer, S. L. & Brewer, S. 2018: Reconciling divergent  
512 trends and millennial variations in Holocene temperatures. *Nature* 554, 92–96.  
513  
514 Martin, L. C. P., Blard, P.-H., Balco, G., Lavé, J., Delunel, R., Lifton, N. & Laurent, V. 2017: The  
515 CREp program and the ICE-D production rate calibration database: A fully parameterizable and  
516 updated online tool to compute cosmic-ray exposure ages. *Quaternary Geochronology* 38, 25–49.  
517  
518 Masson-Delmotte, V., Swingedouw, D., Landais, A., Seidenkrantz, M.-S., Gauthier, E., Bichet, V.,  
519 Massa, C., Perren, B., Jomelli, V., Adalgeirsdottir, G., Hesselbjerg Christensen, J., Arneborg, J., Bhatt,  
520 U., Walker, D. A., Elberling, B., Gillet-Chaulet, F., Ritz, C., Gallée, H., van den Broeke, M., Fettweis,  
521 X., de Vernal, A. & Vinther, B. 2012: Greenland climate change: from the past to the future:  
522 Greenland climate change. *WIREs Climate Change* 3, 427–449.  
523

524 McKay, N. P., Kaufman, D. S., Routson, C. C., Erb, M. P. & Zander, P. D. 2018: The onset and rate of  
525 Holocene Neoglacial cooling in the Arctic. *Geophysical Research Letters*, 45, 22, 12,487-12,496.  
526

527 Moffa-Sánchez, P. & Hall, I. R. 2017: North Atlantic variability and its links to European climate over  
528 the last 3000 years. *Nature Communications* 8, 1726. DOI: 10.1038/s41467-017-01884-8  
529

530 Möller, P., Larsen, N. K., Kjær, K. H., Funder, S., Schomacker, A., Linge, H. & Fabel, D. 2010: Early  
531 to Middle Holocene valley glaciations on northernmost Greenland. *Quaternary Science Reviews* 29,  
532 3379–3398.  
533

534 O’Hara, S. L., Briner, J. P. & Kelley, S. E. 2017: A <sup>10</sup> Be chronology of Early Holocene local glacier  
535 moraines in central West Greenland. *Boreas* 46, 655–666.  
536

537 Pendleton, S., Miller, G., Lifton, N. & Young, N. 2019: Cryosphere response resolves conflicting  
538 evidence for the timing of peak Holocene warmth on Baffin Island, Arctic Canada. *Quaternary  
539 Science Reviews*, 216, 107-115.  
540

541 Schweinsberg, A. D., Briner, J. P., Licciardi, J. M., Bennike, O., Lifton, N. A., Graham, B. L., Young,  
542 N. E., Schaefer, J. M. & Zimmerman, S. H. 2019: Multiple independent records of local glacier  
543 variability on Nuussuaq, West Greenland, during the Holocene. *Quaternary Science Reviews* 215,  
544 253–271.  
545

546 Shakun, J. D., Clark, P.U., He, F., Marcott, S.A., Mix, A.C., Liu, Z., Otto-Bliesner, B., Schmittner, A.,  
547 Bard, E., 2012: Global warming preceded by increasing carbon dioxide concentrations during the last  
548 deglaciation. *Nature* 484, 49–54. <https://doi.org/10.1038/nature10915>  
549

550 Solomina, O. N., Bradley, R. S., Hodgson, D. A., Ivy-Ochs, S., Jomelli, V., Mackintosh, A. N., Nesje,  
551 A., Owen, L. A., Wanner, H., Wiles, G. C. & Young, N. E. 2015 Holocene glacier fluctuations.  
552 *Quaternary Science Reviews*, 111, 9- 34.  
553

554 Spencer, C. J., Yakymchuk, C. & Ghaznavi, M. 2017: Visualising data distributions with kernel  
555 density estimation and reduced chi-squared statistic. *Geoscience Frontiers* 8, 1247–1252.  
556

557 Stone, J. O. 2000: Air pressure and cosmogenic isotope production. *Journal of Geophysical Research:  
558 Solid Earth* 105, 23753–23759.  
559

560 Van der Bilt, W. G. M., Born, A. & Haaga, K. A. 2019: Was Common Era glacier expansion in the  
561 Arctic Atlantic region triggered by unforced atmospheric cooling? *Quaternary Science Reviews* 222,  
562 105860.  
563

564 Vinther, B. M., Buchardt, S. L., Clausen, H. B., Dahl-Jensen, D., Johnsen, S. J., Fisher, D.A., Koerner,  
565 R. M., Raynaud, D., Lipenkov, V., Andersen, K. K., Blunier, T., Rasmussen, S. O., Steffensen, J. P. &  
566 Svensson, A. M. 2009: Holocene thinning of the Greenland ice sheet. *Nature* 461, 385–388.  
567

568 Vinther, B. M., Clausen, H. B., Johnsen, S. J., Rasmussen, S. O., Andersen, K. K., Buchardt, S. L.,  
569 Dahl-Jensen, D., Seierstad, I. K., Siggaard-Andersen, M. -L., Steffensen, J. P., Svensson, A., Olsen, J.  
570 & Heinemeier, J. 2006: A synchronized dating of three Greenland ice cores throughout the Holocene.  
571 *Journal of Geophysical Research: Atmospheres* 111, D13102. DOI: 10.1029/2005JD006921  
572

573 Ward, G. K. & Wilson, S. R. 1978: Procedures for comparing and combining radiocarbon age  
574 determinations: A critique. *Archaeometry* 20, 19–31.  
575

576 Young, N. E., Schweinsberg, A. D., Briner, J. P. & Schaefer, J. M. 2015: Glacier maxima in Baffin  
577 Bay during the Medieval Warm Period coeval with Norse settlement. *Science Advances* 1, e1500806.  
578 DOI: 10.1126/sciadv.1500806

579 Young, N. E., Schaefer, J. M., Briner, J. P. & Goehring, B. M. 2013: A  $^{10}\text{Be}$  production-rate  
580 calibration for the Arctic. *Journal of Quaternary Science* 28, 515–526.