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Mountain glacier fluctuations during the Lateglacial and Holocene on Clavering Island (northeastern Greenland) from ^{10}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}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 ± 0.79 ka to 0.37 ± 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 ± 0.79 ka to 12.31 ± 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 ± 0.3 ka and 10.8 ± 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}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 ± 0.6 , 12.8 ± 0.8 and 12.8 ± 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}Cl CRE
52 ages for four moraines from Lyngmarksbræen glacier dated to the Lateglacial/Holocene transition
53 (11.9 ± 1.7 ka), and during the last millennium (0.82 ± 0.13 , 0.57 ± 0.09 , and 0.3 ± 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 ± 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 ± 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}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}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}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.

80 **Regional setting**

81
82 Clavering Island is located in High Arctic northeast Greenland (74°N) in Gael Hamkes Bugt (Fig.1A).
83 The island has a surface area of ~ 1500 km² and is located ~ 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 ~ 250 km², with a highest point at 1619 m a.s.l. and a depth < 200 m and
87 Taggletscher, a smaller ice cap (~ 16 km²) 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: ~ -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⁻¹ (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 ~ 3.5 km² 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 ~ 7 km² and an elevation range of 1547 to 620 m a.s.l. A proglacial lake (~ 0.3 km²) 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 (~ 6.5 km²) 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 ~ 620 to ~ 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 ~ 690 to ~ 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 μ m fractions then sieved again to retain
129 the 250-500 μ m fractions. The 250-500 μ m grain size fractions were leached in a dilute HF/HNO₃ acid
130 mixture to remove atmospheric ¹⁰Be. Pure quartz was spiked with 500 μ L of a commercial standard
131 solution from the Scharlau Company (1000 mg L⁻¹ of ⁹Be) 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 ¹⁰Be/⁹Be ratio of $1.191 \pm 0.013 \times 10^{-11}$

137 (Braucher *et al.* 2015) using a ^{10}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}Be based VDM for
144 geomagnetic data base. Given the location of the study, the “Arctic” ^{10}Be production rate of 3.93 ± 0.15
145 atoms $\text{g}^{-1} \text{a}^{-1}$ established by Young *et al.* (2013) was applied here. ^{10}Be CRE ages are reported with 1σ
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 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}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 ± 0.82 ka
163 (Cla 48) and 10.6 ± 0.74 ka (Cla 47), resulting in a mean age of 10.8 ± 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 ± 0.1 ka (Zack 40) and 1.41 ± 0.28 ka (Cla 54b), yielding a mean age of 1.2 ± 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}Be
175 CRE age of 14.79 ± 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 ± 0.08 ka) was considered as
178 an outlier based on the Chi^2 test and not further considered for analyses (Fig. 6A). The other samples
179 yielded a mean ^{10}Be CRE age of 11.3 ± 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 ± 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}Be CRE age of 11.3 ± 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}Be CRE ages of these three boulders range from 3.5 ± 0.29 to 2.46 ± 0.2 ka. Based on the Chi^2 test, Cla
189 03 (2.46 ± 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}Be CRE age of 3.3 ± 0.2 ka ($n = 2$).
191 Four boulders collected on moraine M4 (Cla 10, 14, 15 and Zack 34) yielded a mean ^{10}Be CRE age of
192 1.2 ± 0.1 ka ($n = 4$). Upstream of M4, two samples were taken from M5, ~ 10 m above the current lake
193 level (Cla 11, 13). Cla 13 (3.49 ± 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 ± 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 ± 1.2 ka, Cla 29: 19.56 ± 1.08 ka and Cla 31: 16.29 ± 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 Chi^2 test and rejected from the mean calculation.
203 The other samples yielded a mean ^{10}Be CRE age of 16.2 ± 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 ± 0.73 and 10.5 ± 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}Be CRE age of 0.48 ± 0.07 ka, Cla 33 of
209 0.5 ± 0.07 ka, and Cla 34 of 0.21 ± 0.03 ka. According to their 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}Be CRE age of
211 0.49 ± 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}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 ± 0.79 to 12.31 ± 1.3 ka. During the Early
218 Holocene the distribution is modal, with a mean age of 11.11 ± 0.82 ka ($n = 9$). The Late Holocene
219 samples span from 3.5 ± 0.29 to 0.37 ± 0.05 ka ($n = 11$). Two major modes then appear: one centered on
220 the DACP with a mean CRE age of 1.25 ± 0.18 ka ($n = 6$) and the other one during the LIA with a mean
221 age of 0.45 ± 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}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}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 ~ 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 ~ 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, ~ 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}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, ~ 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 ~ 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 ± 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 ± 0.6 and
314 11.3 ± 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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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}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 χ^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}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.

370 *B.* Combination of the all individual ^{10}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, 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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