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Younger Dryas ice-margin retreat in Greenland, new evidence

from Southwest Greenland

Svend Funder[1], Anita H.L. Sørensen[2], Nicolaj K. Larsen[1], Anders Bjørk[3], Jason P. Briner[4], Jesper

Olsen[5], Anders Schomacker[6], Kurt H. Kjær[1]

1Globe Institute, University of Copenhagen, 1350 Copenhagen K, Denmark

2Geosyd, 2730 Copenhagen, Denmark

3Department of Geoscience and Natural Resource Management, University of Copenhagen, 1350 Copenhagen K,

Denmark

4Department of Geology, University at Buffalo, Buffalo, NY 14260, USA

5Department of Physics and Astronomy, Aarhus University, 8000 Aarhus C, Denmark

6Department of Geosciences, UiT, the Arctic University of Norway, N-9037 Tromsø, Norway

Abstract. Cosmogenic [10]Be dates from bedrock knobs on six outlying tiny islands along a stretch of 300 km of the

Southwest Greenland coast, indicate that the Greenland Ice Sheet (GrIS) margin here was retreating on the inner shelf

close to the coast during the Younger Dryas (YD) cold period. A survey of recently published [10]Be and ^{14}C-dated

records show that this unexpected behaviour of the ice-margin has been seen also in other parts of Greenland, but with

very large variations in extent and speed of retreat even between neighbouring areas. In contrast to this, landforms

appearing in high resolution bathymetry surveys on the shelf, have recently been suggested to indicate YD readvance or

long-lasting ice-margin still stand on mid shelf, far from the coast. However, these features have been dated primarily

by correlation with cold periods in the ice core temperature records, and therefore cannot inform about the ice-

margin/climate relation. Ice-margin retreat during a YD cooling has been explained by advection of warm subsurface

water melting the ice-margin, and by increased seasonality of the climate with the temperature drop mainly in winter,

with high impact on sea ice extent and duration, but little effect on glacier mass balance. This study therefore adds to

the complexity of the climate/ice-margin relation, where local factors may for some time overrule or mute overall

temperature change. It also points to the urgent need for climate-independent dating of the rich treasure trove of

information coming from the shelf in these years.

Keywords: Younger Dryas, Greenland ice sheet, Climate change, Cosmogenic exposure dating.

1   Introduction

The Younger Dryas (YD) cold climate oscillation from 12.8 to 11.7 ka BP (thousand years Before Present) was offset

from the preceding Allerød warm period by a 200 yr period of cooling and ended with a 60 yr period of abrupt

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32 warming, as recorded in Greenland ice cores (Steffensen et al., 2008; Morlighem et al., 2017). Over the ice sheet annual

33 mean temperatures dropped between 5 and 9°C (Buizert et al., 2014). The cooling took place at a time when both

34 summer insolation (65° N) and atmospheric CO_2 were increasing (e.g. Buizert et al., 2014). The effects of the climate

35 oscillation were especially concentrated around the north-eastern North Atlantic in the areas of AMOC (Atlantic

36 Meridional Overturning Circulation) (Carlson, 2013). Therefore, similar to the present climate change, the YD

37 oscillation was a result of perturbations in the Earth's climate system, and, with a view to the future, it is of great

38 interest to study the effect of these climate changes on the margin of the Greenland Ice Sheet (GrIS). During YD GrIS

39 in most areas had its margin on the shelf, and much earlier work has concentrated on the behaviour of ice streams in

40 transverse troughs on the shelf, as discussed below. In this study, we present 18 new cosmogenic exposure ages from

41 six localities from the open coast over a distance of 300 km of Southwest Greenland to shed light on the ice-margin

42 behaviour during the final phase of deglaciation of the shelf (Fig. 1). Surprisingly, we find no evidence of ice-margin

43 response neither to the initial YD cooling nor to the abrupt warming in the end, but only of ice-margin retreat

44 throughout the period. Below, these results are discussed in context of previous studies elsewhere in Greenland.

45

46 **2. Background**

47 **2.1. Setting**

48 The continental shelf in the study area in Southwest Greenland tapers from a width of c. 70 km in the north to c. 50 km

49 in the south (Fig. 1). It is composed of an inner c. 25 km wide and up to 500 m deep trough, running along the coast and

50 gouged by glacial erosion in Proterozoic orthogneiss (Henriksen, 2008). On the outer shelf, a belt of shallower banks

51 with an even surface are composed of younger stratified aquatic sediments. The banks are dissected by 400-500 m deep

52 transverse troughs in continuation of the major fjords (Holtedahl, 1970; Henderson, 1975; Sommerhoff, 1975;

53 Roksandic, 1979; Sommerhoff, 1981). At a distance of 10-15 km from the coast, the inner trough forms an archipelago

54 with a multitude of small glacially sculptured rocky islands and skerries, reflecting intensive, but uneven glacial

55 erosion. From these rocky islands we collected our samples (Fig. 2).

56 **2.2. Deglaciation history**

57 Although there is little evidence for glacier overriding it is likely that the ice sheet did cover the rather narrow shelf

58 during LGM (Last Glacial Maximum), and evidence from a marine core in the Davis Strait outside the Fiskenæsset

59 trough suggests that the ice-margin here stood at the shelf break until deglaciation began at c. 18.6 cal. ka BP (Winsor et

60 al., 2015a). At c. 11 ka, the retreating ice-margin reached the present coastline, and the subsequent deglaciation of the

61 fjords and land began, as summarised by Winsor et al. (2015b). This leaves a period of c. 7 ka with the ice-margin

62 located on the shelf, without reaching the shelf break. A candidate for prolonged stay in this period is the lobate

63 moraines, which run along the troughs and impinge on the inner side of the banks (Fig. 1) (Sommerhoff, 1975; Winsor

64 et al., 2015a). From their setting these moraines were correlated with the Fiskebanke moraine system to the north

65 (Funder et al., 2011), and thought to reflect ice-margin readvance. In lack of absolute dating, they were correlated to the

66 YD cold event in the Greenland ice cores (Weidick et al., 2004 ("Neria Stade"); Roberts et al., 2009). A YD readvance

67 for this part of the ice sheet was also suggested by modelling, which indicated that the ice-margin here retreated from

68 the shelf edge to the present coastline in the Bølling-Allerød period, but then returned to the shelf during YD (Simpson
69 et al., 2009; Lecavalier et al., 2014). A grounding zone wedge in Fiskenæsset trough also points to a stillstand or
70 readvance of the glacier front for an unknown period of time during deglaciation (Fig. 1, Ryan et al., 2016). The
71 significance of these features is discussed below in the light of the new cosmogenic exposure dates.

72

73   **3. Field and laboratory methods**

74

75 In the field, the samples were collected from knobs in the glacially sculptured terrain. Unfortunately there were hardly
76 any erratic boulders on the bare rock surfaces, and the samples were generally collected from the bedrock surfaces. This
77 potentially represents a problem because while boulders were ideally incorporated in the ice in a pristine condition
78 without previous exposure to cosmic radiation, the glacial erosion of the bedrock surface may not have been deep
79 enough to remove inherited isotopes from older exposures, which may result in overestimation of the age (Briner et al.,
80 2006; Corbett et al., 2013; Larsen et al., 2014). To minimize the risk for inheritance, we selected sites in the lowland
81 where the overlying ice would have been thickest and most erosive, but above the marine limit to avoid the risk of
82 shielding of the rock surface by the sea. From each site we collected 3-4 samples within a radius of 100 m to be sure
83 that all samples from each locality had been deglaciated at the same time.
84   Contrary to inheritance other potential sources of error may give too young ages. This may occur if the
85 surface for some time has been partially shielded from cosmic radiation by vegetation or snow cover (Gosse and
86 Phillips, 2001). However, it is inconceivable that the rocky tops were ever vegetated, as soil then would have been
87 washed into the depressions of the glacial sculpture, which was not to be seen (Fig. 2). Also, long lasting deep snow
88 cover over the tops is unlikely in the stormy climate at the outer coast. Indeed, we experienced heavy snowfall during
89 the sampling, with thick snow accumulating in hollows, while the tops were left free of snow (Fig. 2). Topographic
90 shielding from nearby mountains was checked with a clinometer in the field, but in all cases was non-existent.
91   The laboratory work comprised sample preparation at the University of Buffalo and measurement of ^{10}Be-
92 concentrations at the AMS facility at Aarhus University. The laboratory procedure for the preparation followed the
93 University at Buffalo's protocol (Briner, 2015). Samples were crushed and sieved to 250–500 μm to obtain grains of
94 single mineral species, then exposed to a magnetic separator to remove the more magnetic minerals and facilitate the
95 subsequent froth flotation. In addition to flotation, some samples (X1509, X1513, X1521) had to undergo heavy mineral
96 separation to obtain sufficient amounts of quartz. Before the next step the samples were examined under a microscope
97 to see if they had been substantially purified. Finally, the samples were etched by hydrogen chloride (HCl) and a
98 mixture of hydrofluoric and nitric acid (HF/NHO$_3$) in order to further isolate pure quartz from remaining minerals.
99 Quartz purity was then verified by inductively coupled plasma optical emission spectroscopy at the University of
100 Colorado. At the University at Buffalo, pure quartz samples were fully dissolved with a ^{9}Be carrier and Be(OH)$_2$ was
101 isolated through column separation. After ignition, the final BeO was measured by accelerator mass spectrometry
102 (AMS) in Aarhus
103   The ages were calculated with the CRONUS-Earth online calculator (Balco et al., 2008), using the ^{10}Be/^{9}Be-
104 ratio measured by the AMS subtracted the processed blank ratio. The processed blank ratio was 2.10×10^{-15} and the
105 blank-corrected sample ratios ranged from 0.76×10^{-13} to 2.58×10^{-13}. The Arctic production rate defined by Young et

106 al. (2013) and the time-invariant scaling scheme for spallation processes given by (Lal, 1991) and Stone (2000) were

107 applied. The time-invariant scaling scheme does not incorporate variations in past geomagnetic field strength, but these

108 usually only affects younger samples, at c. 10 ka, by 1% (Nishiizumi et al., 2007). The maximum deviation between

109 different scaling schemes in this material is around 1%, so they generally, provide consistent ages and do not affect the

110 relative chronology. We used a rock density of 2.65 g cm^3 and made no correction for potential surface erosion or

111 snow/vegetation cover. The study area has undergone glacioisostatic uplift since the deglaciation, and this may

112 potentially influence the ^{10}Be ages. However, the uplift history of each sample site is poorly constrained and this effect

113 is partly counteracted by atmospheric pressure changes in ice-marginal settings (c.f. Young et al. 2020). Accordingly,

114 we present ^{10}Be ages without correcting for glacioisostatic uplift, similar to most other ^{10}Be studies from Greenland.

115 Individual ^{10}Be ages are presented with their 1-sigma analytical uncertainties, which include the uncertainty in the blank

116 correction, the "internal" uncertainty (Table 1). When we compare our ^{10}Be ages with ^{14}C ages or climate records we

117 include the production rate uncertainty, the "external" uncertainty (Balco et al., 2008).

118 Previously published ^{14}C ages have been re-calibrated using the Intcal13 calibration programme (Reimer et

119 al., 2013). Following the procedure adopted for dates on marine shells from Greenland ages on marine shells have been

120 corrected for a reservoir effect of ΔR = 0 for western and -150 yr for eastern Greenland, based on dating modern pre-

121 bomb shells (e.g. Mörner and Funder, 1990), acknowledging that significant, but unknown, changes in the reservoir

122 effect may potentially/likely have affected the ages especially in the turbulent millennia during the early deglaciation

123 phases (e.g. Andrews et al., 2018).

124

125 **4. Results**

126

127 As noted above a problem in using bedrock samples is the risk of inheritance in the rock surface. The knobby terrain is

128 evidence that basal glacial erosion was not uniform, but varies in intensity even over small distances. Therefore the

129 amount of inheritance may also vary over short distances, resulting in a spread of old ages (Corbett et al., 2013). We

130 therefore consider a spread of old ages as "inheritance outliers", while the mean of clustered younger ages gives the

131 most reliable deglaciation age. Where there is no overlap, we regard the youngest age as a minimum age for

132 deglaciation. At each site our new ages are compared with previously published cosmogenic and ^{14}C results from the

133 coastal areas. Much of this information has recently been reviewed by Sinclair et al. (2016). The six sites are described

134 below, and the results are shown in Table 1 and Fig. 3.

135 **4.1 Buksefjord**

136 This site is located on a small island at the outer margin of the strandflat, c. 15 km from the coast and midway between

137 the mouth of Ameralikfjorden and Buksefjorden. The three bedrock samples from this locality were collected at

138 altitudes between 102 and 118 m a.s.l. and gave ages, with their internal uncertainties, of 14.4 ± 0.8 ka (X1524), 12.5 ±

139 0.6 ka (X1525) and 12.1 ± 0.6 ka (X1526). We regard the oldest age as an inheritance outlier, while the two youngest

140 ages have overlapping internal uncertainty, yielding the age of 12.3 ± 0.2 ka in mid-Younger Dryas times as the best

141 estimate of the time of deglaciation at this site.

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142   On the coastal mountains c. 10 km to the east, [10]Be dates from between 82 and 360 m a.s.l. gave an average

143   deglaciation age 10.7 ± 0.6 ka (Larsen et al., 2014). At the mouth of the Nuuk Fjord Complex, 30 km to the north,

144   marine shells in the coastal area have been dated to 11.4 and 10.7 cal. ka BP (Weidick, 1976; Larsen et al., 2014), while

145   [10]Be ages close to Nuuk showed deglaciation at c. 11 ka (Winsor et al., 2015b). This is somewhat later than our

146   deglaciation date in the skaegaard, indicating that the fjord glaciers lingered on in their troughs while the adjacent

147   coastal areas became ice free (Larsen et al., 2014).

148

149   **4.2. Fiskenæsset**

150   Three bedrock samples were collected in the outer archipelago c. 6 km from the coast, from a small ice-scoured island

151   c. 15 kilometres west of the Fiskenæsset settlement. The samples were collected at altitudes of 75-76 m a.s.l and gave

152   congruent ages of 13.0 ±1.0 ka (X1521), 12.9 ± 0.7 ka (X1522), and 13.9±0.8 ka (X1523), and the average, 13.3 ±0.5

153   ka in late Allerød times, gives a robust estimate of the time of deglaciation at this site. This is the oldest deglaciation

154   date of our sites, lying well inside the Fiskebanke moraines in this area (Fig. 1).

155   Further north, at the Sermilik Fjord ^{14}C dates of marine molluscs show that the initial marine transgression

156   and retreat of the ice stream from the outer coast here began before 10.5 cal. ka BP, and [10]Be ages from 450 m a.s.l. on

157   coastal mountains show that the coast became ice free at c. 10.6 ka (Larsen et al. 2014). Even though these ages are

158   minimum constraints for deglaciation, it is not likely that they postdate the deglaciation of the outer archipelago with

159   2000 years. This indicates that also here the major outlet glaciers reached the inner shelf, while adjacent areas had been

160   ice free for some time.

161

162   **4.3. Ravns Storø**

163   Four samples were collected on the island of Ravns Storø, in the middle of the archipelago, c. 5 km from the coast. The

164   samples were collected at elevations between 189 and 209 m a.s.l. The 4 samples were collected within a radius of 200

165   m, but the ages show a spread of more than 5000 years: 13.7 ±0.8 ka (X1519), 17.0 ±1.7 ka (X1520), 11.9 ±0.7 ka

166   (X9364) and 11.5 ±0.8 ka (X9365). The two youngest ages, including our only boulder sample (sample X9365), have

167   overlapping internal uncertainties, and we consider their average, 11.7±0.2 ka, as the best estimate for the time of

168   deglaciation at this site, while the oldest ages are inheritance outliers. From this area there is no supporting information

169   on deglaciation history.

170

171   **4.3. Avigaat**

172   Three samples from the bedrock surface were collected from an islet in the inner archipelago, c. 3 km from the coast

173   and the abandoned Avigaat settlement. The samples were taken at elevations between 42 and 47 m a.s.l. and gave ages

174   of 13.7 ± 1.1 ka (X1516), 12.0 ± 0.5 ka (X1517) and 10.3 ± 2.5 ka (X1518). The variation and uncertainties are very

175   large, but overlap, and we consider the average of 12.0 ± 1.6 as the best estimate for deglaciation at this site. Some

176   support for this comes from a ^{14}C age of 11.3 cal. ka BP for basal gyttja in a lake in coastal Nerutussoq fjord to the

177   south, giving a minimum age for deglaciation at this site (Kelly and Funder, 1974).

178

6

4.4. Paamiut

180 This site is located on a small ice-scoured island on the inner archipelago, c. 5 km from the coast and close to the mouth

181 of Kuanersoq fjord and the town of Paamiut. Here three bedrock samples between 60 and 65 m a.s.l - X1513, X1514

182 and X1515 – are dated to 12.5 ±0.7, 12.1 ±1.3 and 12.0 ±1.4 ka. All three overlap within the internal uncertainty, and

183 the average, 12.2 ± 0.2 ka, indicates that the ice-margin here was retreating over the inner shelf in mid-Younger Dryas

184 times.

185 Around Paamiut and Kuanersoq several studies have supplied both [10]Be and ^{14}C deglaciation dates for the

186 outer fjord. As could be expected these deglaciation dates from further inland are somewhat younger than ours. [10]Be

187 dates from Kuanersoq indicate thinning of the ice stream in the fjord since 11.7 ka, and, by extrapolation, retreat from

188 the fjord mouth at c.11.2 ka (Winsor et al., 2015b). From a ^{14}C age of 11.0 cal. ka BP for basal gyttja in a lake 8 km

189 from our samples and well below the local marine limit Woodroffe et al. (2014) suggested that deglaciation could not

190 have been much earlier than 11 ka. These results from nearby coastal localities therefore indicate deglaciation c. 1000

191 years later than at our site. Much of this work concerned the ice stream in Kuanersoq, while our samples come from the

192 open coast to the south, and we suggest that an ice stream in the Kuanersoq trough remained at the inner shelf while the

193 adjacent coastal areas became ice free.

4.5. Sermiligaarsuk

196 From a small island in the inner archipelago, c. 2 km from the coast and 12 km south of the Sermiligaarsuk fjord we

197 collected two samples at altitudes from 56 to 61 m a.s.l. One from bedrock and one from a 1 m boulder (X1507). The

198 two samples have widely scattered ages of 10.9 ±2.3 ka (X1507) and 14.7 ±0.8 ka (X1509) with a very large

199 uncertainty especially in the youngest age. The oldest age is unrealistic for deglaciation and interpreted as an

200 inheritance outlier, and the age of 10.9 ±2.3 ka (sample X1507), one of our few boulder dates, is considered as a

201 minimum for deglaciation at this site. This age is the youngest for deglaciation of the inner shelf, but the island is also

202 closer to the coast than any of the other sites.

203 Marine shells below the marine limit in the nearby outer Sermiligaarsuk Fjord gave ^{14}C age of 9.7 cal. ka BP,

204 as a minimum for deglaciation at this site (Weidick et al., 2004).

5. Discussion

5.1. Overview of results from Southwest Greenland

208 According to the criteria outlined above, two of the sites, Paamiut and Fiskenæsset, apparently show no inheritance, and

209 give trustworthy deglaciation ages in late Allerød and mid YD times. Also Avigaat has overlapping uncertainties,

210 indicating deglaciation in late YD times, but with a large uncertainty. At two sites, Buksefjord and Ravns Storø, one or

211 two samples in each are apparently affected by inheritance, but the remaining cluster and indicate deglaciation during

212 mid-late YD. Finally, at Sermiligarssuk only one sample is considered free of inheritance, yielding a best estimate for

213 deglaciation in the Early Holocene. The results therefore show that deglaciation on the inner shelf in this part of

214 Greenland was underway during the Allerød-YD period, and the ice sheet margin had reached a position close to the

215 present coastline, 60-40 km from the shelf break. The results also show that even in the archipelago, which is a result of

216 intense erosion by warm based ice, inheritance from previous exposure is a problem, as seen from the six inheritance

217 outliers. At three localities, Paamiut, Fiskenæsset and Buksefjord, our ages are considerably older – up to 2 ka – than

218 deglaciation ages obtained at nearby fjord mouths. This suggests that while the coastal areas became ice free, ice

219 streams remained in the major drainage troughs and reached the inner shelf until the Early Holocene, as also shown

220 previously for ice streams in Disko Bugt and the Sisimiut area to the north (Roberts et al., 2009; Jennings et al., 2014).

221 Together the results show that the ice sheet margin in this area was retreating on the inner shelf during YD,

222 and probably was close to the coast already in late Allerød times. We find no evidence for YD stillstand/readvance, as

223 has previously been suggested from this area (Weidick et al., 2004). The Fiskebanke moraines further out on the shelf

224 as well as the grounding zone wedge in Fiskenæsset trough may reflect long-lasting stillstand/readvance, but they are

225 apparently older than YD (Fig. 1).

226

227 **5.2. YD ice-margins in Greenland**

228 Although it may seem surprising that the ice-margin in this area apparently retreated during the cold YD oscillation this

229 seems not to be unique to our area. From a recent review of YD ice-margins in Greenland Larsen et al. (2016)

230 concluded that ice-margin retreat indeed characterised most areas with a dated record going back through or into YD.

231 This is well constrained by ^{10}Be dating in coastal areas and ^{14}C dated marine cores in and outside major transect

232 troughs, and applies to areas in western, eastern and southernmost Greenland (Fig 4). More recently this has been

233 corroborated by new evidence from the Disko Bugt shelf (Hogan et al., 2016; Oksman et al., 2017) , and from east

234 Greenland (Levy et al., 2016; Andrews et al., 2018; Dyke et al., 2018; Rainsley et al., 2018). However, this has recently

235 been contested by evidence from multibeam bathymetry in major transverse troughs on the shelf, notably the occurrence

236 of Grounding Zone Wedges (GZWs) as discussed below.

237 In the dated records the most dramatic retreat occurred on the shelf at Disko Bugt, where the ice stream

238 apparently retreated over more than 200 km from an Allerød-Early YD position at near the shelf break (Fig. 4), but the

239 retreat was punctuated by periods of topographically conditioned stillstand and a spectacular, but brief, non-climatic

240 readvance (e.g. O'Cofaigh et al., 2013; Hogan et al., 2016). A similar history is recorded on the east side of Greenland

241 (Fig. 4), in Kangerlussuaq trough and fjord, where not only the shelf, but also the better part of the fjord became ice free

242 during YD (e.g. Andrews et al., 2018).

243 In these areas, as well as in southeast Greenland and in our study area the retreat occurred on the shelf (Dyke

244 et al., 2018). In other areas, northernmost and southernmost Greenland and the Scoresby Sund fjord complex, the ice-

245 margin had already retreated behind the present coastline before YD (e.g. Björck et al., 2002; Larsen et al., 2016; Levy

246 et al., 2016). These records therefore generally show ice-margin retreat during YD, but with large differences in rate

247 and areal extent from area to area. None of these records show evidence of ice-margin readvance during the initial YD

248 cooling.

249

250 **5.3 YD moraines on the shelf?**

251 A YD readvance of the ice-margin has previously been suggested, notably from western Greenland. Here, since their

252 first discovery, the Hellefisk and Fiskebanke moraines on the west Greenland shelf have played a prominent role in the

253 discussion of early deglaciation history (Fig.4) (e.g. Kelly, 1985; Funder et al., 2011; Hogan et al., 2016). The

254 outermost and oldest, the Hellefisk moraine system, runs along the shelf break for 200 km at a depth of c. 200 m, c. 120

255 km from the coast and consists of swarms of up to 100 m high ridges (Brett and Zarudski, 1979). To the east of this,

256 halfway towards the coast, the younger Fiskebanke moraines mentioned above impinge on the inner side of the fishing

257 banks c. 40 km from the coast. This deglaciation-stage is composed of single ridges, which occur on and off, on the

258 inner banks and along the sides of transverse troughs for a distance of c. 500 km along the coast (Fig. 4). Although

259 undated, the two moraine systems have generally been regarded as climate signals for two distinct periods of cooling

260 with the Hellefisk moraines marking LGM and the Fiskebanke moraines possibly a YD readvance, seen also in models

261 (Weidick et al., 2004; Roberts et al., 2009; Simpson et al., 2009; Lecavalier et al., 2014).

262 Recently Hogan et al. (2016), from ^{14}C dates in marine cores, found that in their study area south of Disko

263 Bugt, the oldest moraines, the Hellefisk moraine, dated, not from LGM, but marked the establishment of a deglacial

264 calving bay during late YD, while, as noted above, in our study area to the south, the "younger" Fiskebanke moraine is

265 older than YD. Although still sparse, these new results suggest that the two moraine systems may not be climatic signals

266 of distinct periods of cooling, but rather that they are metachronous expressions of differences in ice-margin dynamics

267 during deglaciation. The Hellefisk moraines, formed by an ice-margin at the shelf break and exposed to the ocean,

268 which was especially sensitive to changes in ocean currents, sea ice, and sea level, all of which may vary locally with

269 the depth of the grounding line and extent of exposure to the ocean as described by Jennings et al. (2017). Therefore the

270 timing of retreat from the shelf break varies with several millennia from trough to trough (Winsor et al., 2015a;

271 Jennings et al., 2017), determined by local conditions as much as climate change. The Fiskebanke moraines, on the

272 other hand, were deposited by an ice-margin entrenched in the coastal trough with limited exposure to the ocean, and

273 more resilient to these agents and able to withstand a warming climate. These moraines therefore may reflect, not a

274 response to cooling, but the time at which the retreating ice-margin reached the inner trough and became stabilised for a

275 longer period, as discussed for Melville Bugt, Northwest Greenland, by Newton et al. (2017).

276 Only in northernmost Greenland did glaciers from a local ice cap advance/retreat during the YD

277 cooling/warming, as documented by a combination of cosmogenic [10]Be, ^{14}C and OSL (Optically Stimulated

278 Luminescence) dating (Larsen et al., 2016).

279 The dated records from the GrIS margin therefore generally show YD ice-margin retreat or thinning in all

280 parts of Greenland, but both speed and extent varied greatly from area to area and trough to trough. Clear evidence for

281 readvance/stillstand related to the YD cold oscillation is missing in these records, and moraines on the shelf may not

282 register climate change, but glacio-dynamic response to local topography and bathymetry.

283

5.4. Grounding Zone Wedges and YD readvance/stillstand?

285 Evidence for readvance or long-lasting stillstand has recently been suggested from several major transect troughs. This

286 is based on high resolution multibeam bathymetry, revealing a large variety of glacial landforms in transect troughs

287 formed during retreat of major ice streams. Notably, the occurrence of large GZWs has been suggested to reflect long

288 lasting stillstand on mid shelf. GZWs are wedge-shaped sediment accumulations deposited at the front of an ice stream

289 during a period of stability (e.g. Dowdeswell and Fugelli, 2012). They have now been observed in most of the

290 investigated troughs, and, although not dated, prominent GZWs have tentatively been referred to YD, based on the

291 assumption that they correlate with cold periods in the ice core temperature record (Sheldon et al., 2016; Slabon et al.,

9

292   2016; Arndt et al., 2017; Newton et al., 2017; Arndt, 2018). However, in areas with both a [10]Be - [14]C dated and a

293   "climate-correlated" GZW record for YD, there is a striking difference between the two dating-approaches.

294   In the Uummannaq trough deglaciation of the shelf began before 15 ka and by c. 11.5 cal. ka BP the large ice

295   stream in the trough had disintegrated into fjord glaciers with their front close to the present ice-margin (e.g. Jennings et

296   al., 2017). However, there are two very different views on what happened in the intervening 3.5 millennia. Based on

297   exposure ages on coastal mountains and ^{14}C dates in the fjords Roberts et al. (2013) found that the large Uummannaq

298   ice stream had retreated from the trough and into the fjords during YD, controlled by topography and bathymetry (Fig.

299   4). In contrast to this, Sheldon et al. (2016), from a series of marine cores and a prominent GZW in the transect trough,

300   suggested that the ice stream was stabilised for 2 ka on the outer shelf, 150 km further away from the coast (Fig. 4), and

301   remained here through Allerød and YD and into the Preboreal. This was based on extrapolation from a ^{14}C age and

302   correlation with the ice core temperature record.

303   An even more striking discrepancy between the two dating approaches is in the Scoresby Sund fjord

304   complex. Here Greenland's most spectacular moraines show that already in late Allerød times the outlet ice streams had

305   retreated c. 100 km into the fjord system, and during YD and into Preboreal times the oscillating ice-margin retreated in

306   mid fjord, until rapid retreat in the narrow inner fjords began in Preboreal times. This is shown by Greenland's highest

307   concentration of [10]Be and ^{14}C dates from this period (Denton et al., 2005; Kelly et al., 2008; Hall et al., 2010; Levy et

308   al., 2016). However, from high resolution bathymetry Arndt (2018) advocated a very different sequence of events. In

309   this model, lineaments in the wide Hall Bredning were interpreted to show that fast flowing ice during YD advanced

310   and formed the very large Kap Brewster moraine at the mouth of Scoresby Sund, 100 km outside the Allerød-YD

311   moraines (Funder et al., 1998). The new YD age for this event is based on correlation with the ice core temperature

312   record and the misconception that the mid fjord moraines were formed by local mountain glaciers with no relevance for

313   GrIS. However, these significant moraines were without doubt formed both by local glaciers and by several major

314   outlets from the GrIS (e.g. Denton et al., 2005; Levy et al., 2016), ruling out any possibility that ice streams should have

315   advanced 100 km beyond the moraines in YD. The advance of fast flowing ice must therefore be older, leaving the

316   interesting question: when?

317   Similar outbursts of fast flowing ice streams, reaching mid shelf GZWs were recorded also further north in

318   transect troughs at Kong Oscar Fjord, Kejser Franz Joseph Fjord and the wide shelf of Northeast Greenland, and dated

319   under the same token to YD (Arndt et al., 2017; Arndt, 2018). Also here it has been overlooked that mid fjord moraines

320   in these fjords, 100 km behind the mid shelf GZWs, previously have been dated to late YD/earliest Preboreal (Hjort,

321   1979). Reconciling these two datasets would imply an extraordinarily dynamic behaviour of the ice-margin along the

322   East Greenland seaboard, with both advances and retreats of more than 100 km within YD in a period with increased

323   sea ice along the coast (e,g, Fluckiger et al., 2008; Buizert et al., 2018). Constraining the collapse of the putative fast

324   flowing ice streams in all troughs, the authors have chosen to use uncalibrated ^{14}C ages from land, delaying the

325   deglaciation c. 1.5 ka from late YD to the end of the Preboreal relative to ice core chronology.

326   In Northwest Greenland mid shelf GZWs with a length of more than 100 km have been recorded in transect

327   troughs on the shelf in Melville Bugt (Slabon et al., 2016; Newton et al., 2017). From analogy with the "climate-

328   correlated" Uummannaq GZW they were tentatively referred to YD, although non-climatic, bathymetric conditions may

329   also have determined their position (Newton et al., 2017).

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330   The ^{14}C and [10]Be dated and the "climate-correlated" records therefore paint two very different pictures of ice-

331   margin behaviour in Greenland during YD. Not surprisingly the climate-correlated records of GZWs and submarine

332   landforms show high correlation of ice-margin behaviour with ice core temperatures. More surprisingly, none of the [14]C

333   and [10]Be dated records from marine sediment cores and cosmogenic deglaciation dates on land show a clear signal

334   neither of initial YD cooling, nor of the abrupt terminal warming, but mostly point to retreat of the ice-margin through

335   YD (Fig. 4). This highlights the need for climate-independent dating of the submarine landforms and GZWs, to exploit

336   this rich source of information, and get a better understanding of the ice sheet/climate relation.

337

338   5.5. Ice-margin retreat during the YD cold oscillation?

339   To explain the mismatch between YD cooling, and apparent ice-margin retreat, two agents have especially been called

340   on: advection of warm oceanic subsurface water to the ice-margin, and increased climatic seasonality.

341   In both cases the sequence of events begins with increased production of meltwater around the North Atlantic

342   during the Allerød warm period. The fresher and lighter water eventually sealed off the Atlantic surface circulation

343   from the atmosphere and impeded AMOC. However, warm water from the subtropical areas was still driven into the

344   North Atlantic, but now as subsurface currents (Marcott et al., 2011; Ezat et al., 2014). The subsurface water followed

345   the path of the present North Atlantic surface circulation in the Irminger Current running south along Southeast

346   Greenland, continuing around Greenland's southern tip, and heading northwards as the West Greenland Current (Fig.

347   1). Along the Greenland shelf the warm Atlantic subsurface water was present and caused ice-margin retreat in

348   Southeast and West Greenland at 15-16 cal. ka BP, and it was continuously present at the southeast Greenland shelf

349   edge through Bølling-Allerød and YD times (Kuijpers et al., 2003; Knutz et al., 2011; Jennings et al., 2017; Andrews et

350   al., 2018).

351   Today warm subsurface water from these currents, below a cap of fresher water, causes extensive melting of

352   floating outlet glaciers in Greenland (e.g. Mayer et al., 2000; Motyka et al., 2011), and during the early phase of

353   deglaciation when the GrIS had its entire margin on the shelf it was especially sensitive to the advection of warm

354   subsurface water, causing ice-margin retreat even when temperatures were dropping as discussed extensively in the

355   literature (Kuijpers et al., 2003; Jennings et al., 2006; Knutz et al., 2011; Rinterknecht et al., 2014; Winsor et al., 2015b;

356   Sheldon et al., 2016; Sinclair et al., 2016; Jennings et al., 2017; Oksman et al., 2017; Andrews et al., 2018; Dyke et al.,

357   2018; Rainsley et al., 2018)..

358   Crucial to the impact of the warm water is the depth of the grounding line at the ice-margin, and the

359   accessibility for the warm subsurface water. This is again dependent on local bathymetry and – in the troughs – of the

360   type of connection to the open ocean, which in each area may control the impact of the warm water on the ice-margin,

361   as well as the impact from changing sea level and presence or absence of buttressing sea ice. This may explain why the

362   deglaciation of the shelf and troughs had such a different character even between neighbouring troughs, such as

363   between the rapid deglaciation of the Kangerlussuaq trough and the much slower deglaciation along the adjacent coast

364   to the south (Dyke et al., 2018). It may also explain the differences in the timing of onset of deglaciation in the

365   neighbouring Nuussuaq and Disko troughs in West Greenland as discussed by Jennings et al. (2017).

366   Also increased seasonality owes to the meltwater cap over the North Atlantic, and reduced AMOC. The

367   fresher meltwater-diluted water seals off the ocean surface and cuts off the ocean-atmosphere heat exchange, especially

11

368 in winter (Denton et al., 2005; Hall et al., 2008; 2010; Buizert et al., 2014; Levy et al., 2016; Buizert et al., 2018). This
369 results in very cold and arid winters and increase in extent and duration of sea ice, while summer temperatures – which
370 primarily determines a glacier's mass balance - are less affected and may even warm up (Björck et al., 2002).
371   The role of seasonality has recently been investigated in a model where the deglacial ice-core temperature
372 records in three ice cores are combined with simulated seasonal air temperatures for the whole of Greenland, enabling
373 assessment of variations in seasonality in time and space (Buizert et al., 2018). The varied seasonality model is largely
374 independent of field observations, and it is therefore interesting to note that on some points where it deviates from the
375 previous Huy models (e.g. Lecavalier et al., 2014), do seem be supported by the field observations: 1) The varied
376 seasonality model indicates that the deglacial rate of mass loss peaked already in the Bølling-Allerød period, and not in
377 the early Holocene. As shown above, recent results from many parts of Greenland show that large areas of the shelf had
378 been cleared of ice already before YD; 2). Both model-approaches show mass loss of ice from the GrIS throughout YD
379 although as noted above the Huy models suggest YD readvance on the shelf in West Greenland. However, the dramatic
380 temperature changes in the ice core records at the beginning and end of YD, are muted in the varied seasonality model,
381 in agreement with the field evidence where these rapid changes do not seem to have left a clear signal in the ice-margin
382 behaviour; 3) In the varied seasonality model the amplitude of YD seasonality decreases from southeast to northwest,
383 away from the source of AMOC, as underlined by the YD record from northernmost Greenland – the area farthest away
384 from North Atlantic ocean currents.
385   In summary, the apparent contradiction between ice core temperature records, where temperatures dropped
386 dramatically at the onset of YD, and the dated glacial record where glaciers in most parts retreated, may be explained by
387 the effect of warm subsurface water on the ice-margin, which was, all around Greenland, located on the shelf during the
388 early phase of deglaciation, while local topographic and bathymetric conditions controlled the access of warm water to
389 the ice-margin. Increased seasonality owes to increase in distribution and duration of winter sea ice, and the YD
390 temperature drop in the ice cores was due to a large extent to lowering of winter temperatures with little impact on the
391 ice-margin, but a large effect on distribution and duration of sea ice. This may also explain why neither the rapid initial
392 YD cooling nor the abrupt warming at the end left a clear track in the dated records.
393

394 **6. Conclusions**
395 [10]Be dates from the inner shelf over a stretch of 300 km along the open coast of Southwest Greenland indicate that the
396 ice-margin here was retreating and close to the coast through YD. Mid-shelf moraines and a GZW further out on the
397 shelf may reflect earlier stillstand/readvance of the ice-margin.
398   A survey of [10]Be and ^{14}C dated records, going back through YD elsewhere in Greenland - south, east and
399 west - shows that also here the ice-margin was retreating, but with large differences in speed and extent even between
400 neighbouring basins. Only in northernmost Greenland did glaciers from a local ice cap apparently advance/retreat at the
401 beginning/end of YD. The survey also shows that the shelf in areas both in north, south, east and west Greenland had
402 essentially been cleared of ice before YD, giving some support to recent modelling, implying that the main loss of ice
403 since LGM in the GrIS was in the Bølling-Allerød period, not in the Holocene.
404   The apparent mismatch between the ice core temperature record and the ice-margin behaviour in these
405 records, may be explained by the circumstance that during LGM the GrIS, contrary to other large ice sheets, around the

406 whole perimeter was standing on the shelf and especially sensitive to changes in ocean currents, sea level, and sea ice
407 distribution and thickness. From this, the large variability in ice-margin behaviour between areas may be explained by
408 local differences in topography, bathymetry and basin geometry, allowing or hampering access of the ocean to the ice-
409 margin.

410   Recently, high resolution bathymetry has supplied a wealth of data on ice stream dynamics during
411 deglaciation. However, this evidence is essentially dated only by "climate-correlation". To tap this rich source of
412 information and get a better understanding of the ice sheet/climate relation, climate-independent dating of the
413 submarine features is badly needed.

414

415   To conclude, we fully subscribe to the contention by Andrews et al. (2018, p. 16): "The use of the GrIS's
416 isotopic records as a one-to-one template for coeval changes in glacier and ocean response potentially ignores the
417 different response timescales between the atmosphere, oceans and cryosphere" – with a bearing also on the future.

418

419 **Author contributions**. SF, KK and AB conceptualised the project and carried out the work in the field. AS did the
420 laboratory work, critical assessment and compilation of data under supervision of and according to methodologies
421 developed by JB, NL, AS and JO. Visualization owes to NL and AB. The writing and editing was made by SF in close
422 cooperation with NL and AB. KK was responsible for the funding acquisition.

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431   **References**

432   Andrews, J. T., Cabedo-Sanz, P., Jennings, A. E., Olafsdottir, S., Belt, S. T., and Geirsdottir, A.: Sea ice, ice-
433   rafting, and ocean climate across Denmark Strait during rapid deglaciation (similar to 16-12 cal ka BP) of the
434   Iceland and East Greenland shelves, Journal of Quaternary Science, 33, 112-130, 2018.
435   Arndt, J. E.: Marine geomorphological record of Ice Sheet development in East Greenland since the Last
436   Glacial Maximum, Journal of Quaternary Science, 33, 853-864, 2018.
437   Arndt, J. E., Jokat, W., and Dorschel, B.: The last glaciation and deglaciation of the Northeast Greenland
438   continental shelf revealed by hydro-acoustic data, Quaternary Sci Rev, 160, 45-56, 2017.
439   Balco, G., Stone, J. O., Lifton, N. A., and Dunai, T. J.: A complete and easily accessible means of calculating
440   surface exposure ages or erosion rates from Be-10 and Al-26 measurements, Quaternary Geochronology, 3,
441   174-195, 2008.
442   Björck, S., Bennike, O., Rosen, P., Andresen, C. S., Bohncke, S., Kaas, E., and Conley, D.: Anomalously mild
443   Younger Dryas summer conditions in southern Greenland, Geology, 30, 427-430, 2002.
444   Brett, C. P. and Zarudski, E. F. K.: Project Westmar, a shallow marine geophysical survey on the West
445   Greenland shelf, Geological Survey of Greenland, Reports, 87, 1-27, 1979.
446   Briner, J.: UB Quartz Cleaning Procedure, University at Buffalo, 1-20 pp., 2015.
447   Briner, J. P., Miller, G. H., Davis, P. T., and Finkel, R. C.: Cosmogenic radionuclides from fiord landscapes
448   support differential erosion by overriding ice sheets, Geological Society of America Bulletin, 118, 406-420,
449   2006.
450   Buizert, C., Gkinis, V., Severinghaus, J. P., He, F., Lecavalier, B. S., Kindler, P., Leuenberger, M., Carlson, A. E.,
451   Vinther, B., Masson-Delmotte, V., White, J. W. C., Liu, Z. Y., Otto-Bliesner, B., and Brook, E. J.: Greenland
452   temperature response to climate forcing during the last deglaciation, Science, 345, 1177-1180, 2014.
453   Buizert, C., Keisling, B. A., Box, J. E., He, F., Carlson, A. E., Sinclair, G., and DeConto, R. M.: Greenland-Wide
454   Seasonal TemperaturesDuring the Last Deglaciation, Geophysical Research Letters, Research Letter, doi:
455   10.1002/2017GL075601, 2018. 1-10, 2018.
456   Carlson, A. E.: The Younger Dryas Climate Event, Encyclopedia of Quaternary Science, 3, 126-134, 2013.
457   Corbett, L. B., Bierman, P. R., Graly, J. A., Neumann, T. A., and Rood, D. H.: Constraining landscape history
458   and glacial erosivity using paired cosmogenic nuclides in Upernavik, northwest Greenland, Geological
459   Society of America Bulletin, 125, 1539-1553, 2013.
460   Denton, G. H., Alley, R. B., Comer, G. C., and Broecker, W. S.: The role of seasonality in abrupt climate
461   change, Quaternary Sci Rev, 24, 1159-1182, 2005.
462   Dowdeswell, J. A. and Fugelli, E. M. G.: The seismic architecture and geometry of grounding-zone wedges
463   formed at the marine margins of past ice sheets, Geol Soc Am Bull, 124, 1750-1761, 2012.
464   Dyke, L. M., Hughes, A. L., Andresen, C. S., Murray, T., Hiemstra, J. F., Bjørk, A. A., and Rodés, Á.: The
465   deglaciation of coastal areas of southeast Greenland, The Holocene, Reports, 2018.
466   Ezat, M. M., Rasmussen, T. L., and Groeneveld, J.: Persistent intermediate water warming during cold
467   stadials in the southeastern Nordic seas during the past 65 k.y., Geology, 42, 663-666, 2014.
468   Fluckiger, J., Knutti, R., White, J. W. C., and Renssen, H.: Modeled seasonality of glacial abrupt climate
469   events, Clim Dynam, 31, 633-645, 2008.
470   Funder, S., Hjort, C., Landvik, J. Y., Nam, S. I., Reeh, N., and Stein, R.: History of a stable ice margin East
471   Greenland during the Middle and Upper Pleistocene, Quaternary Sci Rev, 17, 77-123, 1998.
472   Funder, S., Kjeldsen, K. K., Kjaer, K. H., and Cofaigh, C. O.: The Greenland Ice Sheet During the Past 300,000
473   Years: A Review, Quaternary Glaciations - Extent and Chronology: A Closer Look, 15, 699-713, 2011.
474   Gosse, J. C. and Phillips, F. M.: Terrestrial in situ cosmogenic nuclides: theory and application, Quaternary
475   Sci Rev, 20, 1475-1560, 2001.
476   Hall, B. L., Baroni, C., and Denton, G. H.: The most extensive Holocene advance in the Stauning Alper, East
477   Greenland, occured in the Little Ice Age Polar Research, 27, 128-134, 2008.

478 Hall, B. L., Baroni, C., and Denton, G. H.: Relative sea-level changes, Schuchert Dal, East Greenland, with
479 implications for ice extent in late-glacial and Holocene times, Quaternary Sci Rev, 29, 3370-3378, 2010.
480 Henderson, G.: New bathymetric maps covering offshore West Greenland 59 69 30' N, 1975, 761-774.
481 Henriksen, N.: Geological History of Greenland - Four billion years of earth evolution, Geological Survey of
482 Denmark and Greenland, Copenhagen, 2008.
483 Hjort, C.: Glaciation in Northern East Greenland during the Late Weichselian and Early Flandrian, Boreas, 8,
484 281-296, 1979.
485 Hogan, K. A., Cofaigh, C. O., Jennings, A. E., Dowdeswell, J. A., and Hiemstra, J. F.: Deglaciation of a major
486 palaeo-ice stream in Disko Trough, West Greenland, Quaternary Sci Rev, 147, 5-26, 2016.
487 Holtedahl, O.: On Morphology of West Greenland Shelf with General Remarks on Marginal-Channel
488 Problem, Mar Geol, 8, 155-+, 1970.
489 Jennings, A. E., Andrews, J. T., Cofaigh, C. O., St Onge, G., Sheldon, C., Belt, S. T., Cabedo-Sanz, P., and
490 Hillaire-Marcel, C.: Ocean forcing of Ice Sheet retreat in central west Greenland from LGM to the early
491 Holocene, Earth Planet Sc Lett, 472, 1-13, 2017.
492 Jennings, A. E., Hald, M., Smith, M., and Andrews, J. T.: Freshwater forcing from the Greenland Ice Sheet
493 during the Younger Dryas: evidence from southeastern Greenland shelf cores, Quaternary Sci Rev, 25, 282-
494 298, 2006.
495 Jennings, A. E., Walton, M. E., Cofaigh, C. O., Kilfeather, A., Andrews, J. T., Ortiz, J. D., De Vernal, A., and
496 Dowdeswell, J. A.: Paleoenvironments during Younger Dryas-Early Holocene retreat of the Greenland Ice
497 Sheet from outer Disko Trough, central west Greenland, Journal of Quaternary Science, 29, 27-40, 2014.
498 Kelly, M.: A review of the Quaternary geology of western Greenland. In: Quaternary environments eastern
499 Canadian Arctic, Baffin Bay and western Greenland, Andrews, J. T. (Ed.), Allen & Unwin, Boston, 1985.
500 Kelly, M. and Funder, S.: The pollen stratigraphy of late Quaternary lake sediments of South West
501 Greenland, Geological Survey of Greenland, Reports, 64, 1-26, 1974.
502 Kelly, M. A., Lowell, T. V., Hall, B. L., Schaefer, J. M., Finkel, R. C., Goehring, B. M., Alley, R. B., and Denton,
503 G. H.: A Be-10 chronology of lateglacial and Holocene mountain glaciation in the Scoresby Sund region, east
504 Greenland: implications for seasonality during lateglacial time, Quaternary Sci Rev, 27, 2273-2282, 2008.
505 Knutz, P. C., Sicre, M. A., Ebbesen, H., Christiansen, S., and Kuijpers, A.: Multiple-stage deglacial retreat of
506 the southern Greenland Ice Sheet linked with Irminger Current warm water transport, Paleoceanography,
507 26, 2011.
508 Kuijpers, A., Troelstra, S. R., Prins, M. A., Linthout, K., Akhmetzhanov, A., Bouryak, S., Bachmann, M. F.,
509 Lassen, S., Rasmussen, S., and Jensen, J. B.: Late Quaternary sedimentary processes and ocean circulation
510 changes at the Southeast Greenland margin, Mar Geol, 195, 109-129, 2003.
511 Lal, D.: Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models, Earth
512 Planet Sc Lett, 104, 424-439, 1991.
513 Larsen, N. K., Funder, S., Kjaer, K. H., Kjeldsen, K. K., Knudsen, M. F., and Linge, H.: Rapid early Holocene ice
514 retreat in West Greenland, Quaternary Sci Rev, 92, 310-323, 2014.
515 Larsen, N. K., Funder, S., Linge, H., Moller, P., Schomacker, A., Fabel, D., Xu, S., and Kjaer, K. H.: A Younger
516 Dryas re-advance of local glaciers in north Greenland, Quaternary Sci Rev, 147, 47-58, 2016.
517 Lecavalier, B. S., Milne, G. A., Simpson, M. J. R., Wake, L., Huybrechts, P., Tarasov, L., Kjeldsen, K. K., Funder,
518 S., Long, A. J., Woodroffe, S. A., Dyke, A. S., and Larsen, N. K.: A model of Greenland ice sheet deglaciation
519 based on observations of ice extent and relative sea-level, Quaternary Sci Rev, 102, 54-84, 2014.
520 Levy, L. B., Kelly, M. A., Lowell, T. V., Hall, B. L., Howley, J. A., and Smith, C. A.: Coeval fluctuations of the
521 Greenland ice sheet and a local glacier, central East Greenland, during late glacial and early Holocene time,
522 Geophysical Research Letters, 43, 1623-1631, 2016.
523 Marcott, S. A., Clark, P. U., Padman, L., Klinkhammer, G. P., Springer, S. R., Liu, Z. Y., Otto-Bliesner, B. L.,
524 Carlson, A. E., Ungerer, A., Padman, J., He, F., Cheng, J., and Schmittner, A.: Ice-shelf collapse from
525 subsurface warming as a trigger for Heinrich events, Proceedings of the National Academy of Sciences of
526 the United States of America, 108, 13415-13419, 2011.

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15

527   Mayer, C., Reeh, N., Jung-Rothenhausler, F., Huybrechts, P., and Oerter, H.: The subglacial cavity and
528   implied dynamics under Nioghalvfjerdsfjorden Glacier, NE-Greenland, Geophysical Research Letters, 27,
529   2289-2292, 2000.
530   Morlighem, M., Williams, C. N., Rignot, E., An, L., Arndt, J. E., Bamber, J. L., Catania, G., Chauche, N.,
531   Dowdeswell, J. A., Dorschel, B., Fenty, I., Hogan, K., Howat, I., Hubbard, A., Jakobsson, M., Jordan, T. M.,
532   Kjeldsen, K. K., Millan, R., Mayer, L., Mouginot, J., Noel, B. P. Y., O'Cofaigh, C., Palmer, S., Rysgaard, S.,
533   Seroussi, H., Siegert, M. J., Slabon, P., Straneo, F., van den Broeke, M. R., Weinrebe, W., Wood, M., and
534   Zinglersen, K. B.: BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland
535   From Multibeam Echo Sounding Combined With Mass Conservation, Geophysical Research Letters, 44,
536   11051-11061, 2017.
537   Motyka, R. J., Truffer, M., Fahnestock, M., Mortensen, J., Rysgaard, S., and Howat, I.: Submarine melting of
538   the 1985 Jakobshavn Isbrae floating tongue and the triggering of the current retreat, J Geophys Res-Earth,
539   116, 2011.
540   Mörner, N.-A. and Funder, S.: C-14 dating of samples collected during teh NORQUA 86 expedition, and
541   notes on the marine reservoir effect., Meddelelser om Grønland, 22, 57-59, 1990.
542   Newton, A. M. W., Knutz, P. C., Huuse, M., Gannon, P., Brocklehurst, S. H., Clausen, O. R., and Gong, Y.: Ice
543   stream reorganization and glacial retreat on the northwest Greenland shelf, Geophysical Research Letters,
544   44, 7826-7835, 2017.
545   Nishiizumi, K., Imamura, M., Caffee, M. W., Southon, J. R., Finkel, R. C., and McAninch, J.: Absolute
546   calibration of Be-10 AMS standards, Nucl Instrum Meth B, 258, 403-413, 2007.
547   O'Cofaigh, C., Dowdeswell, J. A., Jennings, A. E., Hogan, K. A., Kilfeather, A., Hiemstra, J. F., Noormets, R.,
548   Evans, J., McCarthy, D. J., Andrews, J. T., Lloyd, J. M., and Moros, M.: An extensive and dynamic ice sheet on
549   the West Greenland shelf during the last glacial cycle, Geology, 41, 219-222, 2013.
550   Oksman, M., Weckstrom, K., Miettinen, A., Juggins, S., Divine, D. V., Jackson, R., Telford, R., Korsgaard, N. J.,
551   and Kucera, M.: Younger Dryas ice margin retreat triggered by ocean surface warming in central-eastern
552   Baffin Bay, Nat Commun, 8, 2017.
553   Rainsley, E., Menviel, L., Fogwill, C. J., Turney, C. S. M., Hughes, A. L. C., and Rood, D. H.: Greenland ice mass
554   loss during the Younger Dryas driven by Atlantic Meridional Overturning Circulation feedbacks, Scientific
555   Reports, 8, 11307, 2018.
556   Reimer, P. J., Bard, E., Bayliss, J. W., Beck, P. G., Blackwell, C., Bronk Ramsey, C. E., Buck, H., Cheng, R. L.,
557   Edwards, M., Friedrich, P. M., Grootes, T. P., Guilderson, H., Haflidason, I., Hajdas, C., Hatté, T. J., Heaton, D.
558   L., Hoffmann, A. G., Hogg, K. A., Hughen, K. F., Kaiser, B., Kromer, S. W., Manning, M., Niu, R. W., Reimer, D.
559   A., Richards, E. M., Scott, J. R., Southon, R. A., Staff, C., Turney, S. M., and van der Plicht, J.: IntCal13 and
560   Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP Radiocarbon, 55, 1869-1887, 2013.
561   Rinterknecht, V., Jomelli, V., Brunstein, D., Favier, V., Masson-Delmotte, V., Bourles, D., Leanni, L., and
562   Schlappy, R.: Unstable ice stream in Greenland during the Younger Dryas cold event, Geology, 42, 759-762,
563   2014.
564   Roberts, D. H., Long, A. J., Schnabel, C., Davies, B. J., Xu, S., Simpson, M. J. R., and Huybrechts, P.: Ice sheet
565   extent and early deglacial history of the southwestern sector of the Greenland Ice Sheet, Quaternary Sci
566   Rev, 28, 2760-2773, 2009.
567   Roberts, D. H., Rea, B. R., Lane, T. P., Schnabel, C., and Rodes, A.: New constraints on Greenland ice sheet
568   dynamics during the last glacial cycle: Evidence from the Uummannaq ice stream system, J Geophys Res-
569   Earth, 118, 519-541, 2013.
570   Roksandic, M. M.: Geology of the continental shelf off West Greenland between 61 15'N and 64 00'N,
571   Geological Survey of Greenland, Reports, 92, 1-15, 1979.
572   Ryan, J. C., Dowdeswell, J. A., and Hogan, K. A.: Three cross-shelf troughs on the continental shelf of SW
573   Greenland from Olex data, Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient, 46,
574   167-168, 2016.

16

575 Sheldon, C., Jennings, A., Andrews, J. T., Cofaigh, C. O., Hogan, K., Dowdeswell, J. A., and Seidenkrantz, M.
576 S.: Ice stream retreat following the LGM and onset of the west Greenland current in Uummannaq Trough,
577 west Greenland, Quaternary Sci Rev, 147, 27-46, 2016.
578 Simpson, M. J. R., Milne, G. A., Huybrechts, P., and Long, A. J.: Calibrating a glaciological model of the
579 Greenland ice sheet from the Last Glacial Maximum to present-day using field observations of relative sea
580 level and ice extent, Quaternary Sci Rev, 28, 1631-1657, 2009.
581 Sinclair, G., Carlson, A. E., Mix, A. C., Lecavalier, B. S., Milne, G., Mathias, A., Buizert, C., and DeConto, R.:
582 Diachronous retreat of the Greenland ice sheet during the last deglaciation, Quaternary Sci Rev, 145, 243-
583 258, 2016.
584 Slabon, P., Dorschel, B., Jokat, W., Myklebust, R., Hebbeln, D., and Gebhardt, C.: Greenland ice sheet retreat
585 history in the northeast Baffin Bay based on high-resolution bathymetry, Quaternary Sci Rev, 154, 182-198,
586 2016.
587 Sommerhoff, G.: Geomorphologische Prozesse in der Labrador - und Imingersee. Ein Beitrag zur
588 submarinen Geomorphologie einer subpolaren Meeresregion, Polarforschung, 51, 175-191, 1981.
589 Sommerhoff, G.: Versuch einer geomorphologischen Gliederung des südwestgrönländischen
590 Kontinentalabhanges, Polarforschung, 45, 87-101, 1975.
591 Steffensen, J. P., Andersen, K. K., Bigler, M., Clausen, H. B., Dahl-Jensen, D., Fischer, H., Goto-Azuma, K.,
592 Hansson, M., Johnsen, S. J., Jouzel, J., Masson-Delmotte, V., Popp, T., Rasmussen, S. O., Rothlisberger, R.,
593 Ruth, U., Stauffer, B., Siggaard-Andersen, M. L., Sveinbjornsdottir, A. E., Svensson, A., and White, J. W. C.:
594 High-resolution Greenland Ice Core data show abrupt climate change happens in few years, Science, 321,
595 680-684, 2008.
596 Stone, J. O.: Air pressure and cosmogenic isotope production, Journal of Geophysical Research 105 (B10),
597 23753-23759, 2000.
598 Weidick, A.: C-14 datings of survey material, carried out in 1975, Rapport Grønlands Geologiske
599 Undersøgelse, 80, 136–144, 1976.
600 Weidick, A., Kelly, M., and Bennike, O.: Late Quaternary development of the southern sector of the
601 Greenland Ice Sheet, with particular reference to the Qassimiut lobe, Boreas, 33, 284-299, 2004.
602 Winsor, K., Carlson, A. E., Caffee, M. W., and Rood, D. H.: Rapid last-deglacial thinning and retreat of the
603 marine-terminating southwestern Greenland ice sheet, Earth Planet Sc Lett, 426, 1-12, 2015b.
604 Winsor, K., Carlson, A. E., Welke, B. M., and Reilly, B.: Early deglacial onset of southwestern Greenland ice-
605 sheet retreat on the continental shelf, Quaternary Sci Rev, 128, 117-126, 2015a.
606 Woodroffe, S. A., Long, A. J., Lecavalier, B. S., Milne, G. A., and Bryant, C. L.: Using relative sea-level data to
607 constrain the deglacial and Holocene history of southern Greenland, Quaternary Sci Rev, 92, 345-356, 2014.
608 Young, N. E., Schaefer, J. M., Briner, J., and . A 10Be production-rate calibration for the Arctic, Journal of
609 Quaternary Science 28, 516-526, 2013.

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Table 1. Summary of [10]Be data from Southwest Greenland.

Sample ID	Latitude (N)	Longitude (W)	Elevation (m a.s.l.)	Sample type†	Shielding factor	Thickness (cm)	Quartz (g)	[9]Be carrier weight (g)	[10]Be conc. (atoms/ g)×10⁴	[10]Be uncert. (atoms/ g)×10⁴	[10]Be age (ka) internal (external) uncertainties††
Buksefjord											
X1524	63.83957	51.73826	118	bedrock	1	4.5	40.45	0.6067	6.88	0.36	14.43 ± 0.76 (1.03)
X1525	63.83970	51.73851	117	bedrock	1	5.5	33.19	0.6082	5.90	0.30	*12.48 ± 0.64 (0.88)*
X1526	63.83967	51.73839	102	bedrock	1	6	40.13	0.6086	5.59	0.26	*12.06 ± 0.57 (0.82)*
				Calculated average (number of samples out of total)							*12.3 ±0.4 (n=2/3)*
Fiskenæsset											
X1521	63.04961	50.99505	76	bedrock	0.999962	4.5	21.16	0.6068	5.93	0.43	*12.98 ± 0.95 (1.14)*
X1522	63.05008	50.99449	75	bedrock	0.999969	5.5	26.75	0.6074	5.85	0.31	*12.93 ± 0.68 (0.93)*
X1523	63.05016	50.99454	76	bedrock	0.999969	5.5	36.35	0.6049	6.31	0.36	*13.92 ± 0.81 (1.05)*
				Calculated average (number of samples out of total)							*13.3 ±0.6 (n=3/3)*
Ravns Storø											
X1519	62.71573	50.40947	193	bedrock	0.999986	7	35.09	0.6074	6.95	0.38	13.71 ± 0.76 (1.01)
X1520	62.71573	50.40947	189	bedrock	0.999986	6	45.21	0.6083	8.66	0.87	17.03 ± 1.72 (1.91)
X9364	62.71799	50.41719	209	bedrock	1	4.5	34.47	0.6092	6.26	0.37	*11.91 ± 0.70 (0.91)*
X9365	62.71770	50.41629	208	boulder	1	4.5	39.87	0.613	6.05	0.43	*11.52 ± 0.81 (0.99)*
				Calculated average (number of samples out of total)							*11.7 ±0.2 (n=2/4)*
Avigaat											
X1516	62.17882	49.80153	47	bedrock	1	7	45.06	0.6062	5.94	0.48	*13.68 ± 1.11 (1.29)*
X1517	62.17888	49.80107	44	bedrock	1	6	45.08	0.6089	5.23	0.24	*11.98 ± 0.56 (0.81)*
X1518	62.17894	49.80064	42	bedrock	1	4.5	45.26	0.608	4.55	1.10	*10.31 ± 2.49 (2.54)*
				Calculated average (number of samples out of total)							*12.0 ±1.7 (n=3/3)*
Paamiut											
X1513	61.85744	49.53121	65	bedrock	1	6	32.31	0.6111	5.57	0.29	*12.45 ± 0.66 (0.89)*
X1514	61.85734	49.53098	61	bedrock	1	6.5	25.48	0.6086	5.34	0.56	*12.05 ± 1.28 (1.40)*
X1515	61.85708	49.53045	60	bedrock	1	5.5	35.44	0.607	5.36	0.62	*12.01 ± 1.40 (1.52)*
				Calculated average (number of samples out of total)							*12.2 ±0.2 (n=3/3)*
Sermiligarsuk											
X1507	61.32122	48.86104	57	boulder	0.999672	6	33.35	0.6086	4.81	1.02	*10.86 ± 2.32 (2.38)*
X1509	61.32136	48.86013	61	bedrock	0.999704	5.5	24.76	0.5672	6.55	0.37	*14.66 ± 0.84 (1.10)*
				Best estimate for age of deglaciation							*10.9 ±2.3 (n=1/1)*

†: All samples are coarse grained orthogneiss
†† : Italics: used in average/best estimate (see text)

[10]Be ages were calculated using the online exposure age calculator formerly known as the CRONUS-Earthonline exposure calculator v.3 (Balco et al., 2008), the Baffin Island production rate of 3.96 ± 0.07 at g-1 a-1 (regional SLHL) (Young et al., 2013), and the St scaling scheme (Lal, 1991; Stone, 2000) under A rock density of 2.65 g cm⁻³ was used and we assumed zero erosion. Samples were measured using the Beryllium standard 07KNSTD (Nishiizumi et al., 2007).
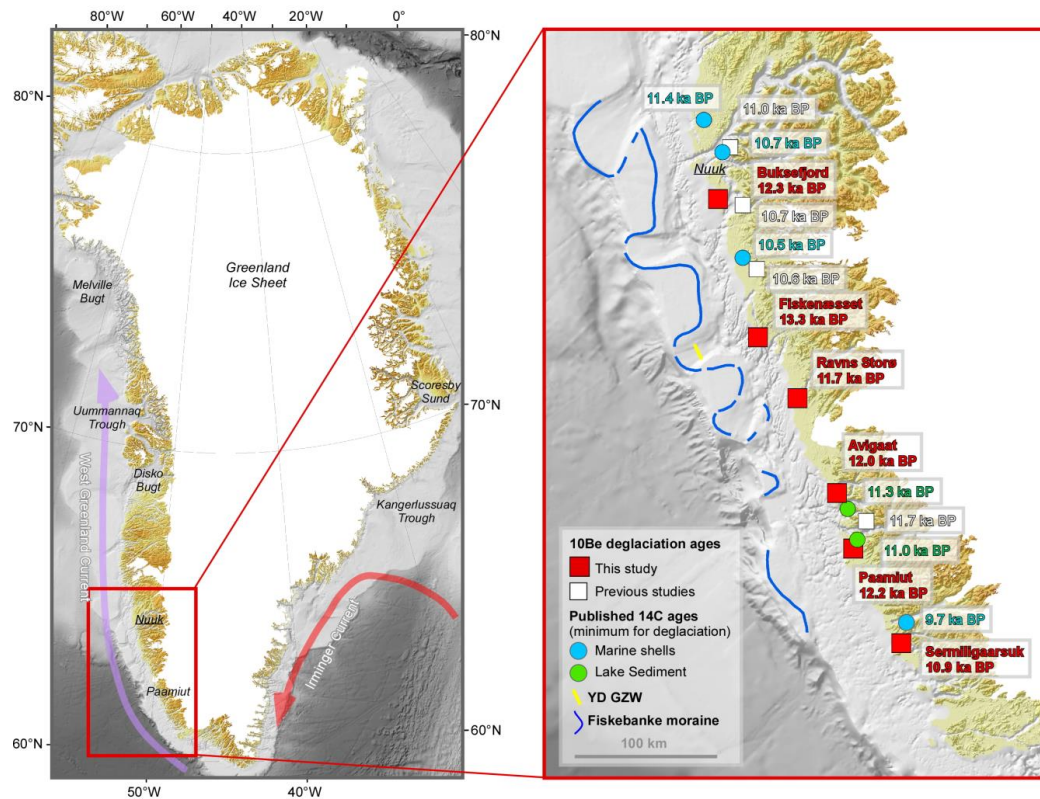
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Fgure 1: Location of study area and cosmogenic ages from Southwest Greenland, Fiskebanke moraines and selected published dates relevant to the deglaciation history of coastal Southwest Greenland. For references to previous results see text. Background map of Greenland and surrounding seas from BedMachine Greenland v.3 (Morlighem et al. 2017.
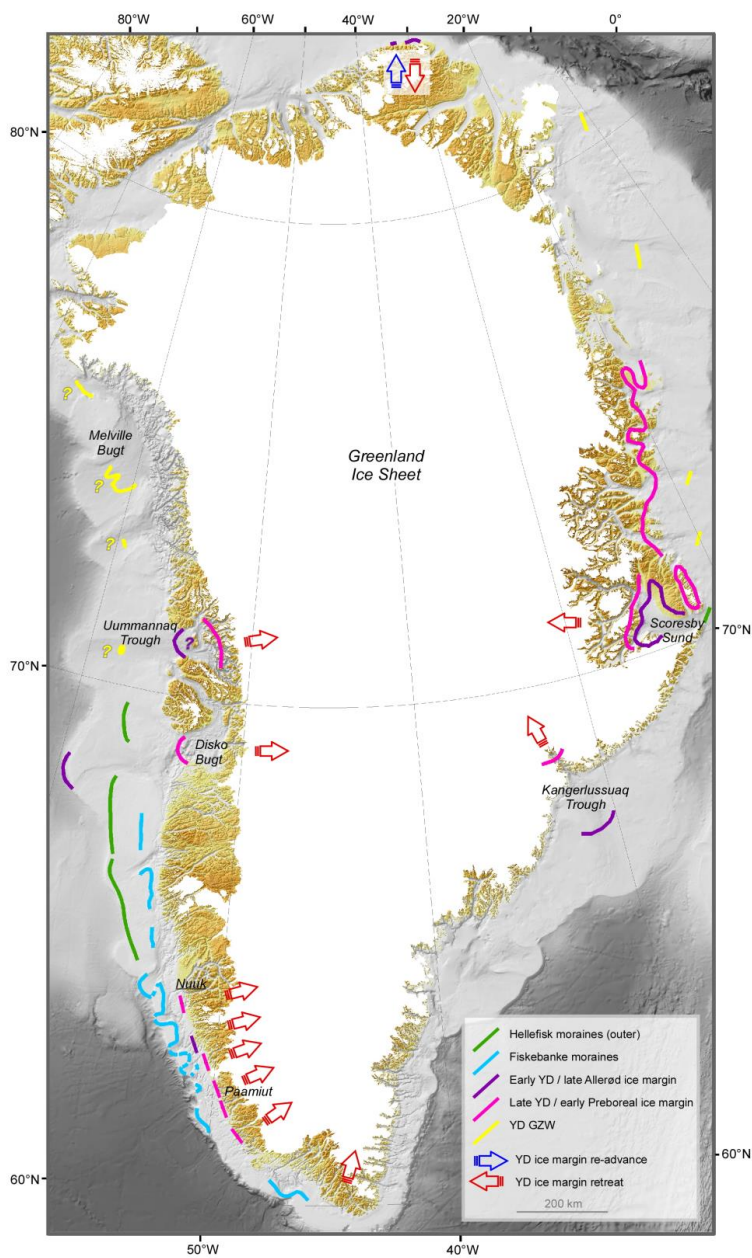
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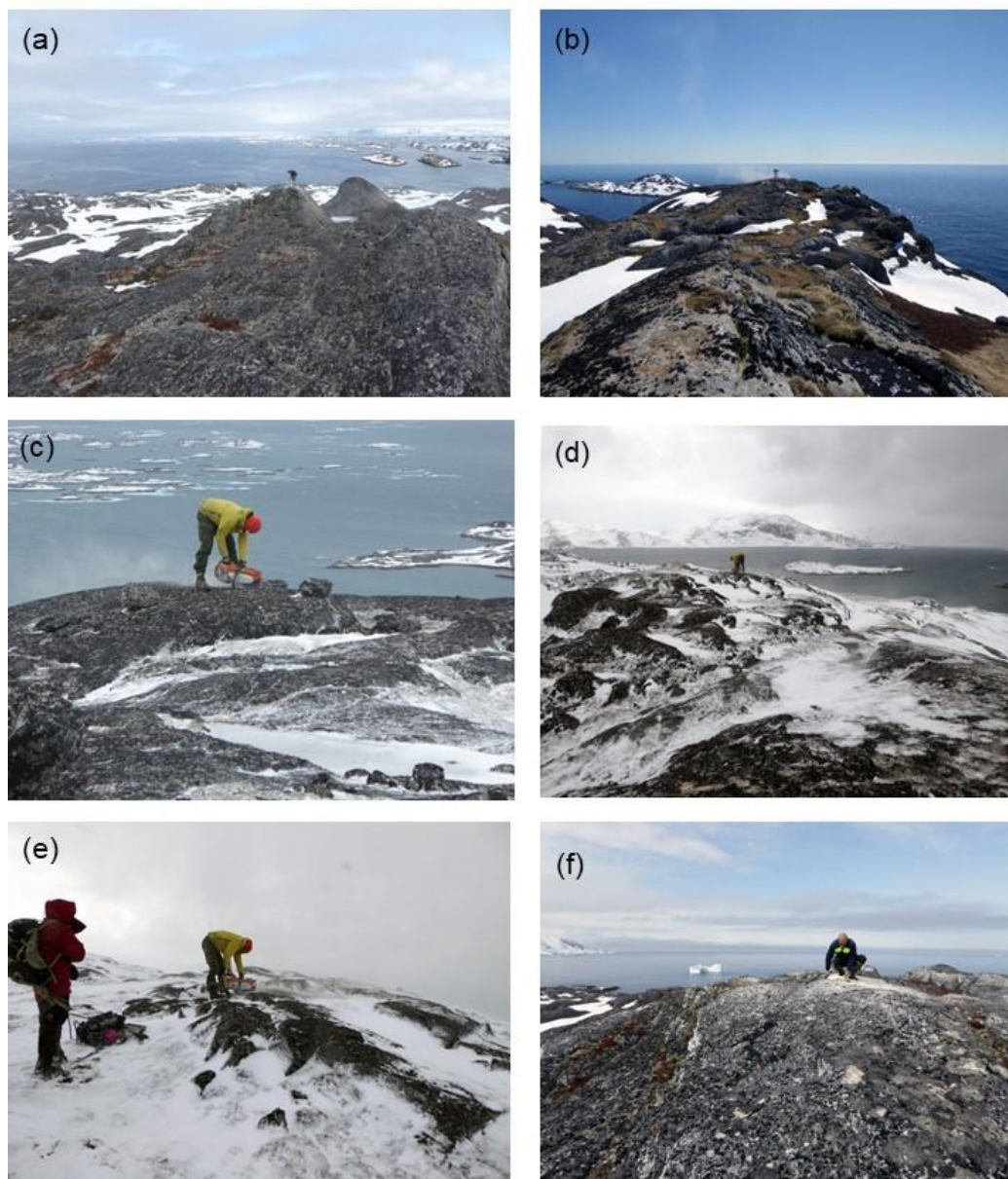
Figure 2: Sampling localities: (a) Buksefjord (Sample X1526, 12.0 ka), (b) Fiskenæsset (Sample X1521, 13.0 ka), (c) Ravns Storø (Sample X1520, 17.0 ka, inheritance), (d) Avigaat (Sample X1518, 10.3 ka), (e) Pamiut (Sample X1515, 12.0 ka), (f) Sermiligarssuk (Sample X1507, 10.9 ka).

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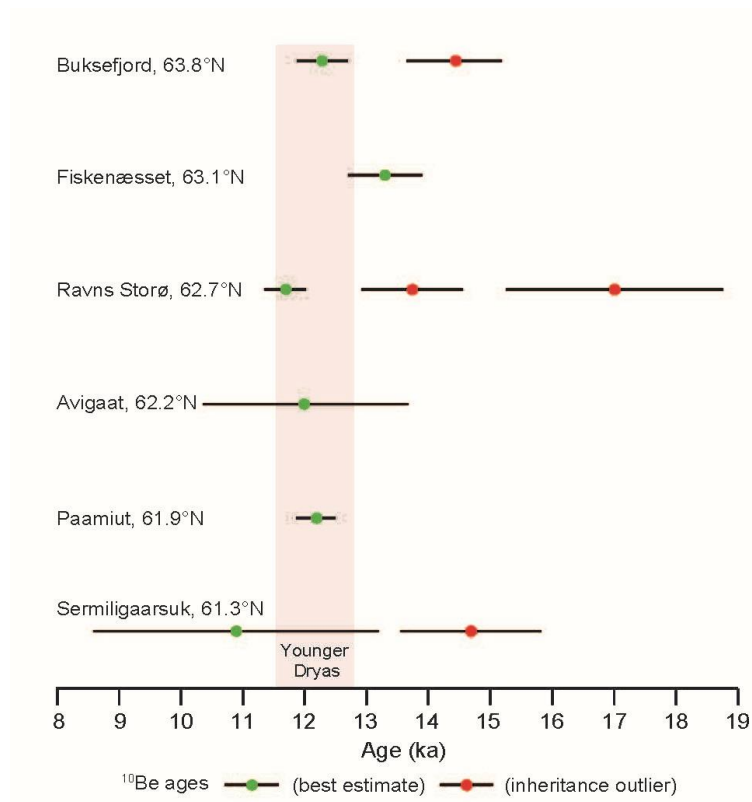
Figure 3: Cosmogenic ages from Southwest Greenland with external uncertainty.

Figure 4: Deglacial ice-margin features in Greenland discussed in the text. (The question marks at GZWs apply to age and come from the original literature). Background map of Greenland and surrounding seas from BedMachine Greenland v.3 (Morlighem et al. 2017)