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1 **A high-resolution elemental record of post-glacial lithic sedimentation in**
2 **Upernavik Trough, western Greenland: history of ice-sheet dynamics and**
3 **ocean circulation changes over the last 9 100 years.**

4
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14

15 **Abstract**

16 A better understanding of the past dynamics of local sectors of the Greenland ice sheet (GIS) with
17 regards to ocean circulation and climate changes can be developed from proxy records derived
18 from marine sedimentary archives. Here we investigate the post 9.1 cal. kyr BP history of the
19 western sector of the GIS from the XRF core scanner-derived geochemistry of a sediment core
20 retrieved from Upernavik Trough, Melville Bay. The elemental signature of material derived from
21 Melville Bay glaciers, Upernavik Isstrom and Rink Isbrae can be inferred from the geology of the
22 bedrocks drained by these major ice streams of the western GIS. Changes in abundance of Fe-rich
23 basaltic material reflect changes in West Greenland Current (WGC) strength. Contributions from
24 Melville Bay glaciers were dominant during the early part of the record as a result of the rapid
25 retreat of this stretch of the NW GIS. Atmospheric warming and strengthened WGC between 7.5
26 and 5 cal. kyrs BP promoted contributions from distal southern sources of lithic material to the
27 sedimentation over Upernavik Trough. The Neoglacial shift in climate and ocean circulation led
28 to a general reduction in the delivery of lithic material from western GIS glacier outlets glaciers.
29 The particular geomorphology of the fjord hosting Rink Isbrae as well as the important depth of
30 the Uummannaq Trough likely explain the high relative contribution of this glacier to the lithic
31 sedimentation over Upernavik Trough during the later part of the Holocene despite a weakened
32 WGC.

33

34

35 **Keywords**

36 West Greenland; Holocene; tidewater glaciers; climate changes; ocean circulation

37 **1 Introduction**

38 Compared to other sectors of the Greenland Ice Sheet (GIS), western and northwestern Greenland
39 from 69°N to 76°N mainly hosts fast moving glaciers with speeds commonly exceeding 3 km/yr
40 (Rignot and Mouginot, 2012; MacGregor et al., 2016). This spatial heterogeneity in ice flow speed
41 illustrates the role on ice sheet dynamics of marine terminating glaciers which drain most of west
42 and northwest Greenland. The cumulative drainage area of western and northwestern glaciers is in
43 the order of 460 000 km² and represents 30% of the total GIS surface (Rignot and Mouginot, 2012).
44 The northward transport of warm Atlantic Water (AW) carried by the West Greenland Current
45 (WGC) in eastern Baffin Bay and its role on the direct melting of major tidewater glacier termini
46 as well as on regional atmospheric temperatures and precipitations explain most of the modern
47 changes in ice flow and mass loss of outlet glaciers in this sector (Chauché et al., 2014; Sakakibara
48 and Sugiyama, 2018). Marine geological studies of sediment cores collected over the slope and
49 within cross-shelf troughs off western Greenland have demonstrated that ocean warming linked to
50 the initiation of the WGC ca. 15 cal. kyrs BP was pivotal in driving, together with the orbitally-
51 induced increase in boreal summer temperature, the retreat of the grounded GIS from the shelf
52 edge to its near-modern position during the last deglaciation (Sheldon et al., 2016; Jennings et al.,
53 2017; Jennings et al., 2018). This ocean – ice-sheet connection is seen as a persistent feature
54 explaining mid to late Holocene glacier changes (advances, retreats) in local sectors of central
55 West Greenland (Schweinsberg et al., 2017). Both ice-sheet model simulations (Lecavalier et al.,
56 2014) and ¹⁰Be and ¹⁴C dating of ice-marginal systems (Young and Briner, 2015; Sinclair et al.,
57 2016; and references therein) suggest that the GIS retreat from the west Greenland shelf (WGS)
58 was completed by ca. 10 cal. kyrs BP. This extensive deglacial retreat of the western GIS was
59 accompanied by a massive delivery of terrigenous material to the shelf and slope *via* iceberg

60 calving, meltwater plumes and sediment gravity flows. These reached the shelf edge through a
61 series of bathymetric troughs interpreted as paleo ice-streams (Fig. 1), namely from south to north
62 Disko Trough, Uummannaq Trough, Upernavik Trough, and Melville Bay (Ó Cofaigh et al., 2013;
63 Hogan et al., 2016; Sheldon et al., 2016; Newton et al., 2017). Following the last deglaciation,
64 sedimentation over the WGS is assumed to derive mainly from iceberg rafting and sediment
65 plumes from proximal and southerly sources and is subjected to subsequent redistribution under
66 the influence of the northward flowing WGC (Andrews et al., 2018). Holocene changes in primary
67 productivity and sedimentation of marine organic matter over the west Greenland shelf are
68 intimately linked to sea ice dynamics. Sea ice and surface conditions in eastern Baffin Bay are
69 mainly constrained by temperature and salinity variations of the WGC, which are themselves
70 controlled by the changing contribution of Irminger water to this current and the variable input of
71 freshwater from the bordering GIS (e.g. Myers et al., 2007). Baffin Bay ice cover is also controlled
72 by the North Atlantic Oscillation (NAO) through its effect on regional atmospheric temperatures.
73 Accordingly, cooler air temperature and greater sea ice extent in Baffin Bay generally occur during
74 positive phase of the NAO (Wang et al., 1994; Stern and Heide-Jørgensen, 2003).

75 High resolution, continuous biotic proxy records obtained from marine sediment cores off western
76 Greenland, especially in the Disko Bay region, have been widely used in the past 10-15 years to
77 shed light on the intricate connection between hydrographic conditions and the behavior of the
78 western GIS over the Holocene (Lloyd et al., 2005 and 2007; Moros et al., 2006; Perner et al. 2012
79 and 2013; Sha et al., 2014; Krawczyk et al., 2016; among others). More recently, mineralogy has
80 been used to assess the provenance of sediment from the various ice-sheets draining into Baffin
81 Bay over the last glacial cycle (Andrews et al., 2012; Simon et al., 2014) by applying a sediment-
82 unmixing program to the bulk mineralogy of marine sediments and taking into account the bedrock

83 geology underlying major ice-streams (Andrews and Eberl, 2011). This methodological approach
84 was pivotal in distinguishing eastern (Greenland), northern (Ellesmere Isl.), and western (Baffin
85 Isl.) contributions to the late Pleistocene sedimentation in Baffin Bay, and hence to discuss the
86 synchronicity in the behaviors of the ice-sheets which drained these regions (Andrews et al., 2018;
87 and references therein).

88 A thorough compilation of chemical analyses of stream sediment samples undertaken by the
89 Geological Survey of Denmark and Greenland (Steenfelt, 2001) showed that the distribution
90 patterns of many major and trace elements closely reflects the various rock complexes of western
91 Greenland, and discriminates local bedrock formations drained by distinct, major marine
92 terminating glaciers between 68°N and 73°N. The present study investigates the geochemical
93 (elemental) composition of a marine sediment core collected over the shelf of western Greenland
94 in order to track potential changes in the delivery of local and distal glacial sources over the last
95 9100 years. The reconstructed continuous, high resolution patterns in lithogenic provenance might
96 unravel distinct post-glacial behaviors of major marine-terminating glaciers of western Greenland,
97 as well as Holocene changes in the strength of the main process (WGC) of transport and
98 redistribution of lithic material over the west Greenland shelf.

99

100 **2 Environmental and geological setting**

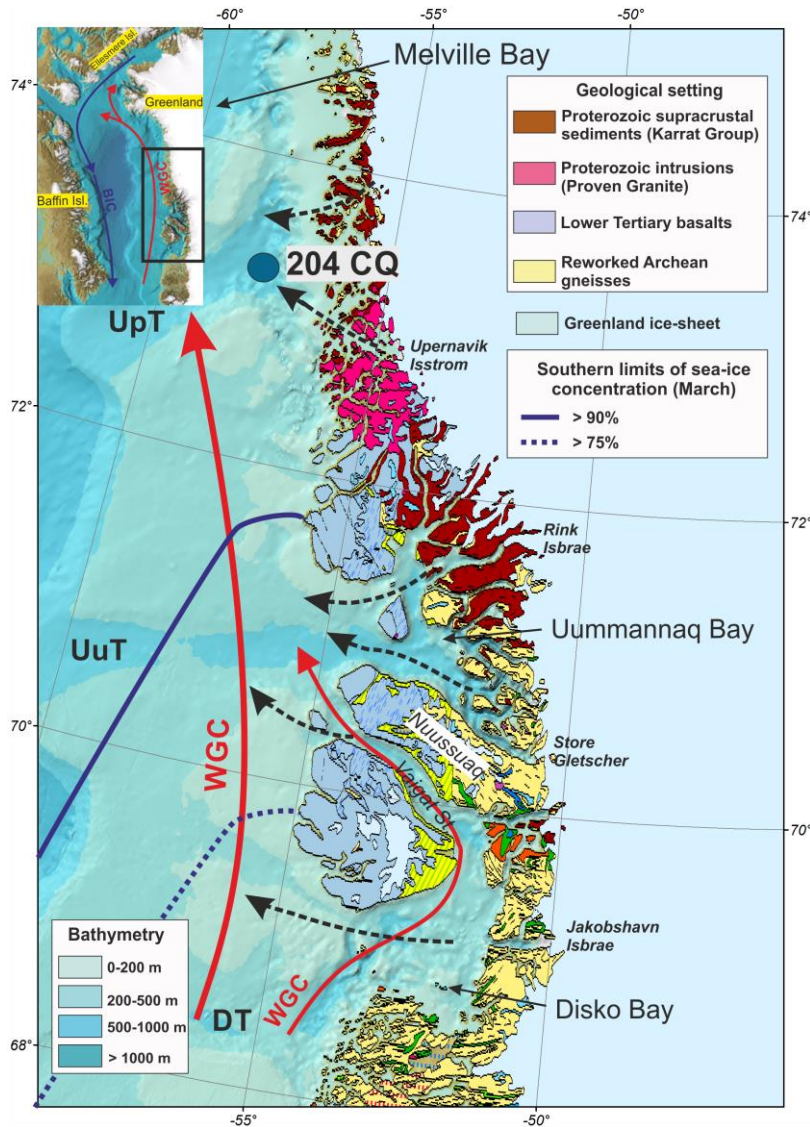
101 The main features of the onshore geology of western Greenland as well as the hydrography and
102 bathymetry of the adjoining shelf are summarized in Figure 1. We restricted this short summary
103 to the region extending from ca. 68°N to 75°N which includes some of the main proximal and
104 distal glacial tributaries which are thought to contribute to the lithic sedimentation at the studied
105 core location (Upernavik Trough).

106 The bedrock of western Greenland varies in age from Archaean to Paleogene (Escher and
107 Pulvertaft, 1995). According to Steenfelt et al. (1998) and the 1:250 000 geological map of
108 Henriksen et al. (2000), the exposed bedrock belongs to 4 main geological formations (Fig. 1):

- 109 - Reworked Archean gneisses in the southern sector of Uummannaq Bay and in Disko Bay which
110 are essentially drained by Store Gletscher and Jakobshavn Isbrae respectively, with rare felsic
111 intrusions and small lenses of unspecified supracrustal rocks;
- 112 - Palaeoproterozoic metasediments (schists) belonging to the Karrat Group in the northern sector
113 of Uummannaq Bay drained by Rink Isbrae, as well as north of 73°N where maximal GIS extent
114 strongly limits surface exposure;
- 115 - A felsic Paleoproterozoic intrusion (Prøven granite) across the Karrat Group formation, which is
116 essentially drained by Upernavik Isstrom and its tributaries;
- 117 - Tertiary (Lower Paleogene) basalts distributed within the western sectors of Disko Bay (over
118 Disko Island) and Uummannaq Bay. Draining of this intrusive formation by the GIS is limited,
119 being restricted to the northernmost basaltic flows immediately south of the Prøven granite.

120 The ocean circulation over the WGS is controlled by the northward flowing WGC. Water masses
121 carried by the WGC reach the calving fronts of major tidewater glaciers in Disko, Uummannak
122 and Melville bays through cross-shelf glacial troughs and deep-silled fjords and therefore
123 influences their dynamics (Chauché et al., 2014). Previous studies, such as those conducted in
124 Melville Bay on Upernavik Isstrom (Fig. 1) and its associated fjord (Upernavik Isfjord) (Weidick,
125 1958; Andresen et al., 2014) highlighted the importance of fjord bathymetry on the dynamics of
126 outlet glaciers, as well as the impact of WGC warming episodes on their recent (20th century)
127 retreat episodes. The main and secondary branches of the WGC redistribute glacier and stream-
128 derived material as well as sediment eroded from exposed coastal formations in a northward

129 direction over the mid to outer shelf (Fig. 1). The WGC is also responsible for the near zonal
130 distribution of sea ice in Baffin Bay: according to the opposing flow of Arctic- and Atlantic-
131 derived water masses on the western and eastern sides of Baffin Bay, respectively, sea ice extent
132 follows a southwest-northeast trend shifting from north to south from September to March. The
133 study area presently hosts the southernmost limit of maximum winter sea ice concentrations
134 (>90%) in eastern Baffin Bay within the northern sector of Uummannaq Bay (Fig. 1; Stern and
135 Heide-Jorgensen, 2003). The physiography and hydrography of Upernavik trough where the
136 marine sediment core studied in this paper has been collected, has been described by Andresen et
137 al. (2014).



138

139 **Figure 1:** Main elements of the bedrock geology of western Greenland (after Henriksen et al., 2000) and of the
 140 hydrology on the nearby shelf. Black dotted arrows highlight the delivery of glacial material to the shelf from the
 141 fastest moving glaciers in the area as well as from the Melville Bay sector of the GIS (according to Rignot and
 142 Mouginit, 2012). Mean sea ice concentrations refers to the month (March) of maximum sea ice extent in Baffin Bay
 143 (after NSDIC climatological maps, and Stern and Heide-Jorgensen, 2003). WGC: West Greenland Current. BIC:
 144 Baffin Island Current. UpT: Upernavik Trough; UuT: Uummannaq Trough; DT: Disko Trough. Blue dot: location of
 145 the studied core 204 CQ. The inserted map (upper left corner) shows the regional oceanography and wider setting of
 146 the studied area.

147

148 **3 Material and Methods**

149 The 734-cm long giant, square, gravity core AMD 204 CQ (hereafter referred to as 204 CQ)
 150 studied here was collected at the head of Upernavik Trough (73°15.66'N, 57°53.98'W, 987 m.
 151 water depth) as part of the 2014 ArcticNet expedition of the CCGS *Amundsen*. The core was

152 immediately sampled onboard using large U-channels. The lithology is homogeneous and consists
153 of bioturbated clayey silts (Caron et al., 2018).

154 3.1 Sedimentological analyses

155 High-resolution images were routinely acquired on the whole U-channels using a computed
156 tomography (CT) scanner (Siemens SOMATOM Definition AS+128 at the Institut National de la
157 Recherche Scientifique, Quebec, Canada) which records down-core changes in bulk density from
158 variations in the CT-numbers (Fortin et al., 2013). The images were also used to locate mollusk
159 shell-rich areas for subsequent ¹⁴C dating, and to check for the presence of lithofacies which might
160 have been missed during visual examination. Grain-size analyses were performed on bulk
161 sediment every 8 cm using a Beckman Coulter LS13320 laser diffraction grain-size analyzer (0.04-
162 2000 µm) and results are expressed as % particles of the various size fractions ranging from clay
163 to very coarse sand. Full details of CT scan and grain size analyses conducted on core 204 CQ are
164 shown in Caron et al. (2018).

165 3.2 XRF core scanning

166 Downcore X-ray fluorescence (XRF) scanning was conducted on core 204 CQ at 0.5 cm resolution
167 using an AVAATECH core scanner with generator settings of 10, 30 and 50 kV to record net
168 intensities of 18 elements ranging from Al to Ba (Table 1). Raw XRF data were normalized to the
169 sum of all element intensities, then log transformed, in order to correct for changes induced by
170 down-core variations in grain size, water content and surface roughness (Bouchard et al., 2011;
171 Martin et al., 2014; Baumann et al., 2017). For simplification, all log-transformed ratios data will
172 be referred to by the symbol of the normalized element in the following text and figures.

173 The database of element (ppm) or oxide (%) concentrations measured in stream sediment samples
174 from western Greenland (Steenfelt, 2001; and Greenland portal of www.greenmin.gl) was

175 extracted to illustrate the concentration ranges, within each of the above-described geological
 176 provinces, of the 18 elements measured in the present study by the XRF core scanner (Table 1).

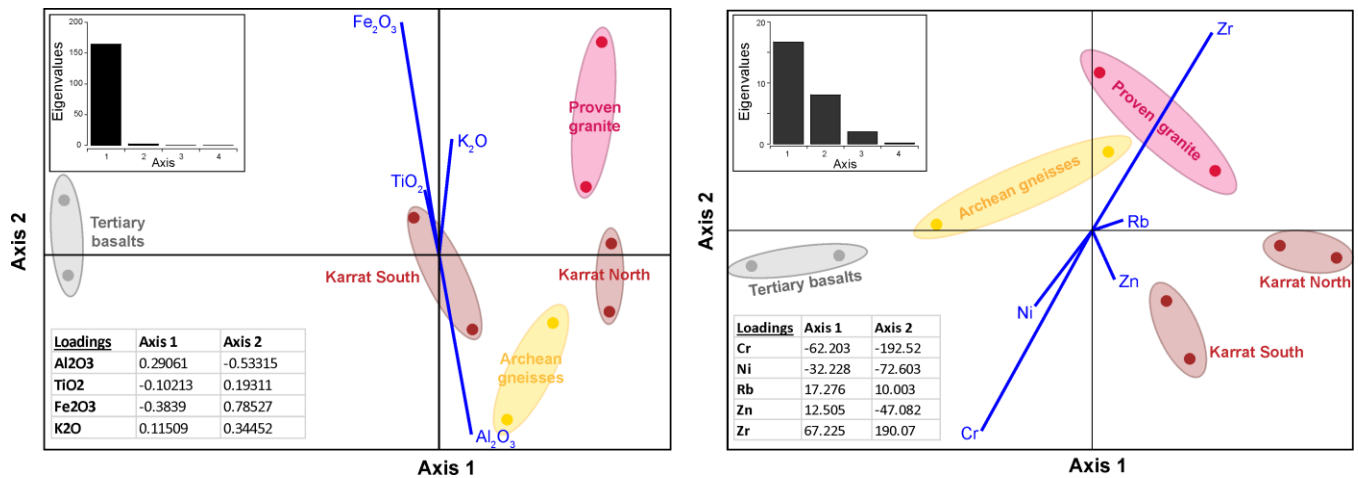
177
 178

	Karrat North (412)	Prøven granite (501)	Tertiary basalts (542)	Karrat South (1010)	Archean gneisses (1274)
Al ₂ O ₃ (%)	13->23 (16)	13-15 (14.5)	<13.6 (12.3)	13-15 (14)	13-16 (14.4)
SiO ₂ (%)	50-70 (66)	50-70 (63)	< 60 (49)	50-70 (65)	50-70 (65)
TiO ₂ (%)	0.4-0.7 (0.6)	~ 1.5	1.5->4.5 (2.2)	0.7-2 (0.8)	<0.5
Fe ₂ O ₃ (%)	5.1-10.6 (7)	5.1-8.7 (8)	13.1-18.6 (15)	5.6-10.6 (9)	3.2-6.1 (4.3)
MnO (%)	0.05-0.1 (0.07)	0.07-0.15 (0.1)	0.18-0.26 (0.2)	0.06-0.18 (0.1)	0.05-0.09 (0.07)
CaO (%)	<1.9 (1.8)	<1.9 (1.8)	1.1-11.8 (9.4)	<1.9 (1.5)	2.6-4.6 (3.6)
K ₂ O (%)	3.1-3.8 (3.2)	3.1-4.2 (3.5)	<0.8 (0.3)	1.9-2.6 (2.4)	1.5-2.6 (2)
Ba (ppm)	450-660 (580)	740-1020 (910)	<290 (96)	510-660 (564)	400-740 (575)
Br (ppm)	2-84 (27)	15-40 (16)	<2-18 (3)	<2	8-120 (16)
Cr (ppm)	60->2900 (89)	20-75 (66)	330->2900 (1140)	110-660 (180)	20-90 (85)
Ni (ppm)	<15-79 (37)	<15-41 (27)	79->630 (285)	79->630 (131)	<15-79 (35)
Rb (ppm)	109-142 (128)	125->142 (105)	<20 (4)	66-109 (90)	30-109 (52)
Sr (ppm)	<218 (166)	175-312 (250)	140-218 (173)	<164 (157)	175-380 (305)
Zn (ppm)	48-127 (74)	80-152 (113)	70-127 (94)	127->620 (213)	<32-70 (40)
Zr (ppm)	310-690 (434)	690-1200 (950)	Below detection limits	Below detection limits	180-690 (344)

180
 181 **Table 1:** Ranges and mean values (between brackets) of element and oxide concentrations within each of the main
 182 geological provinces of western Greenland from 75°N to 68°N according to the geochemical database (Greenland
 183 portal: www.greenmin.gl) compiled by Steenfelt (2001). The number of stream samples used for this compilation and
 184 which are representative of the various geological provinces, is given between brackets within the first line. The
 185 selected elemental markers for bedrock formations and their concentration ranges and mean values are highlighted in
 186 bold and underlined. Grey shadings and italics: elements not considered in this study as unequivocal markers of
 187 bedrock formations in shelf sediments given their affinity to marine biogenic components of marine sediments.

188
 189 These concentration ranges suggest that most bedrock formation can be tentatively characterized
 190 by peak values of elements of no equivalent concentration in another geological setting of the
 191 study area (Table 1). Hence, as a main constituent of ilmenite- and magnetite-rich basalts, Fe is
 192 enriched in material derived from these mafic rocks. As an original component of felsic intrusion,
 193 Zr is particularly concentrated in the restricted area of the Prøven granite drained by Upernavik
 194 Isstrom (Fig. 1). The northern and southern Karrat provinces can be differentiated by peak Zn
 195 concentrations in the later region drained by Rink Isbrae (Fig. 1 and Steenfelt et al., 1998).

196 Conversely, the northern Karrat formation hosts some of the highest K concentrations in stream
 197 sediments of the studied area together with the adjacent Prøven granite province. Finally, Archean
 198 gneisses in the southern Uumannaq and Disko Bay regions bear high concentrations of Sr (Table
 199 1). This last element, as well as Si, Ca, Br, and Ba either show a clear affinity for marine organic
 200 matter export (Br, Ba), are main components of microfossil skeletons (Si and Ca), or are easily
 201 incorporated as trace elements into biogenic carbonates (Sr) (Calvert and Pedersen, 2007; and
 202 references therein). The unequivocal Sr signature of Archean bedrock-derived material in shelf
 203 sediments is therefore questionable and will not be discussed further in the present study.
 204 Part of the dataset summarized in Table 1 was subjected to linear discriminant analyses (LDAs) in
 205 order to sustain the characterization of the different geological provinces by selected element and
 206 oxide concentrations. Separate LDAs were applied on datasets of element (Zr, Rb, Zn, Ni and Cr)
 207 and oxide (Fe_2O_3 , K_2O , TiO_2 and Al_2O_3) concentration ranges with no affinity to marine biogenic
 208 components of marine sediments (Fig. 2, Table S1).



210 **Figure 2:** Summary plots of scores and loadings obtained after linear discriminant analyses of selected element (right
 211 plot) and oxide (left plot) concentration ranges within the five geological provinces of the studied area. The set of data
 212 used to construct these plots is given in Table S1.
 213

214 When applied on oxide concentration ranges, LDA separates two groups of geological provinces
215 along a single discriminant function (axis 1), the tertiary basalts (strong negative scores) vs. the
216 northern Karrat, the Proven granite and the Archean gneiss provinces (positive scores). These two
217 groups are explained by the opposite loadings of Fe (negative) and, K₂O and Al₂O₃ (both positive).
218 Applying the same analysis on element concentration ranges essentially results into two
219 discriminant functions (axes 1 and 2). According to loadings of the vertical axis 2, Zr (positive
220 loadings) and Zn (negative loadings) are the main variables explaining the distribution of scores
221 related to the elemental composition of rocks from the Proven granite and Karrat South,
222 respectively. As suggested from the dataset of element and oxide concentration ranges (Table 1),
223 and as confirmed by LDAs (Fig. 2), Archean bedrock-derived material cannot be characterized by
224 typical element or oxide concentrations of no equivalent values in another geological setting of the
225 study area. LDAs also confirm that Proven granite and northern Karrat rocks, which are both
226 enriched in K₂O, can be differentiated by Zr content (high in Proven granites).

227

228 3.3 Age model of core 204 CQ

229 The age model used for core 204 CQ is an update of the one published by Caron et al. (2018)
230 which was based on a combination of 4 AMS ¹⁴C dates measured on benthic foraminifera (x4) and
231 12 paleomagnetic chronostratigraphic markers. Given the scarcity of benthic foraminifera in the
232 top- and bottommost parts of core 204 CQ, and in order to improve the age model for these
233 intervals, 10 additional AMS ¹⁴C dates were measured on bulk organic matter. Table 2 and Fig.
234 S1 show that organic matter ¹⁴C dates are 2 to 3 000 years older on average than the ages expected
235 from foraminiferal dates with a trend for higher differences with core depth. This inconsistency
236 between biogenic carbonate and organic matter dates has been previously described as a common

237 feature of Deglacial and Holocene sediments in Baffin Bay and Labrador Sea sediments and has
238 been attributed to significant influx of old carbon from reworked marine and/or terrestrial
239 sediments following the Last Glacial Maximum (Andrews et al., 1985; Fillon et al., 1981; Licht et
240 al., 1998).

241 The origin of the organic matter in core 204 CQ was assessed by measuring elemental (total
242 organic carbon vs. total nitrogen (C/N)) and isotopic (delta ^{13}C of organic matter ($\delta^{13}\text{C}_{\text{org}}$)) source
243 identifiers downcore 204 CQ every ca. 10 cm. Total organic carbon content was measured on
244 decarbonated (1N HCl) sediment using a LECO CS 125 analyzer (standard error of measurements
245 $< 0.5\%$). Total nitrogen and $\delta^{13}\text{C}_{\text{org}}$ were measured simultaneously using a Carlo-Erba CN
246 analyzer coupled to a Micromass-Isoprime mass spectrometer (analytical precision = 0.15%). C/N
247 and $\delta^{13}\text{C}_{\text{org}}$ values (Fig. S1) range from 7 to 9.5 (mean = 8.1) and from 21.9% to 24.1% (mean =
248 23.0%) (Fig. S1), respectively, indicating that the organic matter in core 204 CQ is essentially of
249 marine origin (Meyers, 1994). The contribution of reworked terrestrial material to the organic
250 matter in core 204 CQ is therefore minimal, *ie.* not detectable using standard elemental and isotopic
251 source identifiers.

252 Following the method described by Andrews et al. (1985), we corrected the reported ^{14}C dates
253 measured on organic matter using an empirical equation [1] constructed from a comparison of the
254 4 uncalibrated ^{14}C carbonate dates (C) obtained in core 204 CQ with projected organic matter dates
255 (O) at the same core depth (Fig. S1, Table 2):

$$256 \quad [1] \quad O = 1.237C + 1268$$

257 All ^{14}C dates were calibrated with the Calib 7.1 software (Stuiver et al., 2018) using the Marine09
258 calibration dataset and applying the local reservoir correction of 540 ($\Delta R = 140$) \pm 35 years (Lloyd

259 et al., 2011). The final age-depth model (Fig. 3) was constructed with the R-package *Bacon*
 260 (Blaauw and Christen, 2011) which uses Bayesian statistics.

261

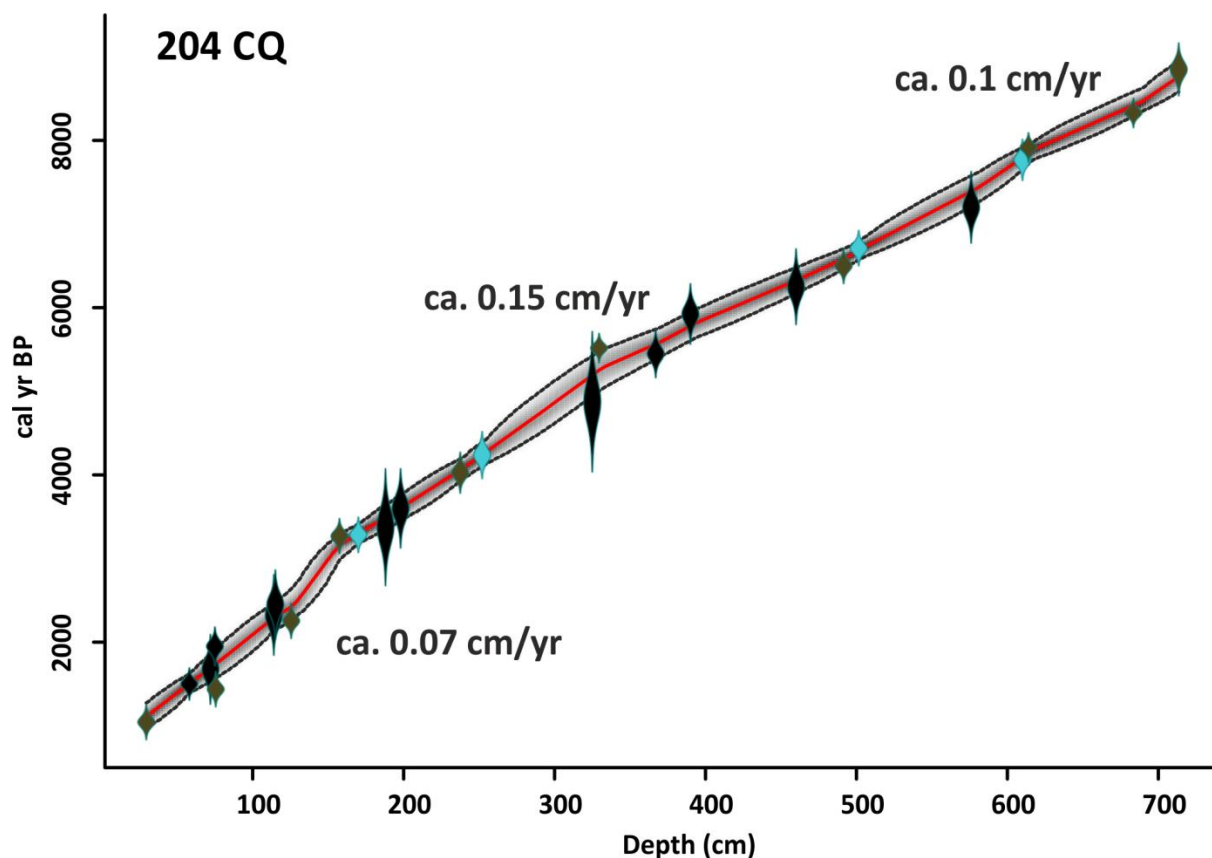
14C dates									
Lab number	Depth (cm)	Material dated	Delta 13C	Reported 14C age (yrs BP)	Reported error (±yrs BP)	Predicted 14C age after [1] (yrs BP)	Calibrated age (yrs BP)	1 sigma	
								from	to
BETA 480648	29-30	Organic matter	-21.6	3290	30	1633	1044	973	1100
BETA 480647	75-76	Organic matter	-21.6	3780	30	2029	1437	1381	1499
BETA 480646	125-126	Organic matter	-21.8	4640	30	2724	2255	2196	2320
BETA 480645	157-158	Organic matter	-21.8	5650	30	3540	3268	3210	3333
SacA 46004	169-171	Mixed benthic & planktonic foraminifera	5.7	3555	35		3283	3222	3350
BETA 480644	237-238	Organic matter	-21.8	6410	30	4154	4026	3952	4096
BETA 467785	251-253	Mixed benthic & planktonic foraminifera	0.3	4300	30		4237	4149	4308
BETA 480643	329-330	Organic matter	-21.9	7820	30	5293	5517	5473	5568
BETA 480642	491-492	Organic matter	-22.5	8960	30	6214	6498	6430	6557
BETA 488641	500-503	Mixed benthic foraminifera	-1.8	6400	30		6711	6652	6768
SacA 46005	609-611	Mixed benthic foraminifera & ostracods	-6.9	7445	50		7767	7692	7831
BETA 480641	613.5-614.5	Organic matter	-22.9	10670	30	7596	7916	7864	7961
BETA 480640	683-684	Organic matter	-22.8	11170	30	8000	8328	8285	8379
BETA 480639	713-714	Organic matter	-22.8	11710	40	8436	8849	8770	8956
Paleomagnetic chronostratigraphic markers									
	Depth (cm)						Calibrated age (yrs BP)	Standard deviation	
I1	58						1500	55	
I2	72						1675	119	
D1	75						1950	66	
P1	114						2325	137	
I3	115						2450	118	
P2	188						3375	199	
D2	198						3600	135	
P3	325						4875	239	
P4	367						5450	82	
I6	390						5925	103	
D3	460						6250	129	
P5	576						7200	122	

262

263

264 **Table 2:** Radiocarbon dates (top) and paleomagnetic markers (bottom) used to construct the age-depth model of core
265 204 CQ. ^{14}C dates measured on calcareous material as well as paleomagnetic markers are taken from Caron et al.
266 (2018). Reported ^{14}C dates measured on organic matter were corrected (“predicted ^{14}C ages”) using an empirical
267 equation ([1], Fig. S1) constructed from a comparison of the foraminiferal ^{14}C dates with projected organic matter ^{14}C
268 dates at the same core depth.
269

270 According to the new age model, core 204 CQ covers a time interval from ca. 0.75 to 9.1 cal. kyrs
271 BP. ^{210}Pb analyses showed no evidence of unsupported ^{210}Pb at the core-top (ie. older than ca. 100
272 years before 2014) hence confirming that core 204 CQ did not recover “modern” sediment (T. J.
273 Andersen, Univ. Copenhagen; pers. comm.). Sedimentation rates average 0.1 cm/yr, peaking at
274 0.15 cm/yr around 6 cal. kyrs BP (Fig. 3).
275



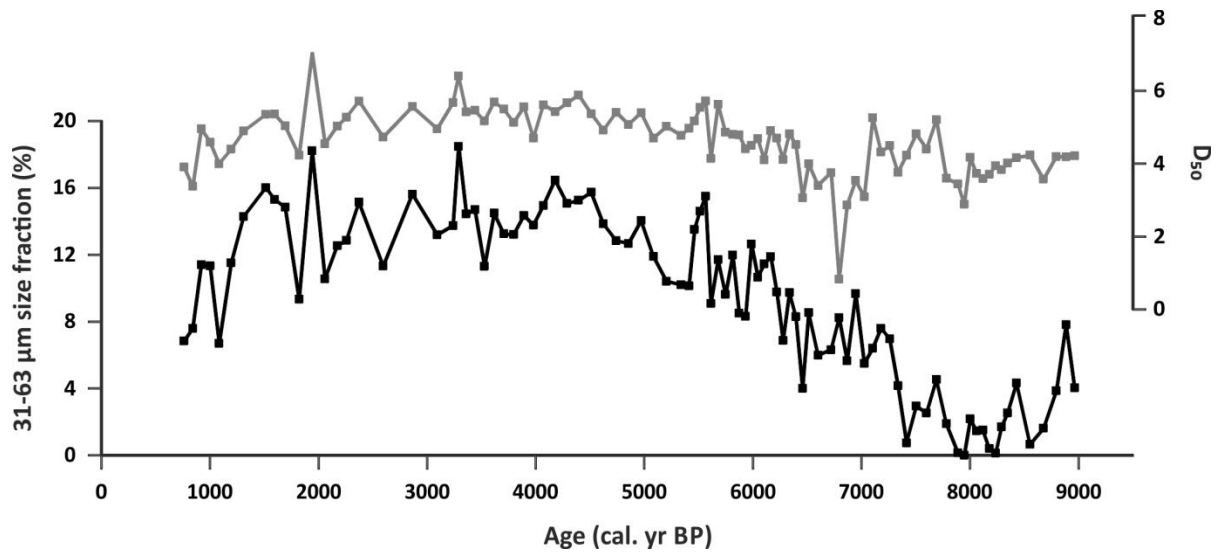
276

277 **Figure 3:** Age-depth model (revised from Caron et al., 2018) of core 204 CQ and mean sedimentation rates based on
278 ^{14}C dates measured on foraminifera (blue diamonds) and organic matter (brown diamonds), and paleomagnetic
279 stratigraphic markers (black diamonds). The black stippled lines bracket the 95% confidence intervals; the red curve
280 shows the single ‘best’ model based on the mean age (Blaauw and Christen, 2011).
281

282 **4 Results**

283 4.1 Sedimentological data

284 Core 204 CQ consists of homogeneous bioturbated hemipelagic clayey silts with very rare and
285 scattered occurrence of ice-rafted debris (IRD > 2 mm) (Caron et al., 2018). The sediment median
286 grain size (D_{50}) which splits the distribution with half above and half below this diameter, ranges
287 from ca. 3 to 6 μm and contains a short interval of dominantly silty clay centered at 6.8 cal. kyrs
288 BP (Fig. 4). Highest grain sizes recorded in core 204 CQ fall within coarse and very coarse silts
289 (31 – 63 μm) with a trend for higher values from ca. 7.2 cal. kyrs BP toward the core-top (Fig. 4).
290 Smear slide analyses showed that this progressive coarsening might be partly induced by the
291 increasing contribution of diatom skeletons to the sediment of core 204 CQ. The CT scan images
292 do not provide any evidence of typical glacio-proximal facies such as laminated glacimarine
293 deposits or coarse-grained subaqueous outwash deposits (Ó Cofaigh and Dowdeswell, 2001). This
294 confirms that the location of core 204 CQ was in a distal position with regards to tidewater glacier
295 termini of the GIS throughout the time interval covered by this sedimentary record, as expected
296 from general reconstructions of the post-glacial dynamics of the western sector of the GIS
297 (Lecavalier et al., 2014; Young and Briner, 2015). The absence of distinct IRD-rich horizons also
298 suggests that catastrophic calving events of marine terminating glaciers along western Greenland,
299 if any over the last ca. 9000 years, did not promote episodic, massive delivery of IRD to the core
300 location.

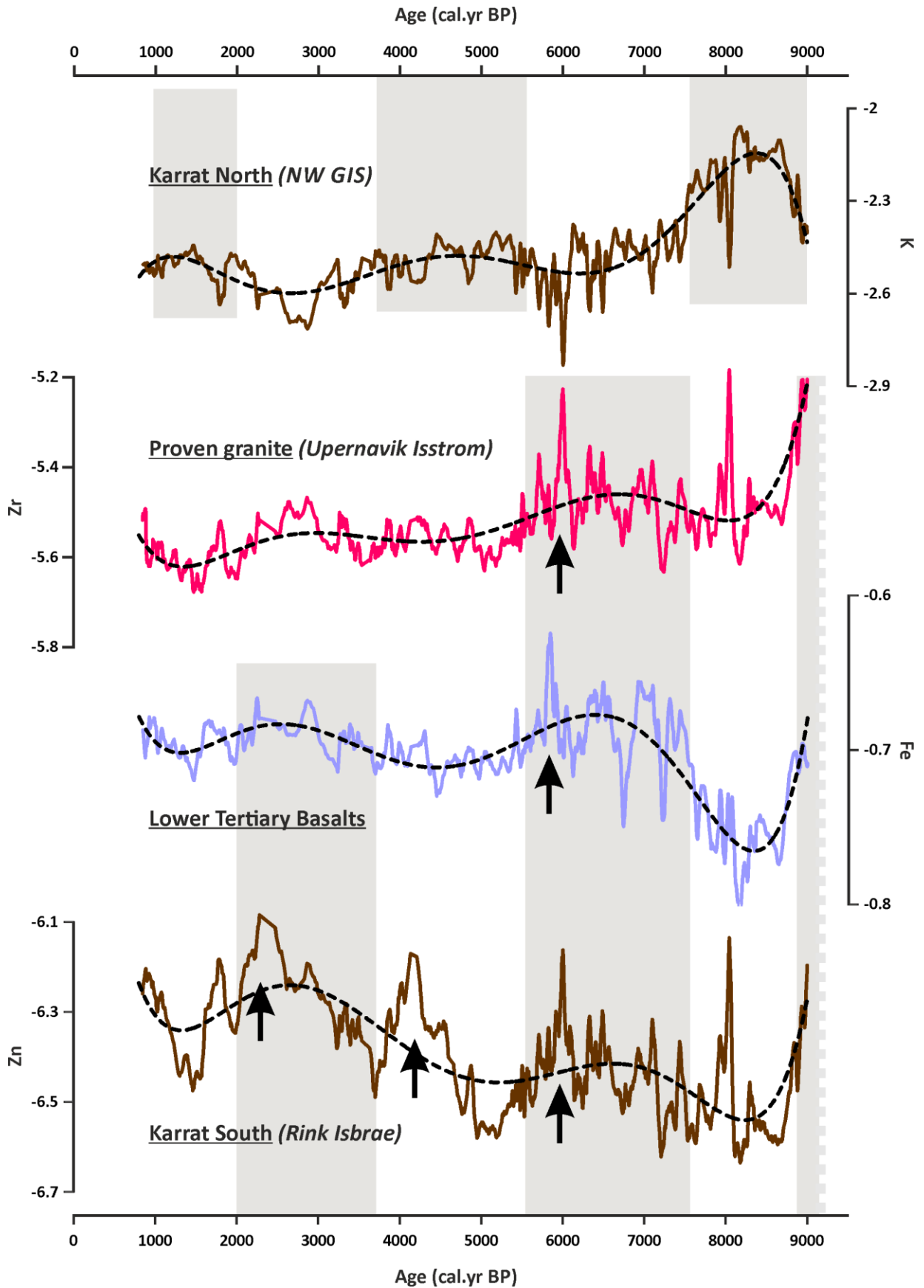


301
 302 **Figure 4:** Median grain size (D_{50} expressed in μm ; full grey square) and contribution (%) of coarse and very coarse
 303 silts to the bulk sediment (full black square) in core 204 CQ.
 304

305 4.2 XRF core scanning data

306 The down-core distribution of K, Zr, Fe and Zn intensities, as elemental markers of the Karrat
 307 North, Prøven granite, Lower Tertiary basalts, and Karrat South formations, respectively, is given
 308 in Figure 5. Those four elements display distinct long- and short-term patterns throughout core
 309 204 CQ over the last 9000 years. K shows high values within the bottom part of the record from 9
 310 to 7.5 cal. kyrs BP. Values thereafter decrease and remain rather low, though with two intervals of
 311 moderately higher intensities between ca. 5.5 and 3.5 cal. kyrs BP, and from 2 to 1 cal. kyrs BP.
 312 Zr shares with K a common long-term decrease in XRF intensity over the last ca. 9000 yrs.
 313 Millennial-scale changes are however opposite with broad peak Zr values occurring at the bottom-
 314 end of the core (ca. 9 cal. kyrs BP) as well as from 7.5 to 5.5 cal. kyrs BP. Outstanding, short-term,
 315 maximum Zr values are recorded at 8 and 6 cal. kyrs BP. Both the short events and the pattern of
 316 millennial-scale changes described for Zr are displayed by Zn. This last element however presents
 317 a long-term trend of increasing intensities from Early to Late Holocene, leading to a broad interval
 318 of maximum values between 3.5 and 2 cal. kyrs BP, as well as two additional short events of peak

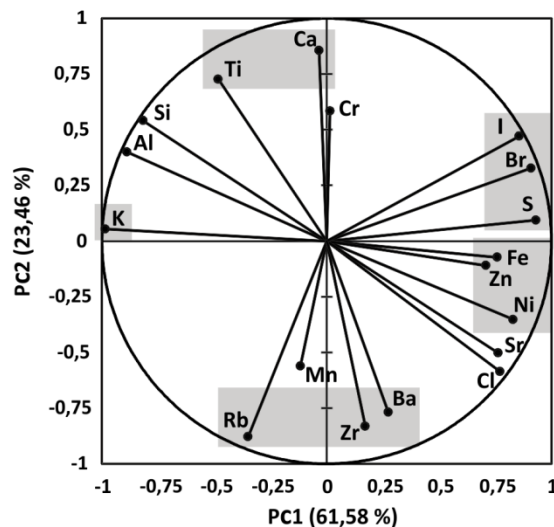
319 intensities centered at 4.1 and 2.3 cal. kyrs BP. Finally the pattern displayed by Fe is intermediate
320 to Zr and Zn, showing the same millennial scale variability but no long-term trend of decreasing
321 or increasing values from ca. 7.5 cal. kyrs BP to the top of core 204 CQ. Maximum Fe intensities
322 characterize a mid-Holocene interval from 7.5 to 5.5 cal. kyrs BP, as well as a single short event
323 slightly after 6 cal. kyrs BP (ie. 5.8 cal. kyrs BP according to our age model).



325 Figure 5: Patterns (10 point moving average) of XRF core scanner-derived elemental markers of bedrock sources in
 326 core 204 CQ: K, Zr, Fe and Zn, from top to bottom. Colors according to the mapped geological formations summarized
 327 in Figure 1. Names of major glaciers draining 3 or the 4 bedrocks are given in italics between brackets. Grey shaded
 328 areas highlight periods of sustained, high intensities of elemental markers according to a 6th order polynomial fitting
 329 curve (dashed black line). The vertical black arrows refer to remarkable events discussed in the text.
 330

331 We applied principal component analysis (PCA) to identify the leading modes of variability among
 332 the whole set of XRF-derived element records. Results indicate that the first two principal
 333 components PC1 and PC2 account for 85% of total variance. PC1 (62% of the variance) is
 334 explained by two groups of positively and negatively correlated elements (Table 3 with inserted
 335 plot). High positive loadings to PC1 are expressed by Fe, Zn, and Ni which trace the distal southern
 336 basaltic (Fe and Ni) and Karrat South (Zn and Ni) sources of bedrock formations (Table 1); Br, S,
 337 and I whose concentrations in marine sediment are partly controlled by the production and
 338 subsequent burial of marine organic matter (Calvert and Pedersen, 2007), also show high positive
 339 loadings to PC1. Negative PC1 loadings are essentially expressed by K, the elemental marker for
 340 the Karrat North geological formation.

	PC1	PC2
Al	-0,889	0,400
Si	-0,817	0,541
S	0,931	0,094
Cl	0,771	-0,586
K	-0,985	0,054
Ca	-0,034	0,855
Ti	-0,482	0,727
Cr	0,015	0,583
Mn	-0,117	-0,561
Fe	0,759	-0,073
Ni	0,830	-0,352
Zn	0,710	-0,110
Br	0,910	0,327
Rb	-0,349	-0,878
Sr	0,763	-0,503
Zr	0,172	-0,832
I	0,856	0,471
Ba	0,275	-0,768



341

342 Table 3: Factor loadings on the first two principal component PC1 and PC2 for XRF core-scanning elemental data in
343 core 204 CQ. Inserted figure: distribution of loadings according to the first and second PC axes.
344

345 PC2, which explains 23% of the total variance, is (negatively) expressed by Zr and Rb and (though
346 with reduced loading) by Ba, those 3 elements being particularly concentrated in the Prøven granite
347 formation drained by Upernavik Isstrom (Table 1). High positive loading to PC2 is found for Ca,
348 an element which traces both marine biogenic (calcium carbonate) and lithogenic (basalts, see
349 Table 1) components of the marine sediments in the study area.

350 The PCA analysis statistically confirms the general patterns of variability described by the
351 elemental markers of specific bedrock formations shown in Figure 5:

352 - Changes in the relative contribution of Karrat North material in core 204 CQ over the last 9100
353 years are inversely related to relative contributions from distal basaltic and Karrat South
354 formations. The PCA grouping of these late distally-sourced elements (positive loadings in PC1)
355 presumably highlights the existence of a common transport vector (WGC) to the core location,
356 regardless of their mode of delivery to the shelf, ie. mainly glacial (Karrat South) vs. both glacial
357 and non-glacial - erosion of exposed coastal formations - (basalt formations).

358 - Holocene changes in the relative contribution of lithogenic material delivered from the proximal
359 Upernavik-draining Prøven granite bear a unique pattern (negative loadings in PC2), which
360 according to PCA orthogonal transformations, is linearly unrelated to the contributions of other
361 sources (explained by PC1).

362 Considering the undiscriminating information given by PC1 scores in terms of lithogenic sources
363 and erosional and transport processes (see above), as well as high loadings in both PC1 and PC2
364 of elements of known affinity with marine biogenic components, downcore records of PCA scores
365 can hardly be used in a straightforward manner to infer changes in provenance of lithogenic
366 material. We will therefore essentially refer hereafter to the XRF-derived profiles of the

367 normalized single elements (1) K, (2) Zr, (3) Fe, and (4) Zn as indicators of the variable
368 contributions to the core location of material derived from (1) the southern Melville Bay sector of
369 the GIS (Karrat North formation), (2) the Upernavik Isstrom which drains the Prøven granite
370 formation, (3) the unglaciated coastal Lower Tertiary basalts, and (4) the Rink Isbrae and
371 tributaries which drains the northern Uummanaq Bay sector of the GIS (Karrat South formation).

372

373 **5 Discussion**

374 The delivery of lithic material to the WGS is assumed to be essentially triggered by processes
375 which are common to such high latitude settings: (1) ice loss from summer surface melting and
376 runoff at the margin of the ice sheet, a process which is further accelerated in marine terminating
377 glaciers under the influence of ocean melting of basal or frontal ice, and (2) the erosion of exposed
378 (unglaciated) coastal formation as well as remobilization of shallow shelf sediment. Sea ice cover
379 and duration might influence the transfer efficiency of lithic material to the ocean by prohibiting
380 the export to the shelf of lithic-laden icebergs and land-fast ice from calving glaciers and the
381 coastline, respectively. Subsequent transport by the WGC redistributes the lithic fraction delivered
382 to the shelf or remobilized from shallow shelf deposits in a northward direction along the west
383 Greenland margin. Modern (Chauché et al., 2014) and geological evidence (Thomas et al., 2016)
384 also links strengthened transport of warm Atlantic Water (AW) carried by the WGC in eastern
385 Baffin Bay to increases in regional atmospheric temperature and precipitation.

386 The observed changes in the relative contribution of K, Zr, Fe, and Zn in the sediments of core
387 204 CQ are therefore believed to be highly constrained by the local-scale responses of their source
388 geological provinces and associated glacier dynamics to both climate and ocean forcing over the
389 last 9100 years as well as by variations in strength of the along-shelf transport vector to the core

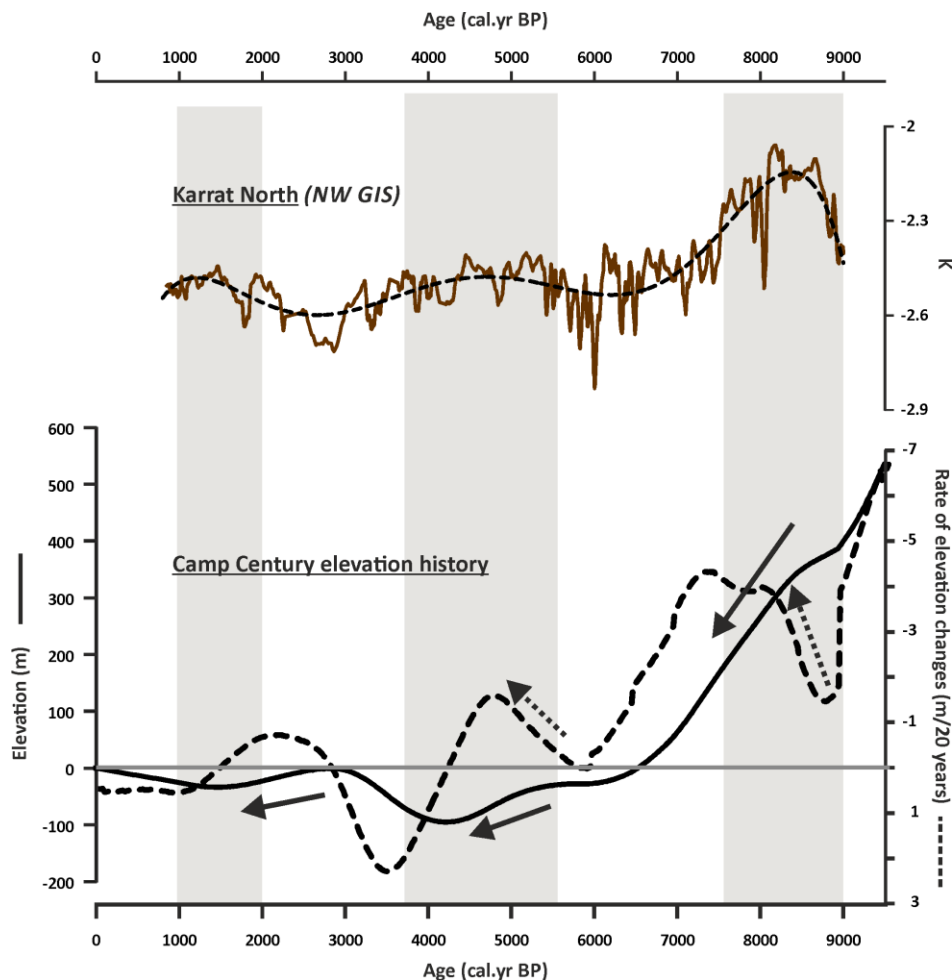
390 location. According to the distinct long and short term patterns displayed by the selected elements
391 (Fig. 5), we suspect that the various source provinces and their associated glacier systems reacted
392 differently to Holocene changes in climate and ocean circulation in the west Greenland region.
393 Asynchronous timing of deglaciation from northern Melville Bay to Jakobshavn Isbrae, Disko Bay
394 (see Fig.1 for location), has indeed been inferred from ^{14}C of ^{10}Be dates in lake sediments and
395 moraine deposits, and was partly attributed to peculiarities in the topography of local glacier outlets
396 in this region (Young and Briner, 2015). This last factor has thus to be considered together with
397 regional changes in atmospheric temperature and oceanic circulation when interpreting our XRF-
398 derived dataset.

399 5.1 The Early Holocene deglaciation of the NW GIS

400 Numerical models (Lecavalier et al., 2014) as well as ^{14}C and ^{10}Be dating (Bennike, 2008;
401 Fredskild, 1985; Weidick, 1978) indicate that the deglaciation of the Melville Bay sector of the ice
402 sheet to its historical ice limit was completed between 9.9 and 9.1 cal. kyrs BP, that is up to 2000
403 years earlier than in central western Greenland. According to Briner et al. (2013) this early ice
404 retreat can be explained by the existence of a marine-based ice sheet along most of Melville Bay
405 which is therefore susceptible to rapid retreat *via* calving.

406 The continuous vast stretch of marine terminating ice in Melville Bay drains a large part of the
407 NW GIS. Holocene thinning of this sector of the GIS is therefore likely to induce major changes
408 in ice flow and mass balance of Melville Bay glaciers and thus in the delivery of lithic material to
409 the shelf from their marine outlets. We consider that the 9-7.5 cal. kyrs BP interval of maximum
410 relative contribution of Karrat North-derived material to the lithic sedimentation at core 204 CQ
411 is an expression of the early Holocene thinning of the NW GIS as depicted from the nearby Camp
412 Century ice-core (Vinther et al., 2009). The updated calculation of elevation changes at Camp

413 Century (Lecavalier et al., 2017) suggests that this sector of the GIS experienced the most dramatic
 414 episode of thinning of the last 9000 years from ca. 9 to 7.5 cal. kyrs BP (Fig. 6) during the Holocene
 415 peak in solar insolation (Berger, 1978). Rates of elevation change throughout this period increased
 416 from ca. 2 m/20 years close to 9 cal. kyrs BP to > 4 m/20 years around 7.5 cal. kyrs BP before
 417 dropping to a 6 cal. kyrs BP standstill at an elevation slightly lower than the present ice-core
 418 altitude (Fig. 6; Lecavalier et al., 2017). Subsequent middle and late Holocene periods of NW GIS
 419 thinning ca. 5.5 to 4 cal. kyrs BP, and 2.5 to 1 cal. kyrs BP, occurred in phase with increasing
 420 (albeit moderate) relative contribution of Karrat North-derived material to sediments of core 204
 421 CQ (Fig. 6), hence suggesting that even subtle millennial-scale evolution of the NW GIS have
 422 implication on the origin of lithic sediments delivered to the nearby shelf.



423

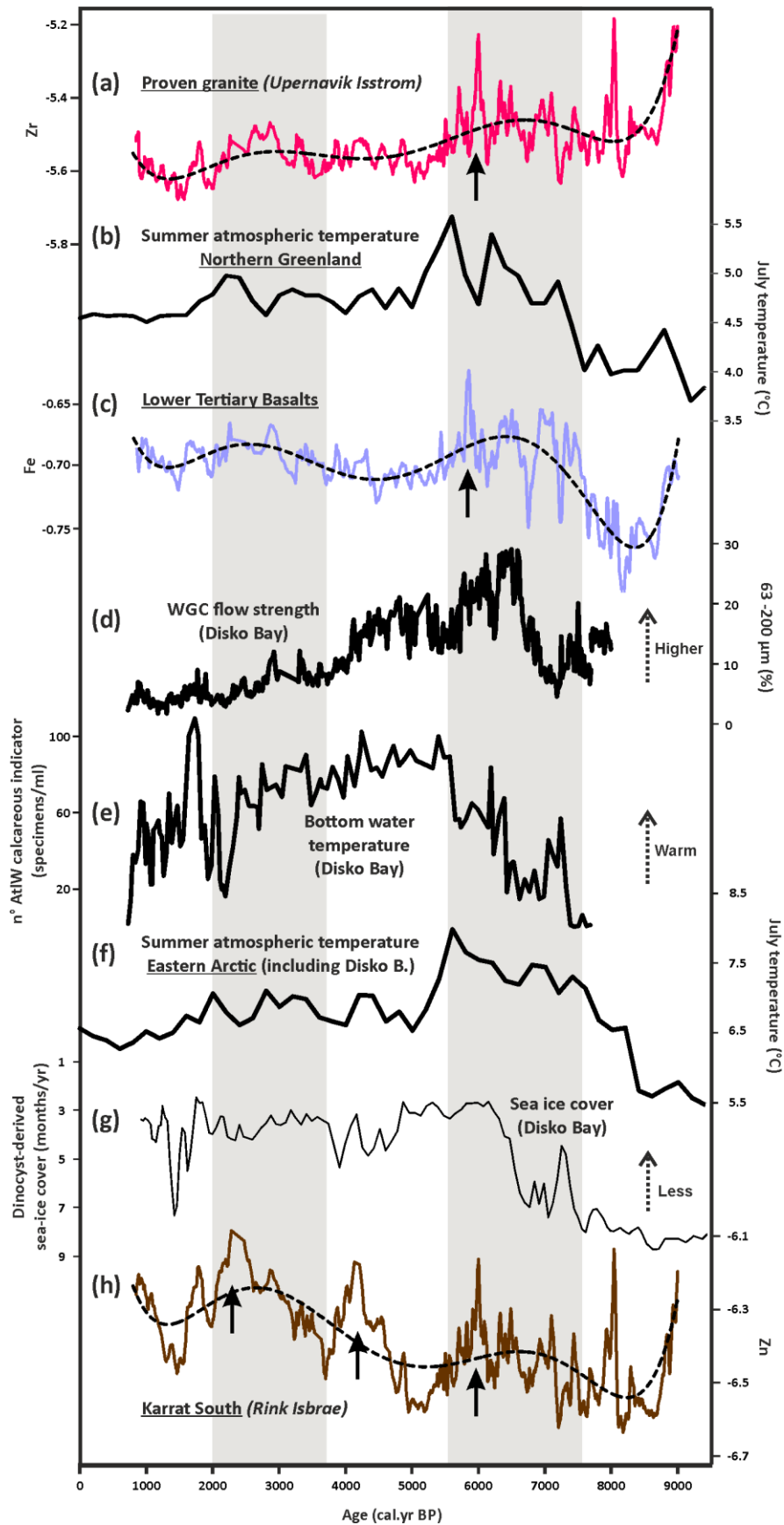
424
425 Figure 6: Downcore pattern of the normalized XRF-derived K counts, the elemental marker for Karrat-North (NW
426 GIS)-derived sediment (top), and elevation history of Camp Century, NW GIS, after Lecavalier et al. (2017) (bottom).
427 Elevation expressed according to the modern altitude (horizontal line crossing 0 on the left axis); negative (positive)
428 rates of elevation change on the right axis corresponds to ice thinning (thickening); plain and dotted arrows point to
429 remarkable periods of elevation decrease and increase rates of thinning, respectively.
430

431 Finally, in addition to the exceptionally high input of terrigenous material from the NW GIS to the
432 shelf of Melville Bay between ca. 9 and 7.5 cal. kyrs BP (Fig. 5 and 6) which diluted the material
433 sourced from southern sectors of the studied area, other factors might explain the low relative
434 contribution of Upernavik Isstrom-, coastal basaltic- and Rink Isbrae-derived material to sediments
435 of core 204 CQ during this time period: an early Holocene low in WGC flow strength (Perner et
436 al., 2012) reduced the northward transport of southern source lithics; also, high duration of
437 seasonal sea ice off western Greenland until ca. 7.5 cal kyrs BP (Ouellet-Bernier et al., 2014)
438 limited the delivery of calved lithic-laden icebergs from marine terminating glaciers to the nearby
439 marine environment (Fig. 7). The very fine grain size of the lithic material feeding the inner sector
440 of the Upernavik Trough, where core 204 CQ is located, during the early Holocene (Fig. 4)
441 suggests that sedimentation from turbid plumes delivered from the proximal Melville Bay sector
442 of the GIS was the main sedimentary processes at play in this area prior to ca. 7.5 cal kyrs BP.
443 Other studies indicate that large-scale melt water discharges from turbid plumes also characterized
444 more southerly sectors of the western GIS such as the Disko Bay region until around 7.5 cal. kyrs
445 BP (Seidenkrantz et al., 2013).

446 5.2 The Holocene Thermal Maximum in western Greenland: response of lithic sedimentation to 447 higher WGC flow strength and summer atmospheric temperatures

448 A broad maximum in relative contribution of Upernavik Isstrom and Rink Isbrae-derived material
449 characterizes the 7.5 to 5.5 cal. kyrs BP interval. This time period is part of the so-called Holocene
450 Thermal Maximum (HTM) in Greenland (8-5 cal. kyrs BP) when borehole temperatures from the

451 GRIP ice core suggest constantly higher values than today (Dahl-Jensen et al., 1998). Threshold
452 lake records indicate that the ice sheet over vast stretches of southwestern Greenland retreated
453 behind its present day extent between 7 and 4 cal. kyrs BP (Larsen et al., 2015; and references
454 therein), if not as early as 6.5 cal. kyrs BP near Jakobshavn Isbrae, Disko Bay (Håkansson et al.,
455 2014). Published ¹⁰Be ages show that while the retreating GIS reached its present limit by 10 cal.
456 kyrs BP in the sector of Upernavik Isstrom and 5.2 cal. kyrs BP at Rink Isbrae, the ice sheet in the
457 regions of Melville Bay, Uummannaq Bay, and Disko Bay continued to retreat behind the present
458 limit until 5-3 cal. kyrs BP (Young and Briner, 2015).



460
461 Figure 7: Patterns (10 point moving average) of XRF core scanner-derived Zr (a), Fe (c) and Zn (h) relative abundances
462 in core 204 CQ, compared with proxy records of climate and ocean circulation changes. (b): Pollen-derived summer
463 (July) atmospheric temperatures in coastal Northern Greenland (Gajewski et al., 2015). (d): Abundance of fine sand
464 in core 343300, Disko Bay, as an indicator of WGC flow strength (Perner et al., 2013). (e): Abundance of calcareous
465 Atlantic water benthic foraminifera in core 343300, Disko Bay, as indicators of warm WGC (Perner et al., 2013). (f):
466 Pollen-derived summer (July) atmospheric temperatures in Eastern Arctic (Gajewski et al., 2015). (g) Dinocyst-
467 derived sea ice cover in core 343300, Disko Bay (Ouellet-Bernier et al., 2014). The vertical black arrows refer to
468 remarkable events discussed in the text.
469

470 There is little evidence that sustained extensive delivery of ice sheet-derived material to the outer
471 WGS occurred after 7.5 cal. kyrs BP (Jennings et al., 2014). This, as well as the HTM trend of
472 decreasing extent of the GIS toward a 5-3 cal. kyrs BP minimum (Young and Briner, 2015; Briner
473 et al., 2016), suggests that most lithic material delivered from marine terminating glaciers during
474 this time period was trapped in the inner part of the WGS. Various Holocene reconstructions show
475 that this GIS expression of the HTM originated as a response to major changes in climate and
476 ocean conditions ca. 7500 years ago, those conditions persisting for several thousand years before
477 Neoglacial cooling. Sedimentological and micropaleontological proxy archives from the shelf and
478 slope off Disko Bay record a combined strengthening and warming of the WGC from ca. 7.5 to 4
479 cal. kyrs BP (Perner et al., 2013; Jennings et al., 2014; and Fig. 7). This strengthened WGC was
480 accompanied by reduced sea ice cover (Ouellet-Bernier et al., 2014; and Fig. 7) as a result of both
481 ocean warming and reduced input of melt water following the early Holocene period of major
482 melting and retreat of the GIS. A synthesis of pollen-inferred summer atmospheric temperature
483 reconstructions clearly highlights this interval as the warmest over the last 10 000 years in coastal
484 settings of North and West Greenland, with positive temperature anomalies relative to the long
485 term average ranging from 1 to 2 °C (Gajewski et al., 2015; and Fig. 7).

486 We consider that our elemental HTM record of high relative contributions of Upernavik Isstrom-,
487 Tertiary basalts-, and Rink Isbrae-derived material to core 204 CQ might, at least partly, explain
488 the observed higher sedimentation rates recorded at the core location during this time period (Fig.

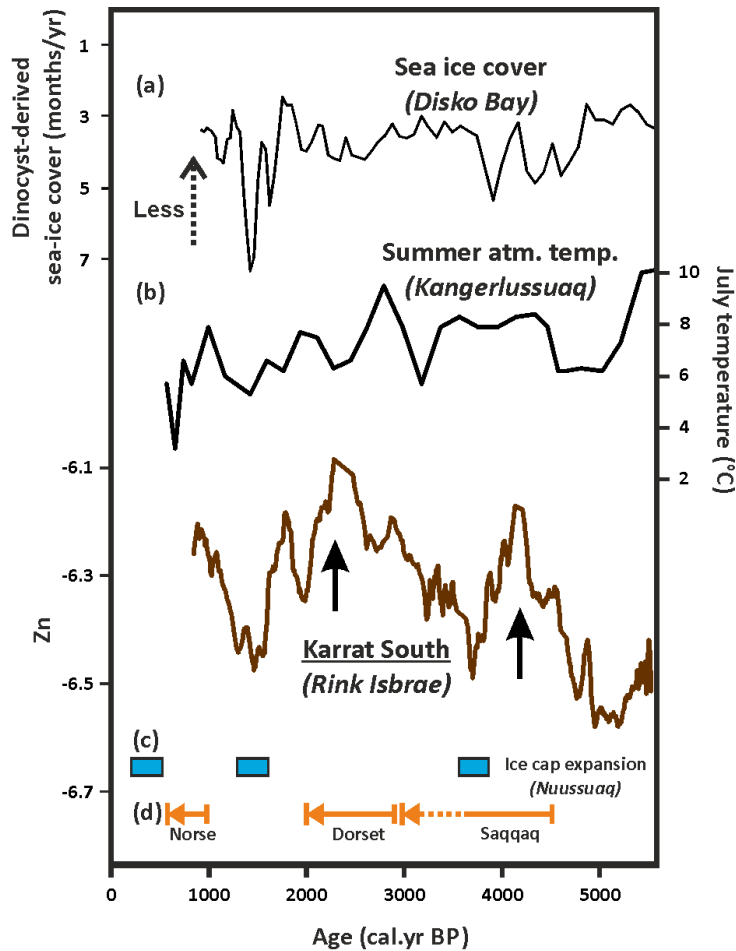
489 3). Such high sedimentation rates were promoted by the combination of (1) an efficient WGC
490 transport of southern source material to the core location, and (2) a sustained delivery of lithic
491 material from the narrow, deeply-incised Upernavik Isstrom and Rink Isbrae whose marine termini
492 interacted with warm Atlantic Water carried by the WGC. Increased winter precipitation during
493 the HTM in western Greenland as documented by Thomas et al. (2016), might have offset the
494 retreat of these glaciers, preventing them to become land-based despite high glacial velocities and
495 calving rates (Levy et al., 2018).

496 The high resolution XRF records in core 204 CQ shown here are characterized by a pervasive
497 ~500 year periodicity in peaks and troughs throughout the HTM, suggesting that either or both the
498 delivery of lithic material to the WGS, and the WGC strength, were subjected to high amplitude
499 changes. To our knowledge, no other climatic or oceanic proxy records in the studied area illustrate
500 such an HTM variability. Some of our highest and lowest elemental values ca. 6 cal. kyrs BP are
501 synchronous with a terrestrial and oceanic event recognized in a sediment core of Disko Bay as
502 the most extensive meltwater pulse of the last 8000 years in this region (Moros et al., 2016). This
503 event is near synchronous with the establishment of the modern-like circulation pattern of the
504 WGC in Disko Bay induced by the opening of Vaigat Strait (see Fig. 1 for location; Perner et al.,
505 2013). This opening resulted in the delivery of basaltic material from Disko Island and the
506 Nuussuaq Peninsula to the outer shelf northwest of Disko Bay where it became available to
507 northward transport *via* the main branch of the WGC. We believe that the recorded peak relative
508 contribution of Rink-Isbrae and Upernavik Isstrom lithic material in the sediment of core 204 CQ
509 (Fig. 7) relates to high melt rates of marine terminating glaciers in western Greenland as initially
510 described by Moros et al. (2016) at ca. 6 cal. kyrs BP in Disko Bay. We also interpret the later
511 peak in the delivery of Fe-rich sediment to core 204 CQ at 5.8 cal. kyrs BP (Fig. 7) as reflecting

512 the opening of the Vaigat Strait and the subsequent northward transport of this excess amount of
513 basaltic material from outer Disko Bay to the Upernavik Trough.

514 5.3 Neoglacial record of Rink Isbrae-derived lithic sedimentation in Upernavik Trough

515 The transition from the HTM to the Neoglacial period in western Greenland is widely documented
516 as a major shift in oceanic circulation and climate dated ca. 5 cal. kyrs BP, which triggered glacier
517 advances over a wide sector of the western GIS, following minimum ice extent (Larsen et al.,
518 2017). Reconstructions of atmospheric temperatures from coastal lakes in northwestern and
519 western Greenland point to a rapid decrease in July temperatures of up to 2°C over ca. 100 years
520 (Fig. 7 and 8; Gajewski et al., 2015). Following an abrupt negative shift around 5 cal. kyrs BP,
521 winter precipitation thereafter briefly returned to HTM values before progressively decreasing to
522 an overall Holocene low at 2 cal. kyrs BP (Thomas et al., 2016). Oceanic circulation during this
523 cold and arid Neoglacial period over western Greenland was characterized by reduced WGC
524 strength (Perner et al., 2013) compared to the HTM situation. However, relatively high -but
525 fluctuating- contributions of warm Atlantic water influenced both bottom and surface waters until
526 a maximum cooling during the Little Ice Age (Moros et al., 2006 and 2016).



527

528 **Figure 8:** Post 5.5 cal. kyrs BP changes in relative contribution of Karrat South (Rink Isbrae)-derived material to core
 529 204 CQ compared with (a) dinocyst-inferred sea ice cover in Disko Bay, core 343300 (Ouellet-Bernier et al., 2014),
 530 (b) pollen-derived summer (July) atmospheric temperatures from Lake 3, Kangerlussuaq sector of western Greenland,
 531 150 km south of Disko Bay (Gajewski et al., 2015), (c) the main phases of ice sheet expansion in the Nuussuaq
 532 peninsula, southern Ummannaq region (see Fig. 1 for locations), from radiocarbon dating of in-situ moss
 533 (Schweinsberg et al., 2017). The vertical plain black arrows refer to remarkable events discussed in the text.
 534

535 Our elemental records of lithic sedimentation at core 204 CQ are indicative of a reduced
 536 contribution of material derived from the proximal northern Melville Bay ice sheet and Upernavik
 537 Isstrom (Fig. 6 and 7) to Upernavik Trough after 5.5 cal. kyrs BP. We interpret this pattern as a
 538 rapid response of this northern sector of the western GIS to the inception of Neoglacial cooling in
 539 the form of reduced flow rates and possibly stillstand or readvance of the ice margin. This change
 540 in glacier dynamics affected both deeply incised fjord areas such as Upernavik Isstrom, and wide
 541 marine glacier termini distributed along Melville Bay. A reduced Neoglacial strength of the WGC

542 as shown by Perner et al. (2012) from Disko Bay proxy records and by our record of basalt-related
543 Fe concentrations in Upernavik Trough (Fig. 7c), likely associated to a progressive southward shift
544 in sea ice cover along western Greenland, were additional factors presumably promoting the lower
545 input of lithic material from proximal, northern tidewater glaciers. Although most model
546 reconstructions and observations agree on a general GIS readvance throughout the Neoglacial from
547 ca. 4 cal. kyrs BP under declining northern hemisphere summer insolation (Lecavalier et al., 2014),
548 our elemental record related to Rink Isbrae-derived material (Fig. 8) suggests that this glacier was
549 an effective sediment supplier to the WGS and core 204 CQ over the last 5000 years, with relative
550 contributions often higher than those recorded during the HTM. Part of this pattern, especially the
551 long term highs in relative concentrations of Rink Isbrae-derived sediments, is obviously induced
552 by the synchronous long term lows in concentrations of material delivered by Melville Bay glaciers
553 and Upernavik Isstrom. However, a reduced WGC strength during the Neoglacial period (Fig. 7,
554 and Perner et al., 2012) suggests that sediment supply by Rink Isbrae to the WGS was particularly
555 enhanced during the Late Holocene despite generally unfavorable climate and ocean conditions
556 over western Greenland. Part of this paradox might lay in the peculiar geomorphology of the Rink
557 Isbrae fjord: according to Chauché et al. (2014), the deep fjord basin hosting the glacier implies
558 that a large proportion of its submerged front is exposed to warm Atlantic waters, resulting in
559 homogeneous, widespread calving and submarine melting across the entire front of this glacier.
560 The sedimentation of Rink-Isbrae material to core 204 CQ (Fig. 8) strongly oscillates at a
561 millennial pace, suggesting that changes in climatic and/or oceanic conditions influenced
562 fluctuations in glacier mass balance. Major events of snowline depression and glacier advance in
563 the Nuussuaq Peninsula, southern Uummannaq Bay, and in southwest Greenland ca. 3.7 cal. kyrs
564 BP and 1.5 cal. kyrs BP have been inferred by Schweinsberg et al. (2017, 2018) from ^{14}C dating

565 of recently ice-entombed moss and the analysis of pro-glacial lake sediment. Interestingly, these
566 two events correspond to periods of reduced delivery of Rink Isbrae material to core 204 CQ (Fig.
567 8). Accompanying proxy records of sea ice cover in Disko Bay (Ouellet-Berniet et al., 2014), of
568 summer atmospheric temperatures in the Kangerlussuaq region (Gajewski et al., 2015), suggest
569 that these glacier advances were broadly linked to colder oceanic and atmospheric conditions (Fig.
570 8). Our XRF-derived high resolution record of Rink-Isbrae dynamics therefore holds a less local
571 significance than initially expected, and might well illustrate the evolution of the climate of
572 western Greenland during the Neoglacial.

573

574 **6 Conclusions**

575 The high resolution geochemical (elemental) proxy records presented in this study reveal major
576 changes in the provenance of lithogenic material in the Upernavik Trough, northern sector of the
577 WGS, over the last 9100 years. Our records reflect the distinct dynamics of the main proximal and
578 distal (southern) marine terminating glaciers of Western Greenland as well as changes in the
579 efficiency of sediment transport and redistribution by the WGC.

580 Contributions from the proximal Melville Bay glaciers were dominant during the early part of the
581 record up to ca 7.5 cal. kyrs BP. This strong influence of local material was the result of the rapid
582 retreat of a vast stretch of the NW GIS during the most dramatic thinning it experienced over the
583 course of the last 9000 years. Limited Early Holocene contributions from southern source areas
584 (basaltic formations, Upernavik Isstrom and Rink Isbrae) are explained by a combination of low
585 WGC strength and the buttressing effect of high sea-ice concentrations on calving glaciers.

586 Atmospheric warming, accelerated melting of marine terminating glaciers under strengthened
587 WGC, and reduced sea-ice concentrations from 7.5 cal. kyrs BP onwards triggered the increasing

588 contributions of distal southern sources to the lithic sedimentation over Upernavik Trough. These
589 contributions, which culminated at ca. 6 cal. kyrs BP, are indicative of sustained high velocities
590 and calving rates of Upernavik Isstrom and Rink Isbrae, under the influence of high winter
591 precipitation over the western GIS during the HTM.

592 The Neoglacial shift in atmospheric and oceanic circulation ca. 5 cal. kyrs BP led to a general
593 reduction in the delivery of lithic material from outlet glaciers of the western GIS to the WGS. The
594 peculiar geomorphology of the (deep) fjord hosting Rink Isbrae, combined with the (great) depth
595 of the cross-shelf Uummannaq Trough likely explain the sensitivity of Rink Isbrae to submarine
596 melting and hence the recorded high sediment supply by this glacier despite lower WGC strength.
597 Millennial-scale oscillations in Rink Isbrae-derived sedimentation at the studied core location are
598 indicative of fluctuations in the mass balance of this glacier which occurred in phase with major
599 glacier advances reported elsewhere in West and Southwest Greenland throughout the Neoglacial
600 period.

601 The present study offers a high-resolution framework of the western GIS dynamics and their link
602 with major changes in regional climatic and oceanic circulation throughout the last 9100 years.
603 This reconstruction is likely to provide a practical basis for future investigations testing the impact
604 of summer Greenland blocking events and North-Atlantic sea-surface temperature changes upon
605 the Holocene variability of western GIS melt (Graeter et al., 2018) as well as the wider ocean
606 dynamics linkages between the WGC, the North Atlantic Current and the strength of the Sub-Polar
607 Gyre (Goslin et al., 2018).

608

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619

620 **References**

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805 Appendix for

806 **A high-resolution elemental record of post-glacial lithic sedimentation in Upernavik Trough,**
807 **western Greenland: history of ice-sheet dynamics and ocean circulation changes over the last 9 100**
808 **years**

809

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817

818 **Contents of this file**

819

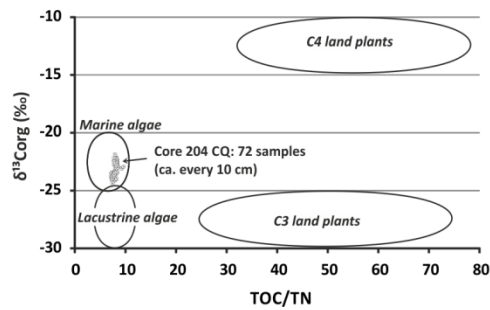
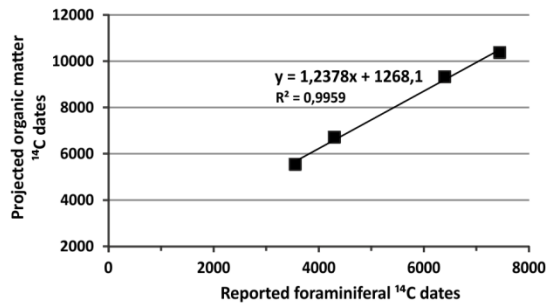
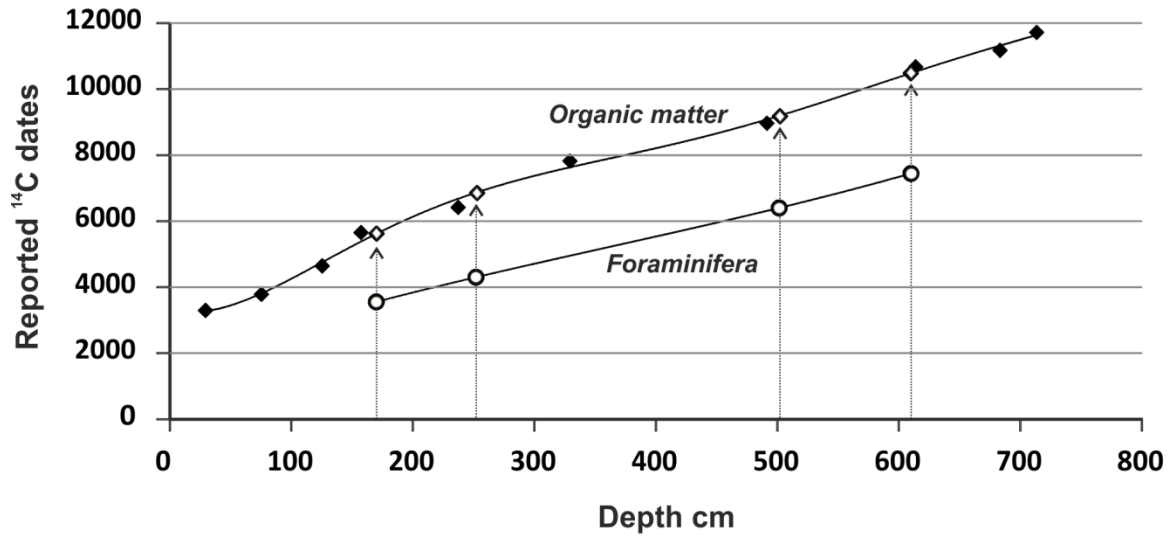
820 Figures S1, Table S1

821

822 **Introduction**

823 The supplementary figure (Fig. S1) provides additional constraints to the construction of the age-depth
824 model of core 204 CQ.

825 The supplementary table (Tab. S1) provides results of the Linear Discriminant Analysis (LDA) applied on
826 ranges of element and oxide concentrations within each of the main geological provinces of western
827 Greenland from 75°N to 68°N according to the geochemical database compiled by Steenfelt (2001).
828 These results are plotted within the main text as Fig. 2.



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Figure S1. Top: Reported (uncorrected, uncalibrated) ¹⁴C dates obtained on foraminiferal (empty circles) and organic matter (full diamonds) samples. Projected organic matter ¹⁴C dates (empty diamonds) at the core depth of foraminiferal ¹⁴C dates according to their intercept with a 4th order polynomial fit of the whole set of ¹⁴C dates measured on organic matter. Bottom left: plot of projected organic matter ¹⁴C dates vs. foraminiferal ¹⁴C dates and linear equation [1] used to correct for ageing by reworked "old" carbon all reported ¹⁴C dates measured on organic matter. Bottom right: elemental and isotopic identifiers of source organic matter (after Meyers, 1994) and plot of C/N ratios and organic $\delta^{13}C$ -values measured in core 204 CQ.

Linear discriminant analyses (LDAs)

Oxides (%)

Elements (ppm)

<u>Axis</u>	<u>Eigenvalues</u>	<u>Percent</u>	<u>Axis</u>	<u>Eigenvalues</u>	<u>Percent</u>
1	164.55	98.04	1	11.14	62.09
2	2.59	1.54	2	5.37	29.94
<u>Loadings</u>	<u>Axis 1</u>	<u>Axis 2</u>	<u>Loadings</u>	<u>Axis 1</u>	<u>Axis 2</u>
Al₂O₃	0.29	-0.53	Cr	-62.20	-192.52
TiO₂	-0.10	0.19	Ni	-32.22	-72.60
Fe₂O₃	-0.38	0.78	Rb	17.27	10.00
K₂O	0.11	0.34	Zn	12.50	-47.08
			Zr	67.22	190.07
<u>Scores (range)</u>	<u>Axis 1</u>	<u>Axis 2</u>	<u>Scores (range)</u>	<u>Axis 1</u>	<u>Axis 2</u>
Karrat North	7.14 to 7.06	0.15 to -0.77	Karrat North	2.54 to 3.31	-0.35 to -0.63
Proven Granite	6,09 to 6.75 -17.55 to -	0,93 to 2,92	Proven Granite	1.66 to 0.09	1.38 to 3.66
Tertiary basalts	17.39	0.75 to -0.28	Tertiary basalts	-3.43 to -4.62	-0.58 to -0.82
Karrat South	1.38 to -1.04	-1.02 to 0.51	Karrat South	1.00 to 1.32	-1.63 to -2.98
Archean gneiss	2.82 to 4.72	-2.26 to -0.93	Archean gneiss	-2.11 to 0.21	0.13 to 1.82

840

841 **Table S1.** Results of the Linear Discriminant Analyses (LDAs) applied on ranges of element and oxide
 842 concentrations within each of the main geological provinces of western Greenland from 75°N to 68°N
 843 according to the geochemical database compiled by Steenfelt (2001). These results are plotted within
 844 the main text as Fig. 2.
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