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Pearce, Danni M, Lea, James M, Mair, Douglas WF, Rea, Brice R, Schofield, J Edward, Kamenos, Nicholas A, Schoenrock, Kathryn M, Stachnik, Lukasz, Lewis, Bonnie, Barr, Iestyn ORCID logo ORCID: <https://orcid.org/0000-0002-9066-8738> and Mottram, Ruth (2022) Greenland tidewater glacier advanced rapidly during era of Norse settlement. *Geology*, 50 (6). pp. 704-709. ISSN 0091-7613

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**Downloaded from:** <https://e-space.mmu.ac.uk/629535/>

**Version:** Accepted Version

**Publisher:** Geological Society of America

**DOI:** <https://doi.org/10.1130/g49644.1>

Please cite the published version

<https://e-space.mmu.ac.uk>

1 Greenland tidewater glacier advanced rapidly during era of  
2 Norse Settlement

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18  
19 **ABSTRACT**

20 Our ability to improve prognostic modelling of the Greenland Ice Sheet relies on understanding  
21 the long-term relationships between climate and mass flux (via iceberg calving) from marine-  
22 terminating tidewater glaciers (TWGs). Observations of recent TWG behavior are widely  
23 available but long-term records of TWG advance are currently lacking. Here we present glacial

24 geomorphological, sedimentological, archeological and modelling data to reconstruct the ~20 km  
25 advance of Kangiata Nunaata Sermia during the first half of the last millennium. The data shows  
26 that KNS advanced ~15 km during the 12<sup>th</sup> and 13<sup>th</sup> centuries CE at a rate of ~115 m a<sup>-1</sup>,  
27 contemporaneous with regional climate cooling towards the Little Ice Age and comparable to  
28 rates of TWG retreat witnessed over the last c. 200 years. Presence of Norse farmsteads,  
29 proximal to KNS, demonstrate a resilience to climate change, manifest as a rapidly advancing  
30 TWG in a cooling climate. The results place limits on the magnitude of ice margin advance and  
31 demonstrates TWG sensitivity to climate cooling, as well as warming. These data combined with  
32 our grounding line stability analysis provides a long-term record that validates approaches to  
33 numerical modeling aiming to link calving to climate.

34

## 35 **INTRODUCTION**

36 Reconstructions of Greenlandic TWGs prior to the observation record are limited in  
37 number and overwhelmingly dominated by retreat behavior (e.g., Kjeldsen et al., 2015). Such  
38 reconstructions are crucial because ice sheet models require validating over longer timescales  
39 than the observational record and should ideally include episodes of both ice margin advance and  
40 retreat. This would improve confidence in long-term model validation of ice sheet behavior and  
41 subsequent projections in sea level change (Pörtner et al., 2019; Vieli and Nick, 2011; Straneo  
42 and Heimbach, 2013; Fahrner et al., 2021).

43 Kangiata Nunaata Sermia (KNS) is the largest outlet TWG south of Jakobshavn Isbræ on  
44 Greenland's west coast. It currently has one of the best constrained records of Holocene ice  
45 margin change in Greenland spanning the retreat from its Little Ice Age maximum (LIA); 1761  
46 CE) to present (Lea et al., 2014a;b; Pearce et al., 2018; Young et al., 2021). Evidence of glacial

47 advances are typically not preserved due to sediment reworking, leaving our understanding of  
48 TWG dynamics in Greenland and elsewhere largely unconstrained (Kjeldsen et al., 2015; Larsen  
49 et al, 2015). We reconstruct the advance of KNS over the last millennium using a multi-proxy  
50 approach supported by novel grounding line stability analysis (Fig.1). The geographic and  
51 temporal focus of our study also permits the new opportunity to consider the resilience of Norse  
52 farmers in the North Western Settlement.

53

## 54 **METHODS**

55 To constrain the pre-LIA maximum advance geometry of KNS, we obtained samples for  
56 radiocarbon ( $^{14}\text{C}$ ) dating from sedimentary sequences in Austmannadalen and Qamanaarsuup  
57 Sermia valleys adjacent to Kangersuneq fjord (Figs.2; 3 and Supp. Methods). To explore the  
58 timing of Norse occupation close to the ice margin, we sampled and dated plant macrofossils  
59 (charcoal and seeds) extracted from an anthrosol adjacent to ruin group V15 at Umiivik, a farm  
60 located beyond, but proximal to, the LIA maximum. Fieldwork was undertaken in  
61 Austmannadalen, Qamanaarsuup Sermia and Umiivik in August and September 2015 and August  
62 2016. Processing of material for AMS  $^{14}\text{C}$  dating was undertaken at the University of Aberdeen  
63 and dating was performed at the  $^{14}\text{CHRONO}$  Centre, Queens University Belfast, and at the Beta  
64 Analytic Radiocarbon Dating Laboratory in Florida. To evaluate the relative stability of KNS  
65 along Kangersuneq, we apply in a novel manner, a well-established equation for determining  
66 whether a grounding line occupies a steady state (Schoof, 2007). Explanation of the  
67 geomorphological and archaeological context of all sites is presented within each of the sections  
68 that follow. For full details see Supp. Methods.

69

70 **PRE-LITTLE ICE AGE MAXIMUM GLACIER GEOMETRIES**

71 Geomorphological mapping demonstrates that KNS retreated by ~23 km from its LIA  
72 maximum, to its present (2021) position, with its lateral margins mostly confined by steep fjord  
73 topography along Kangersuneq (Pearce et al., 2018; Fig.1). Evidence for pre-LIA maximum  
74 glacier geometries at KNS are preserved within three adjoining valleys that have not been  
75 glaciated during the last millennium allowing us to identify locations to reconstruct the advance  
76 of KNS (Pearce et al., 2018).

77 One location is the ice dammed lake Isvand which formed as KNS retreated from its LIA  
78 maximum configuration (Fig.1). As KNS continued to thin and retreat into the 21st century the  
79 meltwater drainage direction switched in 2004 from Isvand discharging via Austmannadalen  
80 (predominantly to the west) to draining subglacially into Kangersuneq (northwest). The river in  
81 Austmannadalen is no longer fed by glacier meltwater, leaving an abandoned river channel fed  
82 only by a network of small streams which diminish the capacity to move sediment (Weidick and  
83 Citterio, 2011) (Fig.1; Fig. SM1). Where the margin of the KNS glacier was at or inland of its  
84 2004 location during the Holocene (Fig.1), as it advanced it would have dammed Isvand and led  
85 to the initiation of glacial meltwater discharge and associated sedimentation through  
86 Austmannadalen.

87 In Austmannadalen, we identified well-preserved overbank deposits of silt and fine sand  
88 overlying an organic horizon (Fig. 2, Supplemental Methods, and SMI). The upper surface of  
89 this organic horizon yielded a AMS  $^{14}\text{C}$  age of  $972\pm 43$  years BP (UBA-31338; cal. 994-1165 CE  
90 [95.4%]; Fig. 3). This is consistent with changes in sedimentation observed elsewhere in  
91 Greenland used to reconstruct ice margin change prior to the LIA maximum (e.g., Briner et al.,  
92 2010). Our evidence provides an earliest date by which KNS advanced to a similar ice margin

93 and location to that of 2004 that resulted in damming of Isvand and initiation of meltwater  
94 discharge into Austmannadalen River.

95 As KNS advanced toward its LIA maximum position, it dammed the forefield of the  
96 Qamanaarsuup Sermia glacier on its northeastern margin, leading to the formation of an  
97 extensive ice-dammed lake where glaciolacustrine sediments accumulated (Fig.1). Following the  
98 drainage of this lake (1808–1856 CE) (Lea et al., 2014a) subsequent gullyng of these sediments  
99 revealed a buried organic horizon interpreted to be the land surface prior to lake damming (see  
100 Figs.2C-E and Supp. Methods). AMS  $^{14}\text{C}$  dating of a pristine terrestrial macrofossil (*bark*  
101 indeterminate sp.) – amongst the most reliable materials available for radiocarbon dating in this  
102 environment (cf. Edwards et al. 2008) from the top of this organic horizon, returned an age of  
103  $800\pm 29$  years BP (UBA-31339; cal. 1181-1278 CE [95.4%]; Fig. 2-3). This provides  
104 chronological control for the damming of Qamanaarsuup Sermia ice-dammed lake by KNS,  
105 which was last directly observed as holding standing water in 1808 (Lea et al., 2014a; Giesecke,  
106 1910) (Fig.1).

## 107 **GLACIER ADVANCE DURING REGIONAL COOLING**

108 The geometries and chronologies of KNS reconstructed from Austmannadalen and  
109 Qamanaarsuup Sermia demonstrate that it advanced by at least 15 km in the early part of the last  
110 millennium at a median rate of  $\sim 115 \text{ m a}^{-1}$  (Figs. 1, 4 and Fig. SM3), before reaching the LIA  
111 maximum configuration in 1761 CE with a total advance of  $\sim 20$  km (Lea et al., 2014a;b). These  
112 reconstructed advance rates are comparable to recent rates of TWG retreat observed across  
113 Greenland (e.g., Fahrner et al., 2021).

114 The period of advance coincides with a reduction in reconstructed summer air  
115 temperatures during the 12th century in west Greenland (Von Gunten et al., 2012; Lasher and

116 Yaxford, 2019), which is superimposed on a longer-term regional cooling indicated by a decline  
117 in summer  $\delta^{18}\text{O}$  from the DYE3 ice core (Vinther et al, 2010; Fig.4). It also coincides with a  
118 known period of land-terminating glacier expansion in Greenland (Jomelli et al., 2016) and  
119 Baffin Island in the Canadian Arctic (Young et al., 2015).

120

## 121 **GLACIER STABILITY**

122 The sequence of continuous glaciolacustrine deposition in Qamanaarsuup Sermia (Fig.3)  
123 indicates that the ice-dammed lake existed for over 500 years from initial damming (1186-1275  
124 CE) to when it drained after 1808. This constrains the margin of KNS between its LIA maximum  
125 and 1808 positions during this time (Fig.4A), indicating that the glacier terminus was relatively  
126 stable at this extended position despite periods of warming and cooling (Figs.4B, 4C). To  
127 evaluate this assertion, and identify other regions of relative margin stability, we implemented a  
128 novel, computationally light application of the grounding line boundary layer theory (Schoof,  
129 2007) (See Supp. Methods). Our approach evaluates the potential for a steady state grounding  
130 line being achieved along the fjord; primarily driven by a range of potential ice fluxes provided  
131 by balance fluxes derived from modern modelled surface mass balance of the KNS catchment,  
132 when the glacier margin is known to have been stable (1980-1995; Lea et al., 2014b; Mottram et  
133 al., 2017). Results show a clear match between predicted steady state grounding line positions  
134 and observed locations where the calving margin was known to be stable during retreat from the  
135 LIA maximum, (~1761), providing confidence in our approach (Fig.1).

136 Both the position at which KNS begins to dam Qamanaarsuup Sermia, and the position of  
137 its LIA maximum, are notable in that they coincide with potential steady state glacier margin  
138 locations identified by our analysis (Fig.1). These results imply that when the margin of KNS

139 was located within this area, between 1230±45 and 1808–1856, the glacier would be capable of  
140 maintaining a steady state grounding line even if ice fluxes were lower than contemporary  
141 values. This helps to explain how KNS maintained an extended configuration that kept  
142 Qamanaarsuup Sermia lake dammed, despite multiple warming and cooling episodes which  
143 occurred between the 13<sup>th</sup> and 19<sup>th</sup> centuries (Fig.4).

144

#### 145 **NORSE PRESENCE DURING RAPID GLACIER ADVANCE**

146 Our reconstruction indicates that prior to the LIA maximum, the terminus of KNS  
147 approached within 5 km of the Norse farmstead at Umiivik (V15) during the occupation of the  
148 Norse Western Settlement (~985-1400 CE; Figs. 1, 3 and Fig.SM4; Schofield et al., 2019). The  
149 farm ruins at Umiivik are currently extremely difficult to reach by boat due to dense  
150 concentrations of icebergs and mélangé in Kangersuneq. Given its location on the eastern margin  
151 of the fjord, surrounded by steep and mountainous terrain, the site is also impractical to access  
152 over land. If similar conditions prevailed during the 11<sup>th</sup>–14<sup>th</sup> centuries, navigation in the fjord,  
153 using even the smaller conventional boats known to have been used by the Norse would have  
154 been extremely challenging, if not impossible (Crumlin-Pedersen, 2010). Radiocarbon dating of  
155 an anthrosol, adjacent to the ruins, returned age estimates within the conventionally accepted  
156 timing for Norse settlement across this region (Fig.3 and SM4). The occupation of the Norse  
157 farmstead at Umiivik was therefore coeval with the rapid advance of KNS and for at least part of  
158 the period where the glacier margin was proximal to it.

159 Since KNS began to retreat from the LIA maximum, between 1761–1808 CE, iceberg  
160 concentrations in Kangersuneq appear to have been similar to present (Lea et al., 2014a).

161 Evidence for this is provided by written accounts, maps and photographs from the 19<sup>th</sup> and 20<sup>th</sup>



162 centuries (Lea et al., 2014a; Giesecke, 1910; Roussell, 1941), as well as aerial photographs and  
163 satellite imagery from the 20<sup>th</sup> and 21<sup>st</sup> centuries (Lea et al., 2014b, Pearce et al., 2018). This  
164 leads us to agree with Roussell's (1941, p16) initial assessment upon visiting Umiivik in 1933  
165 that, *'it must be assumed the conditions [in the fjord] in the Middle Ages were different'*. This  
166 archaeological evidence implies lower calving fluxes during the Norse period than currently  
167 observed, consistent with glaciological behavior that is conducive to our reconstructed glacier  
168 advance.

169

## 170 **CONCLUSIONS**

171 Our reconstruction of the rapid advance of KNS during the early part of the last  
172 millennium demonstrates that regional atmospheric cooling can drive TWG advance at rates  
173 comparable to post-LIA and contemporary retreat observed in Greenland. The analysis of glacier  
174 margin stability provides the first real-world demonstration that the commonly applied ice sheet  
175 model grounding line parameterization can independently identify stable ice margin locations  
176 over multi-decadal to multi-centennial timescales (Fig.1). Lower calving fluxes and associated  
177 iceberg concentrations in the fjord during ice margin advance are inferred from the occupation of  
178 a Norse farmstead proximal to KNS, in an area that is currently very difficult to access by boat.  
179 Together, this supports the counter-intuitive notion that a cooling climate would have allowed  
180 the Norse easier access by boat to the inner fjord network of the Western Settlement, when  
181 viewed relative to the iceberg dominated conditions that exist following the LIA maximum. Our  
182 findings provide insight into the dynamic behavior of Greenlandic TWGs during both periods of  
183 advance and retreat, allowing those who aim to model their response to climate change to  
184 validate their results against a full range of forcing conditions. Confidence in prognostic

185 simulations of future changes in TWGs and their contributions to global sea level rise will be  
186 improved for models that are able to replicate both the advance and retreat phases of this  
187 reconstruction.

188

## 189 **ACKNOWLEDGMENTS**

190 Authors would like to thank the GINR for providing logistical support in Nuuk. Martin Blicher,  
191 Thomas Juul-Pedersen and Johanne Vad for their research and field assistance. We acknowledge  
192 the support of the National Museum of Greenland for permission to undertake excavations near  
193 to Norse ruin sites (Permit number 2015/03). Project funding was provided by the Leverhulme  
194 Trust Research Project Grant 2014-093 and JML was supported by funding from the Quaternary  
195 Research Association, British Society for Geomorphology, and a UKRI Future Leaders  
196 Fellowship (MR/S017232/1). DMP would like to dedicate this paper to her father Richard M.  
197 Pearce.

198

## 199 **FIGURE CAPTIONS**

200 **Figure 1.** Study area with location of sample sites,  $^{14}\text{C}$  dates and the results of the grounding line  
201 stability analysis. The dates from the buried land surfaces (black labels) show how these relate to  
202 the reconstructed locations of KNS (blue labels). Norse ruin group codes follow Bruun (1917).  
203 The reconstructed 992–1160 CE glacier configuration is assumed to be analogous to that of 2004  
204 when Isvand began to drain eastwards below KNS (Weidick and Citterio, 2011). Inset, shows the  
205 distribution of Western Settlement ruins in this area including farms, storehouses and shielings.  
206 Grounding line stability analysis shown for areas where BedMachine v3 bathymetry is available  
207 (grey contour lines) (Morlighem et al., 2017), with relatively less stable locations in blue and

208 more stable locations in red. Selected known ice fronts from last century are shown (white  
209 labels) (Lea et al., 2014b).

210

211 **Figure 2.** A) Soil pit stratigraphy for Austmannadalen (RIVA5).  $^{14}\text{C}$  dates are available from the  
212 organic units at location A5 with ages given in  $^{14}\text{C}$  yr BP with \*indicating fraction modern  
213 ( $\text{F}^{14}\text{C}$ ). The  $^{14}\text{C}$  dates for A5 were taken on the humic acid fraction of organic sediments. B)  
214 Photo shows sample retrieval from soil pit A5 using a monolith tin. C) Qamanaarsuup Sermia  
215 ice-dammed lake and stratigraphy related to lake impoundment and sedimentation in  
216 Qamanaarsuup Sermia following the early LIA advance of KNS. Stratigraphy where sample  
217 UBA-31339 was obtained, from the top contact of the peat and the overlying lacustrine unit.  
218 Only a partial stratigraphy is found at this site, for full description see SM2 D) Location map; E)  
219 Photograph of site UBA-31339.

220

221 **Figure 3.** A) OxCal multiplot comparing the probability distributions of calibrated  $^{14}\text{C}$  dates  
222 discussed within the text. Brackets indicate the confidence limits (95.4%) on the dates. The  
223 vertical dashed lines depict the conventionally acknowledged dates for the start of *landnám* and  
224 the end of occupation (abandonment of the farms likely maximum date for the abandonment of  
225 the Western Settlement. B) Table of  $^{14}\text{C}$  dates from the region around KNS (see Fig.1 for site  
226 locations).

227

228 **Figure 4.** KNS marginal location and climate proxy data for the last millennium. (A) Terminus  
229 advance and retreat showing key advance stages (blue dashed lines). Median advance scenario  
230 (black line, based upon model; see Fig. SM3) shown with 95.4% uncertainty (grey shading)

231 accounting for probability distribution of radiocarbon dates and variable fjord geometry. (B)  
232 Measured  $\delta^{18}\text{O}$  of chironomids from Scoop Lake (60.70° N 45.42° W; black dots; Lasher et al.,  
233 2019), three point moving average (orange line), and  $1\sigma$  moving average uncertainty (orange  
234 shaded area); (C) Alkenone air temperature reconstruction for Braya Sø, Greenland (von Gunten  
235 et al., 2012) (66.99°N 51.03°W), showing sample density (white dots), uncertainty (blue  
236 shading), and JJA mean Nuuk air temperature (Vinther et al., 2006) (red line) with 10-year mean  
237 (black line). (D) 30 year running mean of DYE3 ice core  $\delta^{18}\text{O}$  observations (Vinther et al., 2010)  
238 and standard deviation (red shading). Black dashed lines on panels B-D show the time period of  
239 reconstructed advance indicated on panel A.

240

## 241 REFERENCES CITED

- 242 1. Bassis, J.N., and Walker, C.C., 2012, Upper and lower limits on the stability of calving  
243 glaciers from the yield strength envelope of ice: Proc. Roy. Soc. A-Math. Phys., 468, 913–  
244 931, doi.org/10.1098/rspa.2011.0422.n,
- 245 2. Briner, J.P., Stewart, H.A.M., Young, N.E., Philipps, W., and Losee, S., 2010, Using  
246 proglacial-threshold lakes to constrain fluctuations of the Jakobshavn Isbræ ice margin,  
247 western Greenland, during the Holocene, 29, p. 3861-3874,  
248 [doi.org/10.1016/j.quascirev.2010.09.005](https://doi.org/10.1016/j.quascirev.2010.09.005)
- 249 3. Bruun, D., 1917, Oversigt over Nordboruiner i Godthaab- og Frederikshaab-Distrikter:  
250 Meddelelser om Grønland, 56(3), p. 55–147.
- 251 4. Crumlin-Pedersen, O., 2010, Archaeology and the sea in Scandinavia and Britain:  
252 Maritime Culture of the North Vol. 3. Viking Ship Museum, Roskilde, 184 p.
- 253 5. Edwards, K.J., Schofield, J.E., and Mauquoy, D., 2008, High resolution  
254 paleoenvironmental and chronological investigations of Norse landnám at Tasiusaq,

- 255 Eastern Settlement, Greenland: *Quaternary Research*, 69, p. 1-15,  
256 doi:10.1016/j.yqres.2007.10.010.
- 257 6. Fahrner, D., Lea, J.M., Brough, S., Mair, D.W.F, Abermann. J., 2021, Linear response of  
258 Greenland's tidewater terminus positions to climate: *Journal of Glaciology*, 67(262), p.  
259 193-203, doi:10.1017/jog.2021.13.
- 260 7. Giesecke, K.L., 1910, *Mineralogisches Reisejournal über Grönland 1806-13*.  
261 *Meddelelser om Grønland*, 35.
- 262 8. Jomelli, V., et al. 2016, Paradoxical cold conditions during the medieval climate anomaly  
263 in the Western Arctic: *Scientific Reports*, 6, 32984, doi.org/10.1038/srep32984.
- 264 9. Joughin, I., Smith, B.E., Howat, I.M., Scambos, T., and Moon, T., 2010, Greenland flow  
265 variability from ice-sheet-wide velocity mapping: *Journal of Glaciology*, 56(197), 415-  
266 430, doi:10.3189/002214310792447734
- 267 10. Katz, N.J., Katz, S.V., and Kipiani, M.G., 1965, *Atlas and keys of fruits and seeds*  
268 *occurring in the Quaternary deposits of the USSR*: Nauka, Moscow, 365pp.
- 269 11. Kjeldsen, K.K., et al. 2015, Spatial and temporal distribution of mass loss from the  
270 Greenland Ice Sheet since AD 1900: *Nature*, 528(7582), p. 396 – 400,  
271 doi.org/10.1038/nature16183.
- 272 12. Larsen, N.K., et al. 2015, The response of the southern Greenland ice sheet to the  
273 Holocene thermal maximum: *Geology*, 43(4), p. 291-294, doi.org/10.1130/G36476.1.
- 274 13. Lasher, G.E., and Axford, Y., 2019, Medieval warmth confirmed at the Norse Eastern  
275 Settlement in Greenland: *Geology*, 47(3), p. 267-270, doi.org/10.1130/G45833.1.
- 276 14. Lea, J.M., et al. 2014a, Terminus-driven retreat of a major southwest Greenland  
277 tidewater glacier during the early 19th century: insights from glacier reconstructions and

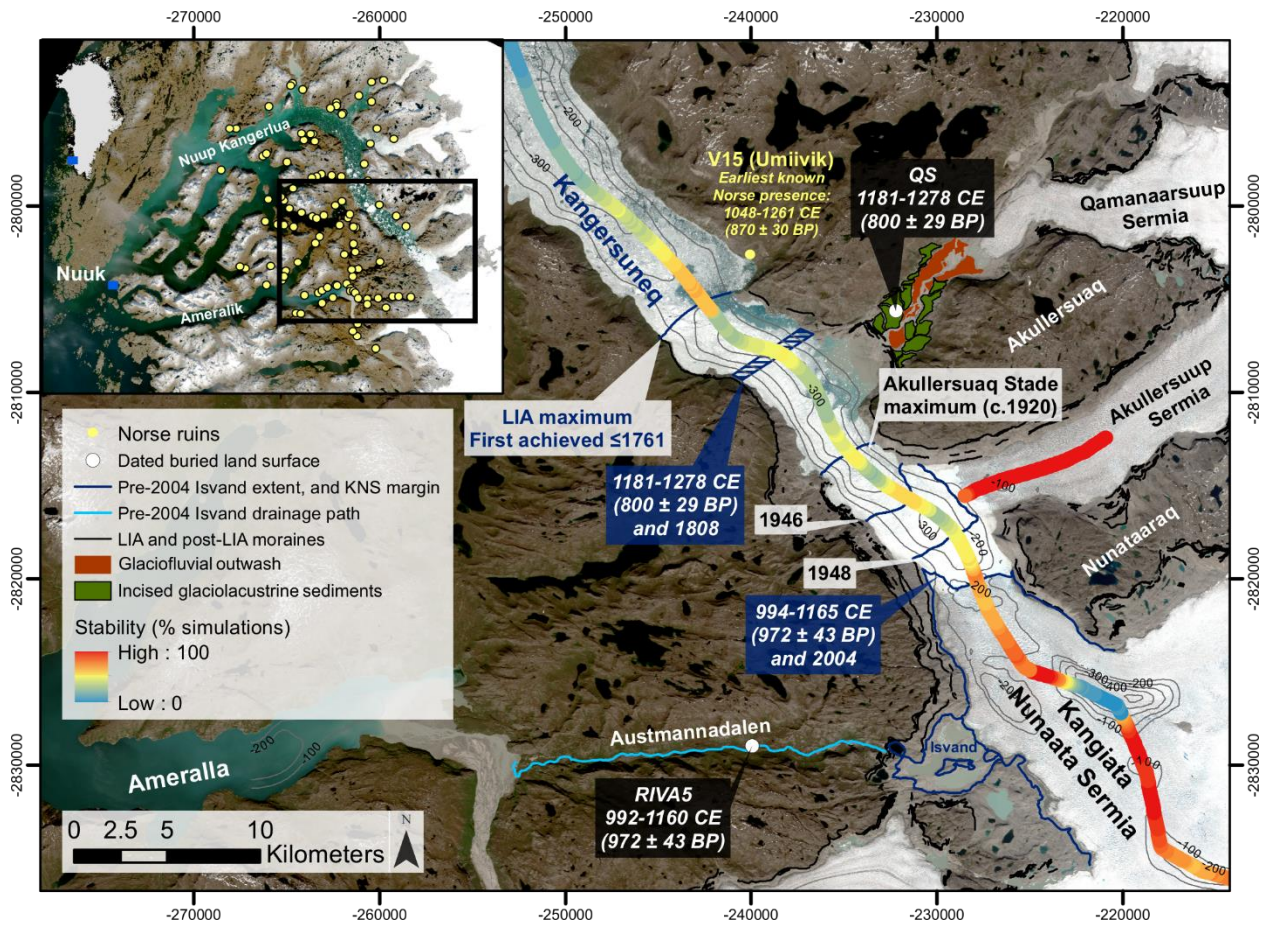
- 278 numerical modelling: *Journal of Glaciology*, 60, p. 333-344,  
279 doi:10.3189/2014JoG13J163.
- 280 15. Lea, J.M., et al. 2014b, Fluctuations of a Greenlandic tidewater glacier driven by changes  
281 in atmospheric forcing: observations and modelling of Kangiata Nunaata Sermia, 1859–  
282 present. *The Cryosphere*. 8(6), p. 2031-2045, doi.org/10.5194/tc-8-2031-2014.
- 283 16. Morlighem, M., et al. 2017, BedMachine v3: Complete bed topography and ocean  
284 bathymetry mapping of Greenland from multibeam echo sounding combined with mass  
285 conservation: *Geophysical Research Letters*, 44(21), p. 11051-11061,  
286 doi.org/10.1002/2017GL074954.
- 287 17. Mottram, R., Boberg, F., Langen, P.L., Yang, S., Rodehacke, C., Jens, C.H., and Madsen,  
288 M.S., 2017, Surface mass balance of the Greenland ice sheet in the regional climate  
289 model HIRHAM5: Present state and future prospects: *Low Temperature Science*, 75, p.  
290 105-115, 10.14943/lowtemsci.75.105.
- 291 18. Oxford Radiocarbon Accelerator Unit (ORAU) 2021, OxCal online v4.4.  
292 <https://c14.arch.ox.ac.uk>. Last accessed: 8 August 2021.
- 293 19. Pearce, D.M., Mair, D.W., Rea, B.R., Lea, J.M., Schofield, J.E., Kamenos, N., and  
294 Schoenrock, K., 2018, The glacial geomorphology of upper Godthåbsfjord (Nuup  
295 Kangerlua) in southwest Greenland: *Journal of Maps*, 14(2), p. 45-55,  
296 doi.org/10.1080/17445647.2017.1422447.
- 297 20. Pörtner, H.O., Roberts, D., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E.,  
298 Mintenbeck, K., Nicolai, M., Okem, A., and Petzold, J., 2019, IPCC Special Report on  
299 the Ocean and Cryosphere in a Changing Climate: IPCC Intergovernmental Panel on  
300 Climate Change: Geneva, Switzerland.

- 301 21. Reimer, P.J., Brown, T.A., and Reimer, R.W., 2004, Discussion: reporting and calibration  
302 of post-bomb <sup>14</sup>C data: *Radiocarbon*, 46(3), p. 1299-1304,  
303 doi:10.1017/S0033822200033154.
- 304 22. Reimer, P.J., et al., 2020, The IntCal20 Northern Hemisphere radiocarbon age calibration  
305 curve (0–55 cal kBP): *Radiocarbon*, 62(4), p.725-757, doi:10.1017/RDC.2020.41.
- 306 23. Roussell, A. 1941, Farms and churches in the mediaeval Norse settlements of Greenland.  
307 *Meddelelser om Gronland*, 89, 354
- 308 24. Schofield, J.E., Pearce, D.M., Mair, D.W.F., Rea, B.R., Lea, J.M., Kamenos, N.A.,  
309 Schoenrock, K.M, Barr, I.D., and Edwards, K.J., 2019, Pushing the limits: palynological  
310 investigations at the margin of the Greenland Ice Sheet in the Norse Western Settlement:  
311 *Environmental Archaeology*, doi.org/10.1080/14614103.2019.1677075
- 312 25. Schoof, C., 2007, Ice sheet grounding line dynamics: Steady states, stability, and  
313 hysteresis: *Journal of Geophysical Research: Earth Surface*, 112(F3),  
314 doi.org/10.1029/2006JF000664.
- 315 26. Straneo, F., and Heimbach, P., 2013, North Atlantic warming and the retreat of  
316 Greenland's outlet glaciers: *Nature*, 504, p. 36-43, doi.org/10.1038/nature12854.
- 317 27. Stuiver, M., and Reimer, P.J., 1993, Extended <sup>14</sup>C data base and revised Calib 3.0 <sup>14</sup>C  
318 age calibration program: *Radiocarbon*, 35(1), p. 215-230,  
319 doi:10.1017/S0033822200013904.
- 320 28. Vieli, A., and Nick, F.M., 2011, Understanding and modelling rapid dynamic changes of  
321 tidewater outlet glaciers: Issues and implications: *Surveys in Geophysics*, 32, p. 437-458,  
322 doi.org/10.1007/s10712-011-9132-4.
- 323 29. Vieli, A., Jania, J., and Kolondra, L., 2002, The retreat of a tidewater glacier:

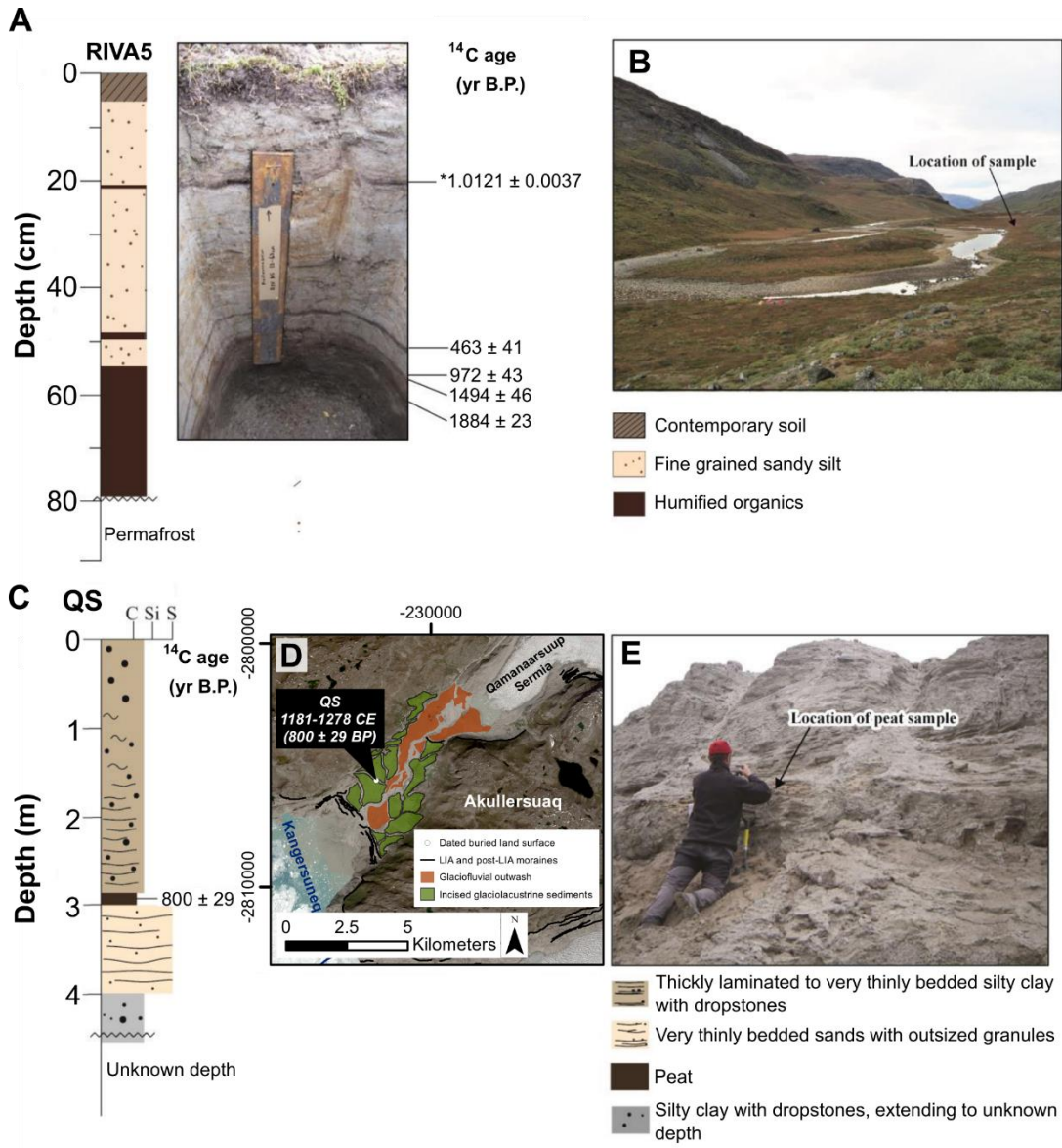
- 324 observations and model calculations on Hansbreen, Spitsbergen: *Journal of Glaciology*,  
325 48(163), 592-600, doi:10.3189/172756502781831089
- 326 30. Vinther, B.M., Andersen, K.K., Jones, P.D., Briffa, K.R., and Cappelen, J., 2006,  
327 Extending Greenland temperature records into the late eighteenth century: *Journal of*  
328 *Geophysical Research: Atmospheres*, 111(D11), doi.org/10.1029/2005JD006810.
- 329 31. Vinther, B.M., Jones, P.D., Briffa, K.R., Clausen, H.B., Andersen, K.K., Dahl-Jensen, D.,  
330 Johnsen, S.J., 2010, Climatic signals in multiple highly resolved stable isotope records  
331 from Greenland: *Quaternary Science Reviews*, 29(3-4), p. 522-538,  
332 doi.org/10.1016/j.quascirev.2009.11.002.
- 333 32. Von Gunten, L., D'andrea, W.J., Bradley, R.S., and Huang, Y., 2012, Proxy-to-proxy  
334 calibration: Increasing the temporal resolution of quantitative climate reconstructions:  
335 *Scientific Reports*, 2, 609, doi.org/10.1038/srep00609.
- 336 33. Weidick, A. and Citterio, M., 2011, The ice-dammed lake Isvand, West Greenland, has  
337 lost its water: *Journal of Glaciology*, 57(201), p. 186-188,  
338 doi:10.3189/002214311795306600.
- 339 34. Young, N.E., Lesnek, A.J., Cuzzone, J.K., Briner, J.P., Badgeley, J.A., Balter-Kennedy,  
340 A., Graham, B.L., Cluett, A., Lamp, J.L., Schwarz, R., Tuna, T., Bard, E., Caffee, M.W.,  
341 Zimmerman, S.R.H., and Schaefer, J.M., 2021, In situ cosmogenic  $^{10}\text{Be}$ - $^{14}\text{C}$ - $^{26}\text{Al}$   
342 measurements from recently deglaciated bedrock as a new tool to decipher changes in  
343 Greenland Ice Sheet size: *Climate of the Past*, 17, p. 419-450, doi.org/10.5194/cp-17-  
344 419-2021
- 345 35. Young, N.E., Schweinsberg, A.D., Briner, J.P., and Schaefer, J.M., 2015, Glacier maxima  
346 in Baffin Bay during the Medieval Warm Period coeval with Norse settlement: *Science*



351 Figure 1:



353 Figure 2:



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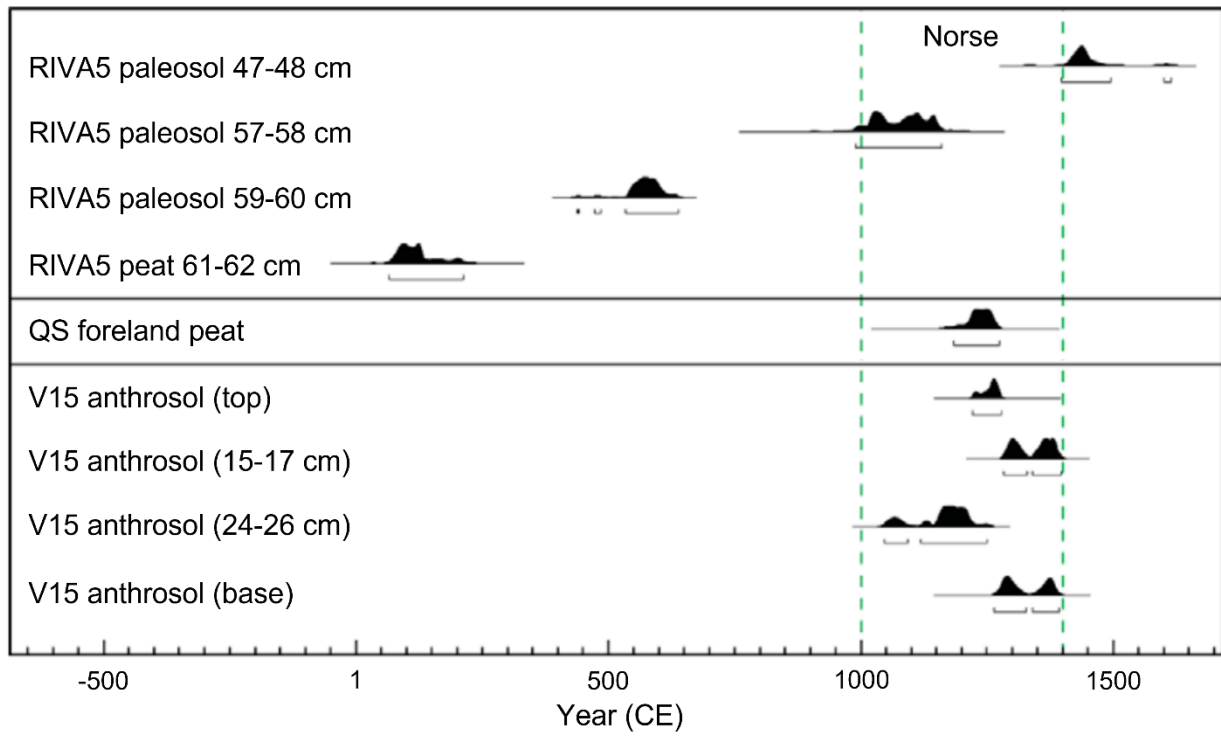
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362 Figure 3:



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365 Figure 4:

