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## Greenlandic debris in Iceland likely tied to Bond 1 ice-rafting in the Dark Ages

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### ABSTRACT

We report the discovery of exotic igneous, metamorphic, and sedimentary cobbles in raised beach deposits near Breiðavík, northern Iceland. These deposits consist of alternating cobble-, sand-, and silt-dominated facies. A nearby package of sands and silts, dated to the Late Antique Little Ice Age (LALIA; ca. 536–660 CE), provides age constraints for the raised terraces. While the upper terraces are composed exclusively of local basaltic material, the lowermost terraces (~2 m above high tide) contain a mix of basaltic and non-basaltic cobbles, including quartzofeldspathic gneiss, granitoid, rhyolite, sandstone, and serpentinite. U–Pb geochronology of zircon reveals dominant age modes of ca. 2800, 1150, 500, and 240 Ma with Lu–Hf isotopic compositions suggesting derivation from Greenland's North Atlantic Craton and Caledonian fold belt.

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23 The colder conditions of the LALIA, coupled with increased iceberg calving from the  
24 Greenland Ice Sheet, would have led to enhanced ice-rafted debris (IRD) transport to  
25 disparate areas south and east of Greenland. The East Greenland and East Iceland  
26 currents transported this IRD from Greenland, with deposition occurring along the  
27 Icelandic coast as the icebergs melted. This IRD was likely transported across the North  
28 Atlantic during Bond Event 1. This process, along with those during other transient  
29 cooling events, may explain the age discrepancies between local bedrock and detrital  
30 zircons in the Arctic.

## 31 INTRODUCTION

32 During the Last Glacial Maximum (LGM), ca. 26,000–19,000 years ago, ice sheets  
33 extended across much of the Northern Hemisphere, dramatically reshaping the  
34 landscape by locally carving bedrocks and depositing glacial regolith. These ice sheets  
35 were highly dynamic, advancing and retreating in response to climatic shifts, and  
36 transporting large volumes of glacial debris into the marine environment (Batchelor et  
37 al., 2019). Following the LGM, shorter-term climate oscillations, such as the Bond  
38 events, involved continued fluctuations in the Northern Hemisphere's climate over the  
39 past 11,500 years (Bond et al., 1993, 2001). These recurring cold phases, likely linked  
40 to changes in ocean circulation and solar activity, intensified glaciation and influenced  
41 ice-rafted debris (IRD) transport. For instance, Bond Event 1, which coincides with the  
42 Late Antique Little Ice Age (LALIA; 536–660 CE after Büntgen et al., 2016), saw a  
43 renewed expansion of the Greenland Ice Sheet (Büntgen et al., 2016; Kjær et al., 2022).  
44 These episodes of climate-driven glaciation and deglaciation highlight the persistent  
45 influence of millennial-scale climate shifts on glacial systems and their role in shaping

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46 the landscapes and sedimentary records of the North Atlantic region (Büntgen et al.,  
47 2016).

48 IRD refers to sedimentary material transported by icebergs or sea ice that is released  
49 into marine or coastal environments when the ice melts. IRD is a key proxy for  
50 understanding past glacial activity and ocean circulation, as its range of materials often  
51 reflects the diverse geology of source regions. Icebergs calved from glaciers can carry  
52 debris as varied as local sediments, large boulders, and exotic rock fragments sourced  
53 from the heart of continental interiors (Gilbert, 1990). As icebergs drift with ocean  
54 currents, they can transport these materials hundreds to thousands of kilometers before  
55 melting and depositing their debris load. IRD is commonly found in ocean sediments  
56 throughout the Northern Hemisphere, particularly in the North Atlantic region, where  
57 icebergs predominately originate from the Greenland Ice Sheet and other Arctic  
58 glaciers. Previous studies of IRD in North Atlantic drill cores have revealed a remarkable  
59 geological diversity (Eldrett et al., 2007; White et al., 2016; Darby et al., 2017), much of  
60 which is traceable to Greenland's geological provinces. These studies have shown how  
61 IRD provides snapshots of glacial dynamics, with debris originating from distinct  
62 geologic formations across Greenland and other northern landmasses, such as  
63 Svalbard and Scandinavia. Through compositional analyses of IRD, it is possible to  
64 pinpoint provenances and reconstruct past iceberg trajectories, ocean current patterns,  
65 and the timing of glacial advances and retreats (White et al., 2016).

66 What makes IRD particularly significant is its ability to transport exotic materials far from  
67 their points of origin, often to locations where the local bedrock contrasts starkly with the  
68 incoming debris (Heinrich, 1988). This process not only provides insights into glacial

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69 transport but also serves as a marker of long-distance oceanic sedimentation (Bailey et  
70 al., 2012). The presence of foreign geological material in ocean sediments often  
71 highlights the expansive reach of glacial systems and their interaction with ocean  
72 currents during glacial periods.

73 However, while the transport of IRD across ocean basins is well documented (Bailey et  
74 al., 2012; White et al., 2016), there is less understanding of its deposition on subaerial  
75 continental environments. This raises important questions about the processes involved  
76 when exotic material, particularly from Greenland, reaches landmasses such as  
77 Iceland—a region dominated by recent basaltic volcanism rather than ancient  
78 continental geology. Here, we present newly discovered non-basaltic material in  
79 northern Iceland in the Breiðavík region. Through zircon U–Pb geochronology and Lu–  
80 Hf isotopic analyses, we identify a range of igneous and metamorphic rock types with  
81 ages and isotopic compositions matching those of Greenlandic provinces. Fingerprinting  
82 of these exotic Greenland-derived clasts in Iceland provides insights into the nature of  
83 late Quaternary IRD at the boundary between the North Atlantic and Arctic oceans.

## 84 GEOLOGIC SETTING

85 Iceland, situated on the Mid-Atlantic Ridge with a supporting mantle plume, is a  
86 geologically young and dynamic island characterized by basaltic lava flows and minor  
87 evolved magmas, driven by seafloor spreading and mantle plume magmatism (Foulger  
88 et al., 2022). The Westfjords in northwest Iceland are among the island's oldest regions,  
89 primarily composed of 10–16 Ma basalt lavas, contrasting with the younger central  
90 volcanic areas. The region is highly eroded, with steep, fjord-lined coastlines that reflect  
91 glacial activity during the Pleistocene. The ice sheets that once covered the Westfjords

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92 during the LGM contributed to the formation of these deep fjords, as glaciers carved  
93 through the landscape, leaving behind distinctive U-shaped valleys. Despite its volcanic  
94 origins, the Westfjords are notable for their lack of recent volcanic activity compared to  
95 other parts of Iceland, contributing to a more stable, though heavily glaciated, geologic  
96 environment.

97 The Breiðavík region, located along the northern coastline of the Westfjords, features  
98 beach deposits consisting of alternating sand and silt, and cobble layers with two  
99 distinct terraces above the high-tide line (Fig. 1A). The higher terrace is primarily  
100 composed of local basaltic material, likely sourced from nearby volcanic flows. In  
101 contrast, the lowermost terraces, closer to present-day sea levels (Fig. 1B), contain a  
102 mix of basaltic and non-basaltic rocks, with the non-basaltic material being the focus of  
103 this study. This distinct stratigraphy suggests multiple phases of deposition, likely tied to  
104 glacial retreat and the influx of offshore sediments. The origin of these terraces has  
105 been linked to stages of deglaciation and subsequent isostatic uplift, and sands and silts  
106 at a similar level (that is, approximately 4 m above mean sea level) exposed to the  
107 southwest of the Breiðavík Bay were formed ca. 1,300–1,400 years BP (Brader et al.,  
108 2017). Corresponding to ca. 600–700 AD, these dates align with Bond Event 1 and the  
109 Late Antique Little Ice Age, which likely enhanced iceberg calving and IRD transport  
110 (Savkina et al., 2018). While not definitive, this date offers a valuable age constraint that  
111 aligns with geological observations of the raised beach context and the presence of  
112 extraneous, likely ice-transported material.

113 Across the Denmark Strait from Iceland is East Greenland (Fig. 2), whose geology is  
114 characterized by diverse lithologies spanning Mesoproterozoic orthogneiss to Paleogene

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115 flood basalts. East Greenland's geology is defined by four primary regions (from south  
116 to north): the Paleoproterozoic Ketilidian Mobile Belt (Vestergaard et al., 2024),  
117 orthogneisses of the Archean Block (Kolb et al., 2013), the Nagssugtoqidian Mobile Belt  
118 (Nutman et al., 2008), Paleogene mafic magmatism (Brooks, 2011), and the Paleozoic  
119 Caledonian Fold Belt (Rehnström, 2010). Except for the Caledonides, the geology in  
120 western Greenland broadly mirrors that of eastern Greenland (White et al., 2016).  
121 Modern iceberg sources include major calving regions such as Disko Bugt in western  
122 Greenland and the Scoresby Sound system in the east. These regions contribute  
123 substantially to the annual flux of icebergs into the North Atlantic (Rignot and  
124 Kanagaratnam, 2006). Icebergs transported by the East Greenland Current (EGC) carry  
125 IRD southward, while local sources dominate IRD deposition in marine-proximal  
126 environments (Andrews et al., 2014). This study focuses on reconstructing the  
127 provenance of IRD deposited on raised beaches near Breiðavík to discern the relative  
128 contributions of Greenlandic source terrains.

## 129 **SAMPLES AND METHODS**

130 Samples were collected from recent beach deposits near Breiðavík in northern Iceland.  
131 The deposits consist of alternating cobble- and sand-dominated facies, with an upper  
132 terrace comprised exclusively of basaltic material and a lower terrace containing a  
133 mixture of basaltic and non-basaltic cobbles. The lower terrace sits ~2 m below the  
134 isolation basin (~2 m a.s.l.) on the western side of the bay sampled by Brader et al.  
135 (2017) corresponding to the horizon dated at 1301–1407 BP. Among the cobble  
136 samples collected, those for which zircon separation was done include a sandstone,  
137 seven (meta)granitoids, and two felsic volcanics. The sandstone is medium-grained,

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138 well-sorted, and quartz-rich. The (meta)granitoids are medium- to coarse-grained and  
139 exhibit variable degrees of deformation and metamorphism. The felsic volcanics are  
140 gray and ochre, fine-grained volcanic rocks rich in silica, typically rhyolite or dacite in  
141 composition. Other collected samples include two mafic volcanics, two fine-grained  
142 siliciclastic rocks, four quartzite/quartz-rich cobbles, and one serpentinized peridotite.  
143 Standard zircon separation and U–Pb/trace element/Hf split stream by LA-ICPMS  
144 methods were used and are detailed in the Supplementary Materials.

## 145 ZIRCON U–Pb AND Hf ISOTOPE RESULTS

146 U–Pb ages from zircon grains from the Breiðavík beach clasts reveal multiple distinct  
147 age populations. Zircon ages from the clasts range from 2960 Ma and 0 Ma with major  
148 age frequency peaks at 2800 Ma, 1150 Ma, 500 Ma, 240 Ma, and 0 Ma and subordinate  
149 peaks at 1600 Ma, 1380 Ma, 720 Ma, and 370 Ma (Fig. 3). Hafnium isotopes of zircon  
150 show a broad range of  $\epsilon_{\text{Hf}}$  values (Fig. 3). The Archean ages have  $\epsilon_{\text{Hf}}$  that range from  
151 4 to -6 (-2 average),  $\epsilon_{\text{Hf}}$  of Proterozoic ages range from 6 to -8 (1.5 average), Cambrian  
152 to Devonian ages have  $\epsilon_{\text{Hf}}$  that range from 3 to -9 (-3 average), Carboniferous to  
153 Cretaceous ages have bimodal  $\epsilon_{\text{Hf}}$  with a more depleted population at 4 to 11 (8  
154 average) and an enriched population at -3 to 1 (-1 average), two Neogene grains have  
155 an average  $\epsilon_{\text{Hf}}$  of 12, and Quaternary ages have  $\epsilon_{\text{Hf}}$  of 1 to 5 (3 average).

## 156 DISCUSSION

### 157 Comparison with Greenlandic sources

158 The Breiðavík clasts' zircon age and  $\epsilon_{\text{Hf}}$  populations closely resemble those reported  
159 from known Greenlandic geological terrains, except for the post-Devonian population



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160 (Fig. 3). The Archean zircons correspond well with known ages and  $\epsilon\text{Hf}$  of the North  
161 Atlantic Craton (Johnston and Kylander-Clark, 2013; Nicoli et al., 2018), while the  
162 Proterozoic ages and  $\epsilon\text{Hf}$  can be linked to the Ketitlides and detritus linked to the  
163 Grenville Orogeny (Olierook et al., 2020). Cambrian–Devonian ages and  $\epsilon\text{Hf}$  are most  
164 closely similar to the Caledonides (Rehnström, 2010; Brueckner et al., 2016) though the  
165 most enriched  $\epsilon\text{Hf}$  values are not represented in the Breiðavík clasts. This raises the  
166 possibility of additional, more distant sources, such as Siberia or the Sverdrup basin,  
167 which host detrital zircon with similar age and Hf isotopic characteristics (Røhr et al.,  
168 2010). These regions, known for their late Paleozoic and Mesozoic magmatism,  
169 plausibly contributed material via trans-Arctic glacial or oceanic transport mechanisms,  
170 suggesting a more complex pattern of sediment provenance than previously thought.

## 171 **Implications for sediment provenance and IRD transport**

172 The age and isotopic diversity of the studied zircons offer new insights into the region's  
173 IRD history. The presence of both ancient Archean cobbles and more recent Mesozoic  
174 zircon points to a mixture of sources, likely including Greenlandic basement rocks and  
175 younger, perhaps rift-related volcanic material. This mixture of zircon ages suggests that  
176 sedimentary material was transported across the North Atlantic, most likely as IRD, and  
177 subsequently deposited along the Icelandic coast. As icebergs drifted into the waters  
178 around Iceland, they would have encountered the warmer Irminger Current, the western  
179 North Atlantic branch of the Gulf Stream Current flowing north along Iceland's western  
180 coast (Fig. 2; Perner et al., 2016). This warmer current likely accelerated melting,  
181 causing the icebergs to 'dump' debris. Clasts dropped by icebergs, whether angular or

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182 rounded and with or without striations (Gilbert, 1990), were likely shaped to some extent  
183 by wave action before deposition.

184 The Hf isotopic data further support a Greenlandic provenance, showing a wide range  
185 of  $\epsilon_{\text{Hf}}$  values consistent with multiple crustal and mantle-derived sources (Fig. 3). The  
186 wide ranges in ages and isotopes likely reflects the mixing of lithologies in moraines and  
187 glacial tills, sampling different catchments, and originating from many iceberg 'dump'  
188 events offshore Iceland. Importantly, the IRD-rich terrace from Breiðavík correlates with  
189 an isolation basin corresponding to Bond Event 1 (1,301–1,407 cal. BP) (Brader et al.,  
190 2017), which is tied to the LALIA, spanning from ca. 536–660 CE (Büntgen et al., 2016).  
191 Further support for an increase in Greenlandic IRD flux during this time comes from a  
192 peak in hematite-stained quartz observed in sediment cores offshore Iceland and the  
193 IRD >2 mm in the Nansen Trough (Andrews et al., 2014). Notably, the LALIA coincides  
194 with intensified volcanic activity, including a large eruption in Iceland around 536 CE  
195 (Büntgen et al., 2022). Those volcanic eruptions and subsequent climatic cooling are  
196 believed to have triggered an expansion of the Greenland Ice Sheet (Kjær et al., 2022),  
197 likely contributing to enhanced iceberg calving.

198 The combined influences of the East Greenland current (EGC) and East Icelandic  
199 current (EIC), modulated by the colder climatic conditions of the LALIA, likely facilitated  
200 the southward transport of Greenlandic IRD along Iceland's coastal margins (Fig. 2;  
201 White et al., 2016). However, the deposition was probably influenced by the warmer  
202 Irminger current, which would have played a critical role in distributing and depositing  
203 IRD in these regions through interactions with the colder currents (Knudsen et al.,  
204 2004). We have now documented an even more diverse assemblage of crustal

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205 materials, linked directly to East Greenland. While there is great potential to use zircon  
206 to evaluate the prospect of ancient continental crust beneath Iceland (Foulger et al.,  
207 2022), it is important to highlight that exotic detrital zircon may be derived from IRD that  
208 are completely unrelated to the presence of continental fragments at depth. The  
209 combined influences of the EGC and EIC, modulated by the colder climatic conditions of  
210 the LALIA, likely facilitated Greenlandic IRD deposition along Iceland's coastal margins.  
211 Isostatic uplift following rapid deglaciation in the Breiðafjörður region further influenced  
212 the placement of these materials, resulting in raised terraces (Brader et al., 2017) that  
213 record the far-reaching effects of glacial and oceanic interactions in the North Atlantic  
214 during the LALIA.

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## 220 FIGURES

221 Figure 1. Raised beach with exotic clasts at Breiðavík, northwest Iceland. (A) Satellite  
222 image of Iceland with insets of the Breiðavík region. The dashed line corresponds to the  
223 location of the lower terrace where the samples were collected ( $65.547945^{\circ}$  N, -  
224  $24.381130^{\circ}$  W). (B) Drone oblique view looking south across the beach terraces.  
225 Footprints, tire tracks, and person for scale in foreground, center, and background,  
226 respectively. (C) Example of an exotic clast found within the lower terrace.

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227 Figure 2. Location of potential source regions of Greenland-derived IRD of the Breiðavík  
228 clasts found in Iceland shown on a simplified geologic map of Greenland (White et al.,  
229 2016). Dashed lines denote Greenland bedrock provinces. Solid lines denote Greenland  
230 ice sheet watersheds. Black arrows denote ocean currents. EGC—East Greenland  
231 current. EIC—East Icelandic current. IC—Irminger current.

232 Figure 3. Fingerprinting the Greenlandic provenance of the exotic Breiðavík clasts.  $\epsilon_{\text{Hf}}$   
233 versus age plot of zircon from the Breiðavík clasts. Compiled Greenlandic detrital zircon  
234 were extracted from the database of Puetz et al., (2024) with data from Johnston and  
235 Kylander-Clark, (2013); Nicoli et al., (2018); Olierook et al., (2020).

## 236 REFERENCES

- 237 Batchelor, C.L., Margold, M., Krapp, M., Murton, D.K., Dalton, A.S., Gibbard, P.L.,  
238 Stokes, C.R., Murton, J.B., and Manica, A., 2019, The configuration of Northern  
239 Hemisphere ice sheets through the Quaternary: *Nature Communications*, v. 10, p. 3713,  
240 doi:10.1038/s41467-019-11601-2.
- 241 Black, L.P., Kamo, S.L., Allen, C.M., Davis, D.W., Aleinikoff, J.N., Valley, J.W., Mundil,  
242 R., Campbell, I.H., Korsch, R.J., and Williams, I.S., 2004, Improved  $^{206}\text{Pb}/^{238}\text{U}$   
243 microprobe geochronology by the monitoring of a trace-element-related matrix effect;  
244 SHRIMP, ID-TIMS, ELA-ICP-MS and oxygen isotope documentation for a series of  
245 zircon standards: *Chemical Geology*, v. 205, p. 115–140.
- 246 Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., and Bonani,  
247 G., 1993, Correlations between climate records from North Atlantic sediments and  
248 Greenland ice: *Nature*, v. 365, p. 143–147.
- 249 Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S.,  
250 Lotti-Bond, R., Hajdas, I., and Bonani, G., 2001, Persistent solar influence on North  
251 Atlantic climate during the Holocene: *Science*, v. 294, p. 2130–2136.
- 252 Brader, M.D., Lloyd, J.M., Barlow, N.L., Norðdahl, H., Bentley, M.J., and Newton, A.J.,  
253 2017, Postglacial relative sea-level changes in northwest Iceland: Evidence from  
254 isolation basins, coastal lowlands and raised shorelines: *Quaternary Science Reviews*,  
255 v. 169, p. 114–130.
- 256 Brueckner, H.K., Medaris, L.G., Belousova, E.A., Johnston, S.M., Griffin, W.L., Hartz,  
257 E.H., Hemming, S., Ghent, E., and Bubbico, R., 2016, An Orphaned Baltic Terrane in  
258 the Greenland Caledonides: A Sm-Nd and Detrital Zircon Study of a High-  
259 Pressure/Ultrahigh-Pressure Complex in Liverpool Land: *The Journal of Geology*, v.  
260 124, p. 541–567, doi:10.1086/687552.

# G53168R

- 261 Büntgen, U., Crivellaro, A., Arseneault, D., Baillie, M., Barclay, D., Bernabei, M.,  
262 Bontadi, J., Boswijk, G., Brown, D., and Christie, D.A., 2022, Global wood anatomical  
263 perspective on the onset of the Late Antique Little Ice Age (LALIA) in the mid-6th  
264 century CE: *Science Bulletin*, v. 67, p. 2336–2344.
- 265 Büntgen, U., Myglan, V.S., Ljungqvist, F.C., McCormick, M., Di Cosmo, N., Sigl, M.,  
266 Jungclaus, J., Wagner, S., Krusic, P.J., and Esper, J., 2016, Cooling and societal  
267 change during the Late Antique Little Ice Age from 536 to around 660 AD: *Nature*  
268 *geoscience*, v. 9, p. 231–236.
- 269 Eldrett, J.S., Harding, I.C., Wilson, P.A., Butler, E., and Roberts, A.P., 2007, Continental  
270 ice in Greenland during the Eocene and Oligocene: *Nature*, v. 446, p. 176–179,  
271 doi:10.1038/nature05591.
- 272 Foulger, G.R., Gernigon, L., and Geoffroy, L., 2022, Icelandia, in *In the Footsteps of*  
273 *Warren B. Hamilton: New Ideas*, Geological Society of America Special Papers 434.
- 274 Gilbert, R., 1990, *Rafting in glacial marine environments*: Geological Society, London,  
275 Special Publications, v. 53, p. 105–120.
- 276 Jackson, S.E., Pearson, N.J., Griffin, W.L., and Belousova, E.A., 2004, The application  
277 of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon  
278 geochronology: *Chemical Geology*, v. 211, p. 47–69,  
279 doi:10.1016/j.chemgeo.2004.06.017.
- 280 Johnston, S.M., and Kylander-Clark, A.R.C., 2013, Discovery of an Eo-Meso-  
281 Neoproterozoic terrane in the East Greenland Caledonides: *Precambrian Research*, v. 235,  
282 p. 295–302, doi:10.1016/j.precamres.2013.07.004.
- 283 Kjær, K.H. et al., 2022, Glacier response to the Little Ice Age during the Neoglacial  
284 cooling in Greenland: *Earth-Science Reviews*, v. 227, p. 103984,  
285 doi:10.1016/j.earscirev.2022.103984.
- 286 Nicoli, G., Thomassot, E., Schannor, M., Vezinet, A., and Jovovic, I., 2018, Constraining  
287 a Precambrian Wilson Cycle lifespan: An example from the ca. 1.8Ga Nagssugtoqidian  
288 Orogen, Southeastern Greenland: *Lithos*, v. 296–299, p. 1–16,  
289 doi:10.1016/j.lithos.2017.10.017.
- 290 Olierook, H.K.H., Barham, M., Kirkland, C.L., Hollis, J., and Vass, A., 2020, Zircon  
291 fingerprint of the Neoproterozoic North Atlantic: Perspectives from East Greenland:  
292 *Precambrian Research*, v. 342, p. 105653, doi:10.1016/j.precamres.2020.105653.
- 293 Paton, C., Hellstrom, J., Paul, B., Woodhead, J., and Hergt, J., 2011, *lolite*: Freeware for  
294 the visualisation and processing of mass spectrometric data: *Journal of Analytical*  
295 *Atomic Spectrometry*, v. 26, p. 2508–2518.
- 296 Puetz, S.J., Spencer, C.J., Condie, K.C., and Roberts, N.M., 2024, Enhanced U-Pb  
297 detrital zircon, Lu-Hf zircon,  $\delta^{18}\text{O}$  zircon, and Sm-Nd whole rock global databases:  
298 *Scientific Data*, v. 11, p. 56.
- 299 Rehnström, E.F., 2010, Prolonged Paleozoic Magmatism in the East Greenland  
300 Caledonides: Some Constraints from U-Pb Ages and Hf Isotopes: *The Journal of*  
301 *Geology*, v. 118, p. 447–465, doi:10.1086/655010.
- 302 Røhr, T.S., Andersen, T., Dypvik, H., and Embry, A.F., 2010, Detrital zircon  
303 characteristics of the Lower Cretaceous Isachsen Formation, Sverdrup Basin: Source  
304 constraints from age and Hf isotope data: *Canadian Journal of Earth Sciences*, v. 47, p.  
305 255–271.

# G53168R

- 306 Savkina, K., Bashirova, L., and Novichkova, E., 2018, Changes in surface conditions  
307 east of the Reykjanes Ridge (North Atlantic) during the Late Pleistocene to Holocene  
308 cold events: *Russian Journal of Earth Sciences*, v. 18, p. 1–12.
- 309 Spencer, C., Kirkland, C., Roberts, N., Evans, N., and Liebmann, J., 2020, Strategies  
310 towards robust interpretations of in situ zircon Lu–Hf isotope analyses: *Geoscience*  
311 *Frontiers*, v. 11, p. 843–853.
- 312 White, L.F., Bailey, I., Foster, G.L., Allen, G., Kelley, S.P., Andrews, J.T., Hogan, K.,  
313 Dowdeswell, J.A., and Storey, C.D., 2016, Tracking the provenance of Greenland-  
314 sourced, Holocene aged, individual sand-sized ice-rafted debris using the Pb-isotope  
315 compositions of feldspars and  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of hornblendes: *Earth and Planetary*  
316 *Science Letters*, v. 433, p. 192–203, doi:10.1016/j.epsl.2015.10.054.
- 317 Wiedenbeck, M., Hanchar, J.M., Peck, W.H., Sylvester, P., Valley, J., Whitehouse, M.,  
318 Kronz, A., Morishita, Y., Nasdala, L., and Fiebig, J., 2004, Further characterisation of the  
319 91500 zircon crystal: *Geostandards and Geoanalytical Research*, v. 28, p. 9–39.

Figure 1. **Figures**

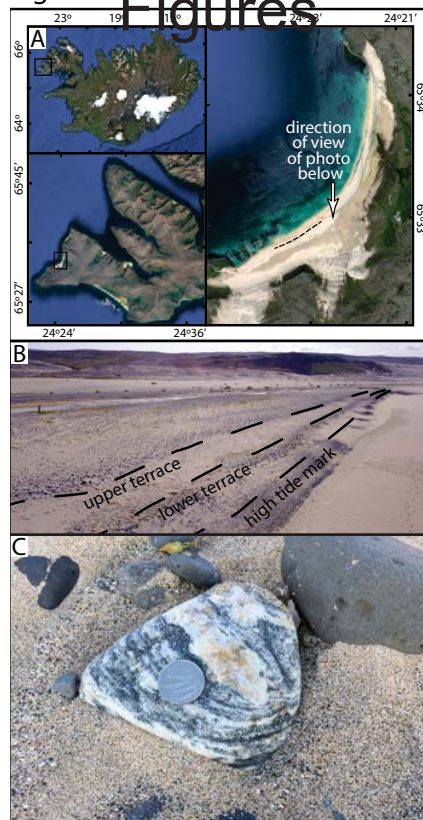


Figure 2. **Figures**

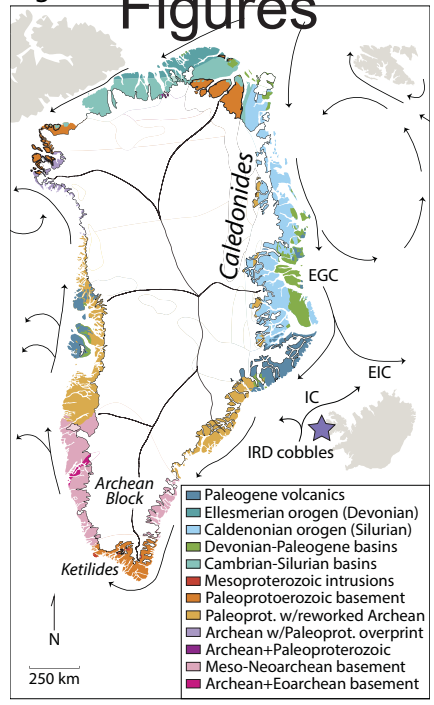




Figure 3. Figures

