Implications of 36Cl exposure ages from Skye, northwest Scotland for the timing of ice stream deglaciation and deglacial ice dynamics

Small, David ; Rinterknecht, Vincent; Austin, William E.N.; Bates, Richard; Benn, Douglas I.; Scourse, James; Bourles, Didier L.; Hibbert, Fiona D.

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Corresponding Author: Dr. David Small, Ph.D

Corresponding Author's Institution: University of Glasgow

First Author: David Small, Ph.D

Order of Authors: David Small, Ph.D; Vincent Rinterknecht; William Austin; Richard Bates; Douglas I Benn; James D Scourse; Didier L Bourlès ; Fiona D Hibbert

Abstract: Constraining the past response of marine terminating ice streams during episodes of deglaciation provides important insights into potential future changes due to climate change. This paper presents new 36Cl cosmic ray exposure dating from boulders located on two moraines (Glen Brittle and Loch Scavaig) in southern Skye, northwest Scotland. Ages from the Glen Brittle moraines constrain deglaciation of a major marine terminating ice stream, the Barra-Donegal Ice Stream that drained the former British-Irish Ice Sheet, depending on choice of production method and scaling model this occurred 19.9 ± 1.5 - 17.6 ± 1.3 ka ago. We compare this timing of deglaciation to existing geochronological data and changes in a variety of potential forcing factors constrained through proxy records and numerical models to determine what deglaciation age is most consistent with existing evidence. Another small section of moraine, the Scavaig moraine, is traced offshore through multibeam swath-bathymetry and interpreted as delimiting a later stillstand/readvance stage following ice stream deglaciation. Additional cosmic ray exposure dating from the onshore portion of this moraine indicate that it was deposited 16.3 ± 1.3 - 15.2 ± 0.9 ka ago. When calculated using the most up-to-date scaling scheme this time of deposition is, within uncertainty, the same as the timing of a widely identified readvance, the Wester Ross Readvance, observed elsewhere in northwest Scotland. This extends the area over which this readvance has potentially occurred, reinforcing the view that it was climatically forced.

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Department of Earth & Environmental Sciences

David Small
Department of Geography and Earth Sciences
University of Glasgow
Glasgow, G12 8QQ
Scotland
12/08/2016

Dear Editor,

We would like the editor to consider our revised manuscript entitled "Implications of ^{36}Cl exposure ages from Skye, northwest Scotland for the timing of ice stream deglaciation and deglacial ice dynamics." for publication in *Quaternary Science Reviews*.

We have included a point-by-point response to the reviewers comments with this submission. As can be seen from this we have adopted the reviewers points in near entirety. Specifically we have added labels to ensure all place names are indicated on maps, or simplified the terminology accordingly. Additionally we have included two new figures which locate the sampled boulders more precisely and depict their geomorphological setting. The 36-Cl age calculations have been checked, in conversation with Shasta Marrero and amended where they were incorrect, as suggested by a reviewer and communicated to us by the editor.

We would like to take this opportunity to thank editor for handling the reviewing process to date, and to thank the reviewers for their considered comments that have improved the manuscript.

Yours sincerely,

Dr. David Small (corresponding author)

Implications of ^{36}Cl exposure ages from Skye, northwest Scotland for the timing of ice stream deglaciation and deglacial ice dynamics.

David Small [a*, 1], Vincent Rinterknecht [a, b], William E. N. Austin [a, c], Richard Bates [a], Douglas I. Benn [a], James D. Scourse [d], Didier L. Bourlès [e], ASTER Team [e, ±], Fiona D. Hibbert [f]

[a] *School of Geography and Geosciences, University of St Andrews, St Andrews, KY16 9AL, UK.*

[b] *Université Paris 1 Panthéon-Sorbonne, CNRS Laboratoire de Géographie Physique, F-92195 Meudon, France.*

[c] *Scottish Marine Institute, Scottish Association for Marine Sciences, Oban, PA37 1QA, UK.*

[d] *School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey, LL59 5AB, UK.*

[e] *Aix-Marseille Université, CNRS-IRD-Collège de France, UM 34 CEREGE, Technopôle de l'Environnement Arbois-Méditerranée, BP80, 13545 Aix-en-Provence, France.*

[e] *Research School of*[f] *Ocean and Earth Sciences, The Australian National University, Canberra, ACT 2601, Australia*

[1] To whom correspondence should be addressed: David.Small@glasgow.ac.uk

[*] Now at Department of Geographical and Earth Sciences, University of Glasgow, Glasgow, G12 8QQ, UK. +44 141 330 5442.

[±] Maurice Arnold, Georges Aumaître, Karim Keddadouche.

Abstract

Geochronological constraints on the deglaciation of former marine based ice streams provide information on the rates and modes by which marine based ice sheets have responded to external forcing factors such as climate change. This paper presents new ^{36}Cl cosmic ray exposure dating from boulders located on two moraines (Glen Brittle and Loch Scavaig) in southern Skye, northwest Scotland. Ages from the Glen Brittle moraines constrain deglaciation of a major marine terminating ice stream, the Barra-Donegal Ice Stream that drained the former British-Irish Ice Sheet, depending on choice of production method and scaling model this occurred 19.9 ± 1.5 - 17.6 ± 1.3 ka ago. We compare this timing of deglaciation to existing geochronological data and changes in a variety of potential forcing factors constrained through proxy records and numerical models to determine what deglaciation age is most consistent with existing evidence. Another small section of moraine, the Scavaig moraine, is traced offshore through multibeam swath-bathymetry and interpreted as delimiting a later stillstand/readvance stage following ice stream deglaciation. Additional cosmic ray exposure dating from the onshore portion of this moraine indicate that it was deposited 16.3 ± 1.3 - 15.2 ± 0.9 ka ago. When calculated using the most up-to-date scaling scheme this time of deposition is, within uncertainty, the same as the timing of a widely identified readvance, the Wester Ross Readvance, observed elsewhere in northwest Scotland. This extends the area over which this readvance has potentially occurred, reinforcing the view that it was climatically forced.

1. Introduction

Concerns over the stability of the remaining ice sheets have been raised by suggestions that irreversible collapse of some marine based sectors is possible or has already begun,

50 with attendant effects on associated terrestrial glaciers (Joughin et al., 2014; Wouters et
51 al., 2015). Marine terminating ice streams are important components of the
52 interconnected ocean-cryosphere system because they discharge large volumes of ice
53 directly into the ocean through calving (Alley and MacAyeal, 1994; Bradwell and
54 Stoker, 2015; Deschamps et al., 2012). While modern observations provide useful
55 information, the temporal coverage is not sufficient to capture the complete response of
56 a marine terminating ice stream to rapid climate change. Researchers are therefore
57 increasingly drawn to analogous palaeo-settings where the complete deglaciation record
58 can be observed (Serjup et al., 2000; Dowdeswell et al., 2014; Svendsen et al., 2015).

59 Of the Pleistocene ice sheets, the British-Irish Ice Sheet (BIIS) provides a useful
60 analogue. Its western margin was marine terminating while its position next to a major
61 surficial artery of the Atlantic Meridionial Overturning Circulation (AMOC) rendered it
62 potentially sensitive to small climatic perturbations (Knutz et al., 2007). This sensitivity
63 is captured in proxy data (Scourse et al., 2009; Hibbert et al., 2010) and numerical
64 modelling experiments (Hubbard et al., 2009). Past reconstructions of the BIIS relied
65 heavily on onshore mapping of landforms that can be inferred to represent former ice
66 limits including terminal, lateral and recessional moraines (Sissons et al., 1973;
67 Ballantyne, 1989, Bennett and Boulton, 1993; Clark et al., 2004). Recent advances in
68 offshore geomorphological mapping, particularly the use of bathymetric and seismic
69 data, have allowed workers to identify sediments and landforms associated with ice
70 extending onto the continental shelf (Bradwell et al., 2008a; Dunlop et al., 2010;
71 Ò'Cofaigh et al., 2012). This has allowed delimitation of fast flowing ice streams that
72 drained much of the western sector of the former BIIS (Scourse et al., 2000; Stoker and
73 Bradwell, 2005; Howe et al., 2012; Bradwell and Stoker, 2015; Dove et al., 2015).
74 Further identification of subsequent landforms associated with confined ice flow casts

75 light on post-ice streaming behaviour inshore of the onset zone of the BDIS (Howe et
76 al., 2012; Dove et al., 2015).

77 The Barra-Donegal Ice Stream (BDIS) drained a large portion of the western
78 BIIS and, at the Last Glacial Maximum (LGM), reached the shelf edge (Knutz et al.,
79 2001) where it deposited glaciogenic sediments in the Barra-Donegal Fan (BDF), the
80 southernmost glaciogenic fan on the Eurasian continental margin (Figure 1). Recent
81 observations using swath bathymetry have revealed a suite of glaciogenic landforms at
82 the bed of the former BDIS, stretching from Skye in the north to Islay in the south
83 (Howe et al., 2012; Dove et al., 2015). The BDIS flowed southwest from the Inner
84 Hebrides before turning west around the Outer Hebrides towards the outer shelf (Howe
85 et al., 2012). Large scale erosional features such as glacially over-deepened basins and
86 streamlined bedrock are observed across large areas of the BDIS and provide important
87 information on past ice flow directions. In comparison, large moraines are confined to
88 the mid-outer shelf with smaller recessional moraines being more abundant in the
89 nearshore (Dunlop et al., 2010; Dove et al., 2015).

90 Offshore evidence from ice rafted detritus (IRD) demonstrates that ice sourced in
91 Scotland reached the shelf edge by 29 ka with a significant reduction in IRD delivery
92 after 23 ka (Knutz et al., 2001; Scourse et al., 2009; Hibbert et al., 2010). To the north,
93 basal marine radiocarbon ages show deglaciation of mid-shelf (Figure 1; Table 1) prior
94 to 16.7 ± 0.3 ka (Peacock et al., 1992; Austin and Kroon, 1996; Small et al., 2013) while
95 cosmogenic exposure and radiocarbon ages (Figure 1) show initial deglaciation of the
96 southern sector of the BDIS before ~20.0 ka (McCabe et al., 2003; Clark et al., 2009).
97 Complete deglaciation of the southern sector occurred before 16.8 ka (Figure 1)
98 (Ballantyne et al., 2014), an inference supported by IRD evidence that the BIIS
99 maintained calving margins throughout the period 23.0-16.0 ka (Scourse et al., 2009,

100 Small et al., 2013). All available geochronological data related to the BIIS was
101 synthesised to produce 1 ka time-slices of the pattern of deglaciation (Clark et al., 2012),
102 this was subsequently refined to include maximum and minimum ice-extents at the same
103 temporal resolution (Hughes et al., 2016). In the BDIS sector both reconstructions depict
104 initial deglaciation from the shelf edge at c.25 ka with ice persisting on the mid-shelf
105 until 19-17 ka. Rapid deglaciation occurs 17-16 ka by which time the ice margin is
106 located near the present day coastline (Figure 1).

107 While the submarine geomorphology and retreat pattern of the BDIS is relatively well
108 established (Howe et al., 2012; Dove et al., 2015), post-ice streaming behaviour and
109 geochronological data relating to deglaciation of the northern sector of the BDIS is still
110 comparatively limited. In northwest Scotland a regional scale readvance, the Wester
111 Ross readvance has been delimited from a suite of onshore moraines and dated with ^{10}Be
112 exposure ages to ~ 16 ka (Robinson and Ballantyne, 1979; Bradwell et al., 2008;
113 Ballantyne et al., 2009). However, to date this readvance has not been identified south of
114 Skye. In this contribution we present bathymetric data from inshore waters near Skye,
115 which highlights ice dynamics following ice stream retreat. Cosmogenic ^{36}Cl cosmic ray
116 exposure (CRE) ages from moraine boulders provide geochronological constraints on
117 the timing of this deglaciation.

118

119 **2. Study Site**

120 Skye is located off the west coast of Scotland, >200 km upstream from the maximum
121 extent of the BDIS at the shelf break (Figure 1). During the LGM the mountains of
122 central Skye (the Cuillin) nourished an independent ice dome, the Skye Ice Dome (SID),
123 which deflected ice moving from the mainland to the west and acted as an ice divide
124 between the BDIS and the Minch Ice Stream (MIS). Together, these ice streams drained

125 the majority of the northern sector of the BIIS (Bradwell et al., 2008a). To the north of
126 Skye, the zone of confluence between mainland ice and the SID is inferred to follow the
127 narrow straits between Skye and the islands of Scalpay and Raasay (Harker, 1901)
128 (Figure 2). To the south, mainland erratics occur on the island of Soay and the
129 orientation of striae on the southern margin of the Cuillin suggest that locally nourished
130 ice was strongly deflected westwards by mainland ice. This implies that the zone of ice
131 confluence lay between Skye and the neighbouring island of Soay (Ballantyne et al.,
132 1991). The southern branch of mainland ice, along with ice flowing south from the
133 Cuillin, fed the embryonic BDIS with ice stream onset beyond Rum (Howe et al., 2012;
134 Dove et al., 2015). The northern branch fed the MIS (Stoker and Bradwell, 2005). Given
135 its central position within the BDIS, Skye is an important location for constraining
136 deglaciation of the BDIS and comparing the deglacial history of neighbouring ice
137 streams that drained a dynamic, marine-based ice sheet.

138 Deglaciation of the MIS is constrained by several CRE ages. Two ^{36}Cl CRE ages
139 from ice smoothed bedrock on a col in Trotternish (Figure 2) show deglaciation at
140 altitude in Northern Skye before ~16 ka (Stone et al., 1998). Further constraint on final
141 deglaciation of the MIS is provided by five ^{10}Be CRE ages with a mean age of 15.9 ±
142 1.0 ka from a boulder moraine at Strollamus (Small et al., 2012), above the strait that
143 separates Skye from Scalpay (Figure 2). In contrast, the only CRE ages from southern
144 Skye are from a moraine related to the later Loch Lomond Readvance (LLR) (Small et
145 al., 2012).

146 Our study focuses on two locations in Southern Skye where there are moraines
147 outside the well mapped LLR limits., Glen Brittle to the west of the Cuillin, and Loch
148 Scavaig, to the south (Figures 2 and 5). At both sites the moraines represent the
149 innermost pre-LLR limit yet identified but without geochronological control it is not

150 possible to determine if they were deposited contemporaneously. In lower Glen Brittle
151 the up-valley termination of raised shorelines coincides with a series of low moraine
152 ridges littered with basalt boulders which have been interpreted as terminal moraines
153 (Walker *et al.,* 1988). These moraines occur well outside the mapped limits of the LLR
154 (Ballantyne, 1989) and thus clearly pre-date them (Figure 3). In Glen Brittle there are
155 two main parallel moraine ridges up to 100 m long and 2-3m high (Figure 3). The ridges
156 are separated by ~50 m.

157 On Soay, which forms the western margin of Loch Scavaig, a small moraine section
158 comes onshore at the northeastern corner of the island (Clough and Harker, 1904). This
159 moraine section is ~200-300 m in length and 4-5 m high in places. Large erratic gabbro
160 boulders are found on its crest indicating that at some time following deglaciation of the
161 BDIS ice sourced from the Cuillin extended into Loch Scavaig and reached Soay which
162 itself is composed entirely of Torridonian sandstone with some Tertiary basalt dykes
163 (Clough and Harker, 1904).

164

165 **3. Methods**

166 *3.1 Bathymetry*

167 To constrain deglaciation of the BDIS we confirmed the presence of ice margin
168 positions in southern Skye from onshore fieldwork in Glen Brittle and a bathymetric
169 survey of Loch Scavaig. This study used a SEA SwathPlus High Frequency System with
170 a central frequency of 468 kHz and a ping rate of up to 30 pings per second giving a
171 potential footprint of less than 5 cm at standard survey speed. Data were acquired with a
172 TSSDMS205 motion reference unit and positioning provided by a Topcon Hiper RTK
173 dGPS. The RTK dGPS base system was established on the loch shore and tied to the

174 BNG datum using Rinex corrections from the OS. An Applied Microsystems MicroSV
175 sound velocity probe was mounted at the sonar head in order to record changes in
176 velocity due to mixing of different waters (and thus potential salinity changes) in the
177 relatively enclosed waters of the loch. Final data were recorded to a position accuracy of
178 better than +/-5 cm, however the final data set was processed to a bin resolution of 2 m
179 with vertical heights given to ± 20 cm. The data was processed using SwathPlus and
180 GridProcessor (SEA Ltd) with further editing using IVS Fledermaus. Bathymetric data
181 points were converted from WGS84 to OSGP using the OSGB36 datum (origin 49°N
182 and 2°W). Final data processing was accomplished within ArcGIS (v10).

183

184 *3.2 Surface exposure dating using ^{36}Cl.*

185 *3.2.1 Sampling*

186 Moraines with suitable material for CRE dating using *in situ*-produced cosmogenic
187 ^{36}Cl were identified in Glen Brittle and on the island of Soay where the onshore
188 continuation of an offshore moraine is located. Eleven samples, four from Glen Brittle
189 and seven from Soay, were collected from basic igneous boulders (basalt and gabbro)
190 for CRE dating. In Glen Brittle two samples were collected from the outer moraine ridge
191 (BRI01 and BRI04) and two samples from the inner moraine ridge (BRI02 and BRI03).
192 On Soay seven samples were collected from the onshore moraine section (Figure 4).

193 We selected boulders from moraine crests with the largest *b*-axis to minimise the
194 potential for disturbance and snow cover. Where possible we sampled sub-rounded
195 boulders considered indicative of sub-glacial transport (Ballantyne and Stone, 2009) to
196 minimise the potential for inheritance. Similarly we sampled boulders with intact top
197 surfaces as they are least likely to have experienced significant chemical weathering and

198 to minimise the potential influence of spallation of material. Samples were collected
199 from the top surfaces of boulders using hammer and chisel. When possible, we sampled
200 flat surfaces but, where necessary, strike and dip were recorded using a compass-
201 clinometer. Detailed site descriptions (e.g. geomorphological context, boulder
202 dimensions, weathering) were made for each sample. Sample locations and elevations
203 were recorded using a hand-held GPS with elevations checked against 1:25000 maps.
204 Skyline measurements were taken using a compass-clinometer at all sites with the
205 topographic shielding factors calculated using the skyline calculator within the
206 CRONUS online calculator (Balco et al., 2008;
207 http://hess.ess.washington.edu/math/general/skyline_input.php; accessed on 14th
208 September 2015). Sample information is shown in Table 2. Sample photos are shown in
209 Figures 5 (Glen Brittle) and 6 (Soay).
210
211 *3.2.2 Processing*
212 The thickness and dry bulk density of samples from each site was measured before
213 samples for ^{36}Cl analysis were crushed and sieved to 250-500 μm at the University of St
214 Andrews. About 2 g of material was retained for elemental analysis with the remainder
215 sent to University of New Hampshire for further preparation and isotopic extraction.
216 Chlorine was extracted and purified from whole-rock samples to produce AgCl for
217 accelerator mass spectrometry (AMS) analysis, following a modified version of
218 procedures developed by Stone et al. (1996). Crushed samples were sonicated first in
219 distilled water and then in 2% HNO_3 to remove any secondary material attached to
220 grains. 13-20 g of pretreated rock was prepared from each sample for subsequent
221 chemical procedures. Samples were spiked with ~0.48 g of isotopically enriched carrier
222 ($^{35}Cl/^{37}Cl = 999 \pm 4$, total Cl concentration = 3.65 mg g^{-1}) before dissolution in an HF –

223 HNO_3 solution. Following complete dissolution, aqueous samples were separated from
224 solid fluoride residue by centrifuging, and ~1 ml of 5% $AgNO_3$ solution was added to
225 precipitate AgCl (and Ag_2SO_4 if sulfates were present). The precipitate was collected by
226 centrifuging and dissolved in NH_4OH solution. To remove sulfates, ~1 ml of saturated
227 $(BaNO_3)_2$ was added to precipitate $BaSO_4$. Final precipitation of AgCl from the aqueous
228 solution was accomplished by addition of 2 M HNO_3 and 5% $AgNO_3$. The final AgCl
229 precipitate was collected by centrifuging, washed repeatedly with 18.2 MΩ-cm
230 deionized water, and dried. Approximately 1.5 – 1.75 mg of purified AgCl target
231 material was produced from each sample for AMS measurement.

232

233 *3.2.2 Analysis and age calculations*

234 ^{36}Cl measurements were carried out at the 5 MV French accelerator mass
235 spectrometry national facility ASTER at CEREGE (Arnold et al., 2013). Use of an
236 isotopically enriched carrier allows simultaneous measurement of $^{35}Cl/^{37}Cl$ and
237 determination of the natural Cl content of the dissolved samples. For normalization of
238 $^{36}Cl/^{35}Cl$ ratios, calibration material 'KN1600' prepared by K. Nishiizumi, was used.
239 This has a given $^{36}Cl/^{35}Cl$ value of $2.11 \pm 0.06 \times 10^{-12}$ (Fifield et al., 1990). Typical
240 uncertainties for raw AMS data are 0.3 – 1.2% for $^{35}Cl/^{37}Cl$ and 4.8 – 8.0% for $^{36}Cl/^{35}Cl$.
241 All samples have $^{36}Cl/^{35}Cl$ ratios in the range of $3.8 – 6.9 \times 10^{-14}$ compared to two
242 process blanks (CLBLK7 and 8) with $^{36}Cl/^{35}Cl$ ratios of 7.83 ± 1.0 and $4.15 \pm 0.75 \times 10^{-15}$, respectively. Resulting blank corrections therefore range between 3.4 and 18.1%.
244 Measurement results and calculated concentrations with uncertainties are shown in
245 Table 3.

246 ^{36}Cl CRE ages were calculated using the CRONUScalc online calculator

247 (http://web1.ittc.ku.edu:8888; accessed 09/02/2016; Marrero et al., 2016a) and a freely
248 available spreadsheet (Schimmelpfennig et al., 2009). ^{36}Cl production rates for
249 spallation (Ca, K) have recently been updated by Marrero et al. (2016b). Consequently,
250 we calculated our exposure ages using sea level-high latitude ^{36}Cl production rates of
251 56.0 ± 4.1, 155± 11, 13 ± 3 and 1.9 ± 0.2 atoms ^{36}Cl g^{-1} a^{-1}, for Ca, K, Ti and Fe,
252 respectively (Marrero et al., 2016b; Schimmelpfennig et al., 2009). In comparison,
253 previous production rates for Ca and K were 42.2 ± 4.8, 145.5 ± 7.7 atoms ^{36}Cl g^{-1} a^{-1}
254 (Schimmelpfennig et al., 2011, 2014; also see Braucher et al., 2011). We report CRE
255 ages calculated using both Ca and K production rates and scaled for latitude and altitude
256 according to Stone (2000), as adapted by Balco et al. (2008), and Lifton et al. (2014) for
257 comparison. CRE ages were calculated assuming no erosion. Correcting for 1 mm ka^{-1}
258 erosion would vary exposure ages by 1-2%. The chemical composition of representative
259 bulk material was determined for each individual sample at the Facility for Earth and
260 Environmental Analysis at the University of St Andrews using X-ray fluorescence
261 (XRF) for major elements and inductively coupled plasma mass spectrometry (ICP-MS)
262 for minor and trace elements. The composition of individual samples is shown in Table
263 4.

264

265 *3.3 Comparison to proximal marine cores:*

266 We compare our surface exposure dating of the marine terminating Barra-Donegal
267 Ice Stream with two proximal marine records, MD02-2822 (Hibbert, 2011; Hibbert et
268 al., 2010) and MD01-2461 (Peck et al., 2006, 2008). Giant piston core MD04-2822 was
269 recovered by the RV *Marion Dufresne* from the deep-water margins of the BDF in the
270 Rockall Trough (Figure 1; 56° 50.54' N, 11° 22.96' W; 2344 m water depth, recovered

271 in 2004). MD01-2461 was collected from the north-western flank of the Porcupine
272 Seabight approximately 550 km to the southwest (51°45'N, 12°55'W; 1153 m water
273 depth, recovered in 2001). This region lies within the zone of meridional oscillation of
274 the North Atlantic Polar Front during the last glacial (Knutz et al., 2007; Scourse et al.,
275 2009; Hibbert et al., 2010) and as a result is ideally positioned to record both the
276 prevailing hydrographic conditions and the dynamics of the proximal BIIS.

277 Each core is plotted on their own age model based on tuning to the Greenland $\partial^{18}O$
278 ice core records (using NGRIP on the GICC05 timescale for MD04-2822 and GISP2 for
279 MD01-2461) and calibrated ^{14}C dates (Figure 10). We have updated the age model for
280 MD04-2822 using: the most recent calibration dataset (IntCal13; Reimer et al., 2013);
281 age uncertainty estimates for each tie-point (a mean squared estimate incorporating
282 uncertainties from both the ice core chronology and tuning procedure) and; a Bayesian
283 deposition model (Bronk Ramsey and Lee, 2013) (Supplementary Table 1).

284

285 **4. Results**

286 *4.1 Multibeam bathymetry*

287 The multibeam bathymetric survey of Loch Scavaig reveals numerous features –
288 both glaciogenic and post glacial – of interest. The most conspicuous of these is a large
289 arcuate ridge that spans Loch Scavaig and connects with the observed onshore moraine
290 section found on Soay. The ridge is ~4.5 km long and up to 10 m high in places (Figures
291 7 and 8). A further small extension (~1 km) of this ridge crosses the Sound of Soay to
292 come onshore on the southern margin of the Cuillin. This ridge is interpreted as a
293 terminal moraine, the Scavaig moraine, that clearly delimits the extent of a glacier that
294 flowed from the central rock basin of the Cuillin and into Loch Scavaig.

295 The submerged glacial land-system preserved in Loch Scavaig is very different,

296 both in morphology and scale, from that associated with surging tidewater glaciers in
297 Svalbard (Ottesen et al., 2008) with a lack of megascale glacial lineations, crevasse fills
298 and eskers. In addition, the scale and shape of the Scavaig moraine is strikingly different
299 from thrust moraines in Svalbard, which are up to 1 km across with large debris flow
300 lobes on their distal slopes (Ottesen et al., 2008; Kristensen et al., 2009). The Scavaig
301 moraine is a much smaller feature with a well-defined crest, it is generally arcuate in
302 planform, with an asymmetric profile. These features are consistent with a push moraine
303 formed at the margin of the former glacier, indicating that the Scavaig moraine was not
304 formed by a surging glacier but instead marks a readvance of ice from the Cuillin or a
305 still-stand during overall retreat. The Scavaig moraine is traceable across the floor of
306 Loch Scavaig and onto the island of Soay (Figures 4 and 8). The onshore section aligns
307 exactly with the offshore moraine, is composed of material from the Cuillin where the
308 glacier that deposited the Scavaig moraine must have been sourced. It is therefore
309 clearly part of the same feature.

310 Within the limits of the large moraine is a suite of shorter but conspicuous linear
311 ridges, most prominent in the east of the survey area and immediately inboard of the
312 large moraine (Figure 8). These are up to 2 km long and 5 m high and are interpreted as
313 recessional moraines formed during deglaciation from the outer limit demarked by the
314 Scavaig moraine.

315 In the east of the survey area, an area of the sea floor is covered with chaotic,
316 hummocky topography (Figure 8). This bears resemblance to features identified as
317 submarine slope failures in bathymetric studies carried out elsewhere in Scotland
318 (Stoker et al., 2010). In addition, the features occur immediately below a conspicuous
319 failure scarp that occurs on Ben Cleat which forms the eastern shore of Loch Scavaig.
320 This feature is interpreted as a post-glacial rock slope failure. Similar terrestrial features

321 in Scotland have been linked to glacial debuttressing and seismic activity associated
322 with post-glacial isostatic rebound (Ballantyne and Stone, 2013).

323

324 *4.2 Surface exposure dating using ^{36}Cl.*

325 The exposure ages calculated following Schimmelpfennig et al. (2009) and Marrero et
326 al., (2016a, b) are shown in Table 5. Due to the differing ways in which each calculator
327 deals with the numerous production pathways of ^{36}Cl and the varying compositions of
328 our samples the difference in calculated CRE age is not consistent between samples
329 although the ages calculated using the Lm scaling show general agreement between the
330 Schimmelpfennig calculator (Schimmelpfennig et al., 2009) and CRONUScalc (Marrero
331 et al., 2016a). Notably, the choice of scaling is important when using the new
332 CRONUScalc online calculator with CRE ages calculated using the Lm scaling (Stone et
333 al., 2000; Balco et al., 2008) being up to 14% older than when calculated with the SA
334 scaling (Lifton et al., 2014). The cause of this discrepancy is currently enigmatic. The
335 dependency of the CRE ages on choice scaling scheme makes interpretation difficult as
336 there is the danger of selecting CRE ages to fit pre-existing or favoured hypotheses.
337 However, given the range of production rate calibrations included in the CRONUScalc
338 programme, the improved agreement with observed atmospheric cosmic-ray fluxes
339 obtained using the SA scaling scheme and for simplicity, we focus discussion on CRE
340 ages calculated using CRONUScalc and the SA scaling. We present the alternative CRE
341 age calculations for completeness.

342 The ^{36}Cl CRE ages range from 19.4 ± 1.7 to 12.9 ±1.2 ka. The Glen Brittle
343 samples (BRI01-04) yield CRE ages between 19.4 ± 1.7 and 15.5 ± 1.7 ka while the
344 Soay samples (SOAY1-7) yield CRE ages between 16.4 ± 1.5 and 12.9 ± 1.2 ka. A plot
345 of all ^{36}Cl CRE ages reveals significant overlap in ages from both locations (Figure 9,

346 Table 5). The 11 samples combined have a reduced Chi-square (χ^2_R) = 4.51 indicating
347 that they are not a single population and are influenced by geological uncertainty. Given
348 this, and the absence of direct geomorphological correlation between the sampled
349 moraines in Glen Brittle and Soay we consider each sample site individually. The Glen
350 Brittle samples have χ^2_R = 1.59 which is an acceptable value for a population with three
351 degrees of freedom (Bevington and Robinson, 2003).

352 The Soay samples have χ^2_R = 2.06 indicating the CRE ages are not a single
353 population. Figure 9 shows two CRE age clusters at ~13 ka and ~15 ka (χ^2_R = 0.02 and
354 0.05, respectively). There are two potential interpretations of these CRE ages. The first
355 is that the younger CRE age population reflects the age of deposition of the Scavaig
356 moraine and that the older CRE ages reflect nuclide inheritance from a previous
357 exposure. An alternative interpretation is that the older CRE ages are representative of
358 the true moraine age and the young CRE ages are the result of some post-depositional
359 adjustment and/or exhumation.

360

361 **5. Discussion**

362 *5.2 Time of moraine deposition*

363 A compilation of exposure ages from boulders suggests that they are more likely to
364 underestimate the true CRE age (Heyman et al., 2011). However, this compilation was
365 solely comprised of ^{10}Be CRE ages. The greater importance of muons in ^{36}Cl production
366 (e.g. Stone et al., 1998; Braucher et al., 2013) means ^{36}Cl CRE ages have a greater
367 propensity for inheritance and thus overestimation of ages. Similarly the more
368 complicated evolution of production rate with depth (cf. Gosses and Philips, 2001)
369 means that erosion and or spalling of boulder surfaces can make CRE ages appear older

than the true boulder age. Despite careful sample selection (Section 3.2.1) the spread in our ages demonstrates that some of our samples were influenced by geological uncertainty. We therefore outline what ages in our view best represent the true moraine age and use these ages as the basis for our interpretation with a general note of caution that our ages may overestimate the true moraine age. We outline some reasons why we consider this less likely however acknowledge it as a possibility.

Given the agreement between the CRE ages from Glen Brittle we consider an arithmetic mean to best represent the timing of moraine deposition. Thus we infer that the Glen Brittle moraines were most likely deposited at 17.6 ± 1.3 ka, the mean of our ages. At this time relative sea level (RSL) around the south coast of Skye was high (Figure 11) and the termination of high shorelines is associated with the dated moraines in Glen Brittle. This led Walker et al. (1988) to speculate that at the time of high RSL ice occupied Glen Brittle, a view supported by our CRE ages. We note that there is considerable spread in the ages from Glen Brittle and that the mean age may over- or underestimate the true moraine age.

As stated in section 4.2 there are two possible interpretations of the exposure ages from Soay. We consider it unlikely that nuclide inheritance would affect the other boulders to the same degree such that they yielded internally consistent CRE ages that give an acceptable χ^2_R value. Additionally, the young CRE ages suggest moraine deposition prior to the LLR (≈ Younger Dryas - 12.9–11.7 ka b2k; Lowe et al., 2008). This would imply ice survival throughout the warm Bølling-Allerød interstadial, a scenario that is considered unlikely in Scotland (Ballantyne and Stone, 2012). If the older CRE age cluster is to be inferred as best representing the true moraine age it does however raise the question of how the three other boulders were exhumed at the same time. We note that these three boulders are located in very close proximity (Figure 4)

and that in comparison to the other sampled boulders they are relatively low lying. Boulder height has been shown to influence the clustering of CRE ages with taller boulders being favoured over shorter boulders (Heyman et al., 2016). Thus while we cannot speculate on the specific mechanism of exhumation the boulder-height relationship identified by Heyman et al. (2016) and the close spatial proximity of the three young Soay samples suggests that contemporaneous exhumation is possible. Given all of these considerations, we favour the second scenario and infer that the Scavaig moraine was most likely deposited 15.2 ± 0.9 ka ago.

The mean ages from the moraines do not agree within their analytical uncertainties which, given the proximity of the sample locations, suggests that they may represent separate glacial events. However, we note that there is considerable overlap between the ages from Glen Brittle and Soay thus we cannot definitively make this conclusion. We therefore propose, as a hypothesis, that two separate readvances occurred on the southern margin of the SID during deglaciation. This hypothesis requires further testing with geochronological data.

5.1 Implications for local ice dynamics

Evidence for readvance of locally nourished ice on Skye has been documented from several localities on the low ground that surrounds the Cuillin (Benn, 1997). Glacio-tectonised sediments, patterns of erratic dispersal and changes in the marine limit, all suggest that locally nourished ice remained dynamically active after its separation from mainland ice. Benn (1997) delimited potential readvance limits of the SID, but whether these were contemporaneous has, thus far, remained untested.

It has previously been suggested that readvance of the SID may have resulted from

419 the removal of constraints imposed by confluent ice allowing the ice to drain radially
420 away from the high ground (Benn, 1997). To the north of the SID a readvance/stillstand
421 is inferred from ice-thrust subaqueous outwash at Suisnish in southern Raasay (Benn,
422 1997). This site is likely to have been proximal to an ice margin when the Strollamus
423 moraine was deposited at 15.9 ± 1.0 ka (Small et al., 2012). This similarity in age to the
424 older CRE exposure ages from Soay suggests that readvance of the northern and
425 southern sectors of the SID may have been synchronous within dating uncertainties.
426 Additionally, the CRE ages of the Scavaig moraine from Soay and the ^{10}Be CRE ages
427 from the Strollamus moraine are the same as a suite of ^{10}Be CRE ages from moraines
428 delimiting the Wester Ross Readvance (Figure 2), ~60 km to the northwest (Robinson
429 and Ballantyne, 1979; Bradwell et al., 2008b, Ballantyne et al., 2009). While the
430 Strollamus moraine has been interpreted as a medial moraine and thus does not record a
431 readvance, it does indicate the existence of a significant ice mass at the time of the
432 WRR. If the Scavaig moraine represents a later readvance, or our CRE ages
433 overestimate the age the Glen Brittle moraine, then, in combination with the evidence
434 for readvance at Suisnish, it is possible that the Wester Ross Readvance may have been
435 more widespread than previously recognized, and involved readvance of local ice on
436 Skye. If this is the case then it implies a common, and likely climatic trigger such as an
437 increase in precipitation associated with climatic warming (c.f. Ballantyne and Stone,
438 2012). We note however that the uncertainties associated with our ages prevent
439 definitive correlation of the Scavaig moraine to moraines dated elsewhere in Scotland.

440

441 *5.2 Deglaciation of the BDIS*

442 The deposition age of the Glen Brittle moraine provides a constraint on final
443 deglaciation of the BDIS as its morphology and lithology demonstrates deposition by

444 valley glaciers fed from the locally nourished SID. As such, it would not be possible to
445 form moraines in Glen Brittle until BDIS deglaciation was complete. Taken at face
446 value, the ^{36}Cl CRE ages from Glen Brittle presented here suggest deglaciation of the
447 northern sector of the BDIS had occurred by 17.6 ± 1.3 ka (SA scaling). Use of the Lm
448 scaling makes deglaciation considerably earlier (19.9 ± 1.1 ka) although the ages do
449 overlap at 1σ. Considered alongside existing geochronological control from the north
450 coast of Ireland and Jura (McCabe and Clark, 2003; Clark et al., 2009; Ballantyne et al.,
451 2014) (Figure 1), our data suggest that the entire marine portion of the former BDIS was
452 deglaciated by 17.6 ± 1.3 ka. Notably, this timing of deglaciation compares well to a
453 reduction in delivery of IRD to the adjacent deep-sea core MD04-2822 (Hibbert et al.,
454 2010) (Figure 10G). Previous reconstructions of the BIIS (Clark et al., 2012; Hughes et
455 al., 2016) depict ice persisting on the mid-inner shelf until ~17 ka with ice reaching the
456 coastline at 16 ka. Our data from Glen Brittle suggest that deglaciation occurred earlier
457 and that ice may have reached the coastline several ka earlier than previously inferred.
458 Notably use of the Lm scaling to calculate the CRE age would exacerbate this
459 difference.

460 Numerous oceanic forcing mechanisms have been linked to observations of marine
461 deglaciation within the palaeoenvironment. Eustatically forced changes in sea-level
462 (ESL) rise has been cited as a potentially important factor in deglaciation of other
463 palaeo-ice streams that drained the BIIS (Scourse and Furze, 2001; Haapaniemi et al.,
464 2010; Chiverrell et al., 2013) and an initial eustatic sea level rise occurs at 19 ka (e.g.,
465 DeDeckker and Yokoyama, 2009; Lambeck et al., 2014), prior to BDIS deglaciation at
466 17.6 ± 1.3 ka, as constrained by our data (Figure B).

467 Additionally, it has been shown that tidal mechanical forcing can impact on
468 grounded ice streams (Murray et al., 2007; Arbic et al., 2008; Rosier et al., 2015). The

469 palaeotidal regime influencing the western ice streams draining the BIIS was enhanced
470 compared to the present day because the open glacial North Atlantic was characterized
471 by megatidal amplitudes (tidal ranges > 10 m) in many sectors south of the Iceland-
472 Faroe-Scotland ridge (Uehara et al., 2006; Scourse et al., submitted). Hitherto it has been
473 difficult to disentangle the relative influence of tidal amplitudes *vis-à-vis* relative sea
474 level (RSL) changes but recent modelling efforts have addressed this issue for the BIIS
475 (Scourse et al., submitted) and generated simulations of the potential influence of
476 palaeotides on the BDIS (Figure 11). These show an enhanced tidal regime in the period
477 immediately prior to deglaciation as constrained by the CRE ages from Glen Brittle in
478 the inner BDIS sector (Figure 11). This raises the possibility that this mechanism is a
479 potentially important driver of deglaciation. However, these large tidal amplitudes are
480 associated, in this area, with falling RSL driven by rapid glacio-isostatic uplift which
481 will have mitigated the impact of large tidal range on, for instance, calving rates and ice
482 stream velocities. Similarly, the deposition of the Scavaig moraine occurred during a
483 period of enhanced palaeotidal amplitude but falling RSL (Figure 11). The continuity of
484 these RSL and palaeotidal trends throughout deglaciation imply that other factors; e.g.
485 climate, topography, ice sheet internal dynamics; were controlling the higher frequency
486 BDIS advance/readvance phases documented by the new data.

487 Finally, changes in ocean circulation that allow warmer water to access the calving
488 front (e.g. Holland et al., 2008) have been cited as a major factor in past deglaciations
489 (Marcott et al., 2011, Rinterknecht et al., 2014). Records of Nps% and $\delta^{18}O_{Nps}$ in MD04-
490 2822 and a Mg/Ca sea surface temperature estimate from MD01-2461 (Peck et al.,
491 2008) (Figure 10C, D, E) show a consistent trend indicating northerly migration of the
492 polar front during Greenland Interstadial 2 (GI-2). Scourse et al. (2009) cite this oceanic
493 warming as a driver of a major phase of BIIS deglaciation represented by high IRD

494 fluxes to the deep sea record from ~23 ka. That the BDIS was likely involved in this is
495 indicated by the IRD records from the proximal cores MD95-2006 (Knutz et al., 2001)
496 and MD04-2822 (Hibbert et al., 2010). The rate at which the BDIS deglaciated in
497 response to GI-2 remains unclear. The IRD record from MD04-2822 retains high IRD
498 fluxes 22-18 ka (Hibbert et al., 2010) indicating that the BIIS, and most likely the BDIS,
499 retained calving margins throughout this period. This implies deglaciation may have
500 been a continuous process with punctuated retreat across the shelf although additional
501 geochronological data from the mid-outer shelf is needed to provide further constraints
502 on the nature of BDIS deglaciation in response to GI-2.

503

504 **6. Conclusions**

505 The data presented here provide insights into the timing of deglaciation of a major
506 palaeo-ice stream that drained a large portion of the former BIIS as well as indicating
507 post-ice stream dynamics of the remnant ice mass. Following de-coupling of ice sourced
508 from mainland Scotland and ice sourced in Skye, our data lead us to hypothesise that
509 there were possibly two local readvances/stillstands at ~17.6 and ~15.2 ka demarked by
510 moraines in Glen Brittle and Loch Scavaig, respectively. Evidence for local readvance
511 of ice sourced in Skye occurs around the periphery of Cuillin and our data suggests that
512 the latter readvance, north and south of the Cuillin, was contemporaneous with the
513 Wester Ross Readvance recorded elsewhere in northern Scotland, strengthening the
514 conclusion that it was climatically forced.

515 The ^{36}Cl CRE ages from Glen Brittle provide constraints on the timing of final
516 deglaciation of a major ice stream that drained the former BIIS. They indicate that
517 deglaciation of the BDIS was complete by 17.6 ± 1.3 ka, in general agreement with
518 offshore IRD evidence. The complex production pathways associated with *in situ*-

519 produced ^{36}Cl lead to large inherent uncertainties on our data that prevent us from
520 definitively linking deglaciation of the BDIS and subsequent readvance to any one
521 forcing factor. Ultimately, disentangling the relative contribution of the various forcing
522 factors requires further data constraining ice margin retreat on the shelf combined with
523 new and more precise geochronological data that constrains final deglaciation.

524

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535 **References**

536 Alley, R.B. and MacAyeal, D.R., 1994. Ice-rafted debris associated with binge/purge
537 oscillations of the Laurentide Ice Sheet. *Paleoceanography*, *9*, 503-511.

538 Arbic, B.K., Mitrovica, J.X., MacAyeal, D.R. and Milne, G.A., 2008. On the factors
539 behind large Labrador Sea tides during the last glacial cycle and the potential
540 implications for Heinrich events. *Paleoceanography*, *23*, PA3211.

541 Austin, W.E.N. and Kroon, D., 1996. Late glacial sedimentology, foraminifera and
542 stable isotope stratigraphy of the Hebridean Continental Shelf, northwest
543 Scotland. *Geological Society, London, Special Publications*, *111*, 187-213.

544 Arnold, M., Aumaître, G., Bourlès, D.L., Keddadouche, K., Braucher, R., Finkel, R.C.,
545 Nottoli, E., Benedetti, L. and Merchel, S., 2013. The French accelerator mass
546 spectrometry facility ASTER after 4years: Status and recent developments on
547 ^{36}Cl and ^{129}I. *Nuclear Instruments and Methods in Physics Research Section B:*
548 *Beam Interactions with Materials and Atoms*, *294*, 24-28.

549 Ballantyne. C.K., 1989, The Loch Lomond Readvance on the Isle of Skye, Scotland:
550 glacier reconstruction and palaeoclimatic implications: *Journal of Quaternary*
551 *Science*, *4*, 95-108.

552 Ballantyne, C.K., and Stone, J.O., 2012, Did large ice caps persist on low ground in
553 north-west Scotland during the Lateglacial Interstade?: *Journal of Quaternary*
554 *Science*, *27*, 297-306.

555 Ballantyne, C.K. and Stone, J.O., 2013. Timing and periodicity of paraglacial rock-slope
556 failures in the Scottish Highlands. *Geomorphology*, *186*, 150-161.

557 Ballantyne C.K., Benn, D.I., Lowe, J.J., Walker, M.J.C., (Eds.), 1991, The Quaternary
558 of the Isle of Skye: Field Guide, Quaternary Research Association, Cambridge.

559 Ballantyne, C.K., Schnabel, C. and Xu, S., 2009. Readvance of the last British–Irish ice
560 sheet during Greenland interstade 1 (GI-1): the Wester Ross readvance, NW
561 Scotland. *Quaternary Science Reviews*, *28*, 783-789.
562 Ballantyne, C.K., Wilson, P., Gheorghiu, D., and Rodés, À., 2014, Enhanced rock-slope
563 failure following ice-sheet deglaciation: timing and causes: *Earth Surface*
564 *Processes and Landforms*, *39*, 900-913.
565 Benn, D.I., 1997. Glacier fluctuations in western Scotland. *Quaternary International*,
566 *38*, 137-147.
567 Bennett, M.R., 2003. Ice streams as the arteries of an ice sheet: their mechanics, stability
568 and significance. *Earth-Science Reviews*, *61*, 309-339.
569 Bennett, M.R. and Boulton, G.S., 1993. Deglaciation of the Younger Dryas or Loch
570 Lomond Stadial ice-field in the northern Highlands, Scotland. *Journal of*
571 *Quaternary Science*, *8*, 133-145.
572 Baltzer, A., Bates, R., Mokeddem, Z., Clet-Pellerin, M., Walter-Simonnet, A.V.,
573 Bonnot-Courtois, C. and Austin, W.E., 2010. Using seismic facies and pollen
574 analyses to evaluate climatically driven change in a Scottish sea loch (fjord) over
575 the last 20 ka. *Geological Society, London, Special Publications*, *344*, 355-369.
576 Berger, A., and Loutre, M.F., 1991, Insolation values for the climate of the last 10
577 million years. *Quaternary Science Reviews*, *10*, 297-317.
578 Bevington, PR and Robinson, D.K., 2003, Data reduction and error analysis: McGraw–
579 Hill, New York, p. 320.
580 Bradwell, T. and Stoker, M.S., 2015. Submarine sediment and landform record of a
581 palaeo-ice stream within the British− Irish Ice Sheet. *Boreas*, *44*, 255-276.

582 Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long, D.,
583 Everest, J.D., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L. and Finlayson,
584 A.G., 2008a. The northern sector of the last British Ice Sheet: maximum extent
585 and demise. *Earth-Science Reviews*, *88*, 207-226.
586 Bradwell, T., Fabel, D., Stoker, M., Mathers, H., McHargue, L. and Howe, J., 2008b. Ice
587 caps existed throughout the Lateglacial Interstadial in northern Scotland. *Journal*
588 *of Quaternary Science*, *23*, 401-407.
589 Braucher, R., Merchel, S., Borgomano, J. and Bourlès, D.L., 2011. Production of
590 cosmogenic radionuclides at great depth: A multi element approach. *Earth and*
591 *Planetary Science Letters*, *309*, 1-9.
592 Bronk Ramsey, C., 2008. Deposition models for chronological records. *Quaternary*
593 *Science Reviews*, *27*, 42-60.
594 Bronk Ramsey, C., 2013. OxCal 4.2. *Manual [online] available at: https://c14. arch. ox.*
595 *ac. uk/oxcalhelp/hlp_contents. html*.
596 Bronk Ramsey, C. and Lee, S., 2013. Recent and planned developments of the program
597 OxCal. *Radiocarbon*, *55*, 720-730.
598 Clark, C.D., Evans, D.J., Khatwa, A., Bradwell, T., Jordan, C.J., Marsh, S.H., Mitchell,
599 W.A. and Bateman, M.D., 2004. Map and GIS database of glacial landforms and
600 features related to the last British Ice Sheet. *Boreas*, *33*, 359-375.
601 Clark, C.D., Hughes, A.L., Greenwood, S.L., Jordan, C., and Sejrup, H.P., 2012, Pattern
602 and timing of retreat of the last British-Irish Ice Sheet: *Quaternary Science*
603 *Reviews*, *44*, 112-146.
604 Clark, J., McCabe, A.M., Schnabel, C., Clark, P.U., McCarron, S., Freeman, S.P.,
605 Maden, C. and Xu, S., 2009. Cosmogenic ^{10}Be chronology of the last

606 deglaciation of western Ireland, and implications for sensitivity of the Irish Ice
607 Sheet to climate change. *Geological Society of America Bulletin*, *121*, 3-16.
608 Clough, C.T. and Harker, A., 1904. *The Geology of West-Central Skye, with Soay:*
609 *Explanation of* (Vol. 70). HM Stationery Office.
610 Chiverrell, R.C., Thrasher, I.M., Thomas, G.S., Lang, A., Scourse, J.D., van
611 Landeghem, K.J., Mccarroll, D., Clark, C.D., Cofaigh, C.Ó., Evans, D.J. and
612 Ballantyne, C.K., 2013. Bayesian modelling the retreat of the Irish Sea Ice
613 Stream. *Journal of Quaternary Science*, *28*(2), pp.200-209.
614 De Deckker, P. and Yokoyama, Y., 2009. Micropalaeontological evidence for Late
615 Quaternary sea-level changes in Bonaparte Gulf, Australia. *Global and*
616 *Planetary Change*, *66*, 85-92.
617 Deschamps, P., Durand, N., Bard, E., Hamelin, B., Camoin, G., Thomas, A.L.,
618 Henderson, G.M., Okuno, J.I. and Yokoyama, Y., 2012. Ice-sheet collapse and
619 sea-level rise at the Bolling warming 14,600 years ago. *Nature*, *483*, 559-564.
620 Dove, D., Arosio, R., Finlayson, A., Bradwell, T. and Howe, J.A., 2015. Submarine
621 glacial landforms record Late Pleistocene ice-sheet dynamics, Inner Hebrides,
622 Scotland. *Quaternary Science Reviews*, *123*, 76-90.
623 Dowdeswell, J.A., Hogan, K.A., Cofaigh, C.Ó., Fugelli, E.M.G., Evans, J. and
624 Noormets, R., 2014. Late Quaternary ice flow in a West Greenland fjord and
625 cross-shelf trough system: submarine landforms from Rink Isbrae to
626 Uummannaq shelf and slope. *Quaternary Science Reviews*, *92*, 292-309.
627 Dunlop, P., Shannon, R., McCabe, M., Quinn, R., and Doyle, E., 2010, Marine
628 geophysical evidence for ice sheet extension and recession on the Malin Shelf:
629 New evidence for the western limits of the British Irish Ice Sheet: *Marine*
630 *Geology*, *276*, 86-99.

631 Fabel, D., Ballantyne, C.K. and Xu, S., 2012. Trimlines, blockfields, mountain-top
632 erratics and the vertical dimensions of the last British–Irish Ice Sheet in NW
633 Scotland. *Quaternary Science Reviews*, *55*, 91-102.
634 Fifield, L.K., Ophel, T.R., Allan, G.L., Bird, J.R. and Davie, R.F., 1990. Accelerator
635 mass spectrometry at the Australian National University's 14UD accelerator:
636 experience and developments. *Nuclear Instruments and Methods in Physics*
637 *Research Section B: Beam Interactions with Materials and Atoms*, *52*, 233-237.
638 Haapanieni, A.I., Scourse, J.D., Peck, V.L., Kennedy, D.P., Kennedy, H., Hemming,
639 S.R., Furze, M.F.A., Pieńkowski-Furze, A.J., Walden, J., Wadsworth, E. and
640 Hall, I.R. 2010. Source, timing, frequency and flux of ice-rafted detritus to the
641 Northeast Atlantic margin, 30-12 ka: testing the Heinrich precursor hypothesis.
642 *Boreas, 39,* 576-591.
643 Harker, A., 1901. Ice-erosion in the Cuillin Hills, Skye: *Transactions of the Royal*
644 *Society of Edinburgh, 40*, 221–252.
645 Heyman, J., Stroeven, A.P., Harbor, J.M., and Caffee, M.W., 2011, Too young or too
646 old: evaluating cosmogenic exposure dating based on an analysis of compiled
647 boulder exposure ages: *Earth and Planetary Science Letters*, *302*, 71-80.
648 Hibbert FD. 2011. Dynamics of the British Ice Sheet and Prevailing Hydrographic
649 Conditions for the Last 175,000 years: An investigation of marine sediment core
650 MD04-2822 from the Rockall Trough. *Unpublished PhD thesis, University of St*
651 *Andrews.*
652 Hibbert, F.D., Austin, W.E., Leng, M.J., and Gatliff, R.W., 2010, British Ice Sheet
653 dynamics inferred from North Atlantic ice- rafted debris records spanning the last
654 175 000 years: *Journal of Quaternary Science*, *25*, 461-482.

655 Holland, D.M., Thomas, R.H., De Young, B., Ribergaard, M.H., and Lyberth, B., 2008,
656 Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters:
657 *Nature Geoscience*, *1*, 659-664.
658 Howe, J.A., Dove, D., Bradwell, T. and Gafeira, J., 2012. Submarine geomorphology
659 and glacial history of the Sea of the Hebrides, UK. *Marine Geology*, *315*, 64-76.
660 Hubbard, A., Bradwell, T., Golledge, N., Hall, A., Patton, H., Sugden, D., Cooper, R.
661 and Stoker, M., 2009. Dynamic cycles, ice streams and their impact on the
662 extent, chronology and deglaciation of the British–Irish ice sheet. *Quaternary*
663 *Science Reviews*, *28*, 758-776.
664 Joughin, I., Smith, B.E., and Medley, B., 2014, Marine ice sheet collapse potentially
665 under way for the Thwaites Glacier Basin, West Antarctica: *Science*, *344*, 735-
666 738.
667 Knutz, P.C., Austin, W.E., and Jones, E.J.W., 2001, Millennial-scale depositional cycles
668 related to British Ice Sheet variability and North Atlantic paleocirculation since
669 45 kyr BP, Barra Fan, UK margin: *Paleoceanography*, *16*, 53-64.
670 Knutz, P.C., Zahn, R., and Hall, I.R., 2007, Centennial-scale variability of the British
671 Ice Sheet: Implications for climate forcing and Atlantic meridionial overturning
672 circulation during the last deglaciation: *Paleoceanography 22*.
673 Kristensen, L., Benn, D.I., Hormes, A. and Ottesen, D. 2009. Mud aprons in front of
674 Svalbard surge moraines: evidence of subglacial deforming layers or proglacial
675 tectonics? *Geomorphology* 111, 206-221.
676 Lambeck, K., Rouby, H., Purcell, A., Sun, Y., and Sambridge, M., 2014, Sea level and
677 global ice volumes from the Last Glacial Maximum to the Holocene:

678 *Proceedings of the National Academy of Science of the United States of America*,
679 *111*, 15296-15303.
680 Lifton, N., Sato, T. and Dunai, T.J., 2014. Scaling in situ cosmogenic nuclide production
681 rates using analytical approximations to atmospheric cosmic-ray fluxes. *Earth*
682 *and Planetary Science Letters*, *386*, pp.149-160.
683 Livingstone, S.J., Cofaigh, C.Ó., Stokes, C.R., Hillenbrand, C.D., Vieli, A. and
684 Jamieson, S.S., 2013. Glacial geomorphology of Marguerite Bay palaeo-ice
685 stream, western Antarctic Peninsula. *Journal of Maps*, *9*, 558-572.
686 Lowe, J.J., Rasmussen, S.O., Björck, S., Hoek, W.Z., Steffensen, J.P., Walker, M.J. and
687 Yu, Z.C., 2008. Synchronisation of palaeoenvironmental events in the North
688 Atlantic region during the Last Termination: a revised protocol recommended by
689 the INTIMATE group. *Quaternary Science Reviews*, *27*, 6-17.
690 Marcott, S.A., Clark, P.U., Padman, L., Klinkhammer, G.P., Springer, S.R., Liu, Z.,
691 Otto-Bliesner, B.L., Carlson, A.E., Ungerer, A., Padman, J. and He, F., 2011.
692 Ice-shelf collapse from subsurface warming as a trigger for Heinrich events.
693 *Proceedings of the National Academy of Sciences*, *108*, 13415-13419.
694 Marrero, S.M., Phillips, F.M., Borchers, B., Lifton, N., Aumer, R. and Balco, G., 2016a.
695 Cosmogenic nuclide systematics and the CRONUScalc program. *Quaternary*
696 *Geochronology*, *31*, 160-187.
697 Marrero, S.M., Phillips, F.M., Caffee, M.W. and Gosse, J.C., 2016b. CRONUS-Earth
698 cosmogenic ^{36}Cl calibration. *Quaternary Geochronology*, *31*, 199-219.
699 McCabe, A.M., and Clark, P.U., 2003, Deglacial chronology from County Donegal,
700 Ireland: implications for deglaciation of the British–Irish ice sheet: *Journal of the*
701 *Geological Society of London*, *160*, 847-855.

Murray, T., Smith, A.M., King, M.A. and Weedon, G.P., 2007. Ice flow modulated by tides at up to annual periods at Rutford Ice Stream, West Antarctica. *Geophysical Research Letters*, *34*, L18503.

Ó' Cofaigh, C., Dunlop, P. and Benetti, S., 2012. Marine geophysical evidence for Late Pleistocene ice sheet extent and recession off northwest Ireland. *Quaternary Science Reviews*, *44*, 147-159.

Ottesen, D., Dowdeswell, J.A., Benn, D.I., Kristensen, L., Christiansen, H.H., Christensen, O., Hansen, L., Lebesbye, E., Forwick, M. and Vorren, T.O., 2008. Submarine landforms characteristic of glacier surges in two Spitsbergen fjords. *Quaternary Science Reviews*, *27*, 1583-1599.

Peacock, J.D., 2008, Late Devensian palaeoenvironmental changes in the sea area adjacent to Islay, SW Scotland: implications for the deglacial history of the island: *Scottish Journal of Geology*, *44*, 183-190.

Peacock, J.D., Austin, W.E.N., Selby, I., Graham, D.K., Harland, R. and Wilkinson, I.P., 1992. Late Devensian and Flandrian palaeoenvironmental changes on the Scottish continental shelf west of the Outer Hebrides. *Journal of Quaternary Science*, *7*, 145-161.

Peck, V.L., Hall, I.R., Zahn, R., and Elderfield, H., 2008, Millennial-scale surface and subsurface paleothermometry from the northeast Atlantic, 55–8 ka BP: *Paleoceanography*, *23*, PA3221.

Peck, V.L., Hall, I.R., Zahn, R., Grousset, F., Hemming, S.R. and Scourse, J.D., 2007. The relationship of Heinrich events and their European precursors over the past 60ka BP: a multi-proxy ice-rafted debris provenance study in the North East Atlantic. Quaternary Science Reviews, 26(7), 862-875.

726 Rasmussen, S.O., Seierstad, I.K., Andersen, K.K., Bigler,M., Dahl-Jensen, D., and
727 Johnsen, S.J., 2008, Synchronization of the NGRIP, GRIP, and GISP2 ice cores
728 across MIS 2 and palaeoclimatic implications: *Quaternary Science Reviews*, *27*,
729 18-28.
730 Rinterknecht, V., Jomelli, V., Brunstein, D., Favier, V., Masson-Delmotte, V., Bourlès,
731 D., Leanni, L. and Schläppy, R., 2014. Unstable ice stream in Greenland during
732 the Younger Dryas cold event. *Geology*, *42*, 759-762.
733 Robinson, M. and Ballantyne, C.K., 1979. Evidence for a glacial readvance pre-dating
734 the Loch Lomond Advance in Wester Ross. *Scottish Journal of Geology*, *15*,
735 271-277.
736 Rosier, S.H.R., Gudmundsson, G.H. and Green, J.A.M. 2015. Temporal variations in
737 the flow of a large Antarctic ice-stream controlled by tidally induced changes in
738 the subglacial water system. *Cryosphere, 9,* 2397-2429.
739 Schimmelpfennig, I., Benedetti, L., Finkel, R., Pik, R., Blard, P H., Bourlès, D.,
740 Burnard, P., and Williams, A., 2009, Sources of in-situ ^{36}Cl in basaltic rocks.
741 Implications for calibration of production rates: *Quaternary Geochronology*, *4,*
742 441-461.
743 Schimmelpfennig, I., Benedetti, L., Garreta, V., Pik, R., Blard, P.H., Burnard, P.,
744 Bourlès, D., Finkel, R., Ammon, K., and Dunai, T., 2011, Calibration of
745 cosmogenic ^{36}Cl production rates from Ca and K spallation in lava flows from
746 Mt. Etna (38° N, Italy) and Payun Matru (36° S, Argentina): *Geochimica et*
747 *Cosmochimic Acta, 75*, 2611-2632.
748 Schimmelpfennig, I., Schaefer, J.M., Putnam, A.E., Koffman, T., Benedetti, L.,
749 Ivy- Ochs, S., ASTER team, and Schlüchter, C., 2014, ^{36}Cl production rate from

750 K- spallation in the European Alps (Chironico landslide, Switzerland): *Journal of*
751 *Quaternary Science, 29*, 407-413.
752 Scourse, J.D. and Furze, M.F.A., 2001. A critical review of the glaciomarine model for
753 Irish Sea deglaciation: evidence from southern Britain, the Celtic shelf and
754 adjacent continental slope. *Journal of Quaternary Science*, *16*, 419-434.
755 Scourse, J.D., Hall, I.R., McCave, I.N., Young, J.R. and Sugdon, C., 2000. The origin of
756 Heinrich layers: evidence from H2 for European precursor events. *Earth and*
757 *Planetary Science Letters*, *182*(2), pp.187-195.
758 Scourse, J.D., Haapaniemi, A.I., Colmenero-Hidalgo, E., Peck, V.L., Hall, I.R., Austin,
759 W.E., Knutz, P.C. and Zahn, R., 2009. Growth, dynamics and deglaciation of the
760 last British–Irish ice sheet: the deep-sea ice-rafted detritus record. Quaternary
761 Science Reviews, 28(27), 3066-3084.
762 Scourse, J.D., Ward, S.L., Wainwright, A., Bradley, S.L. and Uehara, K. Submitted. The
763 role of megatides and relative sea level in controlling the deglaciation of the
764 British-Irish and Fennoscandian Ice Sheets. *Journal of Quaternary Science*.
765 Seierstad, I.K., Abbott, P.M., Bigler, M., Blunier, T., Bourne, A.J., Brook, E., Buchardt,
766 S.L., Buizert, C., Clausen, H.B., Cook, E. and Dahl-Jensen, D., 2014.
767 Consistently dated records from the Greenland GRIP, GISP2 and NGRIP ice
768 cores for the past 104 ka reveal regional millennial-scale $\delta^{18}O$ gradients with
769 possible Heinrich event imprint. *Quaternary Science Reviews*, *106*, pp.29-46.
770 Sejrup, H.P., Larsen, E., Landvik, J., King, E.L., Haflidason, H. and Nesje, A., 2000.
771 Quaternary glaciations in southern Fennoscandia: evidence from southwestern
772 Norway and the northern North Sea region. *Quaternary Science Reviews*, *19*,
773 667-685.

774 Sissons, J.B., Lowe, J.J., Thompson, K.S. and Walker, M.J.C., 1973. Loch Lomond
775 readvance in Grampian Highlands of Scotland: *Nature*, *244*, 75-77.
776 Small, D., 2012 The Deglaciation of the northwest sector of the last British-Irish Ice
777 Sheet: Integrating onshore and offshore data relating to chronology and
778 behaviour. *Unpublished PhD Thesis, University of St Andrews.*
779 Small, D., Rinterknecht, V., Austin, W., Fabel, D. and Miguens-Rodriguez, M., 2012,
780 In situ cosmogenic exposure ages from the Isle of Skye, northwest Scotland:
781 implications for the timing of deglaciation and readvance from 15 to 11 ka.
782 *Journal of Quaternary Science, 27*, 150-158.
783 Small D., Austin W., and Rinterknecht V., 2013. Freshwater influx, hydrographic
784 reorganization and the dispersal of ice-rafted detritus in the sub-polar North
785 Atlantic Ocean during the last deglaciation: *Journal of Quaternary Science, 28*,
786 527-535.
787 Stoker, M. and Bradwell, T., 2005. The Minch palaeo-ice stream, NW sector of the
788 British–Irish Ice Sheet. *Journal of the Geological Society*, *162*, 425-428.
789 Stoker, M.S., Wilson, C.R., Howe, J.A., Bradwell, T. and Long, D., 2010. Paraglacial
790 slope instability in Scottish fjords: examples from Little Loch Broom, NW
791 Scotland. *Geological Society, London, Special Publications*, *344*, 225-242.
792 Stokes, C.R. and Clark, C.D., 2001. Palaeo-ice streams. *Quaternary Science Reviews*,
793 *20*, 1437-1457.
794 Stokes, C.R., Tarasov, L., Blomdin, R., Cronin, T.M., Fisher, T.G., Gyllencreutz, R.,
795 Hättestrand, C., Heyman, J., Hindmarsh, R.C., Hughes, A.L. and Jakobsson, M.,
796 2015. On the reconstruction of palaeo-ice sheets: Recent advances and future
797 challenges. *Quaternary Science Reviews*, *125*, 15-49.

798 Stone, J.O., 2000, Air pressure and cosmogenic isotope production: *Journal of*
799 *Geophysical Research: Solid Earth, 105*, 23753-23759.
800 Stone, J.O., Allan, G.L., Fifield, L.K. and Cresswell, R.G., 1996. Cosmogenic chlorine-
801 36 from calcium spallation. *Geochimica et Cosmochimica Acta*, *60*, 679-692.
802 Stone, J.O., Ballantyne, C.K. and Fifield, L.K., 1998. Exposure dating and validation of
803 periglacial weathering limits, northwest Scotland. *Geology*, *26*, 587-590.
804 Svendsen, J.I., Briner, J.P., Mangerud, J. and Young, N.E., 2015. Early break-up of the
805 Norwegian channel ice stream during the last glacial maximum. *Quaternary*
806 *Science Reviews*, *107*, 231-242.
807 Uehara, K., Scourse, J.D., Horsburgh, K.J., Lambeck, K. and Purcell, A.P., 2006. Tidal
808 evolution of the northwest European shelf seas from the Last Glacial Maximum
809 to the present. *Journal of Geophysical Research: Oceans*, *111*, C09025.
810 Walker, M.J., Ballantyne, C.K., Lowe, J.J. and Sutherland, D.G., 1988. A
811 reinterpretation of the Lateglacial environmental history of the Isle of Skye,
812 Inner Hebrides, Scotland. *Journal of Quaternary Science*, *3*, 135-146.
813 Wouters, B., Martin-Español, A., Helm, V., Flament, T., van Wessem, J.M., Ligtenberg,
814 S.R.M., van den Broeke, M.R., and Bamber, J. L., 2015, Dynamic thinning of
815 glaciers on the Southern Antarctic Peninsula: *Science, 348*, 899-903.
816

817 **Figure Captions**

818 Figure 1. Google Earth Image with extent of the BDIS and related glaciological features.
819 Existing geochronological dates are shown (Table 1) along with location of marine core
820 MD04-2822. Flowlines adjusted from Bradwell et al. (2008). Dashed box shows the
821 location of Figure 2, solid box shows location of Figure 7. Isochrones depicting the most
822 likely ice extent at 24 ka, 17 ka, and 16 ka (shaded for clarity) are taken from Hughes et

al., 2016. BDF = Barra/Donegal Fan, BDIS = Barra/Donegal Ice Stream, MIS = Minch Ice Stream. All ^{10}Be CRE dates have been re-calculated using a local production rate (Loch Lomond Production Rate) of 3.92 ± 0.18 atoms g^{-1} a^{-1} (Fabel et al., 2012).

Figure 2. Location map of Skye and northwest Scotland showing locations mentioned in text. Dashed lines demark inferred zones of confluence between mainland ice and the Skye Ice Dome. Red stars show locations of existing exposure ages from (1) Trotternish (Stone et al., 1998) and (2) the Strollamus moraine (Small et al., 2012). GB = Glen Brittle, LS = Loch Scavaig. Arrows show generalized ice flow directions, MIS = Minch Ice Stream, BDIS = Barra-Donegal Ice Stream. Also shown are inferred limits of Wester Ross Readvance (WRR). Letters A and B denote the locations of the palaeotidal and RSL simulations (Section 5.2; Figure 11). DEM derived from NASNA SRTM 90 m data, available at http://www.sharegeo.ac.uk/handle/10672/5.

Figure 3. Map of Glen Brittle area showing sampled moraines, raised shorelines and locations of sampled boulders. The limits of the Loch Lomond Readvance and associated landforms are shown as adapted from Ballantyne (1989). Contours at 100 m intervals. See Figure 5 for location.

Figure 4. Map of the northeast corner of Soay showing sampled moraine and locations of sampled boulders. Dashed line shows crest of offshore moraine (Figure 8).

Figure 5. Site and sample photographs from Glen Brittle. (*A*) Glen Brittle looking North. Showing two parallel moraine ridges. Southern (outer) moraine with person, northern

(inner) moraine with boulders on near horizon. Ice flow is towards the camera. (*B*) BRI01 boulder. (*C*) BRI-02 boulder. (*D*) BRI-03 boulder. (*E*) BRI-04 boulder.

Figure 6. Site and sample photographs from Soay. (*A*) SOAY1 boulder. (*B*) SOAY2 boulder. (*C*) SOAY3 boulder. (*D*) SOAY4 boulder. (*E*) SOAY5 boulder. (*F*) SOAY6 boulder. (*G*) SOAY7 boulder. (*H*) Soay moraine onshore. The dashed white line marks the crest. The offshore continuation stretches across Loch Scavaig to the far shore (see Figures 5 and 6). Samples were located off-shot in the wooded area to the right. Ice flow was from left to right.

Figure 7. Location of ^{36}Cl samples presented and onshore moraines in Glen Brittle and on Soay. The multibeam bathymetry of Loch Scavaig is shown alongside mapped YD ice limits modified from Ballantyne (1989). Note the distinctive offshore moraine that impinges on Soay. Failure scarp and extent of inferred slope failure (SF) is also shown. The red star in the upper right is the location of the dated Strollamus medial moraine (Benn, 1990; Small et al., 2012). NEXTmap hillshade DEM by Intermap Technologies.

Figure 8. Interpreted bathymetric map of Loch Scavaig showing the distinctive arcuate terminal moraine. Suites of recessional moraines are also highlighted. There is a distinctive glacially over-deepened basin in the western portion of the survey area. The trench in the northeastern sector is the offshore continuation of the Camasunary Fault. The red star shows the location of the vibrocore VC57/-07/844 which yielded a basal radiocarbon age of 12.8 ± 0.1 ka (Small, 2012). Also show is the failure scarp on Ben Cleat and the associated landslide deposits. NEXTmap hillshade DEM by Intermap Technologies.

872

873 Figure 9. Summary CRE age plot of ^{36}Cl samples presented here shown alongside the
874 NGRIP oxygen isotope record ($\delta^{18}O$, ‰) (Rasmussen et al., 2008). Grey boxes show
875 arithmetic means and uncertainties of Brittle and Soay samples respectively. The Soay
876 samples not included in calculating moraine ages shown with hollow circles.
877 Uncertainties are 1σ analytical uncertainties. The Younger Dryas stadial (YD) and
878 Bølling-Allerød interstadial are also shown (B-A).

879

880 Figure 10. Proxy records of deglacial forcing for the time period of BDIS deglaciation
881 indicated by the shaded column. (*A*) Greenland oxygen isotope records ($\delta^{18}O$, ‰) from
882 NGRIP, GRIP and GISP2 on the GICC05 timescale (Rasmussen et al., 2008; Seierstad
883 et al., 2014) [50 yr moving averages shown by black line] (*B*) Reconstructed ESL
884 (Lambeck et al., 2014). Proxies relating to oceanic forcing: (*C*) Mg/Ca (*G.bulloides*)
885 SST estimates from MD01-2461 (Porcupine Seabight, Peck et al., 2008); and MD04-
886 2822 (Rockall Trough, Hibbert, 2011; Hibbert et al., 2010) (*D*) $\delta^{18}O$ *N.pachyderma*
887 sinistral (‰ VPDB), (*E*) % *N.pachyderma* (sinistral), (*F*) XRF core scanning (ITRAX)
888 TiCa (proxy for terrigeneous input) and, (*G*) total IRD flux (> 150 μm cm^{-2} ka^{-1}).

889

890 Figure 11. Relative sea level (RSL) and palaeotidal (PTM) simulations for two locations
891 in the inner part of the BDIS adjacent to Skye. A) 57.04° N, 6.88° W and, B) 57.12° N,
892 6.13° W (see Figure 2 for locations). RSL simulations are based on the modified glacio-
893 isostatic adjustment model of Lambeck and PTM simulations on a modified version of
894 the Princeton Ocean Model forced with dynamic open ocean tide (Uehara et al., 2006).
895 These show mean *M2* tidal ranges > 6 m throughout the deglacial phase from the Last
896 Glacial Maximum to around 11 ka BP (spring tidal ranges would have been significantly

larger). The shaded boxes in A and B show the mean exposure ages from Glen Brittle and Soay, respectively.

Table 1. Published ages referred to in the text and shown on Figure 1. Outliers are shown in italics. Clusters of CRE ages that yield acceptable x_R^2 values are shown in bold, the mean of these is shown in Figure 1. Underlined radiocarbon ages are the oldest from a site and these are used in Figure 1. CRE ages calculated using CRONUS online calculator (http://hess.ess.washington.edu; accessed April 20th 2016), Lm scaling and, Loch Lomond Production Rate of 3.92 ± 0.18 atoms g^{-1} yr^{-1} (Fabel et al. 2012). ^{14}C ages calibrated using OxCal 4.2 (Bronk Ramsey 2013) and Marine14 (Reimer et al.,2013), ΔR=300 yr.

Reference	Location (site no. Fig. 1)	Sample name	Technique	Age (yr)	Uncert. (yr)
Clark et al. (2009)	N Donegal coast (1)	BF-04-01	CRE	17607	1772
Clark et al. (2009)	N Donegal coast (1)	BF-04-03	CRE	33035	2940
Clark et al. (2009)	**N Donegal coast (1)**	**BF-04-04**	**CRE**	**21463**	**1754**
Clark et al. (2009)	**N Donegal coast (1)**	**BF-04-05**	**CRE**	**20924**	**1863**
Clark et al. (2009)	**N Donegal coast (1)**	**BF-04-06**	**CRE**	**20949**	**2060**
Clark et al. (2009)	N Donegal coast (1)	BF-04-08	CRE	23251	2135
Clark et al. (2009)	**N Donegal coast (1)**	**BF-04-09**	**CRE**	**21428**	**2196**
Clark et al. (2009)	**N Donegal coast (1)**	**BF-04-10**	**CRE**	**21799**	**2190**
McCabe & Clark (2003)	N Donegal coast (2)	AA32315	^{14}C	16602	178
McCabe & Clark (2003)	N Donegal coast (2)	AA45968	^{14}C	18676	168
McCabe & Clark (2003)	N Donegal coast (2)	AA45967	^{14}C	17997	188
McCabe & Clark (2003)	N Donegal coast (2)	AA45966	^{14}C	19093	496
McCabe & Clark (2003)	N Donegal coast (2)	AA33831	^{14}C	17913	130
McCabe & Clark (2003)	N Donegal coast (2)	AA33832	^{14}C	20308	148
Peacock (2008)	Islay (3)	SUERC-13122	^{14}C	14457	163
Peacock (2008)	Islay (3)	SUERC-13123	^{14}C	14337	149
Peacock (2008)	Islay (3)	SUERC-13124	^{14}C	14498	166
Ballantyne et al. (2014)	Jura (4)	SNC-02	CRE	14006	1690
Ballantyne et al. (2014)	Jura (4)	SNC-03	CRE	12352	1414
Ballantyne et al. (2014)	**Jura (4)**	**SNC-06**	**CRE**	**16875**	**1102**
Ballantyne et al. (2014)	**Jura (4)**	**SNC-07**	**CRE**	**16819**	**1025**
Baltzer et al. (2010)	W coast of Scotland (5)	UL2853	^{14}C	16587	311
Small et al., (2013)	Mid Shelf (5)	AAR-2606	^{14}C	16664	279

908

909

910 Table 2. Sample information for all ^{36}Cl samples from Glen Brittle and Soay.

Sample Name	Lat.	Long.	Elevation (m)	Shielding correction	Sample thickness (cm)	Lithology	Density (g/cm)
Glen Brittle							
BRI01	57.21595	-6.29651	10	0.9891	2.3	Basalt	2.6
BRI02	57.21652	-6.29641	11	0.9891	3.2	Basalt	2.6
BRI03	57.21667	-6.29678	10	0.9891	1.5	Basalt	2.6
BRI04	57.21602	-6.29554	11	0.9891	2.2	Basalt	2.6
Isle of Soay							
SOAY1	57.16073	-6.18362	13	0.9993	2.5	Gabbro	2.6
SOAY2	57.16079	-6.18352	14	0.9993	1.4	Gabbro	2.6
SOAY3	57.16118	-6.18385	15	0.9993	1.5	Gabbro	2.6
SOAY4	57.16125	-6.18392	15	0.9993	1.7	Gabbro	2.6
SOAY5	57.16120	-6.18389	9	0.9993	1.5	Gabbro	2.6
SOAY6	57.16067	-6.18340	10	0.9993	1.4	Gabbro	2.6
SOAY7	57.16076	-6.18362	15	0.9993	1.6	Gabbro	2.6

911

912

913 Table 3. Chemical and analytical data for all ^{36}Cl samples. Ratios are rounded to two

914 significant figures. Calculated concentrations reflect precision of AMS measurements.

Sample Name	Sample mass (g)	Carrier added (g)	$^{35}Cl/^{37}Cl$	Uncert. (%)	$^{36}Cl/^{35}Cl$	Uncert. (%)	$^{36}Cl/^{37}Cl$	Uncert. (%)	^{36}Cl conc. (at g^{-1})	Uncert. (abs)
Glen Brittle										
BRI01	15.1294	0.4844	9.55E+01	0.931	5.73E-14	6.576	5.46E-12	6.548	110167	7943
BRI02	14.9876	0.4824	1.08E+02	1.216	3.81E-14	6.223	4.11E-12	6.180	70422	5140
BRI03	15.0566	0.4818	1.05E+02	0.646	5.87E-14	5.557	6.16E-12	5.509	112557	6893
BRI04	12.9649	0.4824	1.30E+02	0.692	4.55E-14	8.045	5.91E-12	8.012	98678	8902
Soay										
SOAY01	20.0777	0.4853	5.59E+01	0.571	6.92E-14	4.806	3.86E-12	4.751	98972	5545
SOAY02	20.0711	0.4853	1.73E+01	0.253	6.81E-14	5.188	1.18E-12	5.135	113848	6786
SOAY03	20.0162	0.4787	2.40E+01	0.345	5.70E-14	5.297	1.37E-12	5.247	86176	5447
SOAY04	20.0341	0.478	2.26E+01	0.535	3.79E-14	6.449	8.56E-13	6.408	53701	4515
SOAY05	16.8693	0.4781	2.33E+01	0.883	5.68E-14	5.147	1.32E-12	5.096	108742	6183
SOAY06	20.1048	0.4816	6.39E+00	0.276	6.34E-14	5.954	4.04E-13	5.909	179705	12009
SOAY07	19.9611	0.4818	7.73E+00	0.379	6.19E-14	5.31	4.78E-13	5.262	150704	8986

915

916

Table 4. Whole rock geochemistry of samples from Glen Brittle and Soay.

Sample Name	SiO_2 (wt-%)	Na_2O (wt-%)	MgO (wt-%)	Al_2O_3 (wt-%)	MnO (wt-%)	H_2O (wt-%)	Sm (ppm)	Gd (ppm)	K_2O (wt -%)	CaO (wt-%)	Cl (ppm)	TiO_2 (wt-%)	Fe_2O_3 (wt-%)	P_2O_5 (wt -%)	U (ppm)	Th (ppm)
Glen Brittle																
BRI01	46.19	1.96	8.62	13.17	0.17	2.42	2.61	3.25	0.301	12.16	2.76	1.85	13.06	0.01	0.04	0.16
BRI02	41.99	1.60	13.1	12.04	0.2	2.18	3.9	4.39	0.18	7.90	2.13	2.78	17.85	0.06	0.08	0.32
BRI03	47.64	1.99	8.52	13.68	0.16	2.01	7.26	3.09	0.18	11.97	2.25	1.77	11.98	0.02	0.04	0.15
BRI04	46.71	1.75	8.92	12.05	0.18	1.83	2.66	3.3	0.26	13.08	1.53	2.10	13.01	0.02	0.04	0.12
Soay																
SOAY01	45.77	0.96	11.07	20.13	0.09	0.44	0.5	0.82	0.03	14.08	4.69	0.27	7.11	0.02	0.02	0.11
SOAY02	44.55	1.03	12.49	20.96	0.09	0.41	1.30	0.69	< 0.005	12.99	23.69	0.25	7.17	0.02	< 0.01	0.03
SOAY03	44.92	1.01	13.01	22.26	0.06	0.48	0.15	0.33	< 0.005	13.16	15.14	0.1	4.97	0.01	< 0.01	0.02
SOAY04	42.94	0.07	28.02	10.14	0.13	0.62	0.28	0.5	<0.005	7.28	16.32	0.18	10.34	0.01	0.01	0.06
SOAY05	47.12	1.58	1.88	29.28	0.04	0.56	0.56	0.87	0.02	16.46	19.06	0.34	2.74	0.02	0.02	0.10
SOAY06	47.08	1.25	5.76	23.44	0.09	1.30	0.40	0.71	0.06	15.87	109.82	0.19	4.90	0.02	< 0.01	0.01
SOAY07	48.15	0.51	12.79	8.85	0.18	1.36	1.57	2.66	0.04	15.74	77.84	0.63	11.63	0.02	< 0.01	0.02

Table 5. Comparison of CRE ages from Skye calculated using alternative calculation methods and scaling schemes. Full uncertainties (analytical uncertainties). CRE ages used in interpretation highlighted in bold text.

Calc. method	*Schimmelpfennig et al. (2009)*		*Marrero et al. (2016a)*		Marrero et al. (2016a)	
Prod. rates	*Marrero et al. (2016b)*		*Marrero et al. (2016b)*		Marrero et al. (2016b)	
Scaling	*Lm*		*Lm*		*SA*	
	Age	*Uncert.*	*Age*	*Uncert.*	Age	Uncert.
SOAY1	*17.2*	*2.1 (1.5)*	*17.0*	*1.8 (1.5)*	**15.0**	**1.3 (0.9)**
SOAY2	*19.0*	*2.3 (1.5)*	*19.0*	*2.0 (1.5)*	**16.4**	**1.5 (1.0)**
SOAY3	*14.9*	*1.8 (1.4)*	*14.6*	*1.6 (1.4)*	12.9	1.2 (0.8)
SOAY4	*15.0*	*1.9 (1.6)*	*14.7*	*1.8 (1.6)*	13.0	1.4 (1.1)
SOAY5	*15.2*	*1.8 (1.0)*	*14.9*	*1.5 (1.0)*	13.1	1.1 (0.8)
SOAY6	*17.6*	*2.5 (1.1)*	*16.9*	*2.4 (1.1)*	**14.8**	**1.8 (1.0)**
SOAY7	*17.2*	*2.2 (0.9)*	*17.0*	*2.0 (0.9)*	**14.6**	**1.5 (0.9)**
BRI01	*19.0*	*2.4 (1.4)*	*20.6*	*2.2 (1.5)*	**18.2**	**1.7 (1.3)**
BRI02	*18.9*	*2.2 (1.4)*	*19.4*	*2.1 (1.5)*	**17.3**	**1.6 (1.3)**
BRI03	*21.9*	*2.6(1.4)*	*22.0*	*2.3 (1.4)*	**19.4**	**1.7 (1.2)**
BRI04	*17.3*	*2.1 (1.6)*	*17.5*	*2.1 (1.6)*	**15.5**	**1.7 (1.4)**

Figure 1
Click here to download high resolution image

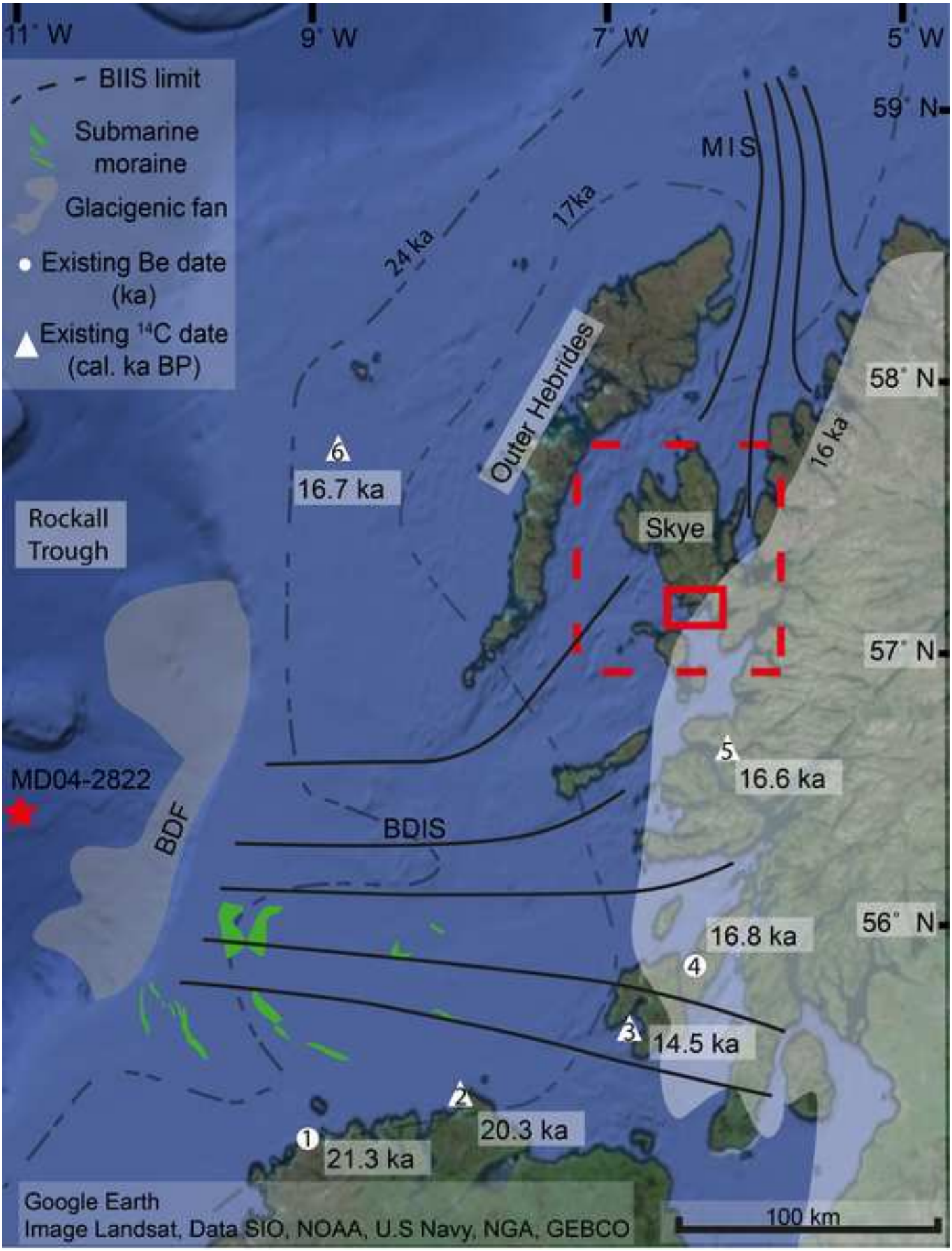

Figure 2

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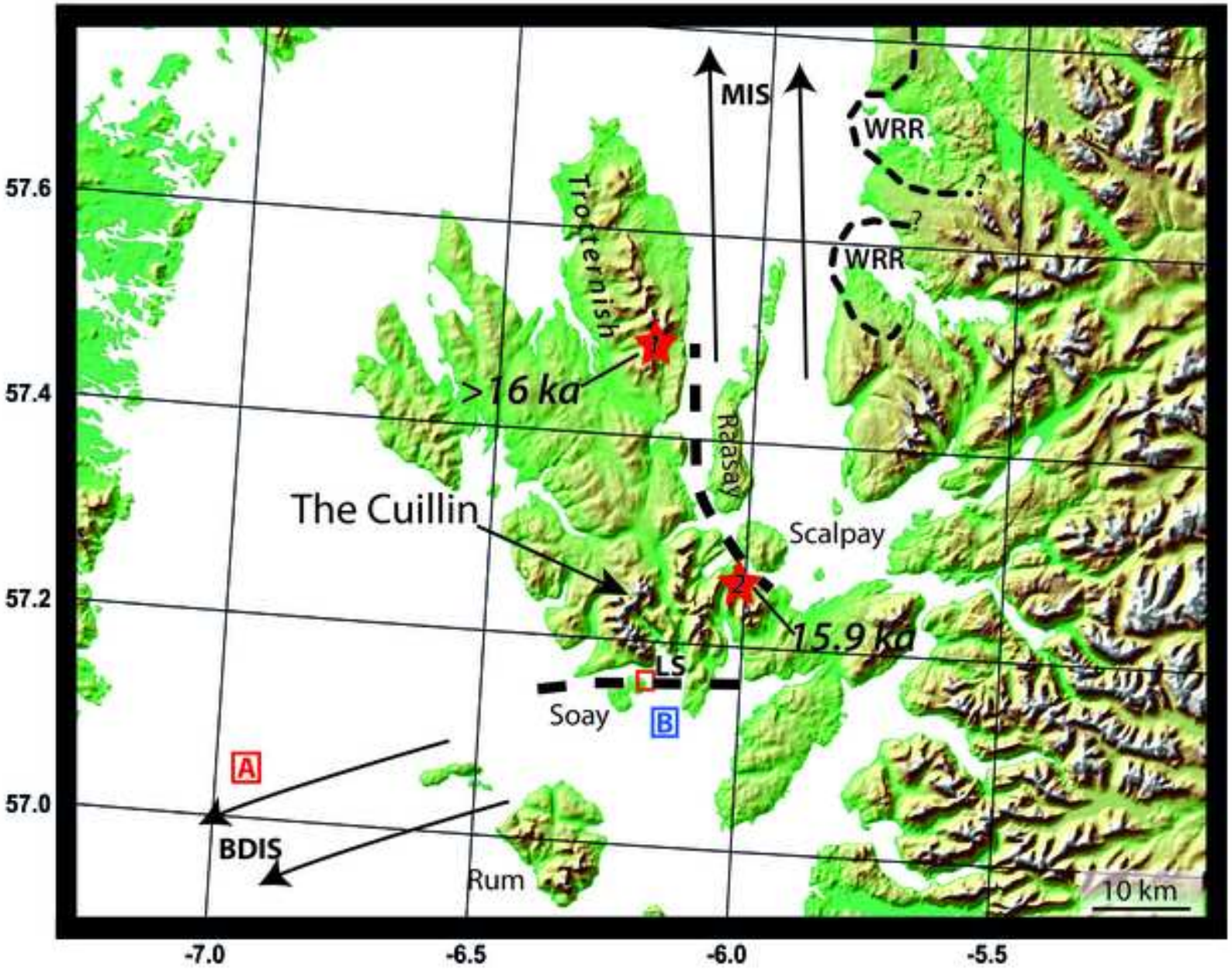

Figure 3
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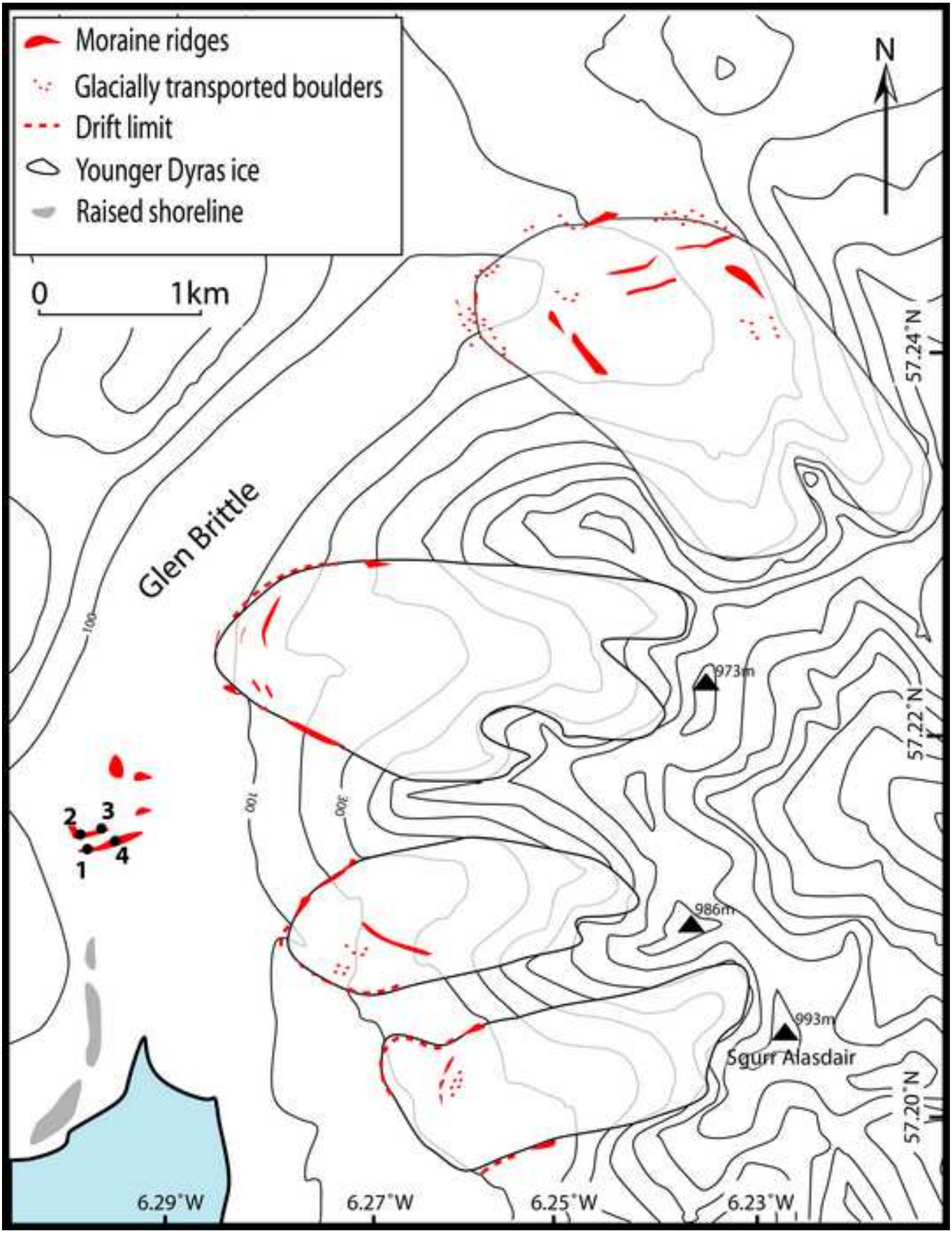

Figure 4
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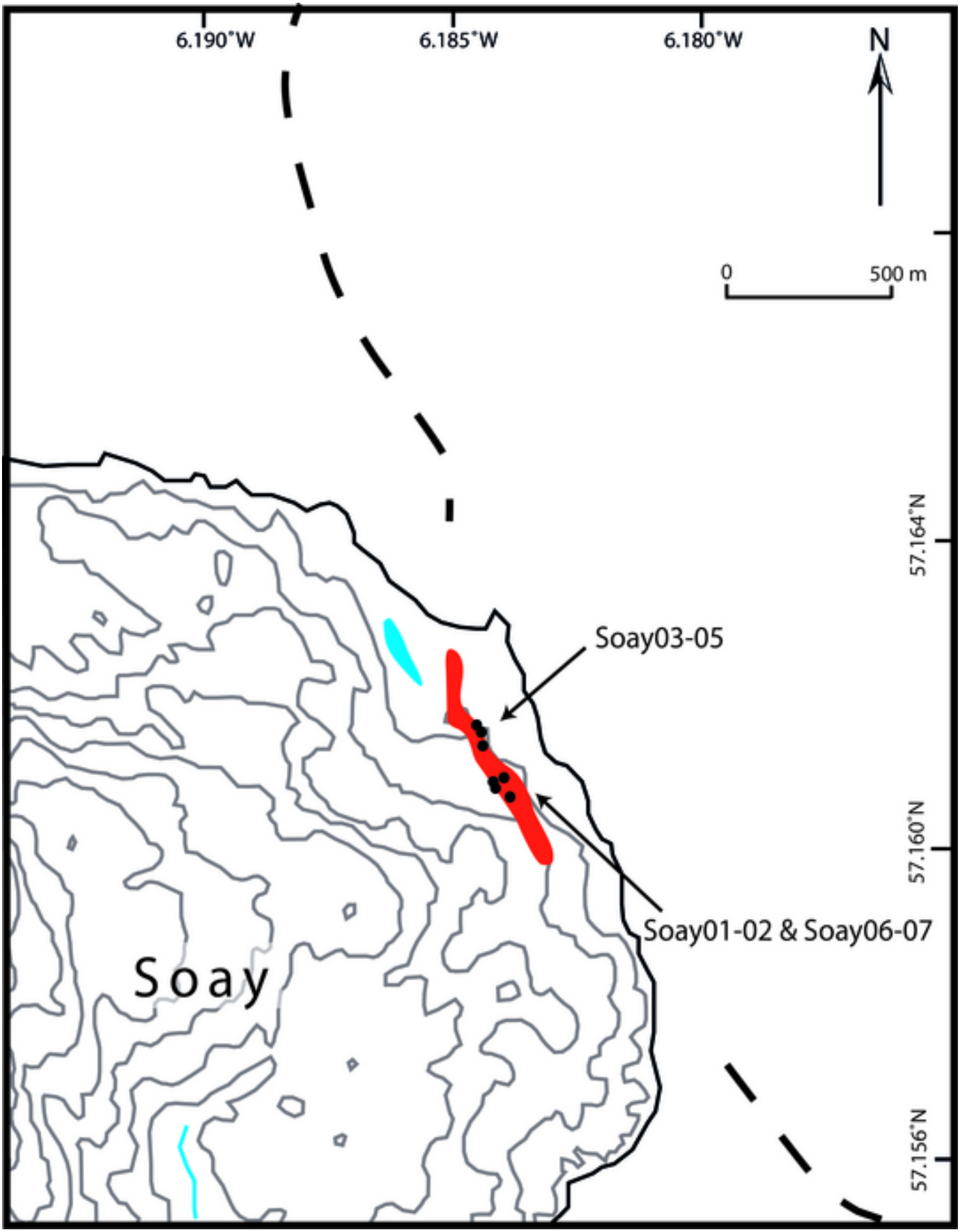

Figure 5
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Figure 6

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Figure 7

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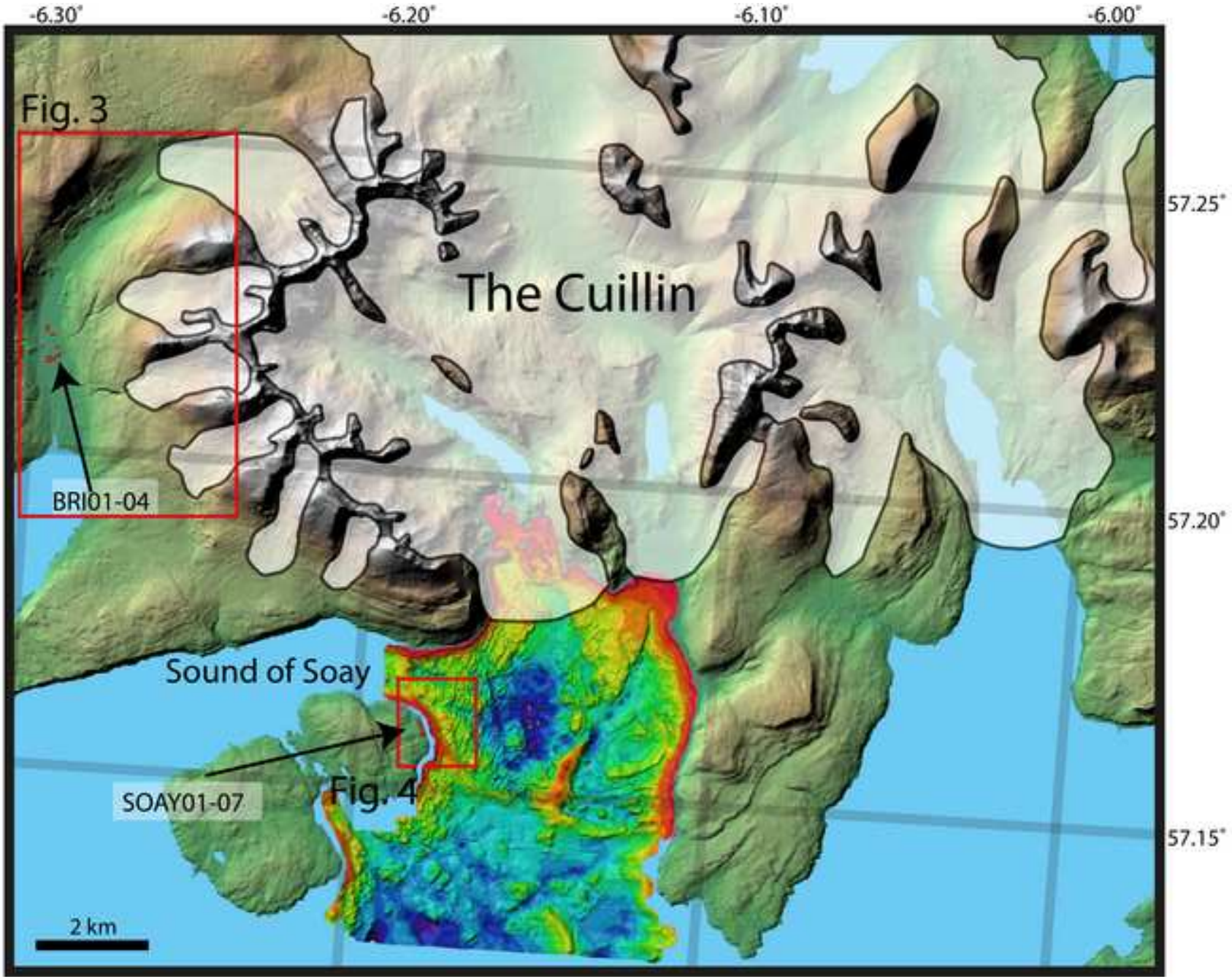

Figure 8

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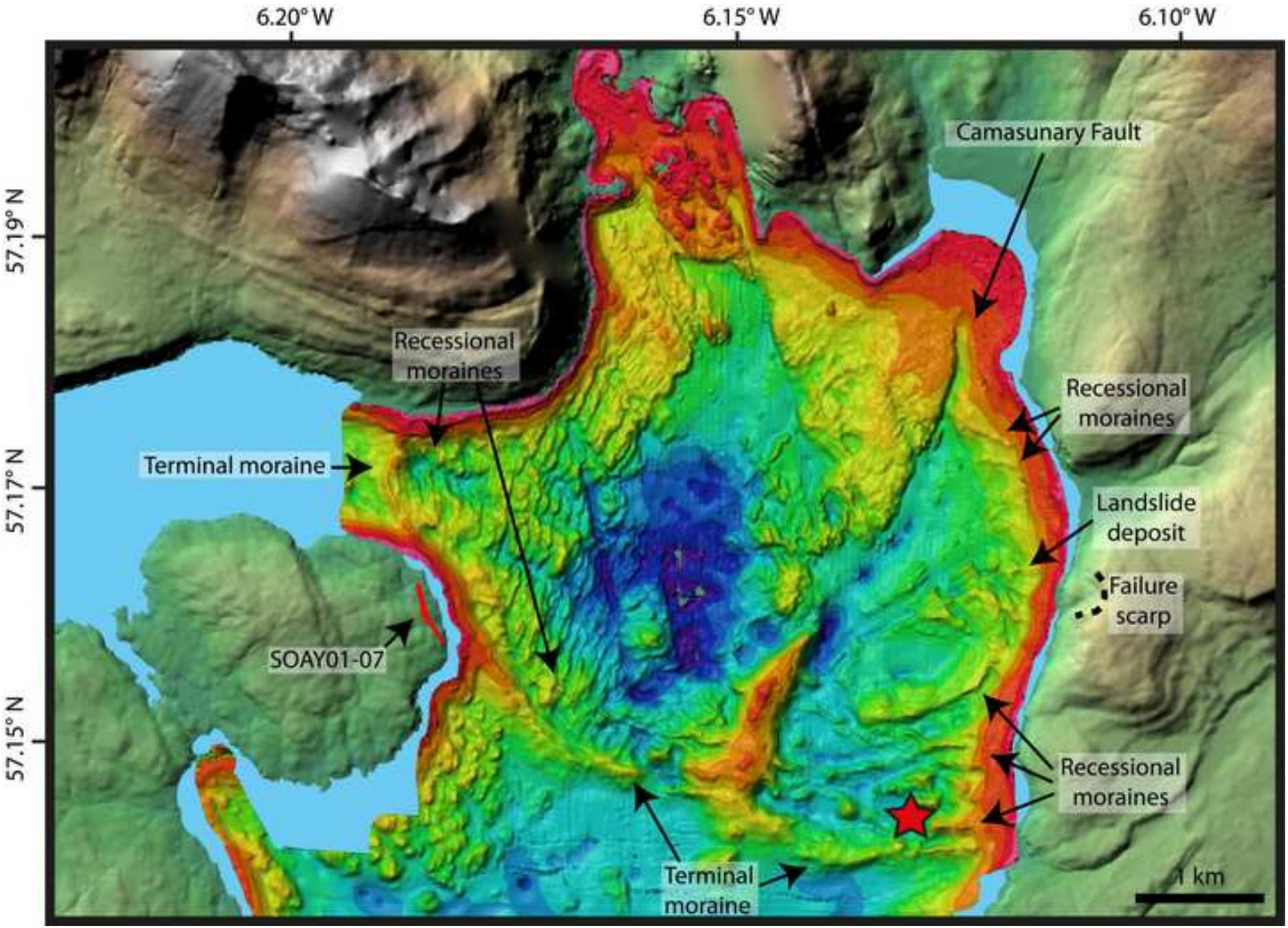

Figure 9

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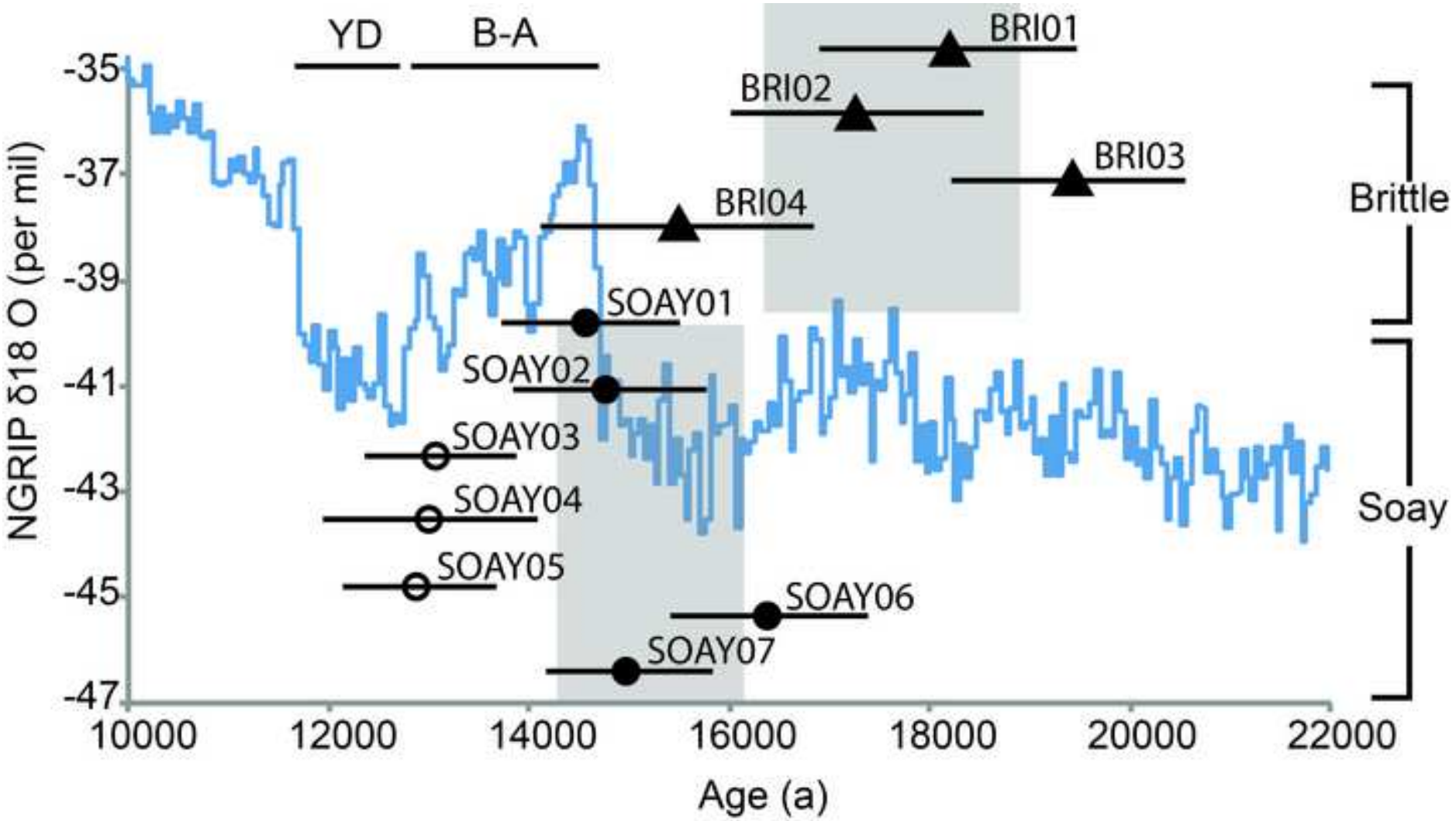

Figure 10

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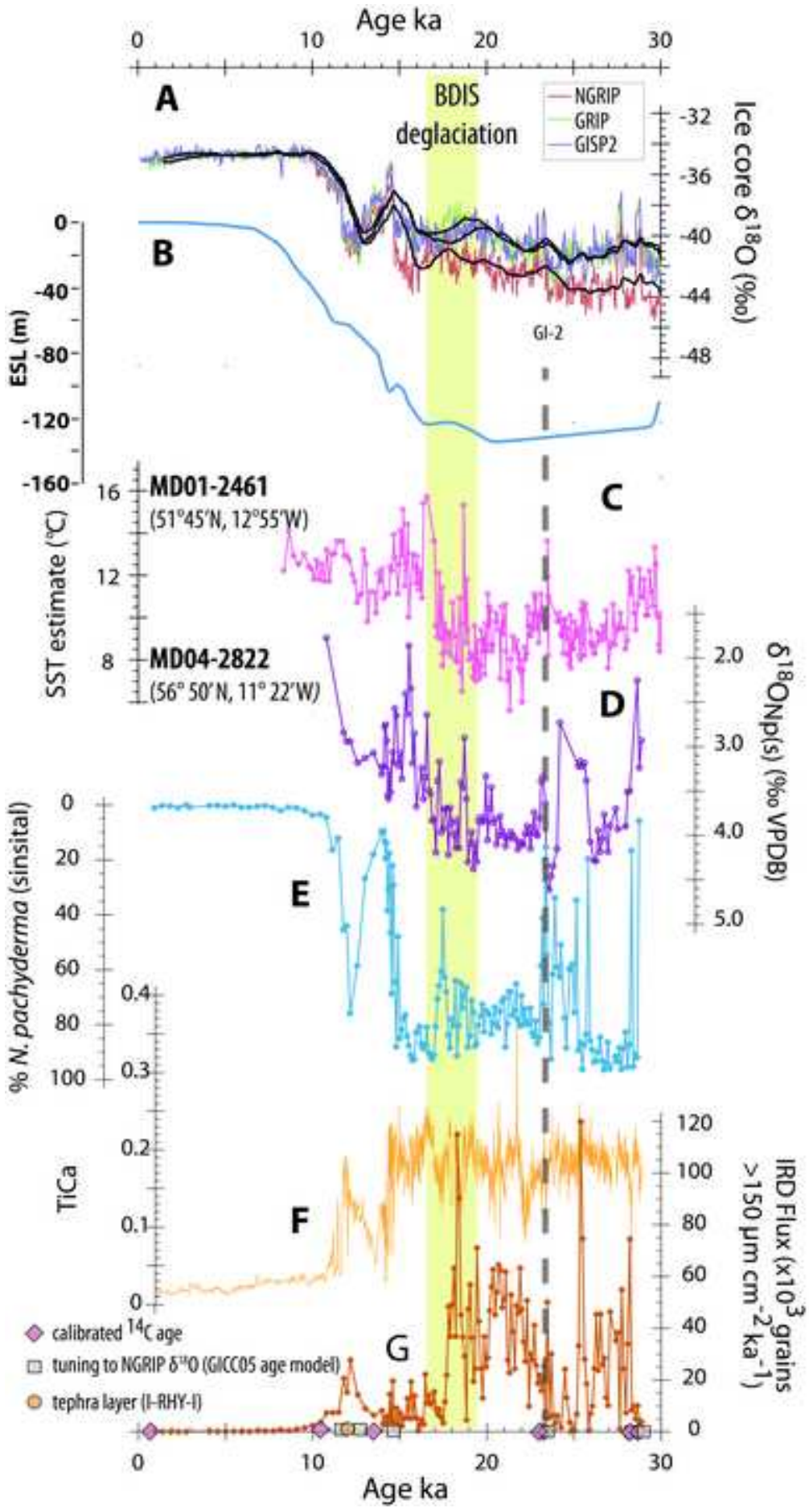

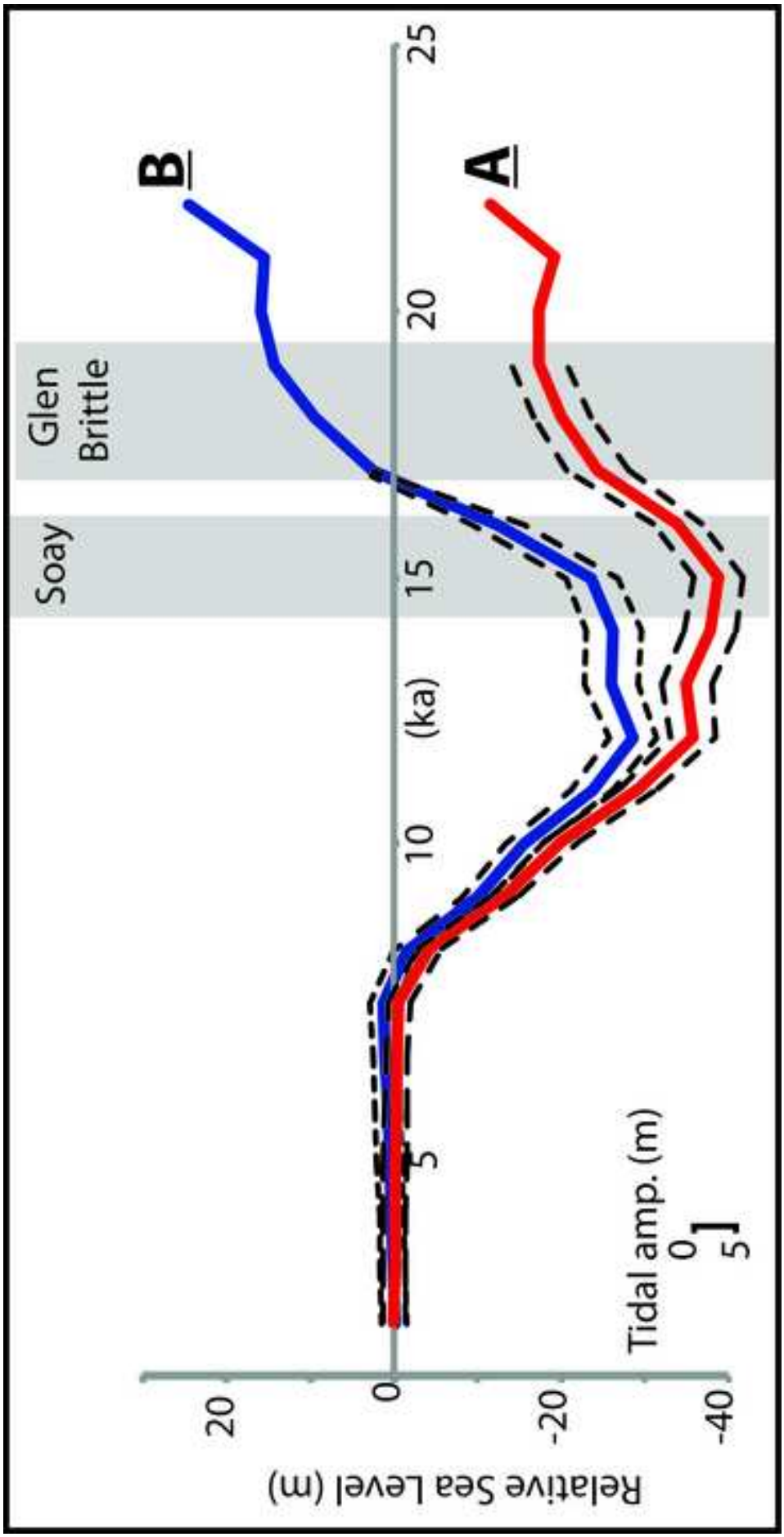

Figure 11
Click here to download high resolution image

Highlights

- We present new ^{36}Cl exposure ages from southern Skye, northwest Scotland.
- Deglaciation of a marine terminating ice stream that drained the BIIS occurred by 17.6±1.3 ka.
- Offshore bathymetry reveals a moraine delimiting a pre-Younger Dryas readvance.
- Dated to 15.2±0.9 ka and occurred at the same time as a regional scale readvance.

***Response to Reviewers**

Reviewers' comments:

Reviewer #1: The paper provides an interesting review of the state of knowledge of deglaciation in the study area, and the results obtained help to improve knowledge on the subject. However, there is a need to improve the clarity of the text and figures in order to help the reader understand the real meaning of these results.

In particular, the rationale for the ages selected to explain the possible stillstand/readvance glacial stages should be improved, and the results obtained should be interpreted more cautiously when relating these stages to regional climatic phases.

I suggest the following improvements in this regard:

Abstract:

Synthesize or remove the general ideas (lines 26 -29), and instead clarify the precise objective of the study and indicate what kind of landforms were sampled and provide more precision in the location data. When describing the results, it would be useful to indicate the range of dates obtained in the datings, according to the different age calculator models applied, as well as the variety of ages obtained for different samples from the same moraine, in order to clarify the actual degree of uncertainty in the ages reported in the study. The chronological relationship between the landforms analysed in this study and recognised climatic phases in the region should be formulated as a hypothesis, not as established fact, due to the degree of uncertainty of the results. *– Abstract has been modified along these lines. There is more detail on location, specifically that the samples are from boulders on two moraines in Skye. The range of mean values for the moraines depending on choice of calculation method/scaling has been included.*

1. Introduction

The first two paragraphs discuss very general aspects (lines 44-64) which are not subsequently analysed in the discussion; they could therefore be considerably condensed. – *These paragraphs have been amalgamated into one introductory paragraph intended to set the scene as to why studying former marine ice stream provides useful information.*

There is a very interesting update of knowledge on the study area (line 83 onward), but it would be very helpful if this were preceded by a new paragraph, however brief, describing the state of knowledge on the stages of deglaciation in the western sector of the British-Irish Ice Sheet, which should then be addressed further in the discussion. I think it would be interesting to cite the data provided in the most recent synthesis papers published, such as Clark et al. (2012) and Hughes et al. (2016) and to include the latest contributions, such as Peters et al. (2016). This would help to improve the paper's focus on its actual contribution: the chronology of landforms. *– A section has been added (lines 103-109). This is after the point the reviewer suggests it be inserted however we feel that it sits better as a synthesis of the pattern of deglaciation after the existing geochronology has been introduced as it was this geochron that was used to create the isochrones We have added selected isochrones to Figure 1.*

2. Study site

A reader who is unfamiliar with the study area will find it difficult to locate the areas described. To remedy this, it is essential to show all geographical names on the maps (Figures 1 and 2) and to include geographical coordinates in Figure 1. *– We have added place names to Figures 1 and 2 (also suggested by Reviewer 2).*

3. Results

The exact location of each sample and its geomorphological meaning is not described in either the text or the figures. Neither is a description given of the geomorphology of the area sampled in the section on the study area. The existence of several moraines in the Glen Brittle sector is mentioned (line 148), but the authors do not clearly state which moraines they took samples from or what geomorphological relationship exists between them. *– Text added in methods section and samples shown on map in new figures.*

Regarding the Soay sector, the authors do not give a detailed explanation as to why the moraine studied should be interpreted as from the same unit as that observed by bathymetry (Scavaig moraine). The geomorphological relationship between the two study areas is not made clear in the text. This difficulty in comprehending the exact geomorphological context of each of the samples is accentuated by the fact that most of the samples from each sector are given exactly the same geographical coordinates. It is unclear whether this coincidence is due to error or to a lack of accuracy regarding the location. In fact, the only place in the paper where reference is made to the geomorphological characteristics of the moraines studied is in the discussion section, when it should be in the results, and the information provided is minimal (line 350 onward). *– The Soay moraine is interpreted as a continuation of the offshore moraine because it is directly traceable onto and off the island and this aligns directly with the moraine seen in the swath bathymetry. The section on the geomorphological characteristics has been moved to the results and the reasoning for interpreting the moraine section on Soay as the same feature as the Loch Scavaig moraine has been added (lines 306-310). Additional text (Line 149-153) has been added to highlight the relationship between the two study areas. The sample locations have been checked and more precision given in the table. There are new figures 3 and 4 that locate each individual sample on its respective moraine.*

To remedy this, a map or image should be included for each sample area, in which each sample is located in detail, within a specific geomorphological context, and this should also be described in sufficient detail in the text. *– Figures have been added and text updated.*

4. Discussion

In the previous section (results), decisions are made when selecting the ages considered as valid for each geomorphological unit. These are selected from different possible ages, according to the different scalings applied (line 308 onward) and according to the results for different samples from the same moraine (line 335 onward). However, this decision should be made in the discussion section, following further analysis. *– The selection of the ages we believe best represent the true moraine age has been moved to the discussion section*

The contrast between the results obtained with the age calculation model and the production rates of Schimmelpfenig et al. (2009, 2011 and 2014) and Marrero et al. (2016 a and b) is very interesting and

requires, if possible, a more detailed explanation. *–We have been in contact with Shasta Marrero and the difference in ages between the Lm scaling using CRONUScalc and Irene's calculator has been rectified. The age difference between the Lm and SA scaling however is real. The LSD scaling schemes (including the SA) treat Muons/Low energy Neutrons differently to the Lal based scalings and this may cause differences in ^{36}Cl ages. Additionally, we could speculate that it may be due to the elevation atmospheric pressure model used. We wish to avoid broad speculation and complexities beyond the scope of the paper. The CRONUScalc paper notes that there may be some difference between Lm and SA in some locations but our difference does seem large. However barring further analysis we are unable to comment further. We have added a line in the results section acknowledging the age difference is currently enigmatic.*

The same is true when assessing the criterion used to establish the ages of some blocks as valid and reject others. For example, in the Soay sector, it is not clear why the authors only considered the age of the oldest samples to be valid (SOAY 1 and 2), although the other three (SOAY 3, 4 and 5) shared a common age. On the one hand, the authors should explain why a possible exhumation of those blocks occurred precisely at the same time, and on the other, they should also explain why, if some blocks were exhumed, others were not in an earlier period. *– We have added additional text outlining why we believe contemporaneous exhumation of the three younger samples is possible (Lines 397-406).*

In addition, if the impossibility of cosmogenic inheritance in Soay samples is accepted, it is not clear why this criterion is not applied to the Glen Brittle sector, where the age of the oldest samples (BRIO 1 and 3) does not serve to explain an advance with this age, as in Soay, but rather the arithmetic mean age is selected between samples from the same sector. Although the solution adopted in the selection of valid ages is one option, it is not the only one, and it should therefore be carefully discussed and clarified. *– We acknowledge that our ages may over or under estimate the age of the Glen Brittle moraine. For Soay we base our interpretation on geomorphic evidence (new lines 417-428; i.e. boulder height, spatial proximity of young samples) and evidence from elsewhere in Scotland that does not favour ice survival through the warm interstadial which would be required if the young Soay ages were the true moraine age.*

As mentioned earlier, the lack of a concrete explanation of the geomorphological context of the samples leaves the reader with many unanswered questions.

The rest of the discussion proceeds as if there were total certainty about the absolute precision of the ages selected as valid. This allows the authors to relate the moraines studied to recognised climatic events in the region. In my opinion, they should be more cautious, leaving the possibility of a wider range of ages open in the discussion, and differentiating in each statement between certainty and what are actually their hypotheses. This difference is made clear in the conclusions, but as already indicated, not in the abstract. *– We have amended the discussion in various places to highlight the uncertainty in our ages and added an additional paragraph (lines 429-435) explicitly stating this and that we are proposing a hypothesis.*

CITED REFERENCES: Hughes, A. L. C., Gyllencreutz, R., Lohne, Ø. S., Mangerud, J., Svendsen, J. I. 2016. The last Eurasian ice sheets - a chronological database and time-slice reconstruction, DATED-1. Boreas, Vol. 45, pp. 1-45.

Peters et al., 2016. Sedimentology and chronology of the advance and retreat of the last British-Irish Ice Sheet on the continental shelf west of Ireland, Quaternary Science Reviews 140 101-124.

Reviewer # 2:

In this paper the authors discuss the timing of possible past ice extent variations on the Isle of Skye during the Lateglacial based on 11 36Cl exposure ages. The paper is well written and interesting to read as it interweaves published data and hypotheses on the timing of ice margin variations.

I think the paper has the potential to be significant, nevertheless the following two deficiencies must be addressed before this paper is publishable:

1. The maps are rather insufficient: a map showing the specific geomorphology of the dated sites is required; a map showing regional relationships would increase the clarity of the presentation.
2. The calculation of the 36Cl ages must be checked again.

These two topics will be discussed in more detail below in addition to further minor suggestions.

I believe this paper could have an important impact on our understanding of glacier variations in western Scotland during the Lateglacial. It is a nice summary although the presentation is rather ineffective and could be quite easily improved.

Unfortunately the cosmogenic data is not portrayed in a way useful to the reader. Actually I have no idea which boulders are where with respect to the moraines (etc.). The photos are somehow ok but do not allow an understanding of what was dated with respect to the landforms, former ice margins etc. Perhaps I have missed a figure? Every dated boulder and the associated landforms must be shown on a map. –*New Figures have been added that show the location of the boulders with respect to the moraines. (i.e. taken from the moraine crest)*

This paper is written as if everyone is an expert in UK geography. I do not think it is appropriate to expect the reader to look up terms in google maps to figure out what the authors are talking about.

Simply labeling the existing figures better could rectify much of this.

The following locations are discussed but not identified on maps:

Inner Hebrides - *Removed*

outer Hebridean platform (where is the boundary between these two?) –*Boundary is concurrent with western shoreline of Outer Hebrides. Text amended and Outer Hebrides labeled on Figure 1.*

St Kilda basin – *Changed to "mid-shelf"*

Sea of the Hebrides – *removed from text*

Sound of Soa – *Labeled in Figure 5.*

Rum- *Labeled in Figure 2*

Cuillin This is referred to several times, seems to be a key location. Where is it? Just put it on a map.

Cuillin is the name of the mountains of Skye. It is Labeled on Figure 2 and Figure 5

Coriusk basin/Scavaig basin – *Coruisk removed from text, Scavaig basin changed to Loch Scavaig*

Loch Scavaig - *Labeled in Figure 2.*

Barra Fan – *Should read Barra-Donegal Fan, changed and shown on figure 1.*

Rockall Trough – *Added to figure 1.*

Location of core MD01 2461, which figure? – *It is not possible to show this core without a dedicated figure. We give its co-ordinates and describe its distance and direction from the study area.*

Study Site

Where is the map that goes with this? Must the reader go find the maps in Walker or Ballantyne? The long-term impact of this paper would definitely increase if the previously dated landforms are shown on a map in relation to the landforms dated in this paper, and of course with respect to postulated former ice margins. *–Added location of Strollamus moraine to Figure 5 (both sites are already shown on figure 2). Walker et al., did not present a map of the moraines in Glen Brittle (the ones that are dated in this paper). We present a new Figure, Figure 3, a larger scale map of Glen Brittle showing the moraines, sampled boulders and relationship to the Younger Dryas limits mapped by Ballantyne. Figure 4 is a very large scale map of the northeast corner of Soay showing trace of the offshore moraine, onshore segment and sample locations.*

36Cl methods

$BaNO_3$? Actually it is $Ba(NO_3)_2$ – *Changed.*

What value is used for Po in the age calculation? Please state this. This number is required so that in the future, we can know exactly how the ages were calculated. – *Value has been added. We apologise for the accidental omission.*

The supplementary data tables are incorrectly labeled. CaO, K_2O are target elements not non-target elements. In any case the elemental data should be combined in one table and should be included in the main paper, not as a supplemental table. All data required to calculate an age must be in the main body of the paper for future recalculations.- *Tables have been combined and included in main body of paper*

It may be irrelevant to use the Schimmelpfennig et al. (2009) production rates.- *The column has been removed from the table*

Actually, I am not sure why there should be such huge differences between the results from the other three calculation methods (last three columns in Table 3). The equations and constants are well known. In detail the calculation methods should be generally the same. Effects due to scaling at this latitude and altitude should not be so great. These numbers need to be carefully checked again. – *We have contacted Shasta Marrero. The discrepancy between the ages as calculated using the Lm scaling using Schimmelpfennig et al. (2009) and Marrero et al (2016a) has been rectified, this was due to a error in the spreadsheet we were using. The difference between Lm and SA scaling is however real as they use the same input data into CRONUScalc (bar the scaling scheme chosen). We could speculate*

that this may be due to the elevation atmospheric pressure model used but this ventures into idle speculation and complexities beyond the scope of the paper. The CRONUScalc paper notes that there may be some difference between Lm and SA in some locations but our difference does seem large. However barring further analysis we are unable to comment further. We have added a line in the results section acknowledging the age difference is currently enigmatic. Again we have discussed this with Shasta who acknowledges that this difference is larger than one might expect but currently the cause in this specific location is not known.

DISCUSSION

Line 323: "The boulder ages are not a single population." This based on statistical treatment. How do the ages look spatially? At this moment the reader has no idea where the boulders are located in space with respect to the landform(s?). Maybe there is some spatial geomorphological relationship between the group of old ages and group of young ages for the SOAY samples. I appreciate that the authors considered this, but the reader should be able to assess the situations himself. – *Text has been added (lines 378-389) to discuss the potential spatial relationship*

328: "....generally cosmogenic moraine ages can underestimate...." This is strictly only true for 10Be ages. The data set of Heyman is made up of 10Be ages. It is well known that because of the stronger depth penetration and higher percentage of production due to muons that 36Cl may have (much) more inheritance than 10Be.

Similarly, the response of the 36Cl age to erosion (which always makes 10Be ages older) is less predictable than for 10Be. Indeed erosion/spalling can make 36Cl ages apparently older. The 36Cl specific issues should be discussed. – *The ^{36}Cl specific issues are mentioned (374-381). We sampled as best we could to avoid inheritance and/or boulder spalling (outlined in text added to methods section) but this is obviously not infallible. We acknowledge the possibility that our ages may overestimate moraine age.*

329: This is true, it is generally unlikely that inheritance would yield a 'pattern'.

335: The location of the core with respect to the ice limit is not shown. Why should an age of 13 ka not agree with deglaciation at 12.8 ka? Please elaborate. – *Reference to the radiocarbon age has been removed.*

372: What/where is the Strollamus moraine? What is the Scavaig moraine? Why is it a medial moraine? Where are all these moraines located? – *The Strollamus moraine is shown on Figure 2 and Figure 5. We explicitly mention it in the captions to these figures so we hope that it is clear where it is located. Its interpretation as a medial moraine is discussed fairly extensively in Benn 1990 and Small et al., 2012. In reference to the Scavaig moraine, it is not a medial moraine. We have found a typo in the text (line 388) where 'Scavaig' should read Strollamus.*

FIGURES

Fig. 1. Please identify the sites with respect to Table 1. – *Sites have been numbered as in an amended*

Table 1.

Fig. 2. Map with previous studies, red stars. Please identify which site is which. –*Stars are now numbered*

Fig. 3. Why are the moraines and boulders shown in the photos not located in detail on any maps? *New Figures (Figures 3 and 4 show the location of the boulders)*

Figure 3A. ".two parallel moraine ridges.." where are these on Fig. 5 or 6? *See Figure 3, the ridges were already depicted on Figure 5 (now 7) although the scale may not be ideal hence the higher scale Figure 3.*

Fig. 7. Use a different symbol for each site. Identify each boulder (add to plot labels BRI01 etc.) as they are shown on the (now non-existent) geomorphological boulder/landform map and listed in the tables. – *Labels have been added and symbols changed.*

TABLES

Table 1. These sites need to be directly connected to the figures. N. Donegal coast, Islay these locations must be shown on a map. Note there are numerous ages listed in Table 1 for each site of the previous work. Did you take a mean for each site? Please specify. Again how do the ages in the table specifically relate to Figure 1? – *Caption amended to indicate that it is the mean of the CRE ages included in Figure 1. Similarly it now explains that it is the oldest 14C age from a site that is shown.*

Table 3. The 36Cl/37Cl ratio uncertainties should match the significant figures on the ratio.

The significant figures on the 36Cl concentrations are overestimated. They should as well match those of the measured 36Cl/37Cl ratio: 11.01x10^4 uncertainty: 0.79x10^4 etc. The precision of the atoms cannot exceed the precision of the AMS measurement. – *The ratios are rounded otherwise the table gets very wide and unwieldy. The concentrations are calculated from the AMS data and match the precision in this. We have added to the caption to highlight this.*

Supplementary Data

Click here to download Supplementary Data: Supp Tab1.xlsx