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1 **Late Pleistocene glaciations on the sub-Antarctic Kerguelen Archipelago: new**
2 **evidence from ³⁶Cl CRE dating and comparison with other southern mid-latitude**
3 **glacier records**

4

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23

24 Abstract:

25 Previous paleo-glacial studies on Kerguelen showed a singular pattern of Holocene glacier
26 evolution on this archipelago in comparison with other southern mid-latitude glacier records.

27 In this study, we aim to test this singularity on a longer timescale, based on 26 new *in situ*-
28 produced ³⁶Cl ages from pre-Holocene glacio-geomorphic features. Samples from moraine

29 boulders and glacially polished bedrock were extracted at six different sites, located near the

30 Port-aux-Français scientific station (PAF site), on Longue Island, Australia Island, on the Port-

31 Jeanne d'Arc Peninsula (PJDA site), on the Gallieni Peninsula at Baie Larose (BLR site) and

32 the McMurdo Island. The moraine ages indicate that glacier culminations occurred during

33 Marine Isotopic Stage 3 (MIS 3) at 42.2 ± 4.9 ka on the PAF site, and during the global Last

34 Glacial Maximum (gLGM) at 21.5 ± 3.2 ka on the PJDA site and at 21.4 ± 3.7 ka and $19.4 \pm$

35 2.6 on Baie Larose site. This is the first time that Late Pleistocene glacier culminations are
36 evidenced on Kerguelen by direct moraine dating, thus allowing comparison with other
37 moraine records from the southern mid-latitudes. While it remains speculative whether or not
38 the MIS 3 glacial maximum at ~ 42.2 ka is in phase with other glaciers at this latitude (due to
39 high age uncertainties), the gLGM glacial maximum is synchronous with that in other southern
40 mid-latitude regions. ^{36}Cl CRE ages of glacially polished bedrock surfaces sampled in different
41 locations of the archipelago vary from ~ 39 ka to ~ 19 ka. We interpret these results as
42 reflecting periods of deglaciation that occurred in between the two glacier culminations and
43 right after the gLGM on Kerguelen. These ages also suggest that some places of the archipelago
44 were free of ice at least since ~ 39 ka. The presence of a MIS 3 moraine at PAF site that has
45 not been obliterated by a gLGM advance suggests that the ~ 42.2 ka glacier extent was at least
46 as large as gLGM glacial maxima on the archipelago. The glacier culmination during MIS 3
47 being larger than that during the gLGM on the Kerguelen Archipelago matches observations
48 in other southern mid-latitude regions. Late Pleistocene glacier culminations on Kerguelen may
49 have been in phase with cold temperatures recorded in SST records, which suggest a cooling
50 around Kerguelen. However, climate drivers responsible for the larger MIS 3 glacier
51 culmination on Kerguelen still remain unclear even if we hypothesize that changes in
52 precipitation may have superimposed on temperature changes.

53 Keywords: glacier fluctuations; paleoclimate; ^{36}Cl CRE dating; Late Pleistocene; Marine
54 Isotopic Stage 3; Marine Isotopic Stage 2; Last Glacial Maximum; Southern mid-latitudes; sub-
55 Antarctic; Kerguelen Islands.

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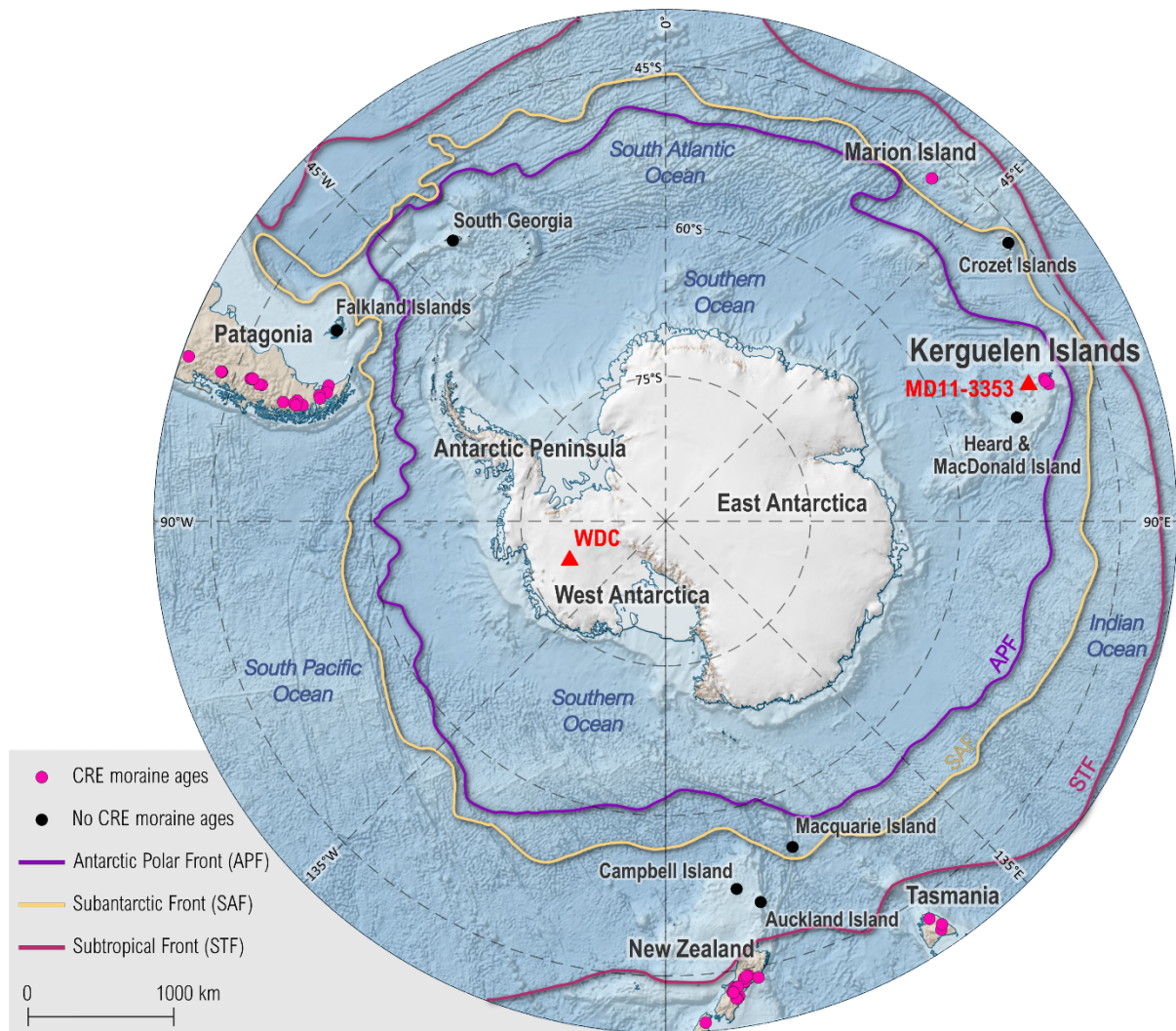
1. Introduction

63 Southern Hemisphere terrestrial glacier evolutions since the beginning of Marine Isotopic
64 Stage 3 (MIS 3; 60 - 26.5 ka) remain less constrained than in the Northern Hemisphere. In
65 addition, most of the existing long-term paleoglacier data are documented in New Zealand
66 (*e.g.*, Denton et al., 2021) and Patagonia (*e.g.*, Garcia et al., 2018) and remain scarce in other
67 parts of the sub-Antarctic sector (*e.g.*, Rudolph et al., 2020), due to the predominance of small
68 islands with underwater moraines and limited terrestrial records of glacier fluctuations (Fig. 1).
69 Yet, the sub-Antarctic islands constitute key targets relevant to the reconstruction of local
70 glacier evolution and regional climate mechanisms with regard to the effects of the latitudinal
71 migration of the Southern Westerly Winds and hydrological fronts (*e.g.*, the Antarctic Polar
72 Front). Recent investigations on Holocene glacier fluctuations in the southern mid-latitudes,
73 based on cosmic-ray exposure (CRE) dating of glacio-geomorphological landforms showed
74 that glacier behavior differs depending on the region during the Holocene (Charton et al.,
75 2022). One of the regions where the glacier pattern during the Holocene was particularly
76 divergent is the sub-Antarctic Kerguelen Archipelago (49°S, 69°E), located in the southern
77 Indian Ocean. Existing chronological constraints from erratic boulders and bedrock surface
78 ages only provided a general idea of the glacier extents and retreat dynamics prior to the Late
79 Glacial period on Kerguelen (Jomelli et al., 2018). However, direct moraine dating from MIS
80 3 and the gLGM are lacking so far, preventing a meaningful comparison with the records in
81 other regions (*e.g.*, New Zealand, Patagonia). Glacier reconstructions from other regions of the
82 southern mid-latitudes indicate major glacier extents during MIS 3 (*e.g.*, in New Zealand,
83 Strand et al., 2019), which are often characterized in the literature as an early local Last Glacial
84 Maximum (*e.g.*, Rudolph et al., 2020), as they constitute a larger glacier advance than during
85 the global Last Glacial Maximum (gLGM; 26.5 - 19 ka; Clark et al., 2009). Moreover, glaciers

86 from the southern mid-latitudes also frequently experienced advances and/or stagnations
87 during the gLGM (*e.g.*, Leger et al., 2021; Tielidze et al., 2022), synchronously with ice sheets
88 reaching their maxima at the time of the globally lowest sea level (Clark et al., 2009).

89 Here we use direct moraine dating to tackle the question whether glaciers located on the
90 Kerguelen Archipelago (*i*) experienced an early local Last Glacial Maximum during the MIS
91 3 period consistent with other regions from the southern mid-latitudes and (*ii*) re-advanced
92 during the gLGM in line with the global-scale maximum extent of mountain glaciers and ice
93 sheets. Answering these questions will also allow us to understand if the archipelago was totally
94 covered by ice during either MIS 3 or the gLGM and explore possible climatic mechanisms.

95 To that end, we provide 26 new ^{36}Cl CRE ages from moraine boulders and glacially polished
96 bedrock samples. This dataset includes samples from six different sites of the Kerguelen
97 Archipelago, which improves our understanding of Late Pleistocene glaciation at the
98 archipelago's scale and therefore the climatic conditions responsible for such glacial activity.



99

100 **Fig. 1** - Regional setting of the Kerguelen Archipelago in relation to other mid-latitude regions of the
 101 Southern Hemisphere and the Southern Ocean, with schematic physical oceanography from Mazloff et
 102 al. (2010). Sites referred to in the text are annotated, in particular the climatic proxies (red triangles)
 103 discussed in section 5.3. Please note that legend refers to CRE moraine ages during the investigated
 104 period, i.e., from ~45 ka to ~19 ka. Background map is from the geospatial data package Quantarctica
 105 (Matsuoka et al., 2021 and references therein).

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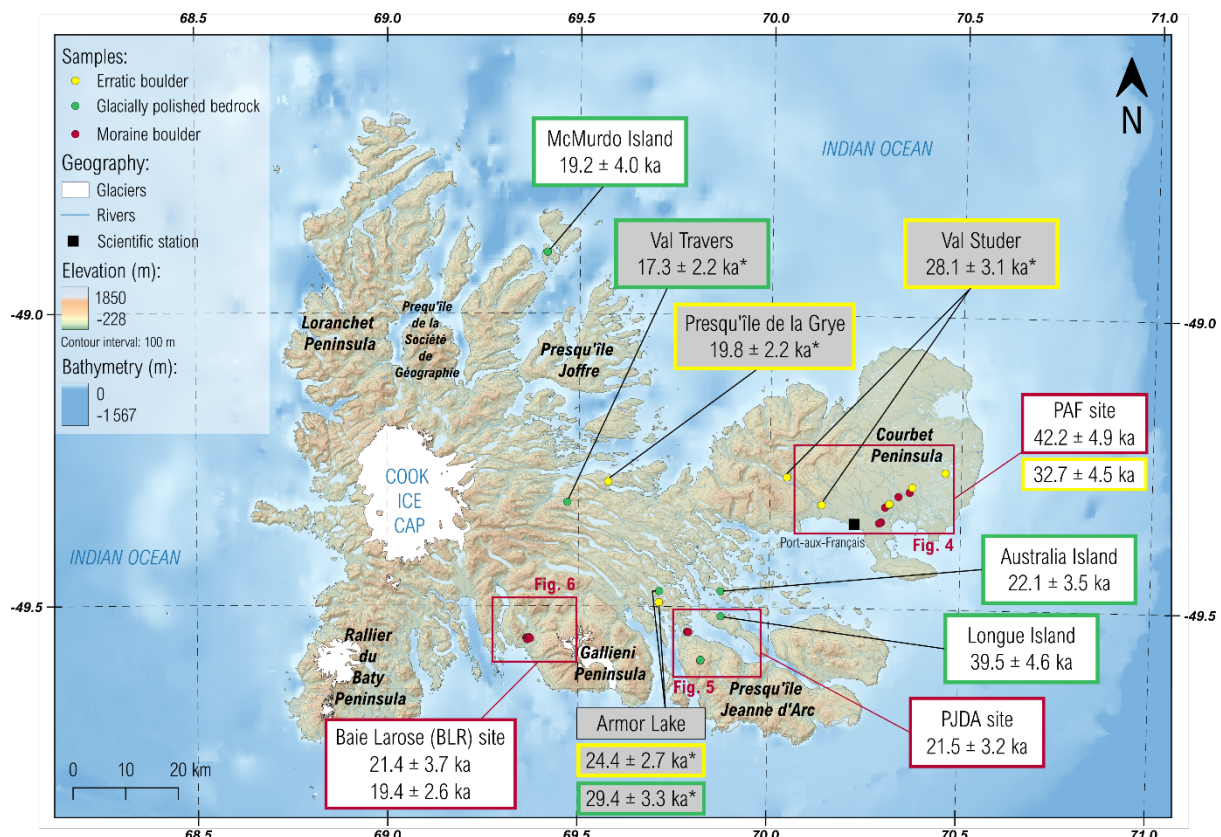
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2. Regional setting

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113 The sub-Antarctic Kerguelen archipelago is located in the southern Indian Ocean at a latitude
114 of 49°S and longitude of 69°E (Fig. 1). Both the volcanic and glacial activities have shaped the
115 topography of the archipelago, whose highest peak Mt Ross culminates at 1850 m asl. Indeed,
116 the landscape of the archipelago is mostly characterized by a basaltic/volcanic substratum, that
117 is almost entirely dissected by large former glacial valleys and fjords and rare vegetation (Fig.
118 2). Kerguelen Archipelago's surface area (7215 km²) is the emerged part of the large
119 Kerguelen-Heard oceanic plateau formed by the Kerguelen plume (Giret et al., 2003). The
120 archipelago is mainly composed of piles of basaltic lavas (flood basalts) emplaced between 30
121 and 24 Ma but younger volcanism occurs in the southeast provinces and during the Quaternary
122 on the Rallier du Baty Peninsula and at Mont Ross in the Gallieni province (<1 Ma) (Fig. 2).
123 Locally some (large) plutonic bodies were emplaced at depth in the crust; the large syenite
124 laccolith in the Rallier du Baty Peninsula being the best example (Ponthus, 2018). At present,
125 Kerguelen is located south of the Antarctic Polar Front (Fig. 1; Mazloff et al., 2010). The
126 archipelago is influenced by the Antarctic Circumpolar Current that flows eastward between
127 45°S and 65°S (Sallée et al., 2008; Solokov and Rintoul, 2009). The Antarctic Circumpolar
128 Current and Southern Annular Mode (Gillett et al., 2006; Sallée et al., 2008) drives the
129 Southern Westerly Winds which creates a humid and slightly cold subpolar climate. Today, the
130 average annual precipitation is about 800 mm per year and the annual temperature is about
131 4.5°C at the scientific station Port-aux-Français (PAF) (i.e., at sea level). However, the
132 precipitation amounts on the main island are affected by a strong W-E gradient due to a foehn
133 effect on the eastern side of Cook Ice Cap (culminating at 1050 m asl and located on the western
134 part of the archipelago), which constitutes a barrier to the dominant westerly winds. At Cook
135 Ice Cap, the precipitation amount reaches 3150 mm per year at 250 m a.s.l. (Verfaillie et al.,
136 2015). Altogether, the current climatic conditions still favor glacier preservation on Kerguelen

137 even at low elevations (*e.g.*, at ~ 400 - 1000 m asl). Indeed, the Kerguelen Archipelago still hosts
 138 currently the largest glaciated areas of the sub-Antarctic islands (552 km² in 2001; Berthier et
 139 al., 2009; Fig. 2). The largest ice body of the archipelago is the Cook Ice Cap located on the
 140 west side of the main island Grande Terre, which covered ~ 400 km² in 2020 (Verfaillie et al.,
 141 2021; Fig. 2). Other mountain glaciers can be found on the Rallier du Baty Peninsula, the
 142 Gallieni Peninsula and the Presqu'île de la Société de Géographie Peninsula (Fig. 2). However,
 143 recent studies on the archipelago showed that the atmospheric drying over Kerguelen since the
 144 1960s, caused by the positive phase of the Southern Annular Mode, led to the shrinking of the
 145 glaciers, which are expected to completely disappear by 2100 CE (Berthier et al., 2009; Favier
 146 et al., 2016; Verfaillie et al., 2021).



147
 148 **Fig. 2** - Map of the Kerguelen Archipelago with available ³⁶Cl ages (this study, literature). Boxes show
 149 arithmetic mean ³⁶Cl ages of samples of moraine boulders (red frames), erratic boulders (yellow frames)
 150 and glacially polished bedrock (green frames) from this study (white boxes) and previous literature
 151 (Grey boxes and asterisk; Jomelli et al., 2017, 2018; Charton et al., 2022) with their inferred total
 152 uncertainties. Three of the study areas are framed in red: Port-aux-Français (PAF) site, Port-Jeanne
 153 D'Arc (PJDA) site, and Baie Larose (BLR) site, for which geomorphological maps are presented in
 154 Figs. 4, 5 and 6, respectively. (data: Digital Elevation Model from NASA/METI/AIST/Japan

155 Spacesystems and U.S./Japan ASTER Science Team, 2019; glacier outlines from the GLIMS database
156 (Raup et al., 2007)).
157

158 **3. Methods**

159

160 **3.1. Sampling and study sites**

161

162 Selecting sample sites on Kerguelen relies on logistic feasibility (*e.g.*, weather, boat cruise
163 availability) as the entire archipelago is very difficult to reach. Also, glacio-geomorphic
164 features are often hard to identify on aerial imagery and are only visible in the field.

165 Sample collection was carried out during a field campaign in 2017-2018. A total of 26 samples
166 from glacially-polished bedrock and moraine boulders were collected for ^{36}Cl CRE dating
167 (Table 1). We used a hammer and a chisel to extract the uppermost 2-3 cm flat and non-
168 weathered moraine boulder and bedrock surfaces (*e.g.*, Fig. 3a, c). We recorded the geographic
169 coordinates and elevations with a handheld GPS device and measured the topographic
170 shielding in the field with a clinometer.

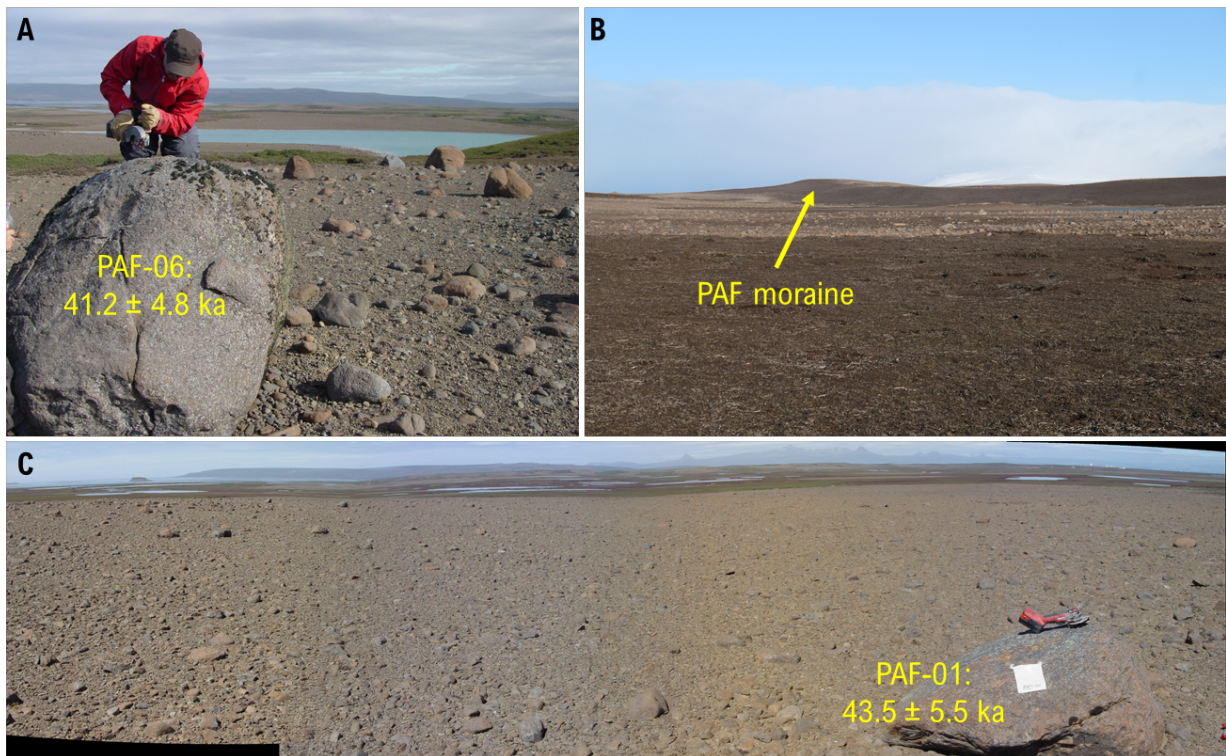
171 We targeted several sites around the archipelago that present glacio-geomorphological
172 landforms expected to be older than the Holocene. For this study two following types of glacio-
173 geomorphological features were dated: (*i*) moraine boulder samples, providing information on
174 the extent and timing of a glacier being in equilibrium with climate at the end of a glacier
175 advance or during a stillstand, hereafter referred to as culmination and (*ii*) glacially polished
176 bedrock samples, informing on the timing of deglaciation during glacier retreat and the
177 corresponding ice extent. While only features unambiguously formed by ice were sampled, the
178 source areas of the glaciers cannot always be clearly identified, as described in the following
179 paragraphs.

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181 **3.1.1. Moraine sampling sites**

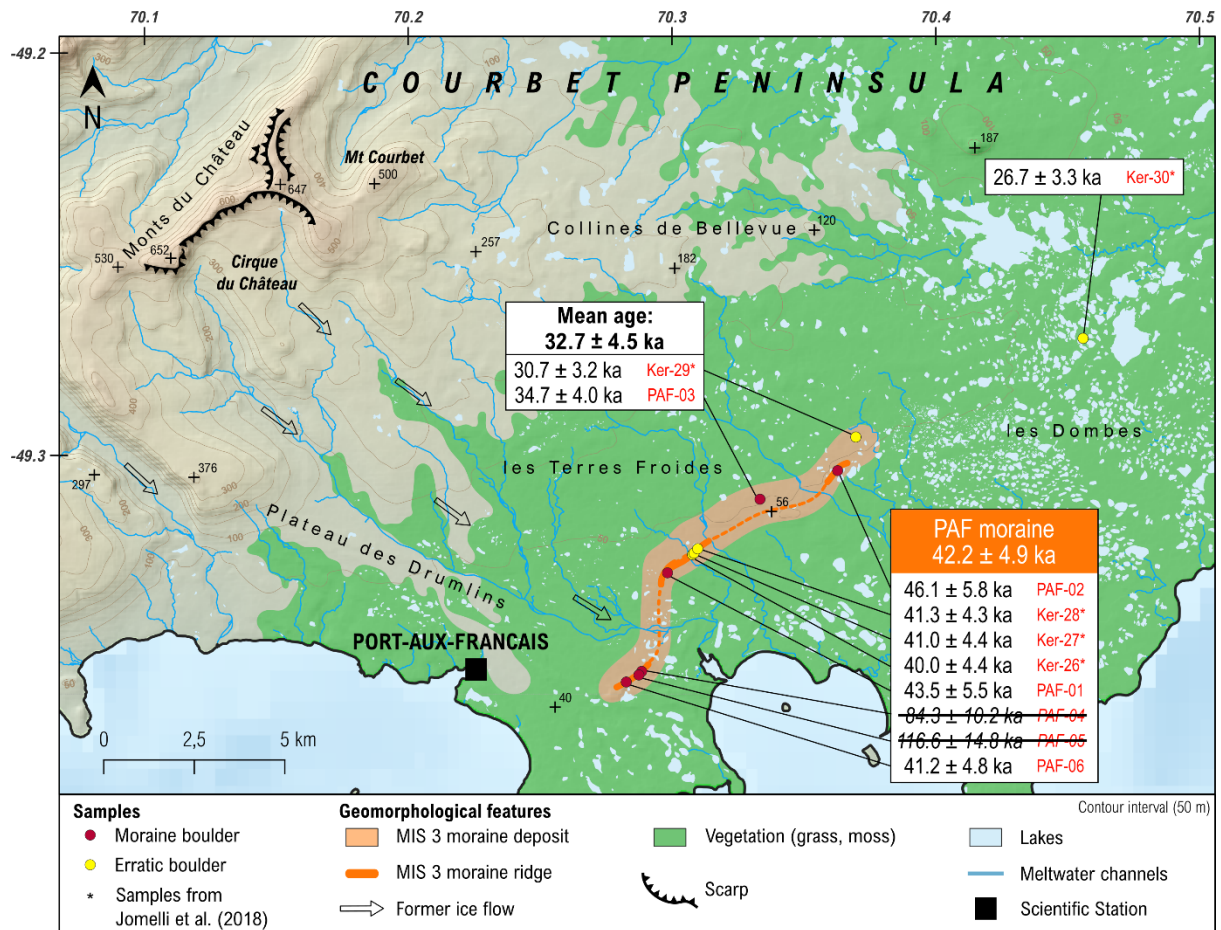
182 Moraines were investigated at the following three sites.

183 We first explored the surroundings of Port-aux-Français (PAF), which is the only scientific
184 station on the archipelago, located in the eastern part of Courbet Peninsula (Fig. 2, 3 and 4).
185 This area hosts features that are expected to document glacier fluctuations since MIS 3, based
186 on the previous erratic boulders dated to 41.4 ± 4.4 ka (n=3) by Jomelli et al. (2018) (Fig. 4).
187 The sampling site near PAF is, at first sight, rather flat and composed of Quaternary deposits
188 with scattered erratic boulders lying on top (Fig. 3a, c). However, during this field campaign,
189 moraine remnants, called here “PAF moraine” were identified. These moraine remains are
190 about 20 m high and have an asymmetric cross profile with a gentle top and steep slopes, the
191 distal slope being steeper than the proximal one (Fig. 3b). They are preserved over 300 m in
192 length and have a north-south orientation. On top of these moraine remains, six large boulders
193 were sampled at ~ 30-70 m asl. This PAF moraine was certainly deposited more than ~ 20 km
194 east of a local paleo-glacier, with the assumed hilly accumulation area located on the ‘*Monts*
195 *du Château*’ (Fig. 4). Nowadays, no glaciers exist in this area. In between the PAF moraine
196 and the assumed accumulation area of the paleo-glacier, some erratic boulders had already been
197 dated (Jomelli et al., 2018) and may be associated with the same glacial advance period (Fig.
198 4).



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Fig. 3 - Photographs of sampled moraine boulders at the Port-aux-Français site, also displayed in Fig. 2 and 4. **A)** PAF-06 moraine boulder and the PAF moraine in the background. **B)** The PAF moraine. **C)** View of PAF moraine around PAF-01 moraine boulder. (Photos taken in 2018).



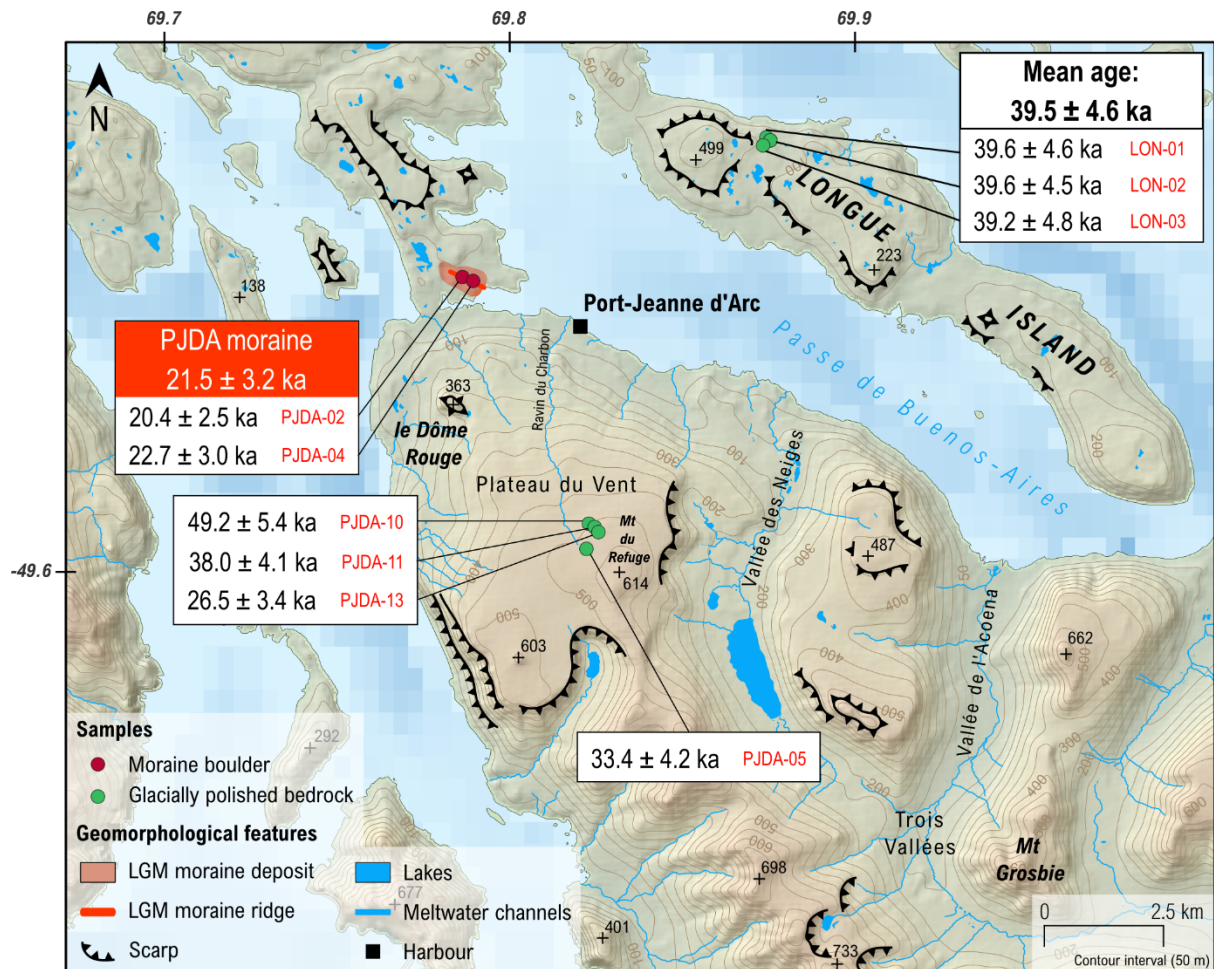
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205 **Fig. 4** - Glacial geomorphological map of the Port-aux-Français site. White boxes show new ^{36}Cl sample
 206 ages of moraine boulders and erratic boulders from Jomelli et al. (2018) with their inferred total
 207 uncertainties. Samples written in striked-through italic text are rejected as outliers and therefore
 208 excluded from the discussion. The arithmetic means for moraine boulder group (colored box) and
 209 glacially polished bedrock group (white box with black bold frame) are shown with their total
 210 uncertainties (*i.e.*, standard deviation, analytical and production rate uncertainties).

211

212 Then, we investigated the Port Jeanne D'Arc Peninsula (PJDA) located in the southeast of the
 213 archipelago (Figs. 2, 5). Here, the moraine remains also belong to disappeared local paleo-
 214 glaciers. Two moraine boulders were sampled on the isthmus of the peninsula at ~ 30 m asl.
 215 We assume that the former ice flowed southeast to northwest from paleo-glaciers located in the
 216 hilly center of the peninsula (~ 570 m asl) (Fig. 5).

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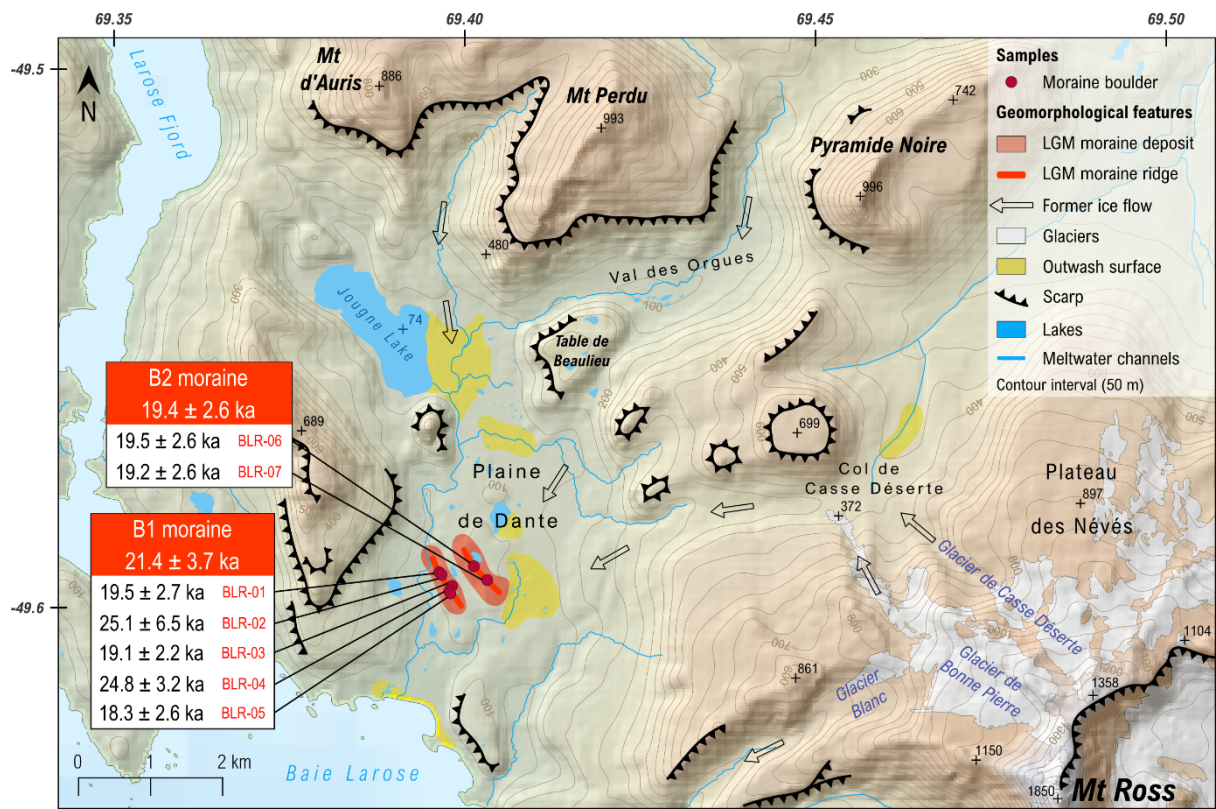
219 **Fig. 5** - Glacial geomorphological map of the PJDA site. White boxes show new ^{36}Cl sample ages of
 220 moraine boulders and glacially polished bedrock with their inferred total uncertainties. The arithmetic
 221 means for moraine boulder group (colored box) and glacially polished bedrock group (white box with
 222 black bold frame) are shown with their total uncertainties (*i.e.*, standard deviation, analytical and
 223 production rate uncertainties).

224

225 Finally, we visited the Baie Larose site located south of the archipelago on the west side of the
 226 Gallieni Peninsula (Figs. 2, 6). This location is of particular interest since this peninsula is
 227 dominated by the highest peak of the archipelago, the stratovolcano Mt Ross (1850 m asl),
 228 around which several cirque glaciers still flow down to the valley but remain poorly
 229 documented so far (*e.g.*, ‘*Glacier de Casse Déserte*’, ‘*Glacier de Bonne Pierre*’; Fig. 6).
 230 Moreover, the already partially surveyed mountain glaciers located on the eastern slope of Mt
 231 Ross are largely debris-covered (Charton et al., 2021), whereas glaciers located on its western
 232 flank are mostly debris-free. Deposited by these debris-free glaciers, two moraines were

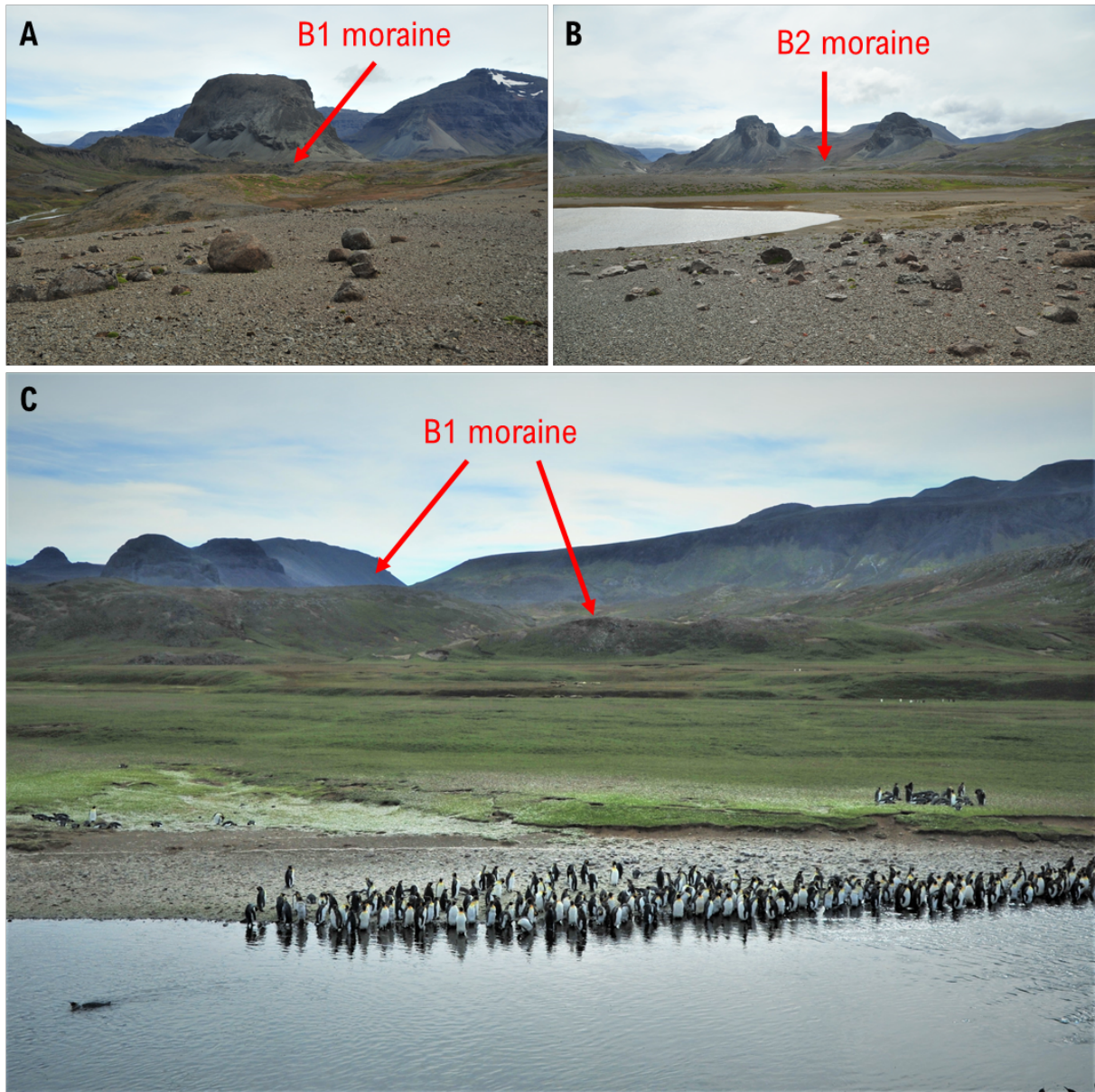
233 targeted for sampling. These moraines were most probably formed by a local glacier on the
 234 northwestern flank of the volcano at ~ 8 km from the current glacier front and at ~ 2 km from
 235 the sea (Figs. 6, 7). The two moraines are separated by a horizontal distance of ~ 390 m. On
 236 the inner B2 moraine (Fig. 7b), two samples were extracted from moraine boulders at ~ 115 m
 237 asl, and five samples were taken on the outer B1 moraine at ~80 m asl (Fig. 7a, c).

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Fig. 6 - Glacial geomorphological map of the Baie Larose site. White boxes show new ³⁶Cl sample ages of moraine boulders with their inferred total uncertainties. The arithmetic means for moraine groups are shown in colored boxes with their total uncertainties (*i.e.*, standard deviation, analytical and production rate uncertainties).



245

246 **Fig. 7** - Photographs of moraines at Baie Larose site. **A)** B1 (outer) moraine at Baie Larose site. **B)** B2
247 (inner) moraine at Baie Larose site. **C)** B1 moraine from the sea.

248

249 **3.1.1. Glacially polished bedrock sampling sites**

250 In addition to the moraines at these three sites, we collected samples from glacially polished
251 bedrock surfaces in four distal areas east- and northward from the Cook Ice Cap (Fig. 2).

252 Two of the sites were located on two small islands: Australia Island and Longue Island. These
253 islands located south of the Courbet Peninsula and in total five samples were extracted from

254 glacially polished bedrock. Two samples were taken on Australia Island at 62 m asl and three
255 others on Longue Island at 110 m asl (Fig. 2).

256 The third site was on the PJDA Peninsula, between the supposed accumulation area of the
257 paleo-glacier and the PJDA moraine deposition. Four glacially polished bedrock surfaces were
258 sampled: one at low elevation (260 m asl) and three at higher elevation (480 m asl) (Fig. 5).

259 The last site was on McMurdo Island, a very isolated area located in the north of the
260 archipelago. We extracted two samples from glacially polished bedrock at ~ 151 m asl (Fig. 2).

261

262 **3.2. *In situ* ³⁶Cl laboratory analysis**

263 The basaltic whole-rock samples were processed for ³⁶Cl extraction at LN₂C (CEREGE,
264 France) according to routine procedures using the same methods as in the previous studies
265 undertaken on Kerguelen (Jomelli et al., 2017, 2018; Charton et al., 2020, 2022; Verfaillie et
266 al., 2021). ³⁶Cl/³⁵Cl and ³⁵Cl/³⁷Cl ratio measurements were performed at the ASTER AMS
267 national facility (CEREGE, France) after normalization to the inhouse standard SM-CL-12,
268 using an assigned value of $1.428 (\pm 0.021) \times 10^{-12}$ for the ³⁶Cl/³⁵Cl ratio (Merchel et al., 2011)
269 and assuming a natural ratio of 3.127 for the stable ratio ³⁵Cl/³⁷Cl. ³⁶Cl CRE ages were
270 calculated with the Schimmelfennig et al. (2009) Excel spreadsheet, assuming no denudation
271 or snow cover and using the time-invariant “St” scaling scheme (Stone, 2000). The chemical
272 composition of the samples used for the calculation are displayed in Tables 2 and 3. Consistent
273 with the earlier studies on Kerguelen, the following ³⁶Cl sea level high latitudes (SLHL)
274 production rates were used for the calculations: 42.2 ± 4.8 atoms of ³⁶Cl (g Ca)⁻¹ yr⁻¹ for Ca
275 spallation (Schimmelfennig et al., 2011), 148.1 ± 7.8 atoms of ³⁶Cl (g K)⁻¹ yr⁻¹ for K spallation
276 (Schimmelfennig et al., 2014), 13 ± 3 atoms of ³⁶Cl (g Ti)⁻¹ yr⁻¹ for spallation of Ti (Fink et
277 al., 2000), 1.9 ± 0.2 atoms of ³⁶Cl (g Fe)⁻¹ yr⁻¹ for Fe spallation (Stone et al., 2005), and $696 \pm$
278 185 neutrons (g air)⁻¹ yr⁻¹ for the rate of epithermal neutron production from fast neutrons in

279 the atmosphere at the Earth/atmosphere interface (Marrero et al., 2016). We applied a value of
280 160 g cm^{-2} for the high-energy neutron attenuation length and 2.4 g cm^{-3} for the bulk rock
281 density. The resulting ^{36}Cl ages with their associated 1σ uncertainties (*i.e.*, the total
282 uncertainties which take into account the analytical and production rate uncertainties) and their
283 analytical uncertainties in brackets are listed in Table 4. Moraine ages and grouped bedrock
284 ages result from the arithmetic means of the individual sample ages that successfully pass a
285 Chi^2 test, calculated with their analytical uncertainties (Ward and Wilson, 1978). In the main
286 text and on the figures, ages are reported with their total uncertainties.

287

288 **3.3. Compilation of CRE moraine boulder ages for comparison with other moraine** 289 **chronologies from the southern mid-latitudes**

290 To get a better understanding of glacier fluctuations in the southern mid-latitudes, we
291 performed a compilation of CRE moraine boulder ages based on version 1 of the alpine
292 informal cosmogenic-nuclide exposure-age database (ICE-D database; now replaced by
293 <https://version2.ice-d.org/alpine/>). All the ^{10}Be , ^{26}Al and ^3He CRE ages gathered within ICE-
294 D are recalculated with the online exposure age calculator v3 (<http://hess.ess.washington.edu/>;
295 after Balco et al., 2008) using the same parameters for all the nuclides, which are the St scaling
296 method (Stone, 2000) chosen for this study, the ERA40 reanalysis atmosphere model (Uppala
297 et al., 2005) and the GLOPIS-75 magnetic field reconstruction (Laj et al., 2004). Regarding the
298 production rates, we chose the default data set calibrated from the CRONUS-Earth primary
299 calibration data sets of Borchers et al. (2016) for ^{10}Be and ^{26}Al in quartz and ^3He in
300 pyroxene/olivine.

301 We also recalculated four ^{36}Cl CRE ages ($n=4$) from Marion Island (Rudolph et al., 2020) with
302 the Schimmelpfennig et al. (2009) Excel spreadsheet using the same parameters and methods
303 as explained above for the Kerguelen ^{36}Cl CRE ages calculation.

304 While compiling, two criteria were considered: (i) we only included CRE-dated moraine
305 boulder ages, and (ii) we considered a moraine only if it was dated with at least two CRE
306 boulder ages that successfully passed a Chi^2 test. For CRE age pools successfully passing the
307 Chi^2 test, an arithmetic mean age and standard deviation of the landform was calculated.

308 All the compiled ^{10}Be , ^{26}Al , ^{36}Cl and ^3He CRE moraine ages are presented in Supplemental
309 Tables 1, 2 and 3 calculated with the St (Stone, 2000) scaling scheme. They are reported with
310 their standard deviation.

311

312 **4. Results**

313 We obtained 26 new ^{36}Cl CRE ages from the six sites on Kerguelen. We first present in
314 chronological order the results of moraine boulder samples collected on the PAF site, PJDA
315 site and Baie Larose site and then those from glacially polished bedrock surfaces at Longue
316 Island, PJDA Peninsula, Australia and McMurdo islands.

317 **4.1. Moraine boulders ^{36}Cl CRE ages**

318 At the PAF sampling site, the five moraine ridge boulders PAF-01, -02, -04, -05 and -06 yield
319 ^{36}Cl ages of 43.5 ± 5.5 ka, 46.1 ± 5.8 ka, 84.3 ± 10.2 ka, 116.6 ± 14.8 ka and 41.2 ± 4.8 ka,
320 respectively (Table 4, Fig. 4). PAF-04 and -05 are probably affected by nuclide inheritance and
321 are rejected as outliers. Due to their close location, these samples from the moraine ridge can
322 morphologically be associated with some of the erratic boulders already published in Jomelli

323 et al. (2018) and may thus be associated with the same glacial event. These erratic boulders are
324 Ker-26, -27 and -28, which gave ages of 39.3 ± 3.6 ka, 40.4 ± 3.6 ka and 39.4 ± 3.5 ka,
325 respectively (Jomelli et al., 2018). Taken together, the six samples PAF-01, -02, and -06, Ker-
326 26, -27 and -28 yield an arithmetic mean age of 42.2 ± 4.9 ka ($n=6$). This mean age confirms
327 the age of the three erratic boulders from this location previously dated by Jomelli et al. (2018)
328 at 41.4 ka \pm 4.4 ka. Boulder PAF-03 is located on the till inboard of the PAF moraine ridge,
329 and gives an age of 34.7 ± 4.0 ka. This boulder has a stratigraphically similar position as the
330 previously dated boulder Ker-29 that gave an age of 30.7 ± 3.2 ka (Jomelli et al., 2018).
331 Altogether the arithmetic mean and total uncertainty of these two boulders are 32.7 ± 4.5 ka (n
332 = 2).

333 On the PJDA Peninsula, samples PJDA-02 and -04, from the PJDA moraine give consistent
334 ages of 20.4 ± 2.5 ka and 22.7 ± 3.0 ka, respectively, and yield a mean age of 21.5 ± 3.2 ka (n
335 = 2) (Table 4, Fig. 5).

336 At the Baie Larose site, the ^{36}Cl ages from the base of Mt Ross BLR-01, -02, -03, -04 and -05
337 of the outermost (oldest) B1 moraine are 19.5 ± 2.7 ka, 25.1 ± 6.5 ka, 19.1 ± 2.2 ka, 24.8 ± 3.2
338 ka and 18.3 ± 2.6 ka, respectively (Table 4, Fig. 6). The arithmetic mean and total uncertainty
339 of B1 moraine are 21.4 ± 3.7 ka ($n = 5$). On the innermost (youngest) B2 moraine, samples
340 BLR-06 and -07 give ^{36}Cl ages of 19.5 ± 2.6 ka and 19.2 ± 2.6 ka, with a mean age of $19.4 \pm$
341 2.6 ka (Table 4, Fig. 6). The nominal moraine mean ages are in agreement with their
342 stratigraphic position, though it is noteworthy that the seven individual ages from both B1 and
343 B2 moraines are indistinguishable.

344 **4.2. Glacially polished bedrocks ^{36}Cl CRE ages**

345 The three bedrock surface samples extracted on Longue Island, LON-01, -02 and -03, yield
346 consistent ages of 39.6 ± 4.6 ka, 39.6 ± 4.5 ka and 39.2 ± 4.8 ka, respectively. The arithmetic

347 mean age and total uncertainty of the bedrock surfaces at Longue Island are 39.5 ± 4.6 ka
348 (Table 4, Fig. 5).

349 On the PJDA Peninsula, glacially polished bedrock samples located ~6 km SE' of the moraine
350 give ^{36}Cl ages of 33.4 ± 4.2 ka at lower elevation (PJDA-05), and 49.2 ± 5.4 ka, 38.0 ± 4.1 ka
351 and 26.5 ± 3.4 ka at higher elevation (PJDA-10, -11 and -13) (Table 4, Fig. 5). These latter
352 three ages are inconsistent with each other according to the Chi^2 test. Also, though the origin
353 of the ice flow remains unclear, the four glacially polished bedrock samples seem to be inboard
354 of the PJDA moraine. Thus, it is most likely that these ages are overestimated for so far
355 inexplicable reason. Indeed, they should be younger than ~ 21 ka.

356 Bedrock surface samples from Australia Island, AUS-02 and -05, give ages of 20.8 ± 2.6 ka
357 and 23.4 ± 3.2 ka, respectively. Together these samples yield a mean bedrock surface age of
358 22.1 ± 3.5 ka (Table 4, Fig. 2).

359 Finally, at the McMurdo Island sampling site, the ^{36}Cl ages of the two bedrock surface samples
360 are 21.5 ± 2.7 ka and 17.0 ± 2.2 ka, respectively. The arithmetic mean age of these two samples
361 at McMurdo Island is 19.2 ± 4.0 ka (Table 4, Fig. 2).

362

363 **5. Discussion**

364 **5.1. Late Pleistocene glacier chronologies on Kerguelen**

365 The 26 new ^{36}Cl ages obtained from moraine boulders and glacially polished bedrock samples
366 at several locations on the Kerguelen Archipelago help refine Late Pleistocene glacier
367 fluctuations (Jomelli et al., 2018; Charton et al., 2022; Fig. 2). The oldest evidence of glacier
368 culmination on the archipelago is shown by the PAF moraine, which was deposited at $42.2 \pm$

369 4.9 ka (n=6). So far, this moraine is the only dated glacio-geomorphological feature that attests
370 to a large glacier advance or stagnation during the MIS 3 period. The PAF moraine was
371 emplaced at ~ 20 km from the assumed paleo-accumulation area of the former glacier near
372 Mont du Château (Fig. 4).

373 Another extensive glacier advance or stagnation happened during the gLGM, as suggested by
374 moraines in two other locations on the archipelago. One is a moraine dated at 21.5 ± 3.2 ka
375 (n=2) located on the Port Jeanne D'Arc Peninsula (PJDA) (Fig. 5). The other moraine site is
376 Baie Larose on the Gallieni Peninsula, where the outer B1 moraine is dated at 21.4 ± 3.7 ka
377 (n=5) and the inner B2 moraine was deposited at 19.4 ± 2.6 ka (n=2) (Fig. 6). Hitherto, this is
378 the first time that gLGM glacier advances are evidenced in the Kerguelen Archipelago and it
379 seems this event was probably synchronous at the archipelago scale. The PJDA moraine and
380 the set of moraines at Baie Larose were emplaced at ~ 8-9 km from the accumulation area of
381 their respective glaciers (Figs. 5, 6). In addition, the moraines are located very close to the
382 shoreline (less than ~ 2 km), suggesting that glacio-geomorphological features of advances pre-
383 dating the gLGM at these sites are nowadays underwater.

384 In between these two extensive glacier culminations, *in situ* ^{36}Cl dating of glacially polished
385 bedrock surfaces at several places on the islands provide new knowledge of the history of
386 deglaciation since the maximum glacier extent on the archipelago (Fig. 2). The oldest CRE ^{36}Cl
387 bedrock ages of ~ 39.5 ka are located on the eastern side of the archipelago on Longue Island,
388 indicating a long period free of ice between MIS 3 and probably nowadays at this relatively
389 low elevation location (~ 110 m asl) (Fig. 5). Assuming that both local mountain and ice cap
390 glaciers experienced events of greater extent at ~ 42.2 ka that covered most of the archipelago,
391 these older bedrock surfaces from Longue Island suggest that the culminations were rapidly
392 followed by a period of deglaciation. It is very likely that since shortly after the MIS 3 glacier

393 expansion, this part of the archipelago has never been covered by ice again. Indeed, we suppose
394 that subsequent local glacier extents as large as the MIS 3 culmination can be excluded or if
395 larger local glacier advances occurred, they did not erode enough rock surfaces to remove the
396 entire previously accumulated ^{36}Cl inventory. Other new bedrock surfaces located on the
397 eastern part of the archipelago, on Australia Island and PJDA Peninsula, provide ^{36}Cl CRE ages
398 varying from ~ 49.2 ka to ~ 22.1 ka and covering a similar age span as five bedrock surfaces
399 at Amor Lake (~ 32 ka to ~ 25 ka) as well as two erratic boulders at Amor Lake (~ 24 ka),
400 five erratic boulders in Val Studer (~ 31 ka to ~ 24 ka) and two erratic boulders in Courbet
401 Peninsula (PAF site; ~ 30 ka to ~ 26 ka) (Jomelli et al., 2018) (Figs. 2, 5). Considering glacier
402 culminations with large extents during MIS 3 (~ 42.2 ka) and MIS 2 (gLGM; ~ 21 -19 ka) on
403 the archipelago, these bedrock ages attest to a general trend of deglaciation in between these
404 two events. However, the dispersed bedrock and erratic boulder ages at the PJDA, PAF, Amor
405 Lake and Val Studer sites (Fig. 2) suggest a complex history of exposure with probably
406 alternating ice-free/ice-covered periods and non-uniform erosion. In addition, these bedrock
407 surfaces are located at varying elevations ranging from ~ 60 m asl to ~ 480 m asl, and the
408 geometry of the paleo-ice cover has not yet been reconstructed in this complex setting of fjords
409 and islands surrounded by higher-elevation topography. Thus, a specific chronology of glacier
410 fluctuations for individual ice bodies in this area is hard to establish. Altogether, these bedrock
411 and erratic boulder ages confirm a general deglacial trend on the eastern part of the archipelago
412 from ~ 42.2 ka to 21-19 ka, in agreement with the scenarios proposed earlier (Jomelli et al.,
413 2017, 2018).

414 Subsequently, younger bedrock surfaces located on the McMurdo Island on the north of Cook
415 Ice Cap show apparent ages of ~ 19.2 ka (Fig. 2). It implies that after the glacier culmination
416 during the gLGM, another period of deglaciation was initiated rapidly. In addition, it is most
417 likely that glaciers never readvanced to this position but remained relatively confined until they

418 disappeared (Fig. 2). These ages are consistent with a bedrock sample from Val Travers valley
419 that gave an age of ~ 17.3 ka (Charton et al., 2022) and an erratic boulder dated at ~ 19.8 ka
420 from Presqu'île de la Grye (Jomelli et al., 2017), that suggested a deglaciation process (Fig. 2).
421 Altogether, the combined ages of glacially polished bedrock and erratic boulder samples from
422 the gLGM - Late Glacial transition indicate that glaciers started to retreat shortly after the
423 gLGM glacier advances. Finally, the last Pleistocene glacier advances occurred on Kerguelen
424 during Heinrich Stadial 1 (17.5 - 14.7 ka; Rasmussen et al., 2014) and the Antarctic Cold
425 Reversal (14.5 - 12.9 ka) events (Jomelli et al., 2017, 2018; Charton et al., 2020, 2022).

426 **5.2. Comparison with other moraine chronologies in the southern mid-latitudes**

427 Our new ^{36}Cl CRE age dataset underlines an advance of mountain glaciers on Kerguelen (49°S,
428 69°E) during MIS 3 (42.2 ± 4.9 ka; moraine deposited at ~ 20 km from the accumulation area)
429 that was greater than during the gLGM (21.5 ± 3.2 ka, at 21.4 ± 3.7 ka and at 19.4 ± 2.6 ka;
430 moraines deposited at $\sim 8-9$ km from the accumulation area). The large uncertainties in the ^{36}Cl
431 age of the PAF moraine preclude a millennial-scale comparison with other glacier records. We
432 therefore focus here on whether glacier culminations during the time range $\sim 47-37$ ka with
433 extents beyond the gLGM advances was a common phenomenon in the southern mid-latitude
434 regions. Indeed, at the study site in the sub-Antarctic sector that is closest to Kerguelen, Skua
435 Ridge site on Marion Island (46°S, 37°E), moraines were dated with ^{36}Cl at 40.0 ± 4.1 ka and
436 at 36.1 ± 3.8 ka (Rudolph et al., 2020; see method section for the ^{36}Cl ages recalculation). The
437 moraines at the following sites were all dated with the ^{10}Be CRE dating method. In New
438 Zealand (43°S, 170°E), the Pukaki glacier also exhibits several lateral moraines during this
439 period, *i.e.*, at 43.0 ± 1.3 ka, 41.1 ± 1.9 ka and 41.1 ± 1.1 ka (Kelley et al., 2014; Strand et al.,
440 2019). In South America, glaciers in almost the entire Patagonian latitudinal belt experienced
441 culminations of large extent during this time span. For instance, moraine ages in the Central

442 Andes show an overall consistency with the timing of glacier culmination on Kerguelen, in
443 particular in Cordon de Dona Rosa (30°S, 70°W) where the glacier culminated at 37.8 ± 2.4 ka
444 (Zech et al., 2007), and in the Rucachoroi Valley where the glacier advanced at 41.3 ± 1.6 ka
445 (Zech et al., 2011). Finally, in the Southern Patagonian Icefield (50-51°S, 71-72°W), moraines
446 are dated to 37.2 ± 1.1 ka and 46.4 ± 2.7 ka in Torres del Paine (Garcia et al., 2018) and 46.6
447 ± 1.5 ka in the Ultima Esperanza Lobe (Garcia et al., 2018). These moraine chronologies are
448 supported by CRE dated glacial features at other sites. Very close to the Ultima Esperanza
449 Lobe, in Cerro Benítez, erratic boulders deposited during ice melting are dated at a minimum
450 age of 35.1 ± 1.6 ka (Girault et al., 2022). And further south (53-54°S), the glacial limit of the
451 Río Cullen of the former Bahía Inútil–San Sebastián ice lobe on Tierra del Fuego gives an age
452 of ~ 45.6 ka based on cosmogenic ^{10}Be and ^{26}Al dating of glacial outwash sediments (Darvill
453 et al., 2015). In conclusion, it seems that the Kerguelen MIS 3 glacier maxima at 42.2 ± 4.9 ka
454 may have been in phase with the other studied localities in the southern mid-latitudes, although
455 the uncertainties associated with the PAF moraine age dating are high (Fig. 8g, h).

456 Regarding the gLGM glacier culminations observed on Kerguelen at 21.5 ± 3.2 ka (PJDA
457 moraine), at 21.4 ± 3.7 ka (B1 moraine) and at 19.4 ± 2.6 ka (B2 moraine), it is noteworthy
458 that evidence of gLGM advances is missing so far on any other sub-Antarctic islands, such as
459 on Marion Island. However, the Alpine ICE-D dataset (^{10}Be , ^{26}Al and ^3He CRE ages;
460 Supplementary Tables 1, 2, 3) provides information on numerous moraines dated within this
461 period in Australia and Tasmania ($n_{\text{moraines}}=5$; e.g., Kiernan et al., 2004), in New Zealand
462 ($n_{\text{moraines}}=23$; e.g., Putnam et al., 2013; Denton et al., 2021; Tielidze et al., 2022) and Patagonia
463 ($n_{\text{moraines}}=21$; e.g., Kaplan et al., 2007; Leger et al., 2021; Çiner et al., 2022). To sum up,
464 Kerguelen glacier culminations during the gLGM are synchronous with the global event that
465 also occurred throughout the southern mid-latitudes (Fig. 8 g, h).

466 5.3. Unresolved Late Pleistocene climatic conditions on Kerguelen

467 ^{36}Cl dating of 26 moraine boulders and glacially polished bedrock samples allowed us to refine
468 our knowledge on glacier evolution on Kerguelen during the Late Pleistocene, in particular
469 since ~ 42.2 ka and until the end of the gLGM. Based on this updated glacier chronology, we
470 now investigate regional climate conditions that may be responsible for such glacier
471 fluctuations on the archipelago. In contrast to the differing trend at a multi-millennial timescale
472 of the glacier evolution in the southern mid-latitudes during the Holocene (Charton et al.,
473 2022), it seems that glaciers during periods around ~ 42.2 ka and ~ 21 -19 ka, may be
474 synchronous in all these regions considering the high uncertainties of ^{36}Cl ages (Fig. 8g, h).

475 The MIS 3 period is characterized by strong climate variability punctuated by several
476 millennial-events such as Heinrich stadials (HS), *i.e.*, cold periods over Greenland and the
477 North Atlantic, and Dansgaard Oeschger events (DO), *i.e.*, abrupt Greenland warming (NGRIP,
478 2004; Menviel et al., 2020; Fig. 8a), as well as their corresponding Southern Hemisphere
479 Antarctic Isotope Maximum (AIM) (EPICA, 2006) (Fig. 8). During the MIS 3 period, the oldest
480 glacio-geomorphological evidence of glacier activity on Kerguelen is a moraine resulting from
481 glacier culmination at ~ 42.2 ka. Thus, it raises the question of whether this glacier culmination
482 resulted from a high- (*i.e.*, centennial to millennial timescale such as the Northern Hemisphere
483 HS) or low-frequency climate driver. So far, the relatively high uncertainty associated with the
484 moraine age prevents us from a clear assignment to a specific climate event during MIS 3, in
485 particular as several climatic events occurred during the time span of the uncertainties (~ 47 -37
486 ka). These climate events are five AIM/DO events (8, 9, 10, 11 and 12; Fig. 8a, b; NGRIP,
487 2004; EPICA, 2006), the HS4 event (Fig. 8a; NGRIP, 2004) and four cold peaks (~ 37 ka, ~ 41
488 ka, ~ 43 ka and ~ 45 ka, Fig. 8b) recorded in the WDC ice core from the West Antarctic Ice
489 Sheet (WAIS Divide Project Members, 2015). If the ~ 42.2 ka moraine on the Kerguelen

490 Archipelago cannot be associated with one of the cold high-frequency climatic events, we then
491 explore the hypothesis that this glacier maximum was driven by low-frequency climate
492 conditions. A study on the current glacier evolution on Kerguelen showed that surface air
493 temperature and sea surface temperatures (SSTs) are correlated (Favier et al., 2016). Therefore,
494 we assume that paleo SST data should be more representative of the local glacier-driving
495 climate than atmospheric temperatures from Antarctic ice cores. Here, we discuss the relevance
496 of reconstructed paleo SSTs from the core MD11-3353 (50°34.02'S, 68°23.13'E; Fig. 8d)
497 located southwest of Kerguelen (Civel-Mazens et al., 2021). Besides, this marine core makes
498 it also possible to document latitudinal changes in the position of the oceanic fronts (that drove
499 the Southern Westerly Winds). Although this local record does not document the period before
500 and around 42.2 ka, relatively cold temperatures are reported around 41-40 ka, so that we can
501 speculate that temperatures were rather cold during the emplacement of the 42.2 ± 4.9 ka
502 moraine on the Kerguelen Archipelago. During MIS 3, SSTs from cores (only shown in this
503 study is core MD11-3353 in Fig. 8d) around Kerguelen suggest a more northward position of
504 the Antarctic Circumpolar Current fronts compared to their present location, in particular the
505 Antarctic Polar Front would have been located north of the Kerguelen Plateau (Civel-Mazens
506 et al., 2021). This northward migration of the Antarctic Polar Front implies long-term glacial
507 conditions around Kerguelen that may have favored the glacier expansion observed at MIS 3.
508 Such cold SSTs conditions were also reported around 45-40 ka (Jomelli et al., 2018) from the
509 Cape Basin 1089/TN057 sediment core (41°S), located on the northwest of Kerguelen in the
510 Atlantic sector of the Southern Ocean (Pahnke and Sachs, 2006)

511 Regarding the gLGM advance on Kerguelen, SSTs from the marine core MD11-3353
512 interestingly show conditions that are approximately as cold at ~42.2 ka as at ~21-19 ka,
513 indicating that hydrological fronts were also located north of the Kerguelen Plateau during the
514 gLGM (Civel-Mazens et al., 2021). However, this marine record does not provide plausible

515 explanations for the larger glacier expansion at MIS 3 than during the gLGM on Kerguelen, as
516 local SST reconstructions show no substantial temperature variation between the two
517 investigated periods. Last but not least, an increase of SSTs in core MD11-3353 (Fig. 8d) from
518 ~ 18 ka implies that the Antarctic Polar Front rapidly migrated southward (Civel-Mazens et al.,
519 2021), which may explain the deglacial trend initiated at that time on Kerguelen.

520 As long-term temperature variations do not change significantly between ~42.2 ka and ~21-19
521 ka, we suppose that precipitations also triggered glacier culmination on Kerguelen. Indeed,
522 previous studies on the archipelago suggest that glaciers are highly sensitive to precipitation
523 changes influenced by the position of the Southern Westerly Winds (*e.g.*, Favier et al., 2016).
524 As precipitation may be a key driver of the investigated glaciers, we explore the possible
525 correspondence between the reconstruction of paleo-precipitation and the glacier evolution on
526 Kerguelen. Unfortunately, terrestrial paleo-precipitation records are rare in the sub-Antarctic
527 sector, in particular on such timescale. Yet, growth rate and stable isotope ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) profiles
528 from a stalagmite (HW3) recovered from Hollywood Cave (41°57'S, 171°28'E; 130m asl) in
529 New Zealand, allow a centennial-scale investigation of the Southern Westerly Winds
530 paleointensity and thus precipitation amounts between 73 and 11 ka for the ~ 41° latitudes
531 (Whittaker et al., 2011; Fig. 8f). Speleothem growth rate increased for several millennia around
532 ~ 42.2 ka, which indicates wetter conditions in favor of glacier expansion. Speleothem growth
533 rate also peaked briefly at ~ 22-21 ka, but quantitatively twice that amount at ~ 42.2 ka. We
534 suggest that the shortly enhanced precipitation combined with the cold temperatures may have
535 triggered the ~ 21.5 ka glacier advance in Kerguelen, but the rapidly following dryer conditions
536 during the gLGM may have prevented glaciers on Kerguelen from advancing as far as their
537 previous MIS 3 extents. Still, due to the geographically remote location of this speleothem
538 climate record, correlating its interpretation to Kerguelen glacier fluctuations remains
539 speculative. However, it is noteworthy that in a transient simulation of the last glacial period

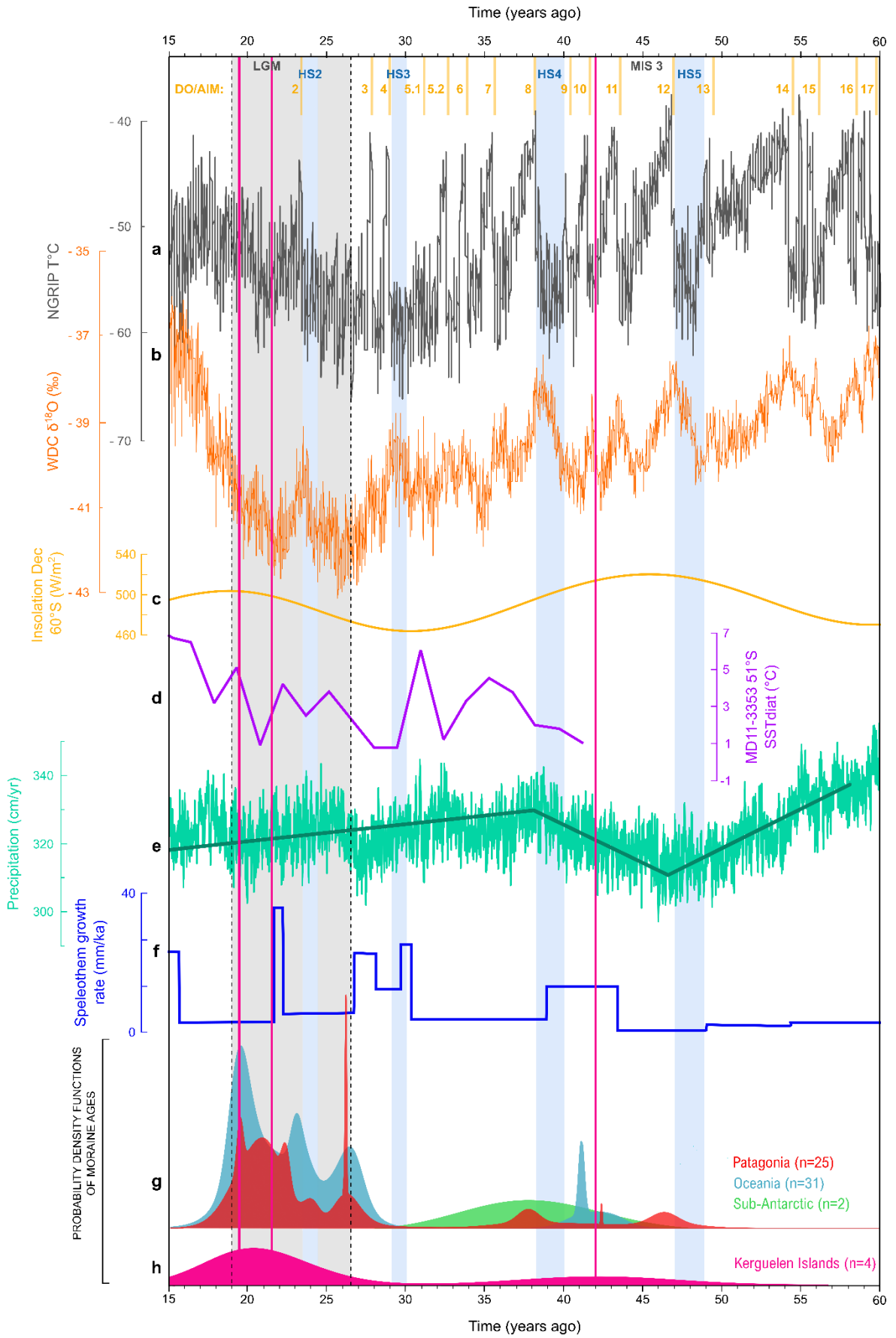
540 (Menviel et al., 2011; 2014) a decreasing trend in precipitation amount is simulated around
541 Kerguelen from ~38 ka to the gLGM, whereas an increasing trend is simulated from ~ 47-38
542 ka (Fig. 8e), which may also support our hypothesis.

543 It remains also challenging to unravel the climatic conditions that drove the glacier evolution
544 in the other mid-latitude regions, and - given their similarity - to understand whether or not all
545 glaciers were driven by the same large-scale mechanisms. The authors of several studies from
546 both New Zealand and Patagonia noticed a discrepancy between southern summer insolation
547 change and glacier change (Kelley et al., 2014; Doughty et al, 2015; Garcia et al., 2018; Strand
548 et al., 2019). They considered it unlikely that summer insolation had a significant effect on
549 glacier evolution, as it varied from high (at ~45 ka), mid (at ~19 ka) to low (at ~60 ka, ~30 ka)
550 intensity during the MIS 3 period and was not in phase with glacier maxima (Kelley et al.,
551 2014; Garcia et al., 2018; Strand et al., 2019; Fig. 8c). Similar to our observations from the
552 Kerguelen Archipelago, Doughty et al. (2015) evidence glacier maxima in New Zealand in
553 phase with regional SST changes from the Southern Ocean. Lastly, Garcia et al. (2018) show
554 that multi-millennial glacier culminations in both Patagonia and New Zealand are closely
555 teleconnected to the Antarctic climate, in particular because most glacial maxima occurred
556 synchronously with cold periods recorded in Antarctic ice cores. Nevertheless, these authors
557 argue that this concordance is not sufficient to explain the advance of glaciers being larger
558 during MIS 3 than during the gLGM, as is recorded at numerous sites in the southern mid-
559 latitudes, including the Kerguelen Archipelago.

560 To sum up, climatic drivers responsible for glacier fluctuations on Kerguelen from the MIS 3
561 period to the end of the gLGM remain puzzling. It seems that there was a long-term mid to
562 high southern latitude cooling broadly in phase that may partly explain the Late Pleistocene
563 glacier maxima on the archipelago at ~42.2 ka and ~21-19 ka, as well as in New Zealand and

564 Patagonia (Garcia et al., 2018). However, so far, none of the climate proxies explored in this
565 study provide a robust explanation for the larger MIS 3 glacier culmination on Kerguelen and
566 elsewhere in the southern mid-latitudes. Here, we hypothesize that temperature alone cannot
567 explain glacier expansion and retreat on the archipelago and that precipitation changes may
568 have created a tipping point that superimposed on the impact of temperature variations. Indeed,
569 the larger MIS 3 glacier advance was certainly caused by a higher amount of precipitation that
570 compensated for comparable to those documented during the gLGM temperatures conditions,
571 while limited amounts of precipitation may have led to smaller glacier extent during the gLGM.
572 To better understand the climatic mechanisms that influenced glacier variations in the
573 Kerguelen Archipelago, additional research on the regional paleoclimatology is needed.

574



576 **Fig. 8** - Comparison of Kerguelen paleoglacier records with Arctic, Antarctic and southern mid-latitude
577 climatic proxies. Proxies for Northern Hemisphere atmospheric temperature fluctuations are **a.** T°C
578 (black curve) from NGRIP (Johnsen et al., 2001) and for the Southern Hemisphere **b.** $\delta^{18}\text{O}$ (orange
579 curve) from the WDC ice core in West Antarctica (WAIS Divide Project Members, 2015). **c.** are the
580 summer (December) insolation changes at 60°S (Berger and Loutre, 1991). **d.** is the reconstructed SSTs
581 from the MD11-3353 core (51°S; Civel-Mazens et al., 2021). **e.** Precipitation changes around Kerguelen
582 from the LOVECLIM transient simulation (Menviel et al., 2011; 2014). **f.** is the growth rate from a
583 stalagmite (HW3) recovered from Hollywood Cave (41°57'S, 171°28'E; 130 m above sea level) in New
584 Zealand (Whittaker et al., 2011). Also shown are **g.** the CRE moraine age probability density
585 distributions with their standard deviation during the investigated period from southern mid-latitude
586 glaciers excluding those on Kerguelen, and **h.** the new ^{36}Cl CRE moraine age probability density
587 distributions with their inferred full uncertainties from Kerguelen (pink vertical bands are the arithmetic
588 mean ages of moraines). Vertical grey band corresponds to the Last Global Maximum (Clark et al.,
589 2009), blue bands to Heinrich Stadials (NGRIP, 2004; Menviel et al., 2020) and yellow bands to
590 Dansgaard Oeschger events (NGRIP, 2004; Menviel et al., 2020)/ Antarctic Isotope Maximum (EPICA,
591 2006).

592

593 6. Conclusion

594 Our new ^{36}Cl CRE age dataset from moraine boulders and glacially polished bedrock surfaces
595 allowed us to refine our understanding of Late Pleistocene glacier fluctuations on Kerguelen.
596 It helped us address the questions of whether glaciers located in the Kerguelen Archipelago (*i*)
597 experienced an early local Last Glacial Maximum during the MIS 3 period in consistency with
598 other regions from the southern mid-latitudes and (*ii*) re-advanced during the gLGM in line
599 with the global-scale maximum extent of mountain glaciers and ice sheets. Moraine mean ages
600 indicate that glacier culminations occurred at ~ 42.2 ka, *i.e.*, during MIS 3, as well as at ~ 21.5
601 ka and ~ 19.4 ka synchronously with the gLGM. Importantly, this is the first time that MIS 3
602 and gLGM glacier maxima are demonstrated by moraine dating on the Kerguelen Archipelago.
603 Results from glacially polished bedrock samples span from ~ 39 ka to ~ 19 ka. These ages
604 combined with previously dated bedrock surfaces and erratic boulders suggest that two periods
605 of deglaciation took place on the archipelago during the time interval investigated in this study:
606 the first one right after the ~ 42 ka glacier culmination and the second one after the gLGM. So
607 far there is no evidence of other glacier culminations between these two events. This study also

608 provides evidence of larger glacier extent during MIS 3 than during the gLGM, similar and
609 broadly synchronous with the other southern mid-latitude regions. It appears that Kerguelen
610 multi-millennial glacier evolution may be synchronous with cold temperatures recorded in SST
611 records. However, the reason why glaciers were larger during the MIS 3 than during the gLGM
612 remains puzzling. We hypothesize that precipitation changes may have superimposed on the
613 impact of long-term temperature variations, as Kerguelen is a small archipelago relatively
614 isolated in the southern Indian Ocean, whose glacier change is very sensitive even to minor
615 latitudinal migration of oceanic fronts and the Southern Westerly Winds belt. Changes in these
616 climate mechanisms are also challenging to study other than by local proxies. Therefore, further
617 regional paleoclimatic investigations need to be undertaken to unravel the climatic mechanisms
618 that may have influenced glacier variations in the Kerguelen Archipelago.

619

620 **Author contributions**

621 J.C. designed the paper. V.J., G.D., D.G., V.F., T.R., V.R. and C.L. conducted the fieldwork
622 on the islands. J.C., I.S. and V.J. participated in producing the cosmogenic data. ASTER Team
623 performed accelerator mass spectrometry measurements. J.C., I.S., and V.J. interpreted the
624 cosmogenic ages. J.C. wrote the first draft of the paper and prepared the figures. All authors
625 contributed to the discussion and final version of the manuscript.

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636

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Table 1: Geographic sample locations. topographic shielding factors. sample thicknesses. and formation age of rock.

Sample Name	Latitude (°S)	Longitude (°E)	Elevation (m)	Shielding factor	Thickness (cm)
Port-aux-Français site					
<i>Till (inboard PAF moraine)</i>					
PAF-03	49.30766	70.33690	58	0.998	3
<i>PAF moraine</i>					
PAF-01	49.32636	70.30222	41	0.999	3
PAF-02	49.30022	70.36621	71	0.999	4
PAF-04	49.35143	70.29258	32	0.999	2
PAF-05	49.35149	70.29245	27	0.998	5
PAF-06	49.35366	70.28725	36	0.999	2
Port Jeanne D'Arc site					
<i>PJDA moraine</i>					
PJDA-02	49.54310	69.78761	33	0.998	2
PJDA-04	49.54381	69.79069	27	0.994	3
<i>Glacially polished bedrocks</i>					
PJDA-05	49.59253	69.82333	260	0.998	2
PJDA-10	49.59112	69.82365	480	0.998	2
PJDA-11	49.59112	69.82365	480	0.994	3
PJDA-13	49.59112	69.82365	480	0.994	3
Baie Larose site					
<i>B1 moraine</i>					
BLR-01	49.55507	69.36555	81	0.998	3
BLR-02	49.55509	69.36559	79	0.998	5
BLR-03	49.55685	69.36816	79	0.998	3
BLR-04	49.55752	69.36758	79	0.998	3
BLR-05	49.55782	69.36781	83	0.998	3
<i>B2 moraine</i>					
BLR-06	49.55428	69.37249	113	0.999	3
BLR-07	49.55605	69.37518	116	0.999	3
Longue Island site					
<i>glacially polished bedrocks</i>					
LON-01	49.51610	69.87526	110	0.988	3
LON-02	49.51610	69.87526	110	0.988	5
LON-03	49.51610	69.87526	110	0.988	3
Australia Island site					
<i>glacially polished bedrocks</i>					
AUS-02	49.42806	69.82468	62	0.985	2
AUS-05	49.42805	69.82467	62	0.985	3
McMurdo Island site					
<i>glacially polished bedrocks</i>					
MCM-02	48.89502	69.41628	151	0.997	4
MCM-05	48.89502	69.41628	151	0.997	2

Table 2: Chemical compositions of the bulk rock samples before chemical treatment. Analysis performed at the SARM-CRPG (Nancy, France) by ICP-OES (major elements), ICP-MS (trace element), atomic absorption (Li), colorimetry (B) and spectrophotometry (Cl).																			
Sample Name	CaO %	K ₂ O %	TiO ₂ %	Fe ₂ O ₃ %	Cl (ppm)	SiO ₂ %	Na ₂ O %	MgO %	Al ₂ O ₃ %	MnO %	P ₂ O ₅ %	CO ₂ %	Li (ppm)	B (ppm)	Sm (ppm)	Gd (ppm)	Th (ppm)	U (ppm)	LOI
Port-aux-Français site																			
<i>Till (inboard PAF moraine)</i>																			
PAF-03	8.02	1.14	2.39	12.41	92	45.58	2.91	8.51	14.10	0.17	0.52	0.80	8.08	3.70	6.46	5.40	5.05	1.04	3.43
<i>PAF moraine</i>																			
PAF-01	8.22	0.67	1.74	13.53	92	44.44	1.87	15.02	11.13	0.17	0.23	1.98	5.54	2.40	3.42	3.26	1.40	0.31	3.29
PAF-02	7.84	0.54	1.62	13.13	67	45.09	2.14	10.53	12.79	0.17	0.19	1.61	4.21	<2	3.52	3.59	1.42	0.30	5.42
PAF-04	10.38	1.39	3.14	11.31	33	44.72	2.64	3.97	18.61	0.14	0.40	1.80	6.47	<2	6.30	5.65	3.36	0.73	2.62
PAF-05	8.62	0.93	2.22	12.59	64	44.96	2.39	9.51	14.16	0.16	0.34	1.80	6.08	2.53	4.92	4.47	2.81	0.60	3.69
PAF-06	8.62	0.93	2.22	12.59	64	44.96	2.39	9.51	14.16	0.16	0.34	1.80	6.08	2.53	4.92	4.47	2.81	0.60	3.69
Port Jeanne D'Arc site																			
<i>PJDA moraine</i>																			
PJDA-02	11.20	0.80	1.85	9.68	35	47.41	3.16	2.82	20.83	0.12	0.25	-	5.37	<2	3.93	3.70	1.80	0.40	1.11
PJDA-04	11.00	1.11	1.28	7.70	50	47.38	3.14	2.26	22.68	0.10	0.33	1.21	6.86	2.40	3.74	3.25	2.35	0.48	3.51
<i>Glacially polished bedrocks</i>																			
PJDA-05	4.30	3.68	1.55	11.59	76	51.05	4.55	2.34	17.16	0.17	1.39	0.64	14.90	2.90	10.30	7.64	10.07	2.08	2.11
PJDA-10	7.40	1.12	3.16	13.33	61	44.05	3.30	8.60	13.31	0.17	0.64	-	9.20	3.40	8.56	7.23	5.91	1.29	3.61
PJDA-11	7.67	0.95	3.15	13.18	69	44.50	3.47	8.42	13.38	0.17	0.64	-	10.49	3.77	8.57	7.18	5.84	1.21	3.95
PJDA-13	7.94	0.77	3.14	13.03	70	44.95	3.64	8.25	13.45	0.18	0.63	0.75	7.38	5.00	8.57	7.14	5.77	1.14	4.29
Baie Larose site																			
<i>B1 moraine</i>																			
BLR-01	11.39	0.77	1.43	7.79	<20	45.93	2.68	3.04	21.49	0.10	0.19	-	5.01	<2	3.19	2.94	1.28	0.28	4.43
BLR-02	11.24	0.77	1.71	9.19	26	46.40	2.90	3.01	20.73	0.12	0.23	-	5.33	<2	3.58	3.34	1.54	0.34	3.11
BLR-03	10.15	0.93	2.33	12.05	<20	46.44	3.16	3.37	17.96	0.16	0.31	-	6.75	<2	4.67	4.45	2.10	0.46	2.80
BLR-04	11.24	0.77	1.71	9.19	26	46.40	2.90	3.01	20.73	0.12	0.23	-	5.33	<2	3.58	3.34	1.54	0.34	3.11
BLR-05	12.19	0.61	1.38	7.73	37	46.84	2.85	2.61	22.73	0.09	0.19	-	4.24	<2	2.88	2.64	1.23	0.27	2.09
<i>B2 moraine</i>																			
BLR-06	11.49	0.67	1.38	8.28	25	46.70	2.80	3.36	21.77	0.10	0.20	-	4.95	<2	3.21	3.03	1.42	0.30	2.48
BLR-07	11.49	0.67	1.38	8.28	25	46.70	2.80	3.36	21.77	0.10	0.20	-	4.95	<2	3.21	3.03	1.42	0.30	2.48
Longue Island site																			
<i>glacially polished bedrocks</i>																			
LON-01	8.26	1.62	3.01	12.21	46	47.63	3.34	3.82	16.70	0.16	0.50	-	7.43	<2	7.09	6.43	3.75	0.82	2.21
LON-02	8.26	1.62	3.01	12.21	46	47.63	3.34	3.82	16.70	0.16	0.50	-	7.43	<2	7.09	6.43	3.75	0.82	2.21
LON-03	8.26	1.62	3.01	12.21	46	47.63	3.34	3.82	16.70	0.16	0.50	-	7.43	<2	7.09	6.43	3.75	0.82	2.21
Australia Island site																			
<i>glacially polished bedrocks</i>																			
AUS-02	6.81	1.71	3.43	15.27	125	45.87	3.51	4.85	15.86	0.19	0.55	0.79	11.0	4.80	7.44	6.50	4.86	1.05	1.77
AUS-05	6.75	1.74	3.50	15.12	130	46.49	3.56	4.71	16.11	0.19	0.53	0.68	11.2	5.40	7.47	6.62	4.85	1.07	1.58
McMurdo Island site																			
<i>glacially polished bedrocks</i>																			
MCM-02	9.78	0.46	1.46	11.75	57	45.09	2.33	8.50	15.78	0.17	0.18	0.22	5.44	2.50	3.30	3.33	0.61	0.14	4.90
MCM-05	9.78	0.46	1.46	11.75	57	45.09	2.33	8.50	15.78	0.17	0.18	0.22	5.44	2.50	3.30	3.33	0.61	0.14	4.90

Table 3: Concentrations of the major element oxides, determined in splits taken from the samples after the chemical pre-treatment (acid etching). Analysis performed at the SARM-CRPG (Nancy, France) by ICP-OES.

Sample Name	CaO %	K ₂ O %	TiO ₂ %	Fe ₂ O ₃ %	SiO ₂ %	Na ₂ O %	MgO %	Al ₂ O ₃ %	MnO %	P ₂ O ₅ %	LOI
Port-aux-Français site											
<i>Till (inboard PAF moraine)</i>											
PAF-03	8.73 ± 0.44	1.39 ± 0.14	2.96 ± 0.30	10.66 ± 0.21	51.15	3.14	6.31	13.53	0.13	0.18	0.65
<i>PAF moraine</i>											
PAF-01	9.86 ± 0.49	0.79 ± 0.16	2.44 ± 0.24	11.13 ± 0.22	48.79	2.22	10.33	11.36	0.14	0.10	1.63
PAF-02	9.40 ± 0.47	0.62 ± 0.12	2.26 ± 0.23	9.87 ± 0.99	53.17	2.49	7.53	11.46	0.14	< L.D. (0.10)	1.93
PAF-04	10.27 ± 0.21	1.36 ± 0.14	4.65 ± 0.47	13.10 ± 0.26	48.11	2.50	3.84	14.64	0.15	0.10	0.51
PAF-05	8.19 ± 0.41	1.12 ± 0.11	3.60 ± 0.36	14.18 ± 0.28	46.61	2.53	9.96	12.36	0.15	< L.D. (0.10)	0.22
PAF-06	8.79 ± 0.44	1.27 ± 0.13	3.27 ± 0.33	12.84 ± 0.26	49.89	3.00	5.10	14.64	0.16	< L.D. (0.10)	-0.29
Port Jeanne D'Arc site											
<i>PJDA moraine</i>											
PJDA-02	11.15 ± 0.22	0.83 ± 0.17	2.06 ± 0.21	8.04 ± 0.80	51.11	3.26	2.44	19.82	0.11	< L.D. (0.10)	-0.17
PJDA-04	12.26 ± 0.25	0.60 ± 0.12	1.52 ± 0.15	5.38 ± 0.54	51.50	2.85	1.77	22.13	0.08	< L.D. (0.10)	1.25
<i>Glacially polished bedrocks</i>											
PJDA-05	3.39 ± 0.51	4.27 ± 0.43	1.74 ± 0.17	7.86 ± 0.79	56.93	5.20	0.45	18.35	0.08	0.52	0.32
PJDA-10	8.31 ± 0.42	1.16 ± 0.12	3.97 ± 0.40	10.66 ± 0.21	51.62	3.45	4.98	13.15	0.12	0.34	1.43
PJDA-11	8.28 ± 0.41	1.15 ± 0.12	3.95 ± 0.40	11.03 ± 0.22	50.69	3.70	5.13	13.15	0.13	0.43	2.06
PJDA-13	8.17 ± 0.41	0.89 ± 0.18	3.75 ± 0.38	11.03 ± 0.22	50.69	3.70	5.13	13.15	0.13	0.43	2.06
Baie Larose site											
<i>B1 moraine</i>											
BLR-01	14.20 ± 0.28	0.14 ± 0.04	0.08 ± 0.02	0.74 ± 0.11	51.61	2.55	0.17	29.15	< L.D. (0.015)	< L.D. (0.10)	0.57
BLR-02	14.33 ± 0.29	0.15 ± 0.04	0.09 ± 0.02	0.88 ± 0.18	50.60	2.51	0.22	29.25	< L.D. (0.015)	< L.D. (0.10)	1.53
BLR-03	9.94 ± 0.50	1.11 ± 0.11	2.59 ± 0.26	8.29 ± 0.83	53.70	3.41	2.94	16.34	0.14	0.10	1.56
BLR-04	11.82 ± 0.24	0.65 ± 0.13	0.13 ± 0.03	0.90 ± 0.14	44.02	2.17	0.41	24.97	< L.D. (0.015)	< L.D. (0.10)	14.19
BLR-05	14.66 ± 0.29	0.14 ± 0.03	0.10 ± 0.02	0.95 ± 0.14	50.04	2.59	0.23	29.96	< L.D. (0.015)	< L.D. (0.10)	0.90
<i>B2 moraine</i>											
BLR-06	14.54 ± 0.29	0.20 ± 0.05	0.13 ± 0.03	0.98 ± 0.15	50.35	2.60	0.42	29.36	< L.D. (0.015)	< L.D. (0.10)	1.16
BLR-07	15.40 ± 0.31	0.10 ± 0.02	0.07 ± 0.02	0.67 ± 0.10	49.49	1.98	0.19	30.48	< L.D. (0.015)	< L.D. (0.10)	1.07
Longue Island site											
<i>glacially polished bedrocks</i>											
LON-01	8.48 ± 0.42	1.70 ± 0.17	4.04 ± 0.40	10.60 ± 0.21	51.27	3.54	2.85	16.50	0.14	< L.D. (0.10)	0.80
LON-02	8.47 ± 0.42	1.76 ± 0.18	3.97 ± 0.40	10.64 ± 0.21	51.64	3.49	2.89	16.45	0.13	< L.D. (0.10)	-0.30
LON-03	7.66 ± 0.38	1.75 ± 0.17	4.20 ± 0.42	12.42 ± 0.25	50.42	3.48	2.53	15.82	0.11	< L.D. (0.10)	0.50
Australia Island site											
<i>glacially polished bedrocks</i>											
AUS-02	7.07 ± 0.35	1.92 ± 0.19	4.04 ± 0.40	12.63 ± 0.25	49.64	3.95	2.54	16.57	0.15	0.19	0.32
AUS-05	6.93 ± 0.35	1.87 ± 0.19	4.21 ± 0.42	13.34 ± 0.27	49.81	3.89	2.52	16.26	0.16	0.20	0.28
McMurdo Island site											
<i>glacially polished bedrocks</i>											
MCM-02	9.25 ± 0.46	0.40 ± 0.10	2.52 ± 0.25	15.61 ± 0.31	50.82	2.26	5.64	11.41	0.17	0.10	2.43
MCM-05	11.28 ± 0.23	0.38 ± 0.10	2.48 ± 0.25	9.54 ± 0.95	51.92	2.39	5.98	13.08	0.17	0.16	2.13

Table 4: ^{36}Cl dating results. Spike is enriched in ^{35}Cl (~99.66%). $^{36}\text{Cl}/^{35}\text{Cl}$ and $^{35}\text{Cl}/^{37}\text{Cl}$ ratios were inferred from measurements at the AMS facility ASTER after normalization to the inhouse standard SM-CL-12, using an assigned value of $1.428 (\pm 0.021) \times 10^{-12}$ for the $^{36}\text{Cl}/^{35}\text{Cl}$ ratio (Merchel et al., 2011) and assuming a natural ratio of 3.127 for the stable ratio $^{35}\text{Cl}/^{37}\text{Cl}$. Samples in *italic* were rejected as outliers and excluded from mean age calculations.

Sample Name	Sample weight (g)	mass of Cl in spike (mg)	$^{35}\text{Cl}/^{37}\text{Cl}$	$^{36}\text{Cl}/^{35}\text{Cl}$ (10^{-14})	[Cl] in sample (ppm)	^{36}Cl (10^3 atoms g^{-1})	Age (yr) ^a	Arithmetic mean age (yr)	Chi ² test
Port-aux-Français site									
<i>Erratic boulder (in till inboard of PAF moraine)</i>									
PAF-03	38.55	1.813	20.91 ± 0.52	20.59 ± 1.04	10.0	193.1 ± 10.3	34700 ± 4000 (3300)	-	-
<i>PAF moraine</i>									
PAF-01	43.39	1.819	19.42 ± 0.49	25.81 ± 1.32	9.8	218.7 ± 11.8	43500 ± 5500 (4300)	42200 ± 4900	Accepted
PAF-02	38.17	1.811	22.33 ± 0.39	23.29 ± 1.20	9.3	217.9 ± 11.8	46100 ± 5800 (4500)		Accepted
PAF-04	39.33	2.026	26.66 ± 0.65	47.04 ± 2.44	3.6	465.7 ± 24.3	84300 ± 10200 (8100)		Rejected
PAF-05	46.05	2.021	19.31 ± 0.35	58.11 ± 3.01	6.6	516.4 ± 26.9	116600 ± 14800 (12000)		Rejected
PAF-06	46.23	2.022	12.35 ± 0.20	22.86 ± 1.25	15.0	227.1 ± 12.5	41200 ± 4800 (3900)		Accepted
Port Jeanne D'Arc site									
<i>PJDA moraine</i>									
PJDA-02	46.64	2.033	16.45 ± 0.28	12.79 ± 0.78	12.6	116.0 ± 7.2	20400 ± 2500 (2000)	21500 ± 3200	Accepted
PJDA-04	44.14	1.815	52.52 ± 0.91	16.19 ± 1.08	2.6	119.9 ± 8.0	22700 ± 3000 (2200)		Accepted
<i>Glacially polished bedrocks</i>									
PJDA-05	37.50	1.814	10.59 ± 0.24	27.28 ± 1.38	25.8	317.6 ± 19.3	33400 ± 4200 (3800)	-	-
PJDA-10	40.54	2.034	15.29 ± 0.27	35.62 ± 1.84	16.0	380.5 ± 19.9	49200 ± 5400 (4200)	-	Rejected
PJDA-11	37.91	2.090	16.83 ± 0.30	25.81 ± 1.31	15.5	295.8 ± 15.2	38000 ± 4100 (3200)	-	Rejected
PJDA-13	41.25	1.812	18.23 ± 0.41	20.98 ± 1.50	11.1	188.6 ± 14.0	26500 ± 3400 (2800)	-	Rejected
Baie Larose site									
<i>B1 moraine</i>									
BLR-01	28.40	2.013	95.13 ± 2.93	8.48 ± 0.54	0	103.8 ± 6.7	19500 ± 2700 (1700)	21400 ± 3700	Accepted
BLR-02	29.57	2.049	82.16 ± 3.70	11.46 ± 2.55	2.2	138.8 ± 31.2	25100 ± 6500 (6000)		Accepted
BLR-03	60.91	1.999	16.64 ± 1.05	16.01 ± 0.91	7.1	109.1 ± 6.5	19100 ± 2200 (1800)		Accepted
BLR-04	26.77	2.036	104.70 ± 1.72	9.90 ± 0.59	1.5	130.3 ± 7.9	24800 ± 3200 (2300)		Accepted
BLR-05	25.39	2.039	120.97 ± 2.04	7.53 ± 0.58	1.1	103.8 ± 8.2	18300 ± 2600 (1800)		Accepted
<i>B2 moraine</i>									
BLR-06	29.93	2.034	75.06 ± 1.37	9.71 ± 0.65	2.5	115.5 ± 7.9	19500 ± 2600 (1800)	19400 ± 2600	Accepted
BLR-07	33.74	2.030	103.62 ± 1.84	11.18 ± 0.72	1.2	116.6 ± 7.6	19200 ± 2600 (1700)		Accepted
Longue Island site									
<i>glacially polished bedrocks</i>									
LON-01	39.92	1.985	12.19 ± 0.39	22.57 ± 1.26	17.3	255.9 ± 14.7	39600 ± 4600 (3800)	39500 ± 4600	Accepted
LON-02	42.56	2.043	13.75 ± 0.24	42.09 ± 1.34	13.7	253.9 ± 14.3	39600 ± 4500 (3900)		Accepted
LON-03	37.77	2.032	6.93 ± 0.24	17.74 ± 0.94	52.8	295.1 ± 17.8	39200 ± 4800 (3700)		Accepted
Australia Island site									
<i>glacially polished bedrocks</i>									
AUS-02	40.78	1.818	8.51 ± 0.16	11.65 ± 0.75	33.3	139.1 ± 10.8	20800 ± 2600 (2300)	22100 ± 3500	Accepted
AUS-05	40.73	1.818	6.65 ± 0.21	11.78 ± 0.76	51.4	168.3 ± 14.8	23400 ± 3200 (2800)		Accepted
McMurdo Island site									
<i>glacially polished bedrocks</i>									
MCM-02	41.47	1.993	13.66 ± 0.41	10.44 ± 0.62	13.7	110.1 ± 6.6	21500 ± 2700 (2000)	19200 ± 4000	Accepted
MCM-05	24.63	1.811	68.62 ± 1.33	7.07 ± 0.49	3.2	92.0 ± 6.4	17000 ± 2200 (1600)		Accepted
Blanks^b									
Bk6	-	1.801	213.3 ± 6.8	0.036 ± 0.025	1.71 ± 0.27	1.11 ± 0.79	-	-	-
Bk9	-	2.016	50.0 ± 1.7	0.130 ± 0.032	25.31 ± 1.19	4.73 ± 1.16	-	-	-
Bk10	-	1.938	41.1 ± 0.8	0.042 ± 0.020	31.11 ± 0.92	1.51 ± 0.70	-	-	-
Bk11	-	2.029	200.3 ± 5.9	0.113 ± 0.036	2.37 ± 0.22	4.0 ± 1.3	-	-	-

^a Age uncertainties are reported at 1 sigma level and were calculated through full propagation of analytical and production rate errors. Numbers in brackets are analytical uncertainties only.

^b Bk6 was processed with the samples PAF-01, -02, -03, PJDA-04, -05, -13, AUS-02, -05 and MCM-05. Bk9 was processed with BLR-01, -03. Bk10 was processed with MCM-02, PAF-04, -05, -06, LON-01, -02, -03. Bk11 was processed with PJDA-02, -10, -11, BLR-02, -04, -05, -06 and -07.