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1 **New cosmogenic nuclide constraints on Late Glacial and Holocene glacier fluctuations**
2 **in the sub-Antarctic Indian Ocean (Kerguelen Islands, 49°S)**

3

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26 Abstract:

27 Cosmogenic nuclide dating of glacial landforms on the Kerguelen Archipelago (49°S, 69°E)
28 gives the opportunity to study multi-millennial glacier fluctuations within the sub-Antarctic
29 sector of the Indian Ocean. We here dated such geomorphic features to provide time
30 constraints over the last 17,000 years using *in situ*-produced ^{36}Cl in three glacial valleys: Val
31 Travers valley, Ampere Glacier valley and Arago Glacier valley. For the first time, a
32 combination of *in situ*-produced ^{36}Cl and ^{10}Be dating and $^{26}\text{Al}/^{10}\text{Be}$ ratios analysis was
33 performed in the quartz-bearing syenite boulders of the Arago Glacier site. In addition, a
34 Bayesian approach was computed to obtain a better constraint on moraine dating. Glacial
35 advances occurred during the Late Glacial at 16.0 ± 1.9 ka and at 12.9 ± 1.7 ka in Val
36 Travers, and at 13.6 ± 1.8 ka in Arago Glacier valley, probably linked to the Heinrich Stadial
37 1 and/or Antarctic Cold Reversal events, respectively. This suggests that all glaciers at this
38 latitude were broadly sensitive to the large-scale climatic signal of the Antarctic Cold
39 Reversal. So far, no Early nor Mid-Holocene moraines have been found in the glacial valleys
40 on Kerguelen, indicating that the glaciers had probably receded significantly during these
41 periods. This is in agreement with previously determined ^{14}C ages from peat bogs, which
42 suggest extensive deglaciation during several millennia of the Holocene period. Samples
43 from glacially-polished bedrock surfaces (ranging from ≈ 4.4 ka to ≈ 14 ka) at Ampere
44 Glacier site also suggest that this valley was ice free for several millennia during the
45 Holocene. Finally, glaciers seem to have re-advanced only during the Late Holocene,
46 especially within the last millennium, at ≈ 1 ka, ≈ 430 yr and ≈ 300 yr. A comparison of this
47 new dataset with the available ^{10}Be ages from other southern mid-latitude regions during the
48 Holocene allows the identification of three different glacier evolution patterns. We suspect

49 that variations of Kerguelen glaciers, which are located in the Southern Indian Ocean, were
50 controlled by the combined effects of sea surface temperature related to the variations of the
51 Antarctic Polar Front and fluctuations of precipitation related to long-term variations of the
52 Southern Annular Mode.

53 Keywords: glacier fluctuations, paleoclimate, ^{36}Cl CRE dating, ^{10}Be CRE dating, Late
54 Glacial, Antarctic Cold Reversal, Holocene, southern mid-latitudes, sub-Antarctic, Kerguelen
55 Islands.

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73 1. Introduction

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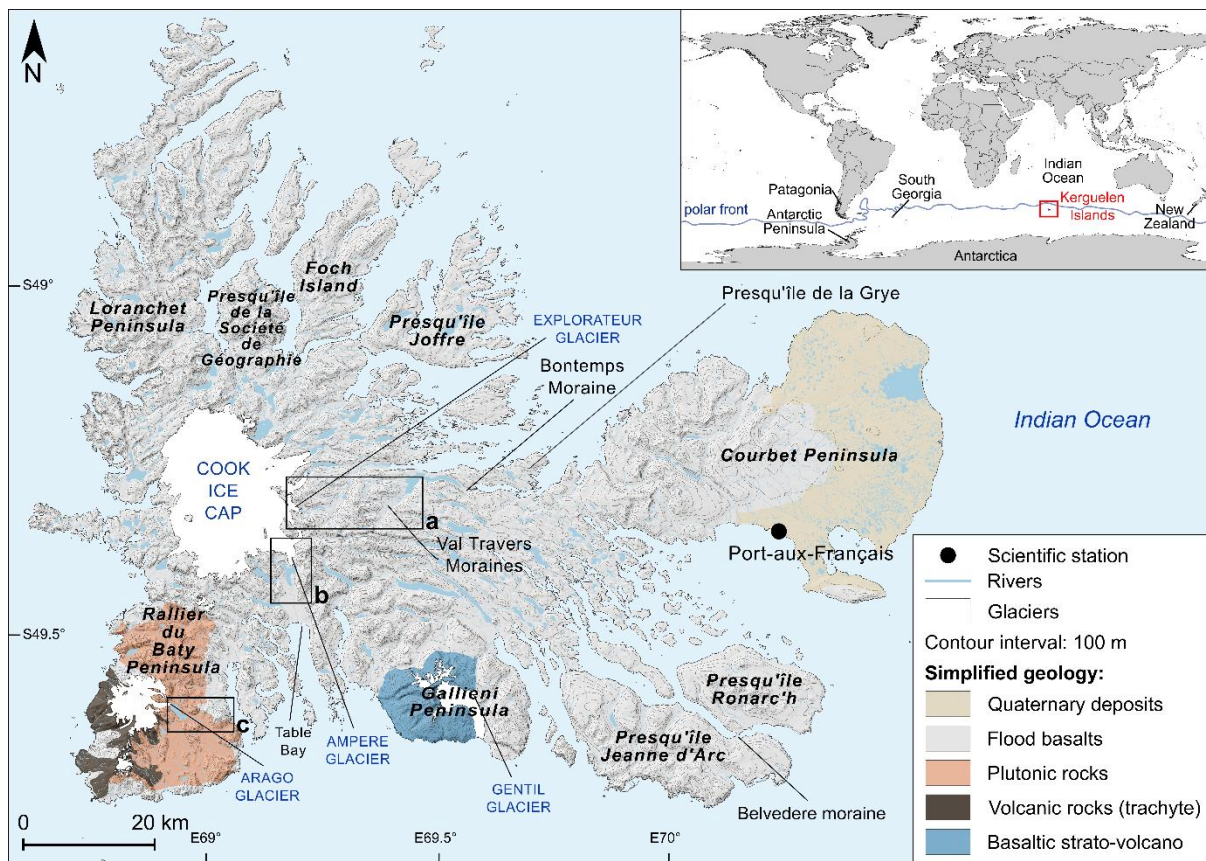
75 Reconstruction of the long-term evolution of glacier fluctuations provides the opportunity to
76 better understand their sensitivity to multi-millennial and -centennial climate change, in
77 particular to the variability of air temperature and precipitation. Cosmic ray exposure (CRE)
78 dating of glacio-geomorphologic formations, such as moraines, erratic boulders and glacially-
79 eroded bedrock, using *in situ*-produced cosmogenic nuclides is particularly suited to
80 reconstruct past glacier chronologies (Balco et al., 2020). Most paleoglacier records in the
81 mid-latitudes of the Southern Hemisphere are based on the well-constrained *in situ* ^{10}Be
82 dating method applied to quartz-bearing moraine boulders (*e.g.* Putnam et al., 2012;
83 Reynhout et al., 2019). In only few studies moraine chronologies are established from the less
84 commonly used *in situ* ^{36}Cl and ^3He (Eaves et al., 2019; Rudolph et al., 2020). A consistent
85 glacier evolution has been evidenced in various regions of the mid-latitudes of the Southern
86 Hemisphere during the Holocene (11.7 ka - present) with glaciers located in New Zealand
87 (*e.g.* Putnam et al., 2012), South Georgia (*e.g.* Bakke et al. 2021) and Patagonia (*e.g.*
88 Reynhout et al., 2019) experiencing their maximal Holocene extent during the Early
89 Holocene (11.6 – 8 ka), followed by a gradual decrease of glacier extent throughout time.
90 This multi-millennial trend is attributed to the variation in summer insolation (Putnam et al.,
91 2012) and at an intra-millennial scale to variations in precipitation intensity (Reynhout et al.,
92 2019, Bakke et al., 2021). However, two additional contrasting patterns of glacier
93 fluctuations have been observed recently. In the Darwin Cordillera (southernmost Patagonia),

94 Reynhout et al. (2021) provided the first ¹⁰Be moraine chronology that shows a maximum
95 Holocene extent during the last millennium corroborating the radiocarbon-dating-based
96 results from previous studies by Hall et al. (2019), while on the Antarctic Peninsula, a
97 maximal glacier advance was recorded during the Mid-Holocene (8 – 4 ka; Kaplan et al.,
98 2020).

99 These asynchronous fluctuation patterns challenge the concept of a homogeneous Holocene
100 glacier evolution within the southern mid-latitudes and raise the question whether regional
101 rather than hemispheric climatic variations have driven glacier behavior during the Holocene.
102 While CRE glacial paleorecords are increasingly numerous in Patagonia and New Zealand,
103 the knowledge on glacier fluctuations in other parts of the southern mid-latitudes remains
104 fragmented. To fill this gap, the Kerguelen Archipelago (49°S, 69°E) provides a precious
105 sentinel in the Southern Indian Ocean to reconstruct glacier evolution (Fig. 1). Indeed,
106 Kerguelen is the largest still glaciated sub-Antarctic archipelago of the southern mid-latitudes
107 (Favier et al., 2016), where several terrestrial moraines are preserved and can be dated.
108 Therefore, establishing a meaningful glacier chronology at Kerguelen is of major interest, as
109 it improves our knowledge of glacier fluctuations at the regional southern mid-latitudes scale
110 within the larger scope of the Southern Hemisphere.

111 Existing studies on Kerguelen glaciers document their fluctuations from Marine Isotopic
112 Stage 3 (MIS-3; 60 – 25 ka) to the last millennium (section 2.2; Jomelli et al., 2017, 2018;
113 Charton et al., 2020; Verfaillie et al., 2021). However, knowledge of the evolution of glaciers
114 at Kerguelen from the end of the Late Glacial (19.0 – 11.7 ka) to the Late Holocene (4 - 0 ka)
115 remains limited. Several discrete radiocarbon ages from peatland (Frenot et al., 1997)
116 revealed by modern recession of the Ampere Glacier suggest that this glacier was at least as
117 small as it is currently during several millennia of the Holocene. Therefore, the aim of this
118 study is to address the paucity of Late Glacial and Holocene glacier constraints at Kerguelen,

119 using ^{36}Cl CRE dating on samples of all lithologies, complemented by ^{10}Be and ^{26}Al CRE
 120 analyses on quartz-bearing syenite samples. To do so, we targeted glacial landforms whose
 121 position and glacial context in the landscape may provide information on Late Glacial and
 122 Holocene glacier fluctuations (section 2.3). Based on the combination of these two dating
 123 methods and a Bayesian approach explained in section 3, we provide an updated Kerguelen
 124 glacier chronology spanning from the Late Glacial to the last millennium (sections 4 and 5.1),
 125 which is explored in the context of the other glacier and climate records from the southern
 126 mid-latitudes (sections 5.2 and 5.3.).
 127



128 **Figure 1.** Map of the Kerguelen Archipelago with the relevant geology in a simplified form.
 129 The inset shows its location in the Southern Indian Ocean. The three study areas are framed
 130 in black, **a.** Val Travers site, **b.** Ampere Glacier site, **c.** Arago Glacier site, for which
 131 geomorphological maps are presented in Figs. 4, 6 and 7, respectively. (data: Digital
 132

133 Elevation Model from NASA/METI/AIST/Japan Spacesystems and U.S./Japan ASTER
134 Science Team, 2019; glacier outlines from the GLIMS database (Raup et al., 2007);
135 geological units from Ponthus (2018)).

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138 2. Study area and geomorphological setting

139 The Kerguelen Archipelago is located in the Southern Indian Ocean, with a total surface area
140 of 7215 km². These 30-million-year-old islands constitute the emerging part of the large
141 underwater basaltic Kerguelen Plateau (Giret et al., 2003; Fig. 1). However, the regional
142 geology varies and the basaltic crust is locally intruded by plutonic rocks of various
143 compositions, such as on the Rallier du Baty Peninsula, where a large volcano-plutonic
144 complex contains Qz-bearing syenites, or in the Galliéni Peninsula, which comprises a young
145 volcano-plutonic complex of less than 1 Ma. The eastern part of the Courbet Peninsula is also
146 different and is only characterized by quaternary deposits but no flood basalts (Fig. 1).

147 2.1. Climate setting

148 Due to its location in the Southern Indian Ocean, the Kerguelen Archipelago is subjected to a
149 subpolar oceanic climate. The related moist and cool air masses, transported by the Southern
150 Westerly Winds (SWW), enabled the formation of ice caps and glaciers. The SWW also
151 drives the Antarctic Circumpolar Current (ACC). The ACC flows eastward between 45°S and
152 65°S (Sokolov and Rintoul, 2009) and is affected by the bathymetry of the Kerguelen Plateau
153 (46-63°S, 62-85°E). Kerguelen is located in between the sub-Antarctic Front (SAF) at □
154 46°S (Solokov and Rintoul, 2009) and the Antarctic Polar Front (APF) at □ 50°S (Park et al.,
155 2014). Nowadays, Kerguelen receives an average of 800 mm of precipitation per year and the

156 mean annual temperature is about 4.5°C at sea level, as recorded daily since 1951 at the
157 scientific station of Port-aux-Français (Courbet Peninsula; Fig. 1). Additional observations
158 have provided information on the spatial variability of the climate in the archipelago
159 (Verfaillie et al., 2015; Favier et al., 2016). In particular, a strong foehn effect has been
160 identified, being responsible for five times more precipitation in the western part than in the
161 eastern part of the archipelago (Verfaillie et al., 2019).

162 2.2. Previous studies on glaciers and their fluctuations at Kerguelen

163 The western part of the main Kerguelen island, Grande Terre, hosts the warm-based Cook Ice
164 Cap (CIC; 1050 m a.s.l.), which covered ~ 400 km² in 2020 (Verfaillie et al., 2021). Several
165 other smaller glaciated areas are also located on the Rallier du Baty Peninsula in the
166 southwest of the archipelago, on the Gallieni Peninsula in the south, and on the Presqu'île de
167 la Société de Géographie north of CIC (Fig. 1).

168 Previous studies on Kerguelen based on ³⁶Cl dating of glacial features revealed that glaciers
169 began to retreat at ~41 ka ago (Jomelli et al., 2018). Erratic and bedrock surfaces located
170 farther inland of the island dated to ~29-24 ka suggest that large expanses of ice were still
171 present at that time. Glaciers receded probably until about 15 ka ago. The general glacier
172 recession during the Late Glacial period was interrupted likely during the Antarctic Cold
173 Reversal (ACR; 14.5 -12.9 ka), as indicated by ³⁶Cl dating of three moraines at different
174 locations – *i.e.* the Bontemps moraine at 13.6 ± 1.5 ka, Belvedere moraine at 15.5 ± 1.8 ka
175 and G1 moraine of Gentil glacier at 14.3 ± 2.3 ka (Jomelli et al., 2017, 2018; Charton et al.,
176 2020). A Late Holocene advance is recorded on the debris-covered Gentil Glacier at 2.62 ±
177 0.97 ka, located at the base of Mount Ross (the highest summit on Kerguelen; 1850 m a.s.l.)
178 (Charton et al., 2020). Finally, ³⁶Cl ages from moraines deposited by Ampere Glacier, an
179 outlet glacier of CIC, reveal - albeit with some scatter - the occurrence of at least two

180 advances of the Ampere Glacier during the last millennium (Jomelli et al., 2017; Verfaillie et
181 al., 2021). One is attributed to the beginning of the Little Ice Age (Solomina et al., 2016), and
182 used to constrain a glaciological model that simulated the extent of the Cook Ice Cap during
183 this period (Verfaillie et al., 2021).

184 Since the 1960s, glaciers at Kerguelen have experienced dramatic wastage, with the surface
185 area of the CIC expected to disappear by 2100 CE (Verfaillie et al., 2021). This is explained
186 by decreasing precipitation mainly attributed to the high index Southern Annular Mode
187 (SAM+) (Thompson et al., 2011; Verfaillie et al., 2015; Favier et al., 2016) and to the long-
188 term increase in atmospheric temperatures (Verfaillie et al., 2021). Mass and energy balance
189 conducted on the CIC reveals that temperature impacts the precipitation phase and the
190 equilibrium line altitude, through changes in the elevation of the 0°C isotherm and therefore
191 of the rain/snow limit with impacts on both the snow accumulation amount and the glacier
192 surface albedo (Favier et al., 2016).

193 2.3. Study sites and sampling strategy

194 Three sites hosting datable geomorphological features (i.e. moraines, glacially-polished
195 bedrock and erratics) that are estimated to belong to the Late Glacial and/or the Holocene,
196 based on a comparison with existing data elsewhere on the islands, were chosen: the Val
197 Travers valley, Ampere Glacier and Arago Glacier (Fig. 1). Moraines were labelled with
198 numbers in ascending order from the oldest to the youngest.

199 The Val Travers site (Fig. 1) is characterized by extended U-shaped valleys that were incised
200 into the basaltic substratum by the eastern outlet glaciers of the CIC. It lies about 10 km
201 upstream of Bontemps Lake (Fig. 4). We sampled the only two preserved terrestrial moraines
202 found in the valley (V1 and V2), which may have been formed by a branch of the Explorateur

203 Glacier (Fig. 4). Four samples (VLT-10, -11, -12, and -13) were taken at 62 m a.s.l from the
204 V1 moraine ridge, which is located at 14.2 km from the present-day frontal area of the eastern
205 glaciers of the CIC (Fig. 4). Five moraine boulders (VLT-05, -06, -07, -08, and -09) were
206 sampled at 73 m a.s.l. on the V2 moraine, which was deposited about 1.5 km upstream of the
207 V1 moraine (Figs. 2a and 4). Finally, one sample (VLT-04) was extracted from a polished
208 bedrock surface, located on the right-lateral plateau near Mount A. Gampert at an elevation of
209 437 m a.s.l. and at a distance of about 9 km downstream of the V1 moraine (Figs. 2a and 4).
210 All boulders sampled at this site have a basaltic lithology.

211 The Ampere Glacier is a lake-terminating outlet glacier of the CIC, which flows south-east of
212 the ice cap on the basaltic substratum (Fig. 1). Currently, the Ampere Glacier (67 km² in
213 2011) is 12 km long (Berthier et al., 2009; Verfaillie et al., 2021) with a large proglacial lake.
214 The Ampere's proglacial margin (9 km long) is characterized by an outwash plain that
215 reaches Table Bay, with a set of six moraines between about 3.5 and 7 km from the current
216 ice front (Figs. 1 and 6). Eleven new basaltic samples, i.e. six erratic boulders (MO-03, -04, -
217 06, -08, -11, and -12) and five bedrock samples (MO-02, -05, -07, -09, and -13) were taken
218 uphill (between 120 and 290 m a.s.l.) on the southern part of the shore of the Ampere Lake at
219 distances ranging from 1.5 to 2.8 km from the glacier's snout (Figs. 2b and 6). Each sampled
220 bedrock surface is paired with at least one erratic (Figs. 2b and 6). These erratic boulders are
221 aligned in a lateral continuum of the frontal moraine sequence.

222 The south-west part of the archipelago hosts the Rallier du Baty Peninsula (Fig. 1), an
223 alkaline volcano-plutonic complex, which mostly consists of syenites with rock
224 crystallization ages ranging from about 12 Ma to 8 Ma (Ponthus et al., 2020). More recent
225 lava flows, composed of trachytes, are also present, resulting from volcanic activity between
226 ~1.15 Ma (Dosso et al., 1979) and the last millennium (900-1000 CE) (Guillaume Delpech,

227 personal communication). Rallier du Baty Peninsula is covered by a small ice cap, with
228 several land-terminating outlet glaciers. Among them, the Arago Glacier, which peaks at
229 1262 m a.s.l., is a 6 km long lake-terminating glacier and flows down on the eastern slope of
230 Mont Henri, towards the east into the Larmor valley (Figs. 1 and 7). The only moraine (A1)
231 so far detected at a distal location (11 km) from the current glacier front, is composed of
232 syenite boulders. Six syenite samples (RDB-23, -24, -25, -26, -27, and -28) were taken at 72
233 m a.s.l. on this outermost A1 moraine (Figs. 2c and 7). Closer to the glacier front, a sequence
234 of four moraines mainly composed of volcanic rocks (trachyte) was identified, but only two
235 of them (the most distant from the current front) were chosen for dating: A2a and A2b (Fig.
236 7). They were formed alongside the moraine-dammed lake at about 3 km from the current
237 glacier front. From the crest of the frontal moraine A2a, four samples (RDB-01, -02, -04, and
238 -05) were taken at 80 m a.s.l., all being syenites (Fig. 7). Another three samples of trachytic
239 composition (RDB-15, -17, and -18) were collected from the ridge of the lateral moraine A2b
240 at 157 m a.s.l. (Figs 2d and 7). In addition, one glacially-polished syenite bedrock sample
241 (RDB-13) was taken at an average elevation of 60 m a.s.l. on the right-lateral flank of the
242 valley, located at about 5 km upstream of A1 moraine (Fig. 7).



243
 244 **Figure 2.** **a.** Photograph of Val Travers site showing V2 moraine and the bedrock surface. **b.**
 245 shows a view of Ampere proglacial margin towards Table Bay presenting the sampled paired
 246 bedrock surfaces and perched erratic boulders. **c.** and **d.** are photographs of A1 moraine and
 247 A2b moraine, respectively, located on Arago Glacier forefield.

248 3. Methods

249 3.1. Sampling

250 Sampling was carried out during a field campaign in 2017-2018. In total, 34 samples from
 251 glacially-polished bedrock, moraine boulders and erratic boulders were collected (Table 1). A
 252 hammer and chisel were used to extract the uppermost 2-3 cm of moraine boulder surfaces,
 253 erratic boulders and bedrock (Fig. 2). Particular attention was paid to sample flat and non-
 254 weathered surfaces. The geographic coordinates and elevations were recorded with a
 255 handheld GPS device and topographic shielding was measured in the field with a clinometer.

256 3.2. *In situ* cosmogenic nuclide dating

257 For CRE dating *in situ* ^{36}Cl is the most suitable cosmogenic nuclide, because Kerguelen's
258 volcanic lithology contains Ca, K, Ti, Fe, and Cl, which are the main target elements for
259 analysis with this method. We also conducted ^{10}Be measurements on samples that allowed
260 the isolation of sufficient quartz. In addition, we measured ^{26}Al in these samples with the aim
261 to verify if the sampled surfaces have been affected by some inheritance from the last
262 interglacial (long-term exposure-burial) or by recent exhumation.

263 3.2.1 Chemical procedures

264 Sample preparation for *in situ*-produced ^{36}Cl , ^{10}Be and ^{26}Al CRE dating was performed in the
265 “Laboratoire National des Nucléides Cosmogéniques” (LN₂C) at CEREGE, Aix-en-provence,
266 France. Samples were crushed and sieved to collect the 250-500 μm fraction.

267 All samples but one (RDB-13) presented in this study were dated with ^{36}Cl . Basaltic and
268 trachytic whole-rock samples were processed according to routine procedures using a method
269 similar to Schimmelpfennig et al. (2011). The low abundance of phenocrysts in these rocks
270 required the use of the whole-rock fractions for these samples, as in the previous studies in
271 the Kerguelen Islands (Jomelli et al., 2017, 2018; Charton et al., 2020; Verfaillie et al., 2021).
272 Aliquots of bulk rocks were selected for analyses of major and trace element concentrations
273 at the Service d'Analyse des Roches et des Minéraux (SARM, Nancy, France) (Table 2).
274 Major and trace elements are needed to evaluate the contribution of the capture of low-energy
275 neutrons on ^{35}Cl and the nucleogenic production to the total ^{36}Cl production. Exposure dating
276 of syenites from Rallier du Baty represented a considerable experimental effort, as they have
277 never been processed before for ^{36}Cl or other cosmogenic nuclides at the LN₂C laboratory.
278 All syenite samples are dominated by alkali feldspars (Na and K-rich) with minor amounts of
279 quartz and other magnetic minerals (mainly amphiboles and pyroxenes). Because the
280 feldspars were expected to have low amounts of natural Cl and they are the dominant non-

281 magnetic mineral phase, they were separated for chemical ^{36}Cl extraction from the magnetic
282 minerals in the syenite samples (RDB-01, -02, -05, -23, -24, -25, -26, -27 and -28) using a
283 Frantz magnetic separator. We then leached all samples with a HF/HNO₃ (Ultrapur) acid
284 mixture with the aim to eliminate atmospheric ^{36}Cl and other potentially Cl-rich mineral
285 phases (Schimmelpfennig et al., 2009). This step removed ~10-20% of the initial feldspar-
286 dominated fractions and ~40% of the initial whole rock sample. Another 2 g aliquot of the
287 rinsed and dried grains for each sample was sent to SARM for major element analyses by
288 ICP-OES, which provides the concentrations of the target elements (*i.e.* Ca, K, Ti and Fe) for
289 ^{36}Cl production by spallation and slow muon capture (Table 3). The final dissolution of the
290 sample grains was performed in a HF/HNO₃ (Ultrapur) acid mixture after addition of a ^{35}Cl -
291 enriched spike (~99%) for isotope dilution (Ivy-Ochs et al., 2004). In total, 6 chemistry
292 blanks (Bk 5, Bk 7, Bk 8, Bk 10, Bk 11 and Bk 12) were processed together with the samples
293 (one with each sample batch, see Table 4 for detailed information). The remaining steps
294 follow the method presented in Schimmelpfennig et al. (2011). Prior to AMS measurements,
295 AgCl targets were pressed into nickel cathodes. $^{36}\text{Cl}/^{35}\text{Cl}$ and $^{35}\text{Cl}/^{37}\text{Cl}$ ratio measurements
296 were performed by Accelerator Mass Spectrometry (AMS) at the French AMS national
297 facility (ASTER) after normalization to the inhouse standard SM-CL-12, using an assigned
298 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
299 natural ratio of 3.127 for the stable ratio $^{35}\text{Cl}/^{37}\text{Cl}$. From these measurements the ^{36}Cl and Cl
300 concentrations were calculated, using the principles of isotope dilution and following the
301 equations in Schimmelpfennig (2009). All concentrations were blank-corrected by
302 subtracting the number of atoms Cl and ^{36}Cl of the batch-specific blank from those of the
303 corresponding samples, respectively (Table 4). An error propagation calculation was
304 performed following the standard procedures given in Taylor (1997).

305 All syenite samples were inspected for the amount of quartz they contained. Eight samples
306 were estimated to have at least 1% of quartz, which was isolated from the magnetic minerals
307 by magnetic separation (using a Frantz magnetic separator) and from K-feldspars by
308 densimetric separation using heavy liquids. The quartz fraction was leached several times
309 using a diluted HF acid mixture in an ultrasonic bath to remove any remaining feldspars and
310 to eliminate atmospheric ^{10}Be from the quartz grains. Finally, only three samples (RDB-13, -
311 24 and -27) yielded sufficient amounts of quartz for ^{10}Be and ^{26}Al chemical procedures (~12-
312 52 g from at least 4 kg of crushed rock). As RDB-13 was collected from a quartz-enriched
313 vein, it yielded the highest amount of quartz (~52 g). The total dissolution of the samples was
314 then performed in a concentrated HF solution after the addition of 150 μl of an in-house ^9Be
315 carrier solution (3025 ± 9 ppm; Merchel et al., 2008). An aliquot of the solution was taken
316 after complete digestion of the samples to quantify the total Al concentration by ICP-OES
317 analysis. Due to the presence of high amounts of natural ^{27}Al in the processed fraction
318 (probably due to small residues of feldspars), no ^{27}Al carrier was added to the aliquot.
319 Beryllium and aluminum were extracted using anion and cation exchange columns and
320 alkaline precipitation. Afterwards, samples were oxidized at 700°C for 1 hour and the final
321 BeO and Al_2O_3 were mixed with niobium and silver powders respectively, and loaded into
322 copper cathodes. AMS measurements of the $^{10}\text{Be}/^9\text{Be}$ ratios were conducted at the French
323 national AMS facility (ASTER) (Arnold et al., 2010). Samples were calibrated against the in-
324 house standard STD-11 ($^{10}\text{Be}/^9\text{Be} = 1.191 \pm 0.013 \times 10^{-11}$; Braucher et al., 2015) and using a
325 ^{10}Be half-life of $1.387 (\pm 0.0012) \times 10^6$ years (Chmeleff et al., 2010; Korschinek et al., 2010).
326 Aluminum measurements were performed against an in-house standard SM-Al-11 with
327 $^{26}\text{Al}/^{27}\text{Al} = (7.401 \pm 0.064) \times 10^{-12}$ which has been cross-calibrated against the primary
328 standards certified by a round-robin exercise (Merchel and Bremser, 2004). Analytical
329 uncertainties include ASTER counting statistics and stability, the latter amounting to ~0.5%

330 for ^{10}Be (Arnold et al., 2010). ^{10}Be measurements were corrected for blank background by
331 subtracting the number of atoms ^{10}Be of the blank from those of the samples (Table 5).

332

333 3.2.2. CRE age calculations

334 The ^{36}Cl CRE age calculations were performed using the Excel® spreadsheet published by
335 Schimmelpfennig et al. (2009), following the methods used in the previous Kerguelen studies
336 (Jomelli et al., 2017, 2018; Charton et al., 2020; Verfaillie et al., 2021). The calculator takes
337 into account all ^{36}Cl production reactions (spallation of the target elements Ca, K, Ti and Fe,
338 slow muon capture by Ca and K, capture of cosmogenic low-energy (*i.e.* thermal and
339 epithermal) neutrons by ^{35}Cl and nucleogenic production) and provides in detail their relative
340 contributions (Supplemental Material Table 1), based on the sea level and high latitude
341 (SLHL) production rates, scaling factors, sample chemical composition (Tables 2 and 3),
342 sample thickness, topographic shielding, and rock formation age (Table 1). The time-
343 invariant “St” scaling (Stone, 2000) was used for the calculation of all samples. As no local
344 production rates exist for the Kerguelen Archipelago, the following ^{36}Cl SLHL production
345 rates, mostly calibrated at mid-latitude sites and previously applied in Kerguelen, were used
346 for the calculations: 42.2 ± 4.8 atoms of ^{36}Cl (g Ca) $^{-1}$ yr $^{-1}$ for Ca spallation (Schimmelpfennig
347 et al., 2011), 148.1 ± 7.8 atoms of ^{36}Cl (g K) $^{-1}$ yr $^{-1}$ for K spallation (Schimmelpfennig et al.,
348 2014), 13 ± 3 atoms of ^{36}Cl (g Ti) $^{-1}$ yr $^{-1}$ for spallation of Ti (Fink et al., 2000), 1.9 ± 0.2 atoms
349 of ^{36}Cl (g Fe) $^{-1}$ yr $^{-1}$ for Fe spallation (Stone et al., 2005), and 696 ± 185 neutrons (g air) $^{-1}$ yr $^{-1}$
350 for the rate of epithermal neutron production from fast neutrons in the atmosphere at the
351 Earth/atmosphere interface (Marrero et al., 2016). We applied a value of 160 g cm^{-2} for the
352 high-energy neutron attenuation length and 2.4 g cm^{-3} for the bulk rock density. The two ^{36}Cl
353 production reactions induced by capture of low-energy neutrons on ^{35}Cl are hard to quantify,

354 as the low-energy neutron flux depends on the rock composition and environmental factors,
355 such as snow cover and presence of water (Zreda et al., 1993; Phillips et al., 2001;
356 Schimmelpfennig et al., 2009; Zweck et al., 2013; Dunai et al., 2014). We therefore attributed
357 a 30% uncertainty to the ^{36}Cl production from capture of cosmogenic low-energy neutrons by
358 ^{35}Cl reaction production, based on empirical and model experiments (Zreda et al., 1993;
359 Schimmelpfennig et al., 2009; Zweck et al., 2013; Dunai et al., 2014; Marrero et al., 2016).
360 The estimation of the nucleogenic ^{36}Cl contribution in the spreadsheet follows the
361 calculations provided by Phillips and Plummer (1996). The nucleogenic ^{36}Cl production is
362 induced by low-energy neutron capture on ^{35}Cl , but in this case the low-energy neutrons
363 result from spontaneous fission of ^{238}U and reactions of alpha-particles generated during U
364 and Th decay. The calculation method further assumes that nucleogenic ^{36}Cl production starts
365 with the rock formation (crystallization) and is not preserved during magmatic processes
366 (Gosse and Phillips, 2001; Schimmelpfennig et al., 2009; Sarikaya et al., 2018; Anjar et al.,
367 2021). After ~1-2 Ma, nucleogenic ^{36}Cl production and decay (half-life of ^{36}Cl : 301 ka) are in
368 equilibrium, which makes the nucleogenic ^{36}Cl contribution sensitive to differences in the
369 formation ages only if they are <1 Ma (Sarikaya et al., 2018). Most rock samples in our
370 dataset have formation ages that are much older than 1 Ma (Table 1; Guillaume Delpech,
371 personal communication). The nucleogenic ^{36}Cl production is therefore in equilibrium with
372 ^{36}Cl decay. Only samples from a recent lava flow on Arago Glacier site (samples RDB-01, -
373 02, -04, -05, -15, -17 and -18) have a young formation age of ~10 ka or less (Guillaume
374 Delpech, personal communication; Table 1), i.e. the nucleogenic ^{36}Cl contribution is much
375 lower than in the older samples. Further, calculations of the nucleogenic ^{36}Cl production in
376 the spreadsheet developed by Schimmelpfennig et al. (2009) are based on the assumption that
377 the nucleogenic flux of neutrons is homogenous within the bulk rock. Thus, the bulk rock
378 composition in U and Th is commonly used to estimate the nucleogenic production of ^{36}Cl in

379 our samples. This assumption is valid when dating volcanic material because the fast cooling
380 of the lava commonly induces little crystallization with the sparse occurrence of bigger
381 phenocrysts in the matrix. In the case of Kerguelen, the basalts and trachytes used in this
382 study are mostly aphyric or have a microlitic porphyric microstructure with only a few
383 percent of phenocrysts. On the contrary, the plutonic syenite samples of our dataset have a
384 coarse-grained microstructure and are composed of large crystals (up to centimeter size),
385 frequently including small inclusions of accessory minerals (hundreds of microns or less)
386 with highly variable U and Th concentrations (eg. zircon, monazite). It is therefore plausible
387 that the nucleogenic neutron flux is not homogeneous in the syenites samples due to the
388 occurrence of accessory minerals in some larger crystals. In order to prevent a bias in the
389 estimation of the nucleogenic production for the plutonic samples, we thus used the U and Th
390 compositions of the feldspar-dominated fractions separated instead of the U-Th
391 concentrations of the bulk fraction because the ^{36}Cl analysis was performed on these feldspar
392 separates. We assign a formal uncertainty of 5% to the nucleogenic ^{36}Cl production, as to our
393 knowledge no specific investigations have been conducted on the uncertainties inherent to the
394 commonly-used calculation approach. In the Excel® spreadsheet, all uncertainties are
395 propagated throughout to the final ^{36}Cl exposure age following the standard procedures given
396 in Taylor (1997).

397 ^{10}Be CRE ages were calculated with the online CREp program (Martin et al., 2017;
398 <http://crep.crpq.cnrs-nancy.fr>) and are listed in Table 5. Scaling to the sample locations was
399 made according to the time-dependent version of the Stone (2000) scaling (Martin et al.,
400 2017), with the ERA40 atmosphere (Uppala et al., 2005) and the atmospheric ^{10}Be -based
401 VDM geomagnetic database (Muscheler et al., 2005). The production rate used to compute
402 the ^{10}Be ages is regional “southern mid-latitudes” mean based on three calibration sites
403 located in Patagonia (Kaplan et al., 2011) and New-Zealand (Putnam et al., 2010b), as

404 available in the online ICE-D dataset (Martin et al., 2017; <http://calibration.ice-d.org/>). Using
405 the Stone time-dependent scaling in CREp, this regional mean ^{10}Be production rate
406 corresponds to a sea level high latitude (SLHL) value of 4.05 ± 0.04 atoms $\text{g}^{-1} \text{yr}^{-1}$. Note that
407 this value is only 1.5% lower than the global average computed with all available worldwide
408 calibration sites (Martin et al., 2017).

409 No correction was made for snow cover nor denudation for both the ^{36}Cl and ^{10}Be age
410 calculations, in line with previously published ^{36}Cl ages from Kerguelen. Current seasonal
411 snow cover corresponds to a thickness of maximum 10 cm, during durations of about 1.5
412 months at 90 m a.s.l. and 3 weeks at 35 m a.s.l. (Verfaillie et al. 2015; Favier et al. 2016).
413 Such cover would correspond to a correction lower than 2 % (Delunel et al., 2014) and can
414 hence be safely neglected. Similarly, given the exposure timescale (< 20 ka), the impact of
415 denudation is probably lower than the analytical uncertainties by denudation processes.

416 The resulting ^{36}Cl and ^{10}Be CRE ages are listed in Table 4 and 5 with their inferred 1σ
417 uncertainties (*i.e.* the total uncertainties which take into account the analytical and production
418 rate uncertainties) and their analytical uncertainties in brackets. Surface exposure ages are
419 also plotted and shown in Figs. 4, 6 and 7. In the main text and on the figures, we indicate the
420 individual ages with their total uncertainties, whereas probability density curves of individual
421 ages are presented with analytical uncertainties only to allow internal comparison (Figs. 3, 5
422 and 9). For a given site, the obtained ages from a single object (moraine, erratic) were
423 compared using a Chi^2 test, and 95% outliers were then removed (Ward and Wilson, 1978).
424 Then, in line with former Kerguelen studies, we computed the arithmetic mean ^{36}Cl age for
425 each object (reported with their total uncertainties in Table 4). All exposure ages are
426 expressed in yr until 1 ka, and in ka for older ages.

427

428 3.3. Bayesian modeling

429

430 To reduce the dating uncertainties, we exploited the stratigraphic relationships between the
431 dated glacial objects and applied a Bayesian filter on a part of our ^{36}Cl moraine age dataset
432 (Cooley et al., 2006; Naveau et al., 2007; Parnell, 2011), following an approach previously
433 developed (Blard et al., 2013; Martin et al., 2018). In practice, we first computed a synthetic
434 probability density function (pdf) for each moraine, summing the individual pdf of all
435 individual ^{36}Cl ages f_{Sample} :

436

$$437 \quad f_{\text{Moraine}}(t) = \frac{1}{n} \sum_{i=1}^n f_{\text{Sample}} \quad (1)$$

438

439 Then, the pdf of ages of moraines that are in successive stratigraphic order were processed
440 using Bayesian filtering. Including these stratigraphic observations permitted to refine the pdf
441 of both younger and older moraines, considering that a distal moraine is necessarily older
442 than a proximal one (Martin et al., 2018). Filtered pdf, f^* of older and younger moraines, are
443 computed according to Equations (2) and (3), respectively:

444

$$445 \quad f_{\text{Older Moraine}}^*(t) = f_{\text{Older Moraine}}(t) \times \int_0^t f_{\text{Younger Moraine}}(\tau) d\tau \quad (2)$$

446

$$447 \quad f_{\text{Younger Moraine}}^*(t) = f_{\text{Younger Moraine}}(t) \times \int_t^\infty f_{\text{Older Moraine}}(\tau) d\tau \quad (3)$$

448

449 This filtering is useful to reduce the total dating uncertainties arising from geological
450 dispersions (erosion or inheritance). In practice, the vicinity of the successive moraines of
451 this dataset implied that this filtering was only applied to moraines V1 and V2 of Val Travers
452 (this study; Fig. 3) and moraines M1 and M2 of Ampere (^{36}Cl ages were first published in

453 Jomelli et al. (2017) and Verfaillie et al. (2021); Fig. 5). It was indeed unnecessary to apply
454 this filtering to other moraine couples, because the corresponding ^{36}Cl ages are too distant.

455

456 3.4. Review of existing Holocene cosmogenic data

457

458 We aim to compare the updated Kerguelen glacial chronologies to those from other southern
459 mid-latitude regions. To address this issue, we focused on studies devoted to alpine glaciers,
460 from the alpine ICE-D database (<http://alpine.ice-d.org/>), which compiles cosmogenic nuclide
461 exposure ages (mostly ^{10}Be) from alpine glacier sites around the world. We preferentially
462 target moraine datasets providing direct dating of the main advances of a glacier. Available
463 data from southern mid-latitude glacier chronologies (n=14) were tabulated as follows: (i)
464 moraine mean ages with their inferred internal uncertainties were attributed to one of the
465 subperiods of the Holocene (Early, Mid- or Late Holocene) based on the nominal age and (ii)
466 we only selected the glacial chronologies for which the entire sequence of Holocene moraines
467 in the valley were preserved and dated. After age compilation, we identified patterns
468 according to either the presence or absence of at least one moraine belonging to a specific
469 subperiod in each valley. The results and interpretation of these patterns are presented in
470 Supplementary Material Table 2, 3 and 4 and in Fig 8. The class of data is shown as
471 qualitative histograms. The x-axis of the histograms represents the three sub periods of the
472 Holocene, namely Early Holocene (11.6 - 8 ka), Mid-Holocene (8 - 4 ka) and Late Holocene
473 (4 - 0 ka). The height of the bar represents the qualitative appreciation of the length of the
474 glacier following the stratigraphic principle.

475

476

477 4. Results and age interpretation

478

479 4.1. ^{36}Cl ages from Val Travers site (n=10)

480

481 Samples VLT-10, -11, -12 and -13 from V1 moraine give ages of 12.6 ± 1.7 ka, 16.0 ± 2.1 ka,

482 16.7 ± 2.2 ka and 14.9 ± 2.0 ka respectively and yield a median age of 16.0 ± 1.9 ka after the

483 Bayesian filtering process, (n=4). (Table 4, Fig. 3, Fig. 4). ^{36}Cl ages of VLT-05, -06, -07, -08

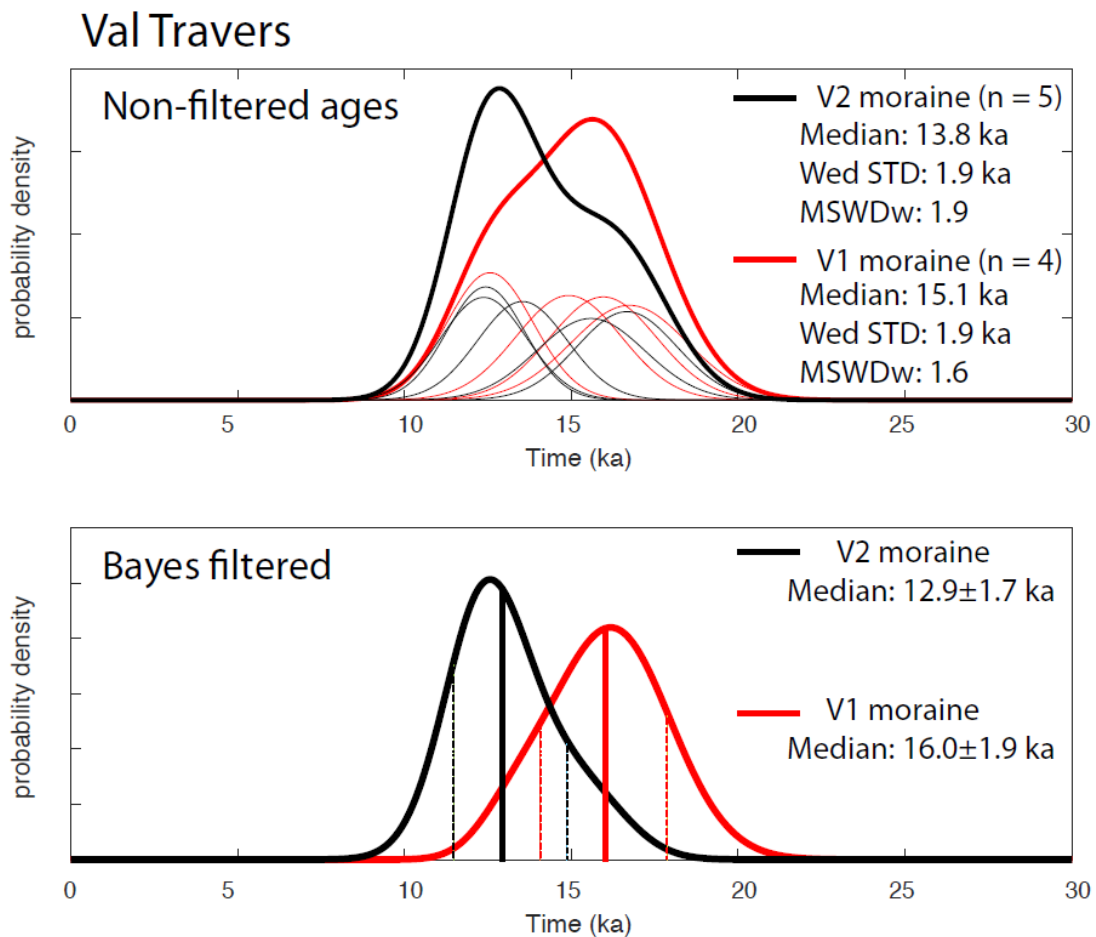
484 and -09, collected on V2 moraine are 15.6 ± 2.0 ka, 12.4 ± 1.6 ka, 12.4 ± 1.5 ka, 16.7 ± 2.0 ka

485 and 13.5 ± 1.7 ka, respectively. The median age and total uncertainty of V2 moraine is $12.9 \pm$

486 1.7 ka (n = 5) (Table 4, Fig. 3, Fig. 4). The ^{36}Cl age of VLT-04, which was extracted from a

487 bedrock atop the U-shaped valley is 17.3 ± 2.2 ka (Table 4, Fig. 4).

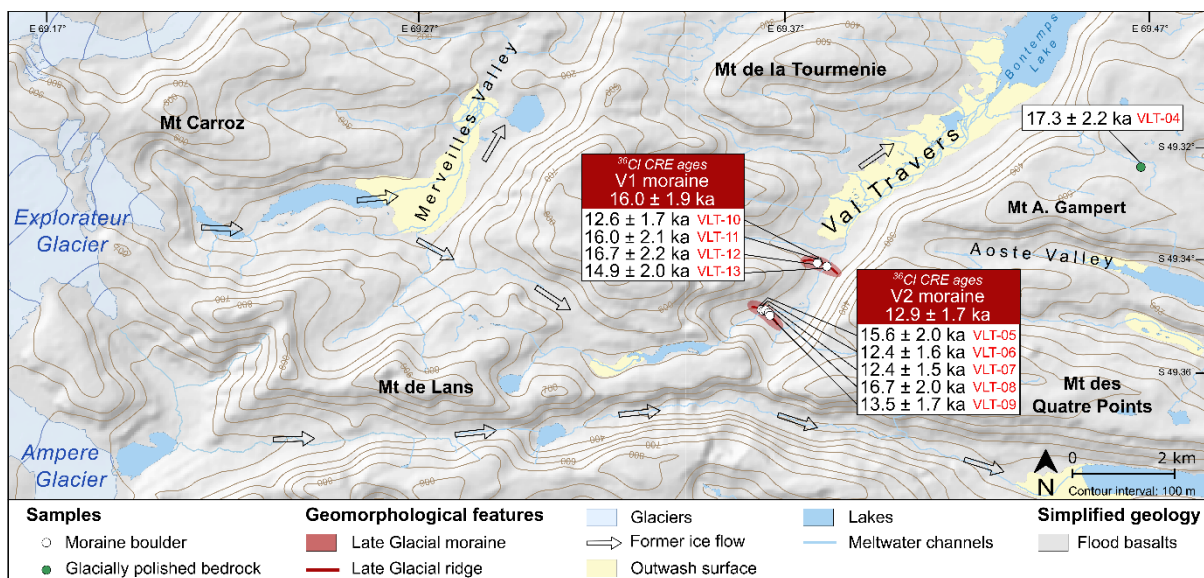
488



489

490 **Figure 3.** Probability plots of ^{36}Cl boulder CRE ages from V1 (red curves) and V2 (black
 491 curves) moraines at Val Travers site before the Bayesian filter (upper panel) and after the
 492 Bayesian filter (bottom panel). Individual ages are represented by Gaussian curves in the
 493 upper panel, which only include the analytical uncertainties. The summed probability is
 494 presented by thick curves. Also shown are the statistical parameters for each landform.

495
 496
 497
 498



499
 500 **Figure 4.** Glacial geomorphological map of the Val Travers site. White boxes show the ^{36}Cl
 501 sample ages of moraine and bedrock with their analytical uncertainties. The median ages for
 502 moraine groups are shown in colored boxes with their total uncertainties (i.e. standard
 503 deviation, analytical and production rate uncertainties).

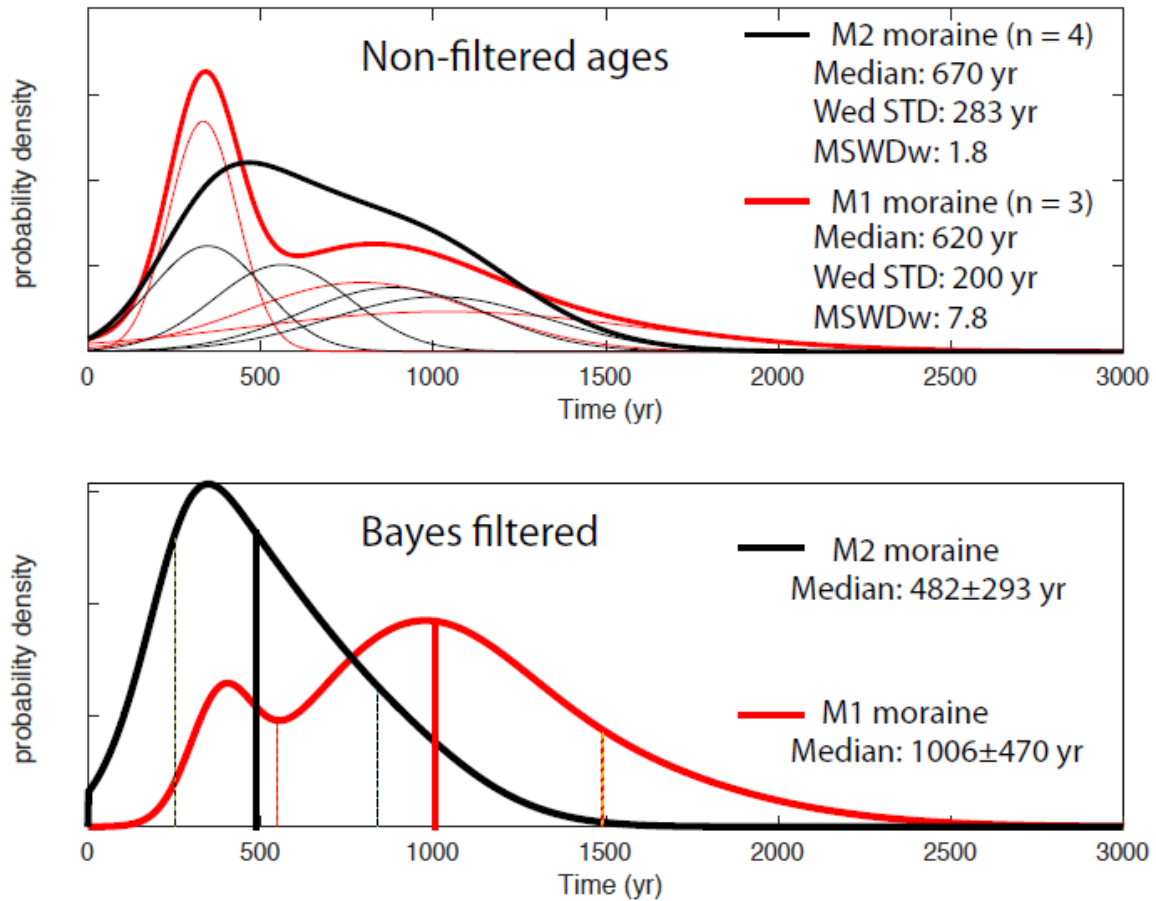
504

505 4.2. ^{36}Cl ages from Ampere Glacier site (n= 11)

506 The erratic boulder samples associated with bedrock surfaces, MO-12, -11, -04, -03, -08 and -
507 06, yield ages of 290 ± 140 yr, 870 ± 180 yr, 80 ± 50 yr, 680 ± 340 yr, 620 ± 170 yr and 2.37
508 ± 0.38 ka, respectively (Table 4, Fig. 6). MO-04 and -06 were identified as outliers based on
509 the Chi^2 test and were therefore excluded from the mean age calculation. MO-04 has an age
510 considered too young probably due to post-depositional rotation or exhumation, whereas the
511 older age of MO-06 is probably affected by inheritance. The remaining samples MO-12, -11,
512 -03 and -06 have a mean arithmetic age of 610 ± 250 yr. The bedrock samples MO-13, -05, -
513 02, -09 and -07 taken from downstream to upstream on the right shore of Ampere Lake yield
514 ages of 11.3 ± 1.6 ka, 14.0 ± 1.8 ka, 10.1 ± 1.3 ka, 4.43 ± 0.59 ka and 8.9 ± 1.1 ka (Table 4,
515 Fig. 6). The interpretation of these ages will be discussed in section 5.1. Individual moraine
516 boulder ^{36}Cl ages presented in Fig. 6 were first published in Jomelli et al. (2017) and
517 Verfaillie et al. (2021). The weighted means of M1 and M2 moraines and associated total
518 uncertainties gave ages of 800 ± 260 yr and 580 ± 310 , respectively. After the Bayesian
519 filtering process, M1 moraine gives a median age of 1000 ± 470 yr ($n=3$) and M2 moraine
520 gives a median age of 480 ± 290 yr ($n=4$) (Fig. 5).

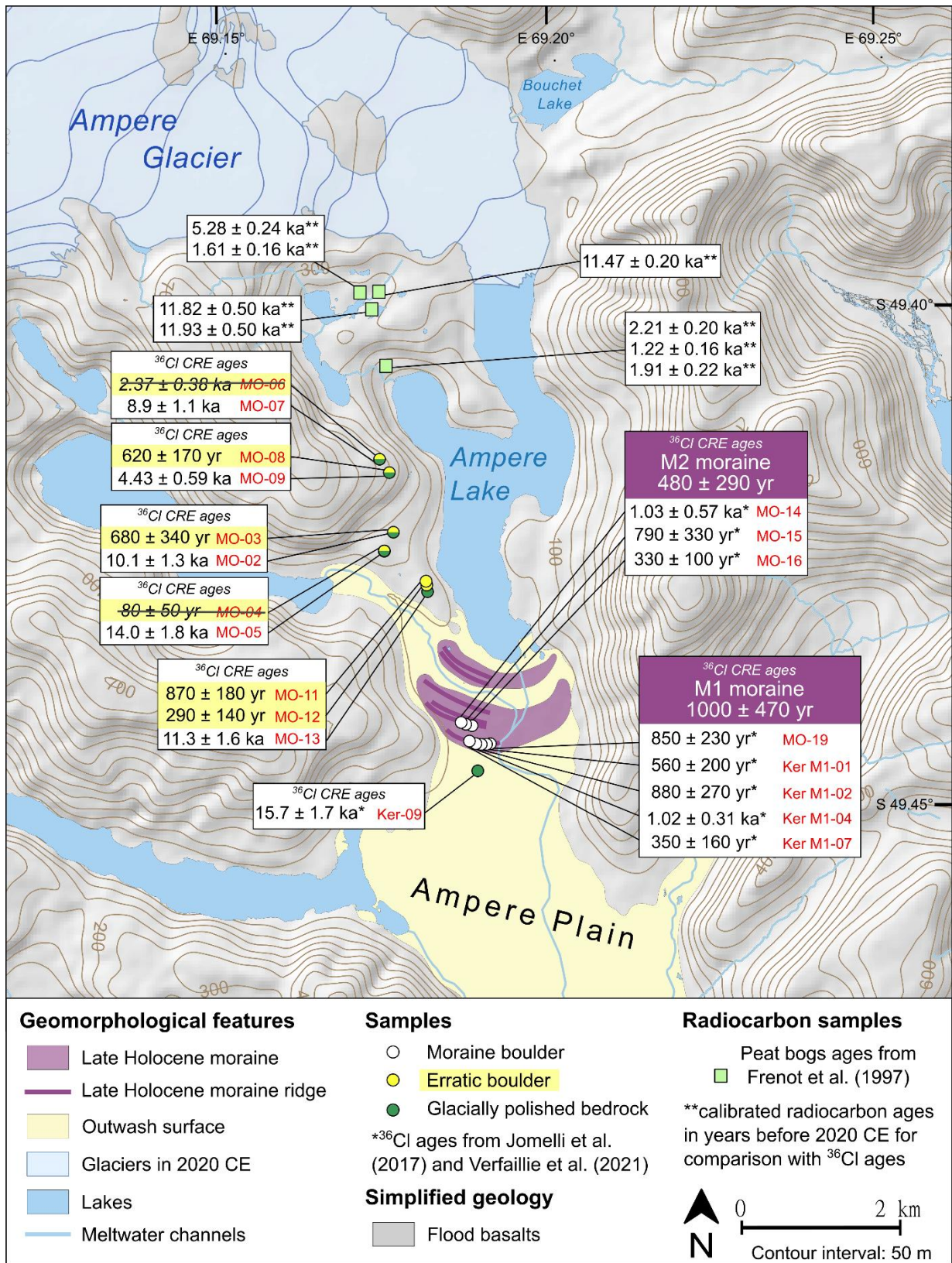
521

Ampere



522

523 **Figure 5.** Probability plots of ^{36}Cl boulder CRE ages from M1 (red curves) and M2 (black
524 curves) moraines at Ampere site (^{36}Cl boulder CRE ages were first published in Jomelli et al.
525 (2017) and Verfaillie et al. (2021)) before the Bayesian filter (upper panel) and after the
526 Bayesian filter (bottom panel). Individual ages are represented by Gaussian curves in the
527 upper panel, which only include the analytical uncertainties. The summed probability is
528 presented by thick curves. Also shown are the statistical parameters for each landform.



529

530 **Figure 6.** Glacial geomorphological map of the Ampere Glacier. White boxes show the ^{36}Cl

531 sample ages of erratic boulders and bedrock with their inferred analytical uncertainties.

532 Samples written in striked-through italic text are rejected as outliers and therefore excluded

533 from the discussion. Moraine boulder ^{36}Cl CRE ages are from Jomelli et al. (2017) and
534 Verfaillie et al. (2021). The median ages for moraine groups are shown in colored boxes with
535 their total uncertainties (i.e. standard deviation, analytical and production rate uncertainties).
536 Radiocarbon ages in cal BP are presented in Jomelli et al. (2017).

537

538 4.3. ^{36}Cl ages (n=13), ^{10}Be ages (n=3) and $^{26}\text{Al}/^{10}\text{Be}$ ratios (n=2) from Arago Glacier site

539

540 At the Arago Glacier sampling site, we dated three moraines, one bedrock surface and three
541 erratic boulders. The outermost A1 moraine, composed of syenites, was dated using ^{36}Cl on
542 feldspar separates from all samples, and ^{10}Be and ^{26}Al on quartz of two samples. The bedrock
543 surface (RDB-13), which was also sampled from a syenite, was dated only with ^{10}Be and ^{26}Al
544 on quartz. Finally, the two innermost moraines A2a-b, composed of trachytes and syenites,
545 were dated with ^{36}Cl on whole rock and feldspar separates.

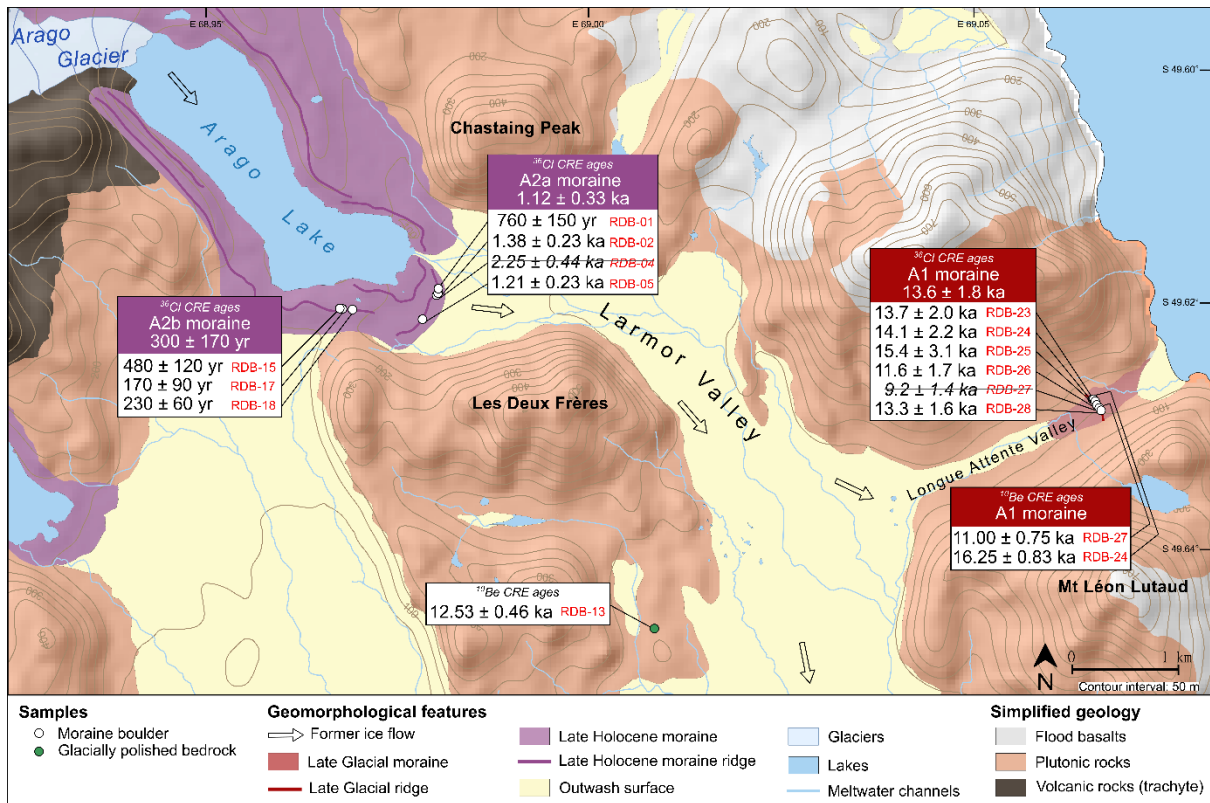
546 The ^{36}Cl surface exposure ages at the Arago Glacier site range from 760 ± 150 yr to $15.4 \pm$
547 3.1 ka (Table 4, Fig. 7) and moraine ages are in agreement with their stratigraphic position.
548 The ^{36}Cl ages RDB-01, -02, -04 and -05 of the outermost (oldest) A2a moraine are 760 ± 150
549 yr, 1.38 ± 0.23 ka, 2.25 ± 0.44 ka and 1.21 ± 0.23 ka, respectively. RDB-04 is probably
550 affected by nuclide inheritance and is rejected as an outlier. The arithmetic mean of the
551 remaining ages of A2a moraine and total uncertainty are 1.12 ± 0.33 ka (n = 3). On the
552 innermost (youngest) A2b moraine, samples RDB-15, -17 and -18 give ^{36}Cl ages of $480 \pm$
553 120 , 170 ± 90 , 230 ± 60 yr and the moraine has a mean age of 300 ± 170 yr.

554 Near Les Deux Frères (in between A1 moraine and A2a-b moraine complex; Fig. 7), the
555 bedrock sample RDB-13, collected in syenites upstream of A1 moraine, yields a ^{10}Be age of
556 12.53 ± 0.46 ka and a $^{26}\text{Al}/^{10}\text{Be}$ ratio of 6.48 ± 0.64 (Table 5), which is consistent with the

557 $^{26}\text{Al}/^{10}\text{Be}$ production ratio of 6.75 calculated by Balco and Rovey (2008) and Balco et al.
558 (2008). This age suggests that this bedrock sample has been continuously exposed at the
559 surface and does not contain any isotopic inheritance from the last interglacial stadial.

560 Samples RDB-23, -24, -25, -26, -27 and -28, which were collected on the top of the
561 outermost (oldest) A1 moraine have individual ages of 13.7 ± 2.0 ka, 14.1 ± 2.2 ka, $15.4 \pm$
562 3.1 ka, 11.6 ± 1.7 ka, 9.2 ± 1.4 ka and 13.3 ± 1.6 ka, respectively. RDB-24 and -27 yield ^{10}Be
563 ages of 16.25 ± 0.83 and 11.00 ± 0.75 ka, respectively (Table 5, Fig. 7). No statistical
564 difference can be observed between ^{10}Be CRE ages and ^{36}Cl CRE ages of these two samples
565 (Tables 4 and 5). The ^{10}Be and ^{36}Cl CRE ages of sample RDB-27 are both the lowest in the
566 whole age population and have to be related to the high RDB-27 $^{26}\text{Al}/^{10}\text{Be}$ ratio of $9.42 \pm$
567 1.41 that may indicate that this surface might have been exposed at depth and then re-expose
568 at surface when recently exhumed (Akçar et al., 2017). Therefore, both ^{10}Be and ^{36}Cl CRE
569 ages are considered as outliers. The ^{26}Al measurement of RDB-24 did not yield a meaningful
570 result probably due to analytical issues and is therefore not considered further. The mean ^{36}Cl
571 age for the A1 moraine, excluding RDB-27, is 13.6 ± 1.8 ka ($n = 5$).

572



573 **Figure 7.** Glacial geomorphological map of the Arago Glacier site. White boxes show ³⁶Cl
 574 and ¹⁰Be sample ages of moraine boulders and bedrock with their inferred analytical
 575 uncertainties. Samples written in striked-through italic text are rejected as outliers and
 576 therefore excluded from the discussion. The arithmetic means for moraine groups are shown
 577 in colored boxes with their total uncertainties (i.e. standard deviation, analytical and
 578 production rate uncertainties).
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588 5. Discussion

589

590 5.1. Timing of glacier fluctuations at Kerguelen Archipelago since the Late Glacial

591 Spanning from ~17,000 to ~70 years, this new surface exposure dataset improves our
592 knowledge on the Kerguelen glacier fluctuations during the Late Glacial period and the
593 Holocene (Figs. 4, 6 and 7).

594 ³⁶Cl dating of a bedrock sample (VLT-04) at an altitude of 437 m a.s.l. at the Val Travers site,
595 suggests that this location became ice free at 17.3 ± 2.2 ka ago (Fig. 4). This finding is
596 consistent with previous ages from erratics at the Presqu'île de la Grye (mean age of $19.8 \pm$
597 2.2 ka) located about 10 km east of Val Travers but at an altitude of about 70 m a.s.l. (Jomelli
598 et al., 2017). These results indicate that during the beginning of the Late Glacial period a
599 general deglaciation was occurring (at least in this sector east of CIC).

600 At the bottom of the adjacent valley, a branch of Explorateur glacier deposited the V1
601 moraine at 16.0 ± 1.9 ka ago, likely during the Heinrich Stadial 1 (HS1; 17.5–14.7 ka;
602 Rasmussen et al., 2014). However, considering the high uncertainty from this V1 mean
603 moraine age (1.9 ka), it cannot be excluded that this moraine was instead deposited during the
604 beginning of the ACR. In any case, this new data provides another evidence of main glacier
605 extent during this period on the archipelago, as the Belvedere moraine has already been dated
606 to the HS1/ACR period (15.5 ± 1.8 ka) on the southwest of the archipelago (Jomelli et al.,
607 2018). Upstream in Val Travers another moraine deposition (moraine V2) occurred at $12.9 \pm$
608 1.7 ka ago. Within the calculated uncertainties, this moraine age is consistent with previous
609 observations near Presqu'île de la Grye, where the Bontemps moraine was formed northeast
610 of the Val Travers site 13.6 ± 1.5 ka ago by the advance of the Explorateur Glacier (Jomelli et

611 al., 2018; 2017). On Rallier du Baty Peninsula, the A1 moraine of Arago Glacier may have
612 been formed during the same period at 13.6 ± 1.8 ka ago. Another small debris-covered
613 glacier (Gentil Glacier) located south of the archipelago on the Gallieni Peninsula, also
614 experienced glacial advances that occurred at 14.3 ± 2.3 ka (Charton et al., 2020). All these
615 earlier dated moraines are indistinguishable within the calculated range of uncertainties with
616 the new age of V2 moraines at Val Travers and the A1 moraine at Rallier du Baty peninsula.
617 Altogether, these data suggest that during the phase of deglaciation that had started earlier
618 than about 20 ka, glaciers of the archipelago stagnated or readvanced at least once.

619 Interestingly, no evidence of Early nor Mid-Holocene glacier extents has been found so far,
620 suggesting that glaciers were smaller at Kerguelen during these periods than they were during
621 the Late Holocene re-advances (Frenot et al., 1997; Jomelli et al., 2017; Charton et al., 2020).
622 These Late-Holocene re-advances are corroborated by new evidence at two sites. One such
623 site is the proglacial margin of Arago Glacier (Fig. 7), where the A2a moraine is dated to the
624 last millennium (1.12 ± 0.33 ka ago). Several moraine ridges upstream of A2a moraine,
625 including the A2b moraine, that was deposited 300 ± 170 yr ago, attest to further glacier
626 advances or stillstands within the last millennium. Given the absence of moraines between
627 A1 (Late Glacial) and A2a moraines, it is assumed that the glacier generally receded to at
628 least this location between the end of the Late Glacial period and the Late Holocene advance.
629 In addition, the bedrock sample (RDB-13) located on the proglacial margin of the Arago
630 Glacier in between A1 and A2a-b moraines is dated at 12.53 ± 0.46 ka ago, which suggests
631 that this area has been ice free since at least 13 ka.

632 In Ampere Glacier's forefield, the oldest Holocene advance is recorded by the outermost M1
633 moraine and, after Bayesian filtering, is now dated at 1000 ± 470 yr ago (1110 ± 470 CE). A
634 subsequent advance led to the formation of the M2 moraine, which is now dated at 480 ± 290

635 yr ago (1590 ± 290 CE) (Fig. 6). These findings are complemented by ^{36}Cl dating of erratic
636 boulders perched on glacially-polished bedrock surfaces on the right-lateral proglacial margin
637 of the Ampere Glacier located $\sim 2\text{-}4$ km upstream and $\sim 90\text{-}250$ m higher than the M2
638 moraine. The erratic boulder samples yield a mean age of ~ 610 yr (Fig. 6), which is
639 indistinguishable from the mean ages of M1 and M2. The prolongation of these aligned
640 boulders can geometrically be connected with the moraine sequence that M1 and M2 are part
641 of (Fig. 6). Therefore, it is very likely that they represent the former ice margin that can be
642 related with the formation of one or several of these last-millennium-moraines. Five of the
643 erratic boulders are paired with glacially-polished bedrock surface samples, with the goal to
644 constrain the timing of deglaciation and detect potential periods of successive exposure and
645 burial, indicated by nuclide inheritance in the bedrock surfaces (e.g. Fabel et al., 2002). The
646 bedrock surfaces at this location were apparently exposed for durations that range between
647 ~ 14 ka and ~ 4 ka. The apparent ^{36}Cl CRE ages of the bedrock being systematically older than
648 those of the erratic boulders (mean age ~ 610 yr), confirm a complex history of bedrock
649 exposure, meaning that the surfaces contain nuclide inheritance from one or several periods
650 of exposure that pre-date the last-millennium-advances. Given that the apparent bedrock
651 exposure durations do not exceed ~ 14 ka and that evidence elsewhere from the Kerguelen
652 Islands shows large glacier extents still at ~ 14 ka and before, we hypothesize the following
653 exposure-burial scenario. Substantial ice cover during the last glacial cycle eroded these
654 locations deeply enough to remove any cosmogenic nuclide inventories that might have
655 accumulated during previous warm periods; following the retreat from the last large glacier
656 extents of the ACR (at ~ 14 ka), the sample locations experienced deglaciation and ^{36}Cl
657 started to accumulate continuously until 1 ka. At this stage, the Ampere Glacier re-advanced
658 and covered these locations again until (latest) ~ 150 yr ago, as approximately suggested by
659 the nearby moraine sequence and the erratic boulders located on these bedrock surfaces.

660 During this last-millennium-ice-cover, the glacier eroded the subglacial bedrock surfaces and
661 thus reduced the ^{36}Cl inventory accumulated between ~14 ka and 1 ka. Varying erosion rates
662 as a function of topography and related ice velocity led to variable nuclide reduction at the
663 five bedrock surface locations, thus explaining the range of apparent bedrock exposure
664 durations. Following this scenario, a first-order estimate indicates that a uniform subglacial
665 erosion (=abrasion) rate of ~1 mm/yr (corresponding to an abrasion depth of ~85 cm during
666 the ~850 yr of ice cover) can explain the apparent exposure duration of the sample with the
667 lowest ^{36}Cl inventory (MO-09; ~4.4 ka), whereas sample MO-05 (~14.0 ka) would not have
668 been eroded. Besides abrasion, deep plucking of bedrock is a common subglacial erosion
669 process that can explain variable Holocene cosmogenic nuclide inventories in nearby bedrock
670 surfaces (Rand and Goehring, 2019). Holocene subglacial erosion rates between 0.02 and
671 >1.8 mm/yr have been inferred in crystalline forefields of Alpine glaciers, based on
672 cosmogenic multi-nuclide methods (Goehring et al., 2011; Schimmelpfennig et al., 2022).
673 Rates of between 0 and ~1 mm/yr in volcanic (less hard) rocks and the warm-based glacier
674 setting in Kerguelen seem realistic to explain the apparent variable bedrock exposure
675 durations and the proposed exposure-burial scenario. We consider the possibility of
676 significant ^{36}Cl inventories inherited from earlier warm periods at these locations unlikely, as
677 no evidence of such warm periods during the last glacial cycle has been provided so far. In
678 addition, significant discrepancies between paired exposure ages of erratics and glacially-
679 polished bedrock elsewhere on Kerguelen may also be expected if nuclide inheritance is a
680 general concern in this setting, like in cold-based glacier sites (Nichols et al., 2019).
681 However, other existing ^{36}Cl dates of glacially-polished bedrock on the islands are in good
682 agreement with nearby erratics and/or the general deglaciation trend for this region since MIS
683 3 (Jomelli et al., 2017, 2018). This scenario thus suggests that the new bedrock surfaces
684 investigated in this study were ice-free for most of the Holocene period and provide new

685 evidence that the Kerguelen glaciers had a little extent during most of the Early and Mid-
686 Holocene.

687

688 5.2. Comparison with other paleoglacial records within the southern mid-latitude region

689 The updated ^{36}Cl dataset consolidates earlier data regarding the Kerguelen glacier
690 chronologies since the Late Glacial, and it also provides new chronological evidence that the
691 Kerguelen glacier behavior followed a different Holocene pattern compared to other regions
692 in the southern mid-latitudes.

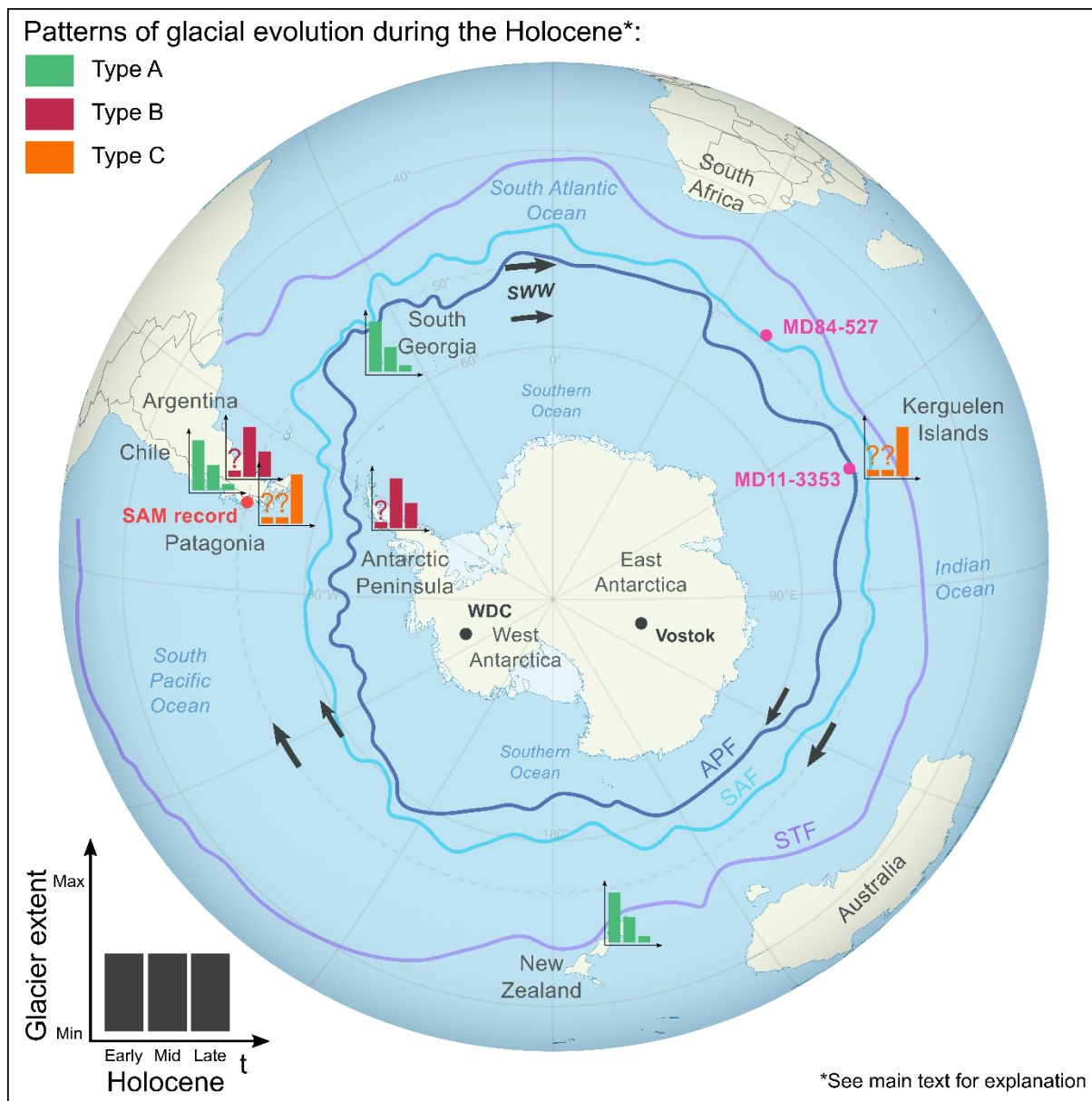
693 Our dataset suggests a possible glacier advance (or stillstand long enough to create a
694 moraine) during HS1 like in Rakaia valley in New Zealand, where glaciers experienced a
695 stillstand at ~16 ka in their global recession trend (Putnam et al., 2013). This is at odds with
696 observations from other southern mid-latitude regions where a global recession of glaciers is
697 generally recorded (e.g. Hall et al., 2013). Our dataset also indicates a glacier advance during
698 the ACR, in agreement with findings from other southern mid-latitude regions (e.g. Putnam et
699 al., 2010a; Pedro et al., 2015; Darvill et al., 2016; Graham et al., 2017). Regarding the
700 Holocene, we performed a review of published moraine CRE ages of glaciers located in
701 Patagonia, New Zealand, Antarctic Peninsula and South Georgia, using the alpine ICE-D
702 database (Balco, 2020) (Fig. 8). Detailed information is available in supplemental material
703 Table 2, 3 and 4. Based on this evaluation, we identified the following three different patterns
704 of glacial evolution in this region of the southern mid-latitudes during the Holocene period
705 (Fig. 8):

706 (i) The first pattern, named type-A (glacier sites n=5), corresponds to a
707 decreasing glacial extent throughout the Holocene, evidenced by several

708 Early, Mid-and Late Holocene moraines dated in numerous glacial valleys.
709 Consequently, glaciers experienced their maximum Holocene advance at
710 the beginning of this period, and then progressively retreated until present-
711 day. Glaciers following the A-type evolution are located in New-Zealand
712 (Putnam et al., 2012), north of 50°S in Patagonia (Reynhout et al., 2019),
713 and South Georgia (Bakke et al., 2021).

714 (ii) The second pattern, type-B (glacier sites n=5), corresponds to small glacial
715 extents during the Early Holocene, glacier re-advances during the Mid-
716 Holocene and glacier recession during the Late Holocene. These moraines
717 exhibit progressively smaller glacier extents, which are dated to the Mid-
718 and Late Holocene only, and provide evidence of severe glacier retreat
719 during the Early Holocene. Glaciers following this trend are located in
720 Patagonia between ~50°S and 55°S (Kaplan et al., 2016) and in the
721 Antarctic Peninsula (Kaplan et al., 2020 and references therein).

722 (iii) The last pattern, type-C (glacier sites n=4), is mainly based on what has been
723 documented so far at Kerguelen. According to the currently available
724 estimates, glaciers were smaller throughout the Early to Mid-Holocene
725 than during their maximum Late Holocene extent. Hitherto, the only other
726 location in the Southern Hemisphere where this atypical pattern has been
727 suggested is in southernmost Patagonia (>55°S) (Reynhout et al., 2021 and
728 references therein).



729

730 **Figure 8.** Different qualitative patterns of glacial evolution within the southern mid-latitudes
 731 during the Holocene. Legend information is explained in sections 3.4 and 5.2. The x-axis bar
 732 of the histograms represents the subperiods of the Holocene (Early Holocene, Mid-Holocene
 733 and Late Holocene), whereas the y-axis bar represents the qualitative appreciation of glacier
 734 length (see section 3.4). The question marks above the histogram bars represent missing
 735 moraines belonging to the referred period in the glacial valley. The black arrow shows the
 736 modern position of the Southern Westerly Winds (SWW, \square 50-60°S), the dark blue line
 737 provides a representation of the modern Antarctic Polar Front (APF), the light blue line is the

738 sub-Antarctic Front (SAF) and the purple line is the sub-Tropical Front (STF). Also shown in
739 pink dots are the positions of the marine cores, black dots depict the locations of the ice cores
740 and the single red dot provides the location of the Southern Annular Mode record discussed
741 in section 5.3.

742 5.3. Assessing potential climate drivers of glacier oscillations in Kerguelen Archipelago 743 during the Late Glacial and Holocene

744 The patterns discussed in section 5.2. provide three regionally contrasting Holocene glacier
745 evolutions within the southern mid-latitude region suggesting complex glacier climatic
746 relationships at a regional scale in the southern mid-latitudes that need to be further explored.
747 Here, we do not address the underlying potential climatic puzzle within the whole southern
748 mid-latitude region but focus on climatic conditions that may have driven glacier fluctuations
749 at Kerguelen (Fig. 9).

750 We suspect paleoglacier variations at Kerguelen to be strongly impacted by the combined
751 influence of sea surface temperatures (SSTs) variations and precipitation changes related to
752 the position of the westerlies, which is partly driven by the SAM. Since air and sea surface
753 temperatures are significantly correlated at Kerguelen (Favier et al., 2016), paleo SSTs data
754 around Kerguelen should be more relevant for local temperatures, than remote Antarctic ice
755 core records. Moreover, reconstructed SSTs combined with subsurface temperatures from the
756 core MD11-3353 (Fig. 9d and e) located southwest of Kerguelen make it also possible to
757 document latitudinal changes in the position of the oceanic fronts (Civel-Mazens et al., 2021).

758 As variations of the SAM and the latitudinal gradient of SSTs are not necessarily in phase
759 through time, they may have acted or not in the same direction on paleoglacier behavior. The
760 impacts of negative phases of the SAM (SAM-) (more precipitation) and cold SSTs would

761 favor a positive mass balance while the effects of a SAM- and warm SSTs would partly
762 compensate for each other.

763 Below, we explore links between these two climate drivers and glacier patterns throughout
764 the Late Glacial and Holocene. Forcings controlling glacier behavior on Kerguelen remain
765 particularly puzzling for the Late Glacial as precipitation changes and the SAM index for this
766 period remain unknown. Our dataset reveals a general deglaciation trend interrupted by at
767 least one glacier advance or stillstand either during HS1 and/or during the ACR. Assuming an
768 advance or a stillstand during HS1, it would have occurred concomitantly with cold, but
769 warming, atmospheric conditions recorded in Antarctica (Petit et al., 1999; WAIS Divide
770 Project Members, 2013; Fig. 9a and b). If occurring during the ACR, it would have been
771 concordant with the cooling recorded from the Antarctic ice cores (Petit et al., 1999; WAIS
772 Divide Project Members, 2013; Fig. 9a and b) and elsewhere in the Southern Ocean (Pedro et
773 al., 2015). We note that warm SSTs seemingly prevailed at that time, as indicated by core
774 MD11-3353 (Fig. 9d), suggesting that the APF and the SAF were already, and remained, at a
775 more southern latitude. However, the SST record presents very low resolution over the
776 deglaciation, and other SST records suggest the ACR was regionally expressed (Labracherie
777 et al., 1989; Ai et al., 2020; Orme et al., 2020; Civel et al., 2021). The subsurface temperature
778 record in core MD11-3353 conversely shows a plateau during the ACR in agreement with air
779 temperature evolution and glacier standstill. During the ACR, increased moisture input has
780 been reported at the Kerguelen Archipelago, based on multi-proxy analyses of peat sequences
781 (van der Putten et al., 2015). This might be due to a potential northward shift of the SWW
782 during this period and might explain a positive glacier mass balance due to enhanced
783 precipitation. This concept is supported by intensified wet conditions documented from
784 different proxy records in Patagonia (Davies et al., 2020) suggesting that the SWW were

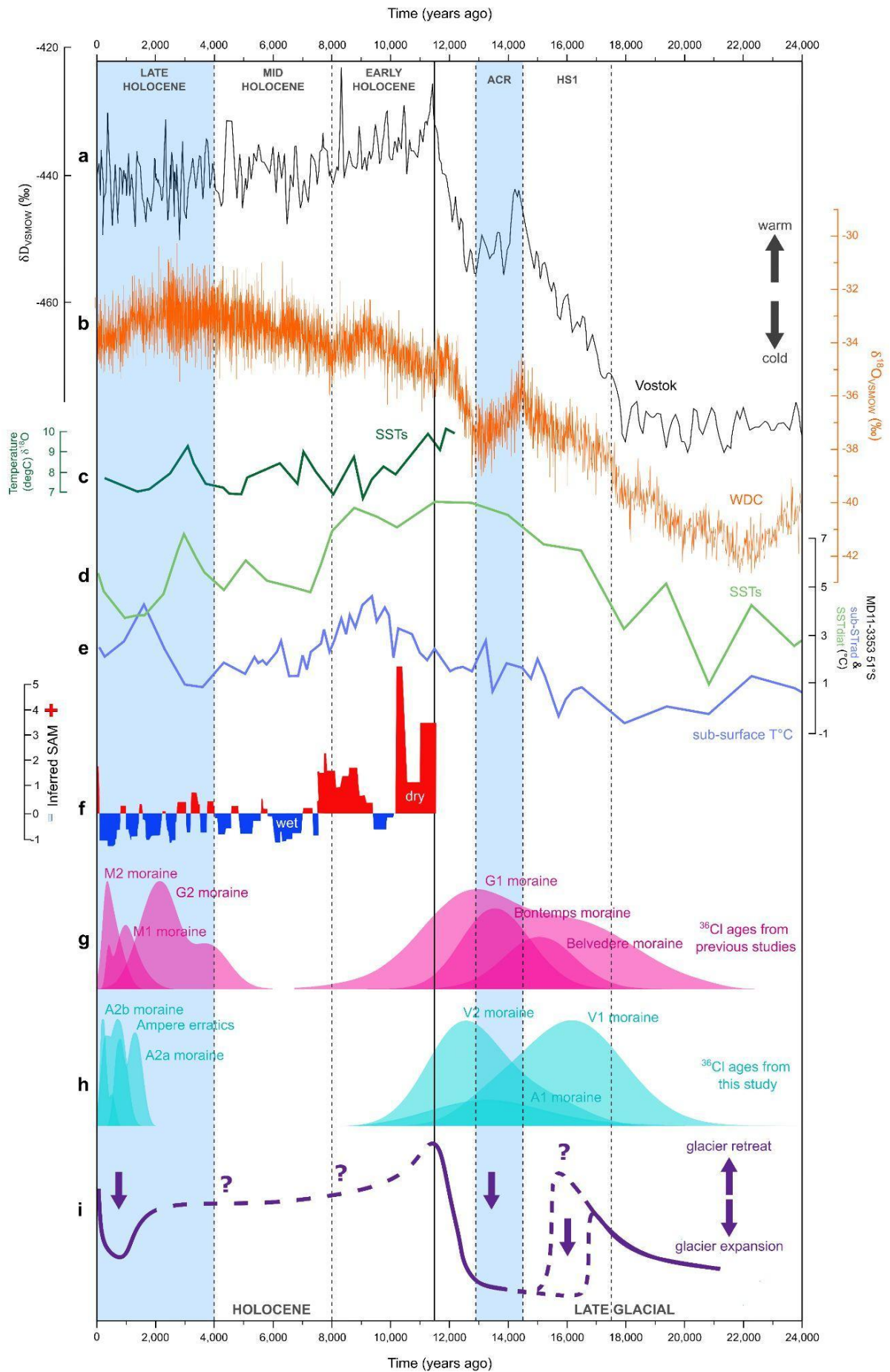
785 centered at $\sim 50^{\circ}\text{S}$ during the ACR, while the modern SWW belt lies between 50°S and 60°S
786 (Garreaud et al., 2009).

787 During the Holocene a reconstruction of precipitation changes attributed to SAM variations
788 offers a good opportunity to analyze the influence of the centennial-to-millennial expression
789 of this climate mode on glacier dynamics at Kerguelen. So far, only one precipitation-SAM
790 reconstruction spanning the Early to Late Holocene exists, and is inferred from the Lago
791 Cipreses non-arboreal pollen (NAP) record in Patagonia (51°S) (Moreno et al. 2018; Fig. 9f).
792 According to this record, SAM is mostly characterized by positive-state-like SAM conditions
793 (less precipitation at the latitude of Kerguelen) during the Early Holocene, i.e. from ~ 11.5 to
794 ~ 10.2 ka, and during the so called ‘Early Warm Dry Anomaly’, from ~ 9.5 to 7.5 ka, which
795 is in agreement with warm and dry climate conditions from the Kerguelen Islands inferred
796 from a multi-proxy analyses on a peat record (reconstruction of wind strength, humidity and
797 relative temperature) investigated by van der Putten et al. (2015). In addition, the Holocene
798 trend of reconstructed SSTs (Kauffman et al., 2020) near Kerguelen in the Southern Indian
799 Ocean (shown in Fig. 9c) and southwest of Kerguelen (Civel-Mazens et al., 2021; shown in
800 Fig. 9d) reveals warmer SSTs during the Early Holocene. Altogether dry conditions, in
801 response to pervasive SAM+ like conditions, and rather warm SSTs in the region would
802 explain the relatively small glacier extents at the Kerguelen Archipelago during the Early
803 Holocene.

804 We notice a cold excursion of SSTs in the Mid-Holocene. Moraines from that time have not
805 yet been identified. Yet, glaciers might have advanced during the Mid-Holocene, but their
806 moraines may have been obliterated by the more extensive Late Holocene glacier advances.
807 However, this potential Mid-Holocene advance may not have lasted long because of the

808 multi-millennial ages of the sampled glacially-polished bedrock, which indicate extensive
809 deglaciation.

810 During the Late Holocene, negative-state-like SAM conditions increased (Fig. 9f), suggesting
811 enhanced precipitation, which, combined with rather cold SSTs in the region (Fig. 9c-e),
812 would have favored glacier re-advance on the Kerguelen Archipelago.



814 **Figure 9.** Comparison of Kerguelen paleoglacier records with Antarctic and southern mid-
815 latitude climatic proxies (locations are shown in Fig. 8). Proxies for atmospheric temperature
816 fluctuations are **a.** δD_{VSMOW} (black curve) from Vostok (East Antarctica; Petit et al., 1999)
817 and **b.** $\delta^{18}O_{VSMOW}$ (orange curve) from West Antarctica (WAIS Divide Project Members,
818 2013). **c.** is the SST reconstruction from $\delta^{18}O$ on planktonic foraminifera (green curve) from
819 MD84-527 marine core, compiled by Kauffman et al. (2020) but first published by Pichon et
820 al. (1992). **d.** is the reconstructed subsurface temperatures and **e.** the SSTs, both from the
821 MD11-3353 core (51°S; Civel-Mazens et al., 2021). **f.** is the Inferred SAM-like index
822 reconstruction for the Holocene period as shaded boxes (red = positive and blue = negative)
823 from Lago Cipreses non-arboreal pollen in Patagonia (Moreno et al., 2018). Also shown are
824 the ^{36}Cl CRE age probability density distributions with their analytical uncertainties only
825 during the Late Glacial and the Holocene periods from Kerguelen of **g.** previous studies
826 (Jomelli et al., 2017, 2018; Charton et al., 2020; Verfaillie et al., 2021) and **h.** this study.
827 Finally, **i.** is a schematic evolution of Kerguelen glacier extents.

828

829 6. Conclusion

830 This study aimed to better constrain the evolution of glaciers on the Kerguelen Archipelago,
831 using *in situ*-produced ^{36}Cl CRE dating from moraine boulders, erratic and glacially-polished
832 bedrock collected on forefields of the Arago Glacier, Ampere Glacier and in the Val Travers
833 Valley. Evidence of a Late Glacial glacier advance at the Val Travers site at ~ 16 ka and ~
834 12.9 ka and at the Arago Glacier at ~ 13.6 is provided, which can likely be related to the HS1
835 and ACR cold spells. While the finding of the HS1 advance is infrequent, the ACR advance
836 is consistent with previous results from other locations on the archipelago, and more

837 generally in the southern mid-latitude region, suggesting that glaciers experienced a broadly
838 synchronous behavior during the ACR.

839 Early and Mid-Holocene glacio-geomorphic features that are testament to glacier advances
840 have not yet been found on the archipelago. In addition, CRE dating of paired erratic
841 boulders (~610 yr) and glacially-polished bedrock surfaces (with exposure duration of up to
842 14 ka) at the Ampere site indicate that this proglacial margin was ice free for several
843 millennia during the Holocene period. These results, when combined with previously
844 published radiocarbon-dated peat ages, suggest that the Ampere Glacier was in a retracted
845 position during most of the Holocene. The new ages also enable refinement of the glacial
846 chronology for Kerguelen and reveal new Late Holocene advances, at ≈ 1.12 ka and ≈ 300 yr
847 at the Arago Glacier site and at ~ 1 ka and ~ 430 yr at the Ampere Glacier site. These findings
848 suggest that Kerguelen glaciers retreated significantly after their (large) ACR extents and
849 were smaller than their last-millennium-extents for most of the Holocene. The data also
850 indicates that the glaciers only re-advanced again from ~ 1 ka. This implies that any moraines
851 potentially formed during Early and Mid-Holocene were obliterated by the more extensive
852 Late Holocene glacier extents.

853 To compare this trend with the glacier evolution in other southern mid-latitude regions, a
854 review of *in situ* cosmogenic data was performed. Three different glacier patterns were
855 identified within the southern mid-latitudes, implying that glacier/climate relationships across
856 this region need further investigations. In the Kerguelen region, a rise in nearby SSTs and a
857 decrease in precipitation, owing to a latitudinal shift of the SWW could explain the relatively
858 smaller extent of Kerguelen glaciers during the Early Holocene. On the contrary, decreasing
859 SSTs and increased precipitation during the Mid- and Late Holocene may have led to glacier
860 expansion in the case of Kerguelen.

861

862 Author contributions

863 VJ, GD, DV, VF, VR, DG and CL conducted the fieldwork on the islands. JC, IS, VJ and GD
864 participated in producing the cosmogenic data. GA, DB and KK (ASTER Team) performed
865 accelerator mass spectrometry measurements. JC, IS, VJ, GD, PHB, RB, LM interpreted the
866 cosmogenic ages; JC, VJ, IS and PHB prepared the figures. All authors contributed to writing
867 the paper.

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