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1 Extensive Holocene West Antarctic Ice Sheet retreat and rebound-
2 driven re-advance

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21 Numerical models used to predict future ice-sheet contributions to sea-level rise use
22 reconstructions of post-Last Glacial Maximum (LGM) ice-sheet retreat to tune model
23 parameterizations¹. West Antarctic Ice Sheet (WAIS) reconstructions have assumed
24 progressive retreat throughout the Holocene^{2,3,4}, due to a lack of broad-scale evidence for a
25 more complex history. Here we show that the WAIS grounding line (GL) retreated several
26 hundred kilometers inland of today's GL, before Holocene isostatic rebound caused it to
27 re-advance to its current position. Evidence includes (1) radiocarbon in sediment cores
28 recovered from beneath Ross Sea Sector ice streams, indicating widespread Holocene
29 marine exposure and (2) ice-penetrating radar observations of englacial structure in the
30 Weddell Sea Sector, indicating ice-shelf grounding. We explore the implications of these
31 findings with an ice-sheet model. Modelled GL re-advance requires ice-shelf grounding
32 caused by isostatic rebound. Our findings overturn the assumption of progressive Holocene
33 GL retreat in West Antarctica and corroborate previous suggestions of ice sheet re-
34 advance⁵. Rebound-driven stabilizing processes were apparently able to halt and reverse
35 climate-initiated ice loss. Whether these processes can reverse present-day loss⁶ on
36 millennial timescales depends on bedrock topography and mantle viscosity – parameters
37 that are difficult to measure and to incorporate into ice-sheet models.

38 Recent evidence suggests that Holocene GL migration in some areas of West Antarctica was
39 more complex than previously assumed^{5,7,8}. In the Weddell and Ross Sea sectors, anomalies in
40 radar-observed englacial structure^{9,10} and isostatic rebound rates⁵ suggest that the GL was
41 recently upstream of its current location. Rebound has been suggested as a negative feedback on
42 ice-sheet retreat^{11,12,13,14} and as a possible cause of GL re-advance⁵, via the grounding of ice
43 shelves^{15,16}. Better constraints on GL history are important. If this history differs significantly
44 from often-used ice-sheet reconstructions² over wide areas, better constrains on past changes

45 could lead to improved ice-sheet models¹ and measurements of ice-sheet mass change¹⁷. To this
46 end, we present new evidence for widespread Holocene GL re-advance in Antarctica from
47 subglacial sediments and radar-observed englacial structure.

48 Multiple boreholes drilled through the Ross Ice Shelf (RISP, WGZ) and the Whillans (WIS/UpB,
49 SLW), Kamb (KIS) and Bindschadler (BIS) ice streams¹⁸ allowed recovery of subglacial
50 sediment cores up to 200 km inland of the present Ross Sea Sector GL (Fig. 1). Radiocarbon
51 analyses of 36 till samples indicate the widespread presence of young organic carbon
52 stratigraphically distributed through the upper meter(s) of till. Total organic carbon concentration
53 is low, ranging from 0.2 to 0.4%, the majority of which is derived from Tertiary marine
54 deposits¹⁹. Nevertheless, organic carbon in all subglacial sediments analyzed includes readily
55 measurable radiocarbon (Extended Data Table 1).

56 Basal melting of meteoric ice is a negligible source of radiocarbon to the subglacial environment
57 (Methods). Subglacial microbes cannot introduce young carbon, as they rely on legacy carbon²¹.
58 Contamination of samples by modern carbon is discounted because samples were curated and
59 sealed in different laboratories, yet yielded consistent results. Hydropotential gradients²⁰ and
60 high basal water pressures¹⁸ drive subglacial water towards the GL in this region, discounting
61 subglacial transport of ¹⁴C-bearing materials from the ocean to the core sites. In contrast,
62 observations of an active marine community just downstream of the GL, more than 600 km from
63 the open ocean (Methods), demonstrate that radiocarbon is introduced virtually everywhere that
64 ocean waters reach beneath the ice shelf.

65 We conclude that a small proportion of the organic carbon contained in the sediments was laid
66 down under sub-ice shelf conditions at or upstream of the sediment cores recently enough to
67 allow persistence of measurable radiocarbon. This implies that the Siple-Gould Coast GL was at

68 least 200 km inland of its current position sometime after the LGM. Calculated radiocarbon ages
69 (Extended Data Table 1) are probably significantly older than the most recent marine incursion,
70 due to dilution by more abundant radiocarbon dead material^{4, 21} (Methods; Extended Data Fig.
71 5). Ice flow transports till downstream¹⁸, so the GL may have retreated even farther inland than
72 the core sites (Fig. 1). The proximity of the cores to Siple Dome (SD; Fig. 1), where 350 m of
73 thinning coincided with rapid sea-level rise during Meltwater Pulse 1a (MWP-1a) around 14.5
74 kyr before present (BP) (ref. 22), hints that MWP-1a could have triggered GL retreat, though this
75 does not necessarily imply a significant WAIS sea-level contribution to MWP-1a (ref. 4).

76 On the other side of the WAIS we conducted a 700 km-long ground-based ice-penetrating radar
77 survey of Henry Ice Rise (HIR; Figs. 1 & 2; Methods). HIR is 7000 km² in area and grounded
78 310-800 m below sea level. Our survey revealed englacial structures inconsistent with present-
79 day slow (<10 m a⁻¹) and cold-based flow conditions (Methods).

80 A series of steep englacial reflectors (Fig. 2d) cluster around a basal topographic high at the
81 northern end of HIR (Fig. 2a). These features intercept the bed, penetrate to 200-300 m above the
82 bed and cross-cut smoothly-undulating isochrones (Fig. 2d; Extended Data Fig. 2). They have
83 similar lateral extents, orientations and spacing to extensional surface crevasses at Doake Ice
84 Rumples (DIR; Fig. 1; Extended Data Fig. 1). At ice rumples, ice that was floating upstream
85 flows onto and over a bedrock high. We interpret the buried features in HIR as marine-ice-filled
86 relic crevasses formed when ice-rumple flow persisted on HIR. The crevasses were probably
87 near-vertical while active and have been buried and deformed to varying extents into steeply-
88 dipping structures by complex ice flow (Methods). Further evidence that parts of HIR were
89 previously floating include prominent synclines in internal isochronal layers that increase in
90 amplitude with depth, are unrelated to basal topography and truncate at the bed (Figs. 2b, 2c,
91 Extended Data Fig. 2) – characteristics indicative of past ocean melting⁹.

92 Ice-shelf grounding on the topographic high beneath HIR – first forming ice rumples, then
93 thickening to form the ice rise – can explain the unusual englacial structures. Contact with the
94 ocean generates isochrone synclines where melting is focused at a static GL for long enough²³.
95 Ice-rumple flow generates surface crevasses similar to those observed on and downstream of
96 DIR, which were preserved in HIR as flow stagnated. Prior to grounding, the ice shelf likely
97 flowed approximately northward in the location of HIR. Post-grounding thickening upstream of
98 the topographic high explains today's configuration, with the initial grounding point beneath
99 HIR's northern extreme. An alternative interpretation is that HIR persisted throughout the
100 Holocene and recently grew to its current size. However, we argue that complete ungrounding is
101 more likely (Methods). Under either scenario, we interpret a contrast in surface texture,
102 approximately coincident with the onset of relic crevassing (Fig. 2b), as a signature of a past GL
103 configuration (Methods). The formation or re-growth of HIR is expected to have increased the
104 buttressing force exerted by the Ronne Ice Shelf on the upstream ice sheet, with implications for
105 GL migration and mass balance.

106 To explore the cause and implications of ice-rise formation (revealed by radar observations) and
107 ice stream GL retreat and re-advance (revealed by radiocarbon analyses), we turn to numerical
108 ice-sheet modelling. We simulate the post-LGM evolution of the WAIS using the Parallel Ice
109 Sheet Model (PISM)²⁴ with improved descriptions of sub-shelf melting and solid Earth rebound,
110 forced by paleo-sea-level and ice-core temperature reconstructions (Methods). A model
111 ensemble investigated first-order sensitivities to independent variations in parameters related to
112 ice flow, glacial isostatic adjustment (GIA), calving, sub-shelf melting, basal traction and
113 accumulation (Methods).

114 After partially compensating for uncertainty in bed topography (Methods), our simulations
115 display remarkable agreement with the conclusions of our radiocarbon and radar analyses. Our

116 reference simulation (Methods) demonstrates this agreement (Fig. 3; Supplementary Video 1). In
117 this simulation, rising sea level and surface temperatures during the last glacial termination drive
118 GL retreat through regions currently occupied by the Ronne and Ross ice shelves. The GL
119 reaches a quasi-stable position around 10 kyr BP, up to approximately 300 km inland of the
120 present-day GL (Fig. 3; Extended Data Fig. 3). Retreat exposes nearly all of our core sites and
121 the bed of HIR to the ocean. Approximately 352,000 km² of the area currently covered by
122 grounded ice ungrounds during retreat, resulting in lithospheric rebound of up to 175 mm yr⁻¹.
123 The rising bed eventually causes the Ross and Ronne ice shelves to ground on bathymetric highs
124 in the locations of present-day ice rises, including HIR. Ice-rise formation increases ice-shelf
125 buttressing, causing the GL to re-advance towards its present-day location (Fig. 3; Extended
126 Data Fig. 4; Methods). In the Amundsen Sea Sector, the GL retreats to its modern position
127 without significant inland retreat and re-advance.

128 Rebound-driven re-advance causes WAIS to gain ice above flotation equivalent to 33 cm of sea
129 level fall during this simulation (Weddell Sector, 2 cm; Ross Sector, 31 cm). Ice-volume minima
130 in each sector are asynchronous and the minimum in whole ice-sheet volume occurs 1.5 kyr BP,
131 at which time the ice sheet is 20 cm sea-level equivalent smaller than present.

132 The timing and magnitude of simulated GL retreat and re-advance depend on model parameters,
133 forcings, bed topography and spatial resolution (Extended Data Figs. 6 & 7; Methods). For
134 example, increasing mantle viscosity expedites retreat, increases maximum retreat and delays re-
135 advance. Ice-rise formation greatly enhances GL re-advance and is sensitive to bed topography,
136 which is regionally uncertain, and dynamically-relevant topographic features are poorly-
137 represented at the spatial resolution of the model (Extended Data Fig. 4; Methods).

138 Notably, although GL re-advance was not their focus, four previous Antarctic ice-sheet

139 modelling studies, employing alternative parameterizations of basal sliding, GL flux and
140 lithosphere response, also simulate Holocene GL retreat and re-advance in these sectors in some
141 simulations^{25,26,27,28}.

142 Radiocarbon in subglacial sediments, radar-observed relic crevassing and ice-sheet modelling,
143 provide corroborating evidence that two large Antarctic catchments re-advanced to their present-
144 day configurations during the Holocene (Fig. 3). Previous work is consistent with this
145 conclusion, but cannot confirm or rule-out Holocene retreat and re-advance (Methods).
146 Moreover, previous authors have found evidence for localized re-advance and suggested rebound
147 as a cause^{5,10}. However, ice-sheet reconstructions used to tune ice-sheet models and correct mass
148 balance observations currently do not include large-scale GL re-advance^{1,2}. Updating these
149 reconstructions to include re-advance could impact ice-sheet gravimetry and altimetry¹⁷, and sea-
150 level projections. Furthermore, we hypothesize that the GL in the Weddell and Ross Sea Sectors
151 may be capable of retreating far inland of its current position without triggering runaway ice-
152 sheet collapse.

153 Our model does not simulate retreat and rebound-driven re-advance in the Amundsen Sea Sector
154 (Fig. 3), where present-day GL retreat is causing concern about future runaway collapse⁶ and
155 recent re-advance could explain observed sub-shelf iceberg ploughmarks²⁹. Our findings
156 motivate future work to examine if rebound-driven mechanisms could slow or reverse this retreat
157 on millennial timescales.

158 Rising eustatic sea-level and temperatures were major climate-related drivers of ice-sheet retreat
159 during and after the last glacial termination. In contrast, it appears that climate-independent
160 lithospheric rebound and ice-shelf grounding were the main drivers of Holocene GL re-advance.
161 The impact of rebound on the ice sheet depends sensitively on bedrock topography and mantle

162 viscosity (Methods). Accurate mapping of potential grounding points and improved
163 parameterization of uplift are needed to forecast the direction and rate of future GL migration in
164 West Antarctica.

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165

166 **Supplementary Information**

167 A supplementary video accompanies this submission.

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200 **Author contributions statement**

201 All authors contributed to manuscript preparation. TA, JK and RS are co-lead authors with equal
202 contributions; others are listed alphabetically. JK designed and conducted the Weddell Sea
203 Sector ice-penetrating radar survey and led the preparation of the manuscript. RS, JC, RP, and
204 ST collected and analyzed sub-ice sediment samples as part of the WISSARD and earlier drilling
205 projects in the Ross Sea Sector. NS and JC prepared samples and interpreted ^{14}C and ^{13}C results.
206 TA ran the PISM simulations with extended analysis of parameter sensitivity. RR designed and
207 analyzed experiments for disentangling drivers of re-advance. MW analyzed radar data from the
208 Weddell Sea Sector. PLW provided input on parameterization of solid Earth rebound and sea-
209 level forcing for the model experiments.

210 **Additional information**

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212 declare no competing financial interests. Correspondence and requests for materials should be
213 addressed to j.kingslake@columbia.edu.

214 **Figure 1: Basal topography and surface ice flow speed in the Weddell and Ross sea sectors**
215 **of West Antarctica. a**, Basal topography and bathymetry³⁰ and **b**, ice-surface flow speed³¹ in the
216 Ross Sea Sector. The locations of sediment recovery are shown in green. **c**, Basal topography
217 and bathymetry³⁰ and **d**, flow speed³¹ in the Weddell Sea Sector. In all panels the present-day
218 GL³² is in red, the (asynchronous) modelled minimum extent of the GL in each sector is in blue.
219 Axes show polar stereographic coordinates in km. Insets show locations in West Antarctica.
220 Labels not defined in the text: Whillans Ice Stream (WIS), Subglacial Lake Whillans (SLW),
221 Ross Ice Shelf Project (RISP)³³. Also labelled are the Institute, Möller and Foundation Ice
222 Streams.

223 **Figure 2: Ice-penetrating radar evidence for grounding of the Ronne Ice Shelf. a**, Radar-
224 derived ice-bed elevation beneath HIR. See Fig. 1c for location in the Weddell Sea Sector. The
225 present-day GL³² is in red. **b**, Radar lines coloured according to where relic crevasses are found.
226 **c**, Normalized elevation ζ_i of an isochrone (Methods). Background images in **a–c** are from the
227 MODIS mosaic of optical (red band) imagery over Antarctica (MOA), which reveals Antarctic
228 surface morphology^{34,35}. Green curves in **b** and **c** highlight a contrast in surface texture
229 (Methods), running parallel to the present-day GL, the onset of relic crevassing and, on the East
230 side, a prominent isochrones syncline **d**, Radargram displaying examples of undulating
231 isochrones. One isochrone is mapped using the colour map from **c**. **e**, Close-up view of near-bed
232 relic crevasses with mean spacing of approximately 450 m.

233 **Figure 3: Modelled grounding-line retreat and re-advance due to lithospheric rebound.**

234 WAIS GL position in the reference simulation at 20 kyr BP (violet), with a recent LGM ice-sheet
235 reconstruction in black (ref. 2, scenario B). The ice sheet asynchronously reaches a minimal
236 extent in the Weddell and Ross sea sectors at 10.2 kyr BP and 9.7 kyr BP respectively (blue).
237 The GL re-advances towards its present-day GL location³⁰ (red). Final simulated GL position is
238 in green. The locations of Siple-Gould Coast sediment cores and selected ice rises are indicated.
239 Brown dashed lines show cross-sections used for Extended Data Figs 3, 6 & 7. Red dotted lines
240 show longitude-defined sectors. Background shading shows basal topography and bathymetry³⁰.

241 **Methods**

242 **Sediments**

243 *Radiocarbon and ¹³C analyses of glacial tills.*

244 Subglacial sediments have been recovered during multiple field seasons by hot-water drilling
245 through the southern Ross Ice Shelf and grounded West Antarctic Ice Sheet. Sub-ice shelf core
246 samples include the Ross Ice Shelf Project (RISP, 1978) and the Whillans Ice Stream Grounding
247 Zone (WGZ, 2015), recovered as part of the Whillans Ice Stream Subglacial Access Research
248 Drilling (WISSARD) Project. The WISSARD Project also included cores from beneath
249 grounded ice at Subglacial Lake Whillans (SLW, 2013). Sub-ice stream samples further
250 upstream were recovered from the Whillans (WIS/UpB, 1989, 1991, 1995, SLW, 2013), Kamb
251 (KIS, 1995, 1996, 2000) and Bindschadler (BIS, 1998) ice streams¹⁸. The sediments recovered
252 are tills with a matrix derived in part from strata that accumulated during multiple intervals of
253 terrestrial, coastal and open marine deposition in West Antarctica. Source strata integrated into
254 the tills are dated by microfossils^{36,37}. They include terrestrial plant spores dating back to the
255 Devonian, but are dominantly Miocene age diatoms, reflecting the abundance of Miocene marine
256 strata in the embayment. The youngest diatoms present are of Pleistocene age, representing
257 direct precipitation in open water during intervals of past ice sheet collapse during MIS-5e (120
258 kyr BP) or earlier Pleistocene interglacials³⁸. These microfossils predate any measurable
259 radiocarbon source in the sub-glacial environment.

260 Bulk sediment samples for radiocarbon measurements were wet sieved with nanopure water
261 through a 63- μ m screen to remove coarser mineral matter, then pre-treated using standard acid-
262 base-acid protocols³⁹. The remaining insoluble fraction for each sample was combusted to
263 convert to CO₂ and then graphitized. Samples were then measured using accelerator mass
264 spectrometry at the W.M. Keck Carbon Cycle Laboratory at the University of California, Irvine.

265 A subset of samples was also independently pretreated and measured at the Uppsala radiocarbon
266 facility, Sweden, following the same protocol. Due to the inherent age uncertainties, radiocarbon
267 “ages” are presented as raw, uncalibrated values that are not corrected for known reservoir
268 effects. Acid-insoluble organic ^{13}C ratios were generated separately at the Environmental Isotope
269 Lab at University of Arizona, following standard methods.

270 In order to minimize the potential for contamination of small samples during analysis, we
271 processed large samples (>150 mg), producing ~1 to 2 mg of carbon that was combusted and
272 reduced to graphite, while simultaneously processing numerous primary and secondary
273 standards, ranging in size from very small (<0.1 mg) to large (1.8 mg). To further demonstrate
274 that we have thoroughly explored a wide range of radiocarbon systematics, we also dated base-
275 soluble fractions for a subset of samples. The base-soluble fraction (humic acid) resulted in ages
276 that were somewhat older (~1 to 2 ka) than the bulk sediment samples. These age differences are
277 not significant and the results are consistent with our other findings. Multiple fractions that yield
278 similar ages further rule out contamination as a possible explanation of our radiocarbon results.

279 We considered and ruled out sample contamination by modern carbon prior to analysis as a
280 potential explanation of the radiocarbon results. Subglacial samples were recovered between
281 1989 and 2013 and sub-ice shelf samples were recovered in 2015 (WGZ) and 1978 (RISP). SLW
282 (2013) samples were recovered and handled using full clean-access protocols⁴⁰, where all
283 instruments were peroxide washed prior to recovery. Cores and samples were sealed and
284 maintained in a +4 °C environment. Clean access protocols were not employed during earlier
285 sample recovery (WIS, KIS and BIS), though every effort was made to maintain appropriate
286 cleanliness in the field and in the laboratory. These samples were sealed and maintained at 4 C.
287 Subsamples were stored in sealed sections of plastic core liner, plastic bags or in plastic vials.
288 Many of the samples in vials dried out and some of the dried samples have been stored at room

289 temperature in the intervening years. The fact that the older subglacial samples demonstrate the
290 oldest apparent radiocarbon ages argues against introduction of new carbon from microbial or
291 fungal growth on the sample. RISP cores were stored at the Florida State University Antarctic
292 sediment core repository, sealed and chilled. The somewhat younger ages there are readily
293 explained by the long-term exposure to the sub-ice shelf ocean cavity. Despite the different
294 sample storage methods used, radiocarbon results are very consistent, which argues against
295 contamination. Given the small concentration of organic carbon in the samples, a very small
296 amount of contamination with modern carbon would result in some anomalous younger ages, yet
297 all of our results fall within a narrow range. Given the range of sample sources and storage
298 methods, equal contamination of all the samples consistent with our results is extremely unlikely.

299 *Apparent and true ages of sediments.*

300 Given the dominant concentration of old (radiocarbon dead) organic carbon in the samples⁴¹, all
301 ages presented are older than the likely age of the pure radiocarbon component; note the
302 calculated “percent modern” column in Extended Data Table 1. We infer post-LGM ages for all
303 samples. Apparent radiocarbon ages for 11 till samples from beneath Whillans, Kamb, and
304 Bindschadler ice streams were obtained for Acid Insoluble Organics (AIO) and span from ca. 20
305 to 35 kyr BP (Extended Data Fig. 5). Rare, small biogenic carbonate fragments from molluscs,
306 foraminifera and calcareous nanofossils have been found in several samples, but these are all
307 Tertiary in age, based on biostratigraphic assessment¹⁹, and no attempt was made to radiocarbon
308 date them.

309 Sediments recovered from beneath the southern Ross Ice Shelf (RISP cores; Fig. 1) were
310 radiocarbon dated, generally yielding somewhat younger ages than the ice streams, likely
311 reflecting the longer period of contact with the sub-ice shelf marine cavity. For the most part, the

312 raw ages appear to correspond to the LGM of the WAIS, which started ca. 29 kyr BP and ended
313 13.9-15.2 kyr BP (ref. 42). Many lines of geologic evidence document that the LGM GL of the
314 WAIS was located at or near the Ross Sea continental shelf break⁴³ at the time that corresponds
315 with the apparent, uncorrected radiocarbon ages in our samples.

316 For the apparent ¹⁴C ages to represent the true sediment ages, the GL of the WAIS would have to
317 be upstream of the core sampling locations and also require all of the carbon pool in the samples
318 to initially have had the standard, modern ¹⁴C/¹²C ratio. However, due to the large oceanic
319 reservoir effect in Antarctica even modern amphipods sampled by us in January 2015 through a
320 borehole at the GL of Whillans Ice Stream (WGZ; Fig. 1; Extended Data Table 1) had the
321 fraction of modern radiocarbon at only 0.8669-0.8746, corresponding to apparent ages of 1075-
322 1145 ¹⁴C years. Moreover, it is well documented that radiocarbon dates on acid insoluble organic
323 matter (AIO) obtained from bulk Antarctic glacial sediments are typically biased by
324 admixture of old, ¹⁴C-depleted organic matter^{4,44,45,46}. This old organic material comes from
325 glacial erosion of sediments deposited earlier in the Cenozoic³⁷. The tills of the Ross ice streams
326 are dominated by Tertiary, mostly Upper Miocene^{37,38}, marine source beds that are being
327 actively eroded by grounded ice³⁶. Given the uncertainty concerning the initial mixture between
328 'young' and 'old' sources of organic matter, we only know that the real age of the radiocarbon
329 falls somewhere along the exponential-decay lines of ¹⁴C in Extended Data Fig. 5, which
330 intersect the left-hand vertical axes of this figure at the measured values of ¹⁴C fraction modern.

331 Rather than the apparent ¹⁴C ages representing the true sediment ages, it is more reasonable to
332 assume that the WAIS GL was upstream of the till sampling locations subsequent to LGM, and
333 that the calculated ages are biased toward older dates due to the high concentration of ancient
334 carbon (Extended Data Fig. 5). Our assumption is also compatible with relatively low initial
335 fractions of ¹⁴C in sampled sediments, which we expect given that the sampled subglacial areas

336 were exposed to influx of marine-sourced radiocarbon over a geologically short period of time
337 and were located very far from the main locus of regional biological productivity in the Ross
338 Sea. For instance, if our sediment samples received ^{14}C -bearing marine organics in the Mid
339 Holocene, or ca. 5 kyr BP, the initial fractions of ^{14}C for these samples could be quite low (ca.
340 0.03 to 0.14) to explain the obtained apparent ages. In contrast, if one chooses a time period
341 predating the WAIS LGM, say 30 kyr BP, most of our samples would need to have all of their
342 organic matter completely equilibrated with the oceanic pool of ^{14}C at that time. Such conditions
343 are difficult to find even in the modern open marine sediments of Ross Sea^{44,45}.

344 The balance of evidence favors post-LGM origin of ^{14}C -bearing organics in our till samples.
345 However, the radiocarbon data do not allow us to pinpoint more precisely when the proposed
346 retreat and re-advance of WAIS GL took place in the Ross Sea Sector of the ice sheet, or the
347 specific duration of exposure.

348 *Potential Input of Radiocarbon from Basal Melting.*

349 Here we check if ^{14}C in subglacial sediment samples from beneath three different ice streams
350 may have been entirely, or at least to significant extent, supplied by basal melting of meteoric
351 ice. Meteoric ice may contain as much as 140 mm^3 of air per gram⁴⁷, which translates into ca.
352 0.02 grams of Total Inorganic Carbon (TIC) per m^3 of ice, assuming ice density of 910 kg/m^3
353 and pre-industrial Holocene atmospheric concentration of carbon dioxide (280 ppm). Meteoric
354 ice also contains organic matter deposited from the atmosphere^{48,49}. From the latter two
355 publications we select $100\text{ }\mu\text{g}$ per liter as an upper bound on Total Organic Carbon (TOC)
356 concentration in ice coming from the interior of the ice sheet. This assumption yields ca.
357 0.1 grams of TOC per m^3 of ice. TIC and TOC combined give 0.12 grams of carbon per m^3 of
358 meteoric glacial ice. Basal melting rates vary beneath the Ross Sea Sector of the WAIS but 0.003

359 m/year provides a representative estimate for the region⁵⁰. At this rate 0.36 grams of carbon per
360 m² of the bed area would be entering the subglacial zone of the ice sheet in each thousand years.
361 Some of this material would be entering subglacial sediments already as organic carbon melted
362 out of the ice whereas the component derived from carbon dioxide trapped in the melting ice
363 would exist as Dissolved Inorganic Carbon (DIC). We assume that the latter could be relatively
364 quickly sequestered by subglacial microbial activity and converted into organic matter²¹.

365 The basal flux of carbon estimated above needs to be compared to the total stock of carbon in the
366 subglacial till from which our samples are derived. Our radiocarbon measurements show that ¹⁴C
367 is present at least within the top 1 m of till recovered from beneath three Ross Sea Sector ice
368 streams. Analyses performed in the University of California, Santa Cruz stable isotope laboratory
369 (UCSC CF-IRMS) on 27 subglacial sediment samples show average TOC of 0.33% (with
370 standard deviation of 0.14%, both expressed in weight % of the dry sedimentary matter).

371 Because the dry density of the till is ca. 1,600 kg m⁻³ (ref. 51), a 1m-thick layer of till contains
372 about 5 kg of organic carbon per m³ of sediment. Even if we assume that all of the carbon
373 entering the subglacial zone with basal meltwater is sequestered within the top 1 m of till, it
374 would take about 14 million years to supply the total amount of carbon found in these sediments
375 just from basal melting at the rate of 0.36 grams per 1,000 years. Due to ¹⁴C decay only the
376 carbon released by basal melting during the last tens of thousands of years can contribute to the
377 current stock of this radioisotope in till. The remaining ratio, R , of undecayed ¹⁴C in a pool of
378 carbon accumulating through time, t , by addition of new ¹⁴C-bearing matter at a constant rate can
379 be calculated from

$$380 \quad R_{\{t\}} = \frac{R_0}{t} \int_0^t e^{-\frac{\zeta}{\lambda}} d\zeta = R_0 \frac{\lambda}{t} \left(1 - e^{-\frac{t}{\lambda}}\right),$$

381 where R_0 is the initial ¹⁴C ratio (e.g., modern atmospheric ¹⁴C /¹²C ratio), ζ is a dummy variable

382 of integration, and λ is a constant given as the product of ^{14}C half life, 5,730 years, and the
383 natural logarithm of 2 (i.e., 3,972 years). After 14 Myr the hypothetical subglacial carbon pool
384 resulting solely from a continuous accumulation of carbon released from basal melting of
385 meteoric ice would have average ^{14}C ratio of only 0.00028 of its initial (e.g., modern) value. This
386 is two orders of magnitude too low to explain the fractions of ^{14}C measured in our samples. From
387 the equation above we can calculate that the observed fractions of ^{14}C could only be explained by
388 constant accumulation of carbon with modern initial ^{14}C over periods of time around 100 kyr
389 years or less. However, the flux rate of carbon from basal melting would then have to be around
390 50 grams per thousand years per unit area of the ice base in order to explain the total stock of
391 carbon in the sampled subglacial sediment layer (ca. 5 kg m^{-3}). As per our discussion above, such
392 rates of carbon delivery from melting basal ice is implausibly high.

393 The analyses presented here did not even take into account the fact that any carbon released from
394 the base of the ice streams has spent thousands to tens of thousands of years stored in the ice
395 itself, which would further decrease its ^{14}C content. Furthermore, an ice stream base can also be
396 composed of basal ice that has been formed by freezing of subglacial waters. Such basal ice
397 would not contain ^{14}C -bearing carbon dioxide or organic matter. Hence, we conclude that release
398 of ^{14}C from the base of the ice sheet does not represent a significant source and that inclusion of
399 recent marine organic matter during a recent ice sheet retreat is needed to explain the
400 concentrations of this isotope measured in our samples. Furthermore, the radiocarbon results we
401 report are completely consistent with ice-sheet retreat ages inferred by the radar profiles and
402 modeling reported here.

403 *A modern analogy from the present-day sub-shelf cavity*

404 Hot water drilling through 760 m of ice into 10 m of water in a sub-ice shelf embayment more

405 than 600 km from the open ocean, at the Whillans Ice Stream grounding zone⁵² (WGZ; Fig. 1)
406 revealed a diverse community of organisms – including diverse amphipods, zoarcid and
407 notothenioid fishes, and medusoid and ctenophorid jellies – thriving in fully-marine water.
408 Radiocarbon analysis of appendages from 3 live-captured amphipods yielded raw ages between
409 1075±20 and 1145±20 yr BP (Extended Data Table 1), comparable to the Ross Sea surface water
410 reservoir age⁵³. This GL-proximal community of organisms demonstrates that radiocarbon is
411 introduced from the open ocean virtually everywhere that ocean waters reach beneath the ice
412 shelf. A retreating GL would have opened a subglacial marine environment that was immediately
413 colonized by organisms that leave a radiocarbon tracer on their death. This modern sub-ice shelf
414 process illustrates a likely pathway for Holocene radiocarbon to be deposited upstream of the
415 current GL following past GL retreat. Furthermore, porewater chemistry indicative of seawater at
416 Subglacial Lake Whillans (SLW; Fig. 1)²¹ demonstrates that marine waters previously occupied
417 the subglacial lake basin.

418 **Henry Ice Rise: observations, interpretation and flow history.**

419 Henry Ice Rise (HIR) is one of several ice rises in the Weddell Sea that influence the flow of
420 Ronne Ice Shelf and its ice streams. It is currently slow-flowing³¹ and cold based⁵⁴. Based
421 primarily on new ground-based ice-penetrating radar data, we hypothesise that HIR formed
422 during the Holocene as the Ronne Ice Shelf grounded on a bathymetric high. Here we describe
423 the radar system and our processing steps, and discuss possible links between surface roughness
424 and englacial structure, which pertain to a potential past GL configuration. We also discuss an
425 alternative interpretation that HIR existed throughout the Holocene, but was in the past
426 significantly smaller than it is today.

427 *Radar system*

428 We used the British Antarctic Survey's DEep LOoking Radio-Echo Sounder (DELORES) on
429 HIR to map basal topography and englacial structure⁵⁵. A transmitter producing 2500 broadband
430 radio-wave pulses per second was connecting to a 20 m, resistively-loaded dipole antenna, so
431 that the center frequency of the system in ice was 4 MHz. A receiver unit, positioned 100 m from
432 the transmitter connected to an identical dipole antenna was, triggered by the air wave and
433 sampled the return signal at 250 MHz. The system was towed 50 m behind a snowmobile, driven
434 at $\sim 15 \text{ km hr}^{-1}$. After stacking, this configuration produced traces every $\sim 85 \text{ cm}$ along the track.

435 *Data processing*

436 Traces were geo-located in three dimensions using data from a dual-band GPS unit, mounted at
437 the midpoint of the transmitter and receiver, then interpolated onto a regularly-spaced grid, band-
438 pass filtered and compiled into radargrams. Radargrams were migrated with a 2D Kirchoff
439 scheme, assuming a constant radio-wave velocity, 0.168 m ns^{-1} (ref. 55).

440 Elevations of the ice-bed interface and one of many englacial reflecting horizons, interpreted as
441 isochrones, were determined using the software package Petrel by Schlumberger. The conversion
442 from two-way travel time of the radar signal to depth was made assuming a constant radio-wave
443 velocity (0.168 m ns^{-1}). Correcting for the impact of the lower density of the firn on radio-wave
444 velocity would decrease the elevation by up to 10 m. As firn densities are unknown on HIR and
445 likely vary spatially, we plot the uncorrected elevation of the ice-bed interface, z_b , (Fig. 2a). The
446 normalized elevation of the isochrone ζ_i is computed from $\zeta_i = (z_i - z_b)/(z_s - z_b)$, where z_i is the
447 elevation of the isochrone and z_s is the ice surface elevation measured with the dual-band GPS
448 (Fig. 2c).

449 *Surface texture contrasts visible in satellite imagery and surface elevation data.*

450 Antarctic satellite imagery can be used to reveal subtle ice-surface topography⁵⁶. The MODIS

451 Mosaic of Antarctica image in Fig. 2 highlights contrasting regions near the northern end of HIR,
452 which we interpret as indicative of contrasting surface roughness. The green curves in Fig. 2b &
453 2c highlight the boundaries between the regions. The area between the two green curves appears
454 smoother than the two regions between the green curves and the present-day GL. This
455 interpretation is consistent with surface slopes estimated from elevation data collected by the
456 GPS unit mounted on the DELORES radar system (not shown).

457 The surface-texture contrasts are approximately parallel to the present-day GL and align
458 approximately with the following features revealed by our ice-penetrating radar survey: extensive
459 synclines in internal isochrones (Fig. 2c; Extended Data Fig. 2a), locations where isochrones
460 intercept the bed (Fig. 2b; Extended Data Fig. 2f) and the onset of buried crevasses (Fig. 2b).
461 Here we explain these alignments by proposing that all these features are the signatures of a past
462 GL configuration that persisted during a period either following the grounding of the ice rise, or
463 alternatively, when HIR was at its minimum extent (see next section).

464 Today on the ice-shelf side of the eastern GL of HIR, ice undergoes lateral shear as the ice shelf
465 moves past the relatively slow ice rise. This shear generates a region of dense crevassing
466 (Extended Data Fig. 2g). Deformation in shear margins also warms englacial ice and generates
467 ice-crystal fabric. Both can impact ice effective viscosity, as can crevassing. As the GL swept
468 through the region between the surface-texture contrast and the present-day GL, crevasses
469 generated on the ice-shelf side of the GL would have become inactive, buried and then deformed
470 in the slow moving ice. Simultaneously, englacial temperature and crystal fabric would have
471 evolved in a complex manner as the shear margin migrated in step with GL migration. We
472 hypothesise that, along with spatially heterogeneous basal melting, these changes resulted in the
473 complex pattern of tilted crevasses we observe today.

474 Under this interpretation, the rougher surface texture in the region currently occupied by buried
475 crevasses (Fig. 2) results from spatially-variable ice viscosity caused by variability in the
476 orientation and height of crevasses as well as spatially-variable ice fabric and temperature that
477 have evolved enough to still affect ice flow. In contrast, the ice in the region between the two
478 green curves (Fig. 2) has undergone a simpler flow history, without significant lateral shearing,
479 either because it was immediately upstream of the initial location of grounding (the subglacial
480 high in Fig. 2a) and experienced only longitudinal compression, or because it did not unground.
481 We discuss the latter scenario next.

482 *An alternative interpretation: a smaller-than-today, but persistent HIR*

483 In the main text and in the previous section we interpret our radar observations to indicate that
484 HIR became completely ungrounded post-LGM, then formed through re-grounding on the
485 topographic high at the northern end of HIR. Some of our radar observations can be explained by
486 an alternative ice-flow history. The GL surrounding HIR may have retreated significantly,
487 exposing areas of the ice base to the ocean, where heterogeneous basal melting deformed and
488 truncated isochrones at the bed. Subsequent re-advance of the GL would have buried crevassing
489 as described above. This would have had an effect on regional ice-shelf dynamics and
490 buttressing, but HIR would have persisted throughout the Holocene. However, if the locations
491 where isochrones are truncated at the bed correspond to areas that ungrounded, then the simplest
492 minimum extent suggested by mapping the layer truncations (Fig. 2b) would involve the ice rise
493 ungrounding over the highest basal topography (Fig. 2a), while remaining grounded over deeper
494 bathymetry. We do not yet understand ice-rise dynamics sufficiently to fully assess if this is
495 possible. However, such a pattern of ungrounding during deglaciation is inconsistent with recent
496 numerical modelling of idealized ice-rise formation⁵⁷. Therefore, we argue that full ungrounding
497 and later regrounding is more likely than partial ungrounding.

498 Whether the ice rise ungrounded completely or partially, the buttressing force exerted by the ice
499 shelf on the ice sheet upstream would have been affected. These scenarios could be tested by
500 drilling to the ice-rise base to obtain sediments for radiocarbon analysis and to allow
501 measurement of the englacial temperature profile⁵⁸.

502 **Ice-sheet modelling**

503 *Model description and forcings*

504 We used the open-source Parallel Ice Sheet Model (PISM)^{24,59,60}, to perform pan-Antarctic
505 simulations using glacial-cycle climate forcings. PISM is a three-dimensional, thermo-
506 mechanically coupled ice-flow model with a freely evolving GL and calving front. The hybrid
507 shallow approximation of Stokes flow allows for large-scale, long-term simulations of ice-sheet
508 evolution. Unless otherwise stated, we used surface temperature anomalies from the WAIS
509 divide ice-core (WDC) reconstruction⁶¹, which show a sharp increase of 11 K starting around 17
510 kyr BP. For surface accumulation we use the 1980-2000 mean accumulation from the output of a
511 regional climate model (RACMOv2.1, HadCM3, ref. 62) as a base accumulation pattern and
512 scale this pattern by 2% per degree of climatic temperature change from present⁶³ (using the
513 WDC reconstruction) and by 43% per km surface elevation change. The latter assumes a linear
514 dependence of air temperature on elevation combined with an exponential dependence of
515 precipitation on temperature. At the ice-ocean interface we use the Potsdam Ice-shelf Cavity
516 mOdel (PICO)⁶⁴, which calculates melt patterns underneath the ice shelves for given ocean
517 conditions⁶⁵. Ocean temperature anomalies are computed from ice-core derived surface
518 temperature anomalies convolved with a response function to produce a damped and delayed
519 response⁶⁶. The calving front can freely evolve with calving parameterized to be dependent on
520 principal strain rates at the ice-shelf front⁶⁷. Basal sliding is parameterized using an iterative

521 optimization scheme⁶⁸ modified for the till-friction angle, mimicking the distribution of marine
522 sediment and bedrock, such that the mismatch to modern surface elevation observations is
523 minimized.

524 Sea-level change drives GL migration through the flotation criterion, which determines GL
525 position⁶⁹. We prescribe sea-level changes by considering the height of the sea surface and the
526 height of the sea floor separately. Unless otherwise stated, we use global mean sea surface
527 heights prescribed by the ICE-6G GIA model⁷⁰. According to this model, mean sea-surface
528 height has risen by about 100 m since 14.5 kyr BP. Alternative sea-surface height records were
529 considered as part of the sensitivity analysis discussed below.

530 Changes to the height of the sea floor and bed topography are modelled using an approach that
531 reflects the deformation of an elastic plate overlying a viscous half-space. Calculations are
532 carried out using the computationally efficient Fast Fourier Transform to solve the biharmonic
533 differential equation for vertical displacement in response to ice load change⁷¹. This approach
534 can also be used to calculate vertical displacement in response to spatially-varying water load
535 changes (more details below). A key advantage this approach has over traditional Elastic
536 Lithosphere Relaxing Asthenosphere (ELRA) models is that the response time of the sea floor is
537 not considered a constant, but depends on the wavelength of the ice-load perturbation. This
538 formulation closely approximates the approach used within many GIA models⁷¹. Since our
539 ice-sheet model is not coupled to a GIA model we are unable to prescribe self-consistent water
540 load changes or account for feedbacks associated with post-glacial changes to the rotational state
541 of the Earth⁷². The effect of neglecting these processes is discussed below in the section on sea-
542 level forcing.

543 *Bed elevation adjustment*

544 With a resolution of 15 km and uncertain bed elevation, basal conditions and climate forcings,
545 matching the present-day GL position in the Weddell Sea required raising the ice-sheet bed in
546 one key location (Bungenstock Ice Rise) to compensate for topographic information lost during
547 remapping.

548 The present-day elevations of the sea bed and ice-sheet bed are regionally highly uncertain^{30,73}.
549 Furthermore, when remapping observed bed elevations (Bedmap2; ref. 30) from a relatively fine
550 spatial grid (1 km) to the spatial resolution of our simulations (15 km), we lose bed-elevation
551 information in key places. Remapping introduces inherent uncertainty into any low-resolution
552 ice-sheet modelling study, but it is particularly important for the process of ice rise re-grounding
553 that we highlight. For example, at present-day ice rises the remapping of the bed elevation data
554 reduces the apparent peak bed elevation by 36-135 m, while at their steep flanks this difference
555 can be a few hundred meters (Extended Data Fig. 4). We find that in our simulations, if we use
556 bed topography remapped directly from the Bedmap2 compilation, (using a first-order
557 conservative technique⁷⁴), the GL in the Weddell Sea Sector does not re-advance across a
558 1.300m-deep trough and often remains near to its Holocene minimum position, far inland of its
559 present-day location, until the end of simulations. This is unrealistic.

560 We have experimented with various approaches to dealing with the uncertainty introduced by
561 remapping bed topography to lower spatial resolutions. These include adopting the maximum
562 Bedmap2 value in each model gridcell either in the regions of individual ice rises or across the
563 whole ice sheet. We also experimented with a sub-grid pinning point scheme, dependent on the
564 thickness of the water column underneath the ice shelf within some uncertainty range⁷⁵ and with
565 a simpler uniform adjustment in the region of individual ice rises. Which approach we take
566 affects the timing and magnitude of GL retreat and re-advance. Without clear motivation to
567 adopt a more complex approach, we made the minimum adjustment to the bed that allowed the

568 GL to re-advance in the Weddell Sea Sector: we uniformly raised the bed by 150 m in a 165 km
569 by 180 km area centered on Bungenstock Ice Rise (BIR) only. This rather arbitrary choice is a
570 major limitation of this model ensemble, which prevents us (along with other uncertainties
571 associated with model resolution, forcings, parameters and physics, see below) from extracting
572 information about the timing of GL retreat and re-advance from our simulations.

573 The purpose of our model experiments is to explore the mechanisms that could have caused re-
574 advance and what impacts these mechanisms. It is beyond our scope to explore the range of
575 options to compensate for basal topographic re-mapping errors, but our work highlights that, at
576 least for studying ice-rise re-grounding, resolving this issue will be required if we are to make
577 quantitative predictions of millennial-scale ice sheet behavior.

578 *Model ensemble and the reference simulation*

579 We performed an ensemble of simulations, each spanning 205 kyr BP to present, in which
580 uncertain parameters were systematically varied and the results were compared to paleo-ice-
581 sheet datasets and present-day observations^{76,77}. The full results of the ensemble represent a
582 likely range of Antarctic ice-sheet chronologies and will be presented elsewhere. Here we are
583 focused on the possible extent and triggers of large-scale GL re-advance during the Holocene
584 and so only discuss in detail mechanisms relevant to this process. We choose one of the
585 ensemble members to act as a reference simulation to demonstrate aspects of model behavior.
586 The reference simulation is chosen from many ensemble members that employ parameters that
587 lie within physically-plausible bounds (Extended Data Table 2) and also achieve reasonable
588 agreement with a commonly-used ice-sheet GL position reconstruction². Despite this GL
589 reconstruction not including GL re-advance during the Holocene, as discussed in the main text,
590 many ensemble members, including our reference simulation, simulate the GL retreating

591 significantly inland of its present-day position and subsequently re-advancing towards its current
592 position. We express ice-mass changes as the above-flotation volume in units of global sea-level
593 equivalent, assuming a constant ocean area of $3.61 \times 10^{14} \text{ m}^2$ (ref. 78).

594 *The drivers of GL re-advance*

595 We performed three model experiments (separate from the full ensemble, above) to disentangle
596 the causes of re-advance in the Weddell and Ross Sea sectors. We find that both uplift of the bed
597 at the GL and buttressing caused by the formation of ice rises drive re-advance of the GL
598 towards its present-day position in both the sectors (Extended Data Fig. 4). The first experiment
599 ('No uplift'; Extended Data Fig. 4) is identical to the reference simulation except that uplift is
600 halted after 10 kyr BP, i.e. at approximately the time at which the GL in the reference simulation
601 reaches its most retreated position in both sectors (Fig. 3). The GL in the Weddell Sea remains at
602 its 10 kyr BP position for the remainder of the simulation. In the Ross Sea the GL retreats further
603 into the interior of the ice sheet. This additional retreat can be prevented by buttressing, as
604 demonstrated in the second experiment ('No uplift, grounding of ice rises'; Extended Data Fig.
605 4), where uplift is again halted 10 kyr BP, but ice-rise formation is enforced by raising the
606 seafloor in the locations of the Crary, Steershead, Henry and Korff ice rises and Doake Ice
607 Rumples. In this simulation further retreat in the Ross Sea is prevented, but re-advance still does
608 not occur in either sector. We further test the relevance of buttressing via ice-rise formation in a
609 third experiment ('Uplift, no grounding of ice rises'; Extended Data Fig. 4) in which uplift of the
610 bed is allowed, but ice-rise formation is prevented by lowering the seafloor. In this simulation
611 ice-shelf buttressing is reduced compared to the reference simulation. Consequently, the GL
612 remains at its 10 kyr BP position in the Weddell Sea (Extended Data Fig. 4a) and relatively little
613 re-advance occurs in the Ross Sea (Extended Data Fig. 4b). Hence we identify the grounding of
614 HIR, as evident from our radar survey, as critical for GL re-advance in the Weddell Sea in these

615 simulations, while in the Ross Sea neither uplift in the GL region nor buttressing due to ice-rise
616 formation, is alone sufficient to drive GL re-advance to the present-day position.

617 *Model sensitivity to forcings*

618 Extended Data Fig. 6 plots selected results from our analysis of the sensitivity of the model to
619 various forcings. The retreat of the GL inland of its present-day location and subsequent re-
620 advance is a common behaviour of the model, however the Holocene minimum extent, and how
621 fast and how far the GL re-advances are all sensitive to forcings.

622 Since **sea-level forcing** is highly relevant for deglaciation, the responses to four different eustatic
623 sea-level reconstructions were compared (Extended Data Fig. 6a). In our reference simulation we
624 use the sea-level curve from the ICE-6G model⁷⁰. Ref. 79 and ref. 80 provide similar sea-level
625 reconstructions and hence similar model results, with the strongest changes after around 15 kyr
626 BP. The SPECMAP timeseries⁸¹ was used in the SeaRISE intercomparison⁷⁸ and shows a
627 delayed LGM sea-level lowstand as well as a delayed sea-level rise to Holocene conditions and
628 hence the modelled ice sheet exhibits a later retreat and re-advance (Extended Data Fig. 6).

629 In order to mimic the first-order effects of GIA coupling⁸² (including rotational feedback and
630 self-gravitational effects) we experimented with scaling the sea-level forcing time-series by
631 factors of 0.9 and 0.8 (initiated at 35 kyr BP, Extended Data Fig. 6b). We do not attempt to
632 prescribe spatially-varying sea-level forcing, but comparison with independent GIA model
633 output⁸³ suggests that neglect of rotational feedback and self-gravitation of the ocean may result
634 in local errors in sea-level forcing on the order of 15-20 m (this range reflects the likely error
635 associated with prescribing sea surface height; deformation of the seabed is self-consistently
636 modeled within PISM). Scaling the uniform sea-level forcing by a factor of 0.9 causes the
637 lowstand to be less pronounced at the LGM (approximately 10 m higher), in comparison to the

638 reference simulation. This affects the LGM GL position, particularly in the Ross Sea, which in
639 turn affects the retreat and re-advance of the GL, because the depression of the bed depends
640 sensitively on the ice-sheet's LGM extent. Scaling by 0.8 may be unrealistic (based on
641 comparison with GIA model output generated using an independent ice-sheet history⁸³; results
642 not shown), and interestingly, we note that retreat behind the present-day GL position is not
643 reproduced in this scenario (Extended Data Fig. 6b). We also experiment with a sea-level forcing
644 that is identical to that used in the reference simulation (ICE-6G model⁷⁰) except that the curve
645 has been uniformly shifted 2 kyr earlier. The result is that the GL responds with an earlier retreat.
646 This response emphasizes the key role of the sea-level forcing in triggering large-scale GL
647 retreat.

648 Sea-level changes also impact the load of the ocean on the sea bed. This triggers bed deformation,
649 which will affect GL migration. By default, this second-order effect is not accounted for in PISM.
650 However, we carried out exploratory simulations that do account for it (not shown), and find that
651 when GL retreat is accompanied by an increase in eustatic sea-level, the additional ocean load
652 partly counteracts the unloading associated with GL retreat. Accordingly, the GL retreats further
653 inland than in the reference simulation. On the other hand, sea bed uplift following GL
654 retreat reduces the water load in marine sectors, this further amplifies uplift, which supports GL
655 advance. These interesting second-order effects do not qualitatively affect model behavior, but
656 they do impact the magnitude of GL retreat and re-advance via their influence on LGM extent in
657 both the Weddell and Ross sectors.

658 For surface **temperature forcing** our reference simulation uses a reconstruction of the WAIS
659 divide ice core (WDC)⁶¹. The results are similar when an alternative reconstruction from the
660 EPICA Dome C ice core (EDC)⁸⁴ is used (Extended Data Fig. 6c). However, the GL responds to
661 the slightly warmer LGM conditions in the EDC case with less LGM advance and hence a less

662 severe retreat in the Ross Sea Sector. For comparison, we also force one simulation with a
663 temperature record pertaining to the start of the Last Interglacial Period (from the EDC core), in
664 which an earlier and stronger warming leads to an earlier and stronger GL retreat, particularly in
665 the Ross Sea Sector.

666 **Accumulation** in the reference simulation is coupled to changes in surface temperature by
667 imposing a 2% precipitation change for each degree variation from present-day temperatures
668 (Extended Data Fig. 6d, violet curves) due to climatic changes (constrained by ice core data) and
669 a 43% precipitation per km of surface elevation change. We experimented with two alternative
670 time-dependent accumulation forcings and two constant accumulation scenarios. Using either a
671 scaling of 5% per degree of WDC-temperature change or an independent WDC-derived
672 accumulation reconstruction⁸⁵ leads to lower mean accumulation and a less advanced LGM GL
673 position(Extended Data Fig. 6d). The less advanced LGM GL almost eliminates GL retreat
674 inland of its present position and re-advance, particularly in the Weddell Sea. When
675 accumulation is kept constant at LGM conditions (2% per degree scaling of the EDC temperature
676 at 25 kyr BP; Extended Data Fig. 6d), which correspond to lower accumulation than today, the
677 GL retreats inland of its present-day location in both sectors, but only partially re-advances in the
678 Ross Sea and does not re-advance in the Weddell Sea. When accumulation is kept constant at
679 present-day values (Extended Data Fig. 6d) GL retreat starts earlier than in the reference
680 simulation, particularly in the Ross Sea. In both sectors the GL retreats and re-advances in a
681 similar way to the reference simulation, but with different timings: in the Weddell Sea the GL re-
682 advances several thousand years earlier than in the reference simulations, while in the Ross Sea
683 re-advance is delayed in comparison to the reference simulation.

684

686 Next we use selected members of the ice-sheet model ensemble to demonstrate the sensitivity of
687 the model to various parameter values. Analysis of the full model ensemble, including a
688 systematic validation of the full range of parameter combinations against present-day conditions
689 and reconstructions of paleo conditions^{28,77}, will be presented elsewhere. Here we present the
690 impact of single parameter perturbations. In general, we find that retreat of the GL inland of its
691 present-day location and subsequent re-advance occurs over a wide range of parameter choices,
692 but the Holocene minimum extent, and how fast and how far the GL re-advances are all sensitive
693 to these choices.

694 **Mantle viscosity** affects model behavior because it defines the rate and pattern of the
695 deformation of the ice-sheet bed and sea floor. Our reference simulation uses a mantle viscosity
696 of 5×10^{20} Pa s. The ensemble also covered a value considered typical for pan-Antarctic model
697 simulations and used as the default value in PISM (1×10^{21} Pa s; Extended Data Fig. 7a). We
698 selected the lower value for our reference simulation to account for the weaker mantle beneath
699 the WAIS⁸⁶. An even lower viscosity ($\sim 1 \times 10^{20}$ Pa s; Extended Data Fig. 7a) has also been tested.
700 In the lowest viscosity case, GL retreat inland of the present-day position is prevented as the bed
701 responds too quickly to ice unloading. We find the fastest GL retreat rates for higher viscosities.
702 The most inland position reached by the GL is similar in each case, except the lowest viscosity
703 case, and re-advance occurs earlier for lower mantle viscosity. In summary, we find that GL
704 retreat and re-advance occurs in a plausible but confined range of mantle viscosity values.

705 **Flexural rigidity** is associated with the thickness of the elastic lithosphere and has an influence
706 on the horizontal extent to which bed deformation responds to changes in load. Previous studies
707 based on gravity modeling suggest appropriate values for our study with a focus on West

708 Antarctica lying within the range of 5×10^{23} to 5×10^{24} N m (refs. 87, 88). Our reference
709 simulation marks the upper end of this range (Extended Data Fig. 7a). For lower values,
710 1×10^{24} to 5×10^{23} N m, we find GL retreat beyond its present-day location and re-advance as in
711 the reference simulation. However maximum retreat is delayed in the Ross Sea sector, so re-
712 advance of the GL does not reach its present-day location in that sector.

713 **Enhancement factors** are used in ice modeling to account for anisotropy and other unresolved
714 rheological properties. PISM employs one enhancement factor for the shallow-shelf
715 approximation (SSA) component of the constitutive law and a second enhancement factor for the
716 shallow-ice approximation component. Increasing the SSA-enhancement factor (Extended Data
717 Fig. 7b) and/or decreasing the SIA-enhancement factor (Extended Data Fig. 7c) produces a less
718 advanced LGM GL position. This is because larger values of the SSA-enhancement factor
719 produce faster ice streams and thinner ice shelves, and smaller values of the SIA-enhancement
720 factor produce thicker grounded ice. For a less advanced LGM GL, retreat initiates earlier and
721 progresses more slowly, and does not reach as far inland before retreat is halted.

722 PISM uses a generalized sliding parameterization formulated as an exponential sliding law⁶⁰. In
723 the reference simulation we use a **sliding exponent**, $q = 0.75$ (Extended Data Fig. 7d). In the
724 plastic case ($q = 1$), the LGM GL is less advanced and retreat starts earlier (Extended Data Fig.
725 7d). For smaller values of q retreat occurs generally later in the Weddell Sea and retreat in the
726 Ross Sea is less pronounced.

727 Two other parameters associated with the sliding parameterization are the **decay rate of till**
728 **water** and the **effective overburden pressure**⁶⁰. Within the range explored by the ensemble,
729 both parameters have only a moderate effect on LGM GL extent and the timing of retreat, and do
730 not affect whether or not the GL retreats inland of its present-day location and re-advances

731 (Extended Data Fig. 7e).

732 A final sliding-related parameter is the **till friction angle**, which varies spatially and for our
733 reference simulation is optimized⁶⁸ to minimize the mismatch between modelled and observed
734 surface elevation, but is constrained to be larger than 2°. Reducing the minimum value to 1°
735 leads to a smaller LGM extent and hence a slower retreat and larger minimum extent (preventing
736 retreat past the present-day GL position in the Weddell Sea) (Extended Data Fig. 7f). Instead of
737 optimizing the till friction angle using observed surface elevations, it can also be defined as a
738 linear piece-wise function of bed topography, with 2° used in areas below -500 m (this is the
739 default approach in PISM)⁶⁰. This also reduces the LGM extent and, in the Ross Sea, reduces the
740 retreat of the GL inland of its present-day extent.

741 Ocean forcing in our simulations is modelled with PICO⁶⁴. PICO employs parameters for
742 **overturning strength** and **heat exchange**. Modification of the parameter values affects the
743 LGM GL extent and hence the rate and timing of retreat (Extended Data Fig. 7g). However, GL
744 retreat and re-advance are produced as robust features for extreme parameter values, even if
745 melting is omitted or prescribed as a constant at present-day values.

746 Calving is parameterized as **eigencalving** (dependent on strain rates)⁶⁷. A parameter K is the
747 constant of proportionality between calving rate and horizontal spreading rate of ice
748 shelves(Extended Data Fig. 7h). K is assumed constant and uniform. Our reference simulation
749 uses $K = 1 \times 10^{17}$ m s. LGM GL position is less advanced for smaller eigencalving values, and GL
750 retreat less pronounced, likely due to additional ice-shelf buttressing resulting from less calving.

751 **Resolution dependence**

752 Our simulations, in common with all millennial-timescale ice-sheet simulations, suffer from
753 significant limitations related to the maximum practical spatial resolution that they can employ.

754 Just like the model parameters considered in the previous section, the spatial resolution can be
755 treated as a quantity that affects the results of the simulations and should be investigated. This is
756 particularly true in our study as ice-shelf grounding on bathymetric highs with relatively small
757 horizontal dimensions has proven to be so important for the large-scale evolution of the ice sheet.

758 A sensitivity analysis aimed at examining the sensitivity of this behavior to resolution (analogous
759 to the exercise described above) is highly limited by computational resources. For example,
760 doubling the spatial resolution incurs at least a ten-fold increase in computational cost.

761 Ensembles with systematically-varied parameters of simulations that span the full spin-up over
762 two glacial cycles (205 kyr) currently are only possible with a spatial resolution of 15 km.

763 Shorter duration simulations (that only cover the last 20 kyr) are possible using a resolution of up
764 to 7 km, if they are initiated at 20 kyr BP by remapping the spun-up state of a 15 km resolution
765 simulation. (Unfortunately, this remapping means that, despite higher resolution, the bed
766 topography is no better resolved with respect to observations³⁰ than the 15 km resolution
767 simulations.) Higher resolution simulations generally reproduce the pattern of GL retreat and re-
768 advance, but the increase in resolution strongly impacts the timing and magnitude of changes
769 (Extended Data Fig. 8). Due to the influence of resolution on other model parameters, a full
770 ensemble analysis at higher resolution would be required to fully characterize the resolution
771 dependence of our simulations. Furthermore, these simulations would need to use the higher
772 resolution throughout the 205 kyr spin-up period in order to benefit from better-resolved bed
773 topography. This is unfeasible with currently-available computing resources.

774 **Geophysical and terrestrial evidence consistent with re-advance.**

775 Previous geophysical and terrestrial observations are consistent with our proposed sequence of
776 retreat and re-advance, but do not yet provide a coherent pattern of retreat and re-advance. Their

777 spatial coverage is currently insufficient to reveal the full complexity of Holocene retreat and re-
778 advance. In the Weddell Sea, ref. 55 presented evidence that Korff Ice Rise (KIR; Fig. 1) has
779 been in a steady configuration since around 2.5 kyr BP. However, prior to that time KIR could
780 have undergone significant flow disturbance, including near-complete ungrounding and
781 regrounding (as occurs in our reference simulation; Supplementary Video 1), if subsequent
782 steady ice flow has had sufficient time to remove englacial evidence of such a flow disturbance.
783 See ref. 55 for details of this interpretation. Radar over Bungenstock Ice Rise (BIR; Fig. 1)
784 suggests a reorganization in flow as early as 4 kyr BP (ref. 89), while regional uplift rates
785 suggest that BIR may have been ungrounded between 4-2 kyr BP (ref. 5). In the Ellsworth⁹⁰ and
786 Pensacola Mountains^{91,92}, exposure dates do not provide evidence for, but are consistent with
787 thinning below present and re-thickening within the last ~4 kyr (ref. 93). Ref. 94 noted that
788 radar-derived basal topography upstream of a subglacial basin beneath the Institute and Möller
789 ice streams suggests a former GL position more than 100 km upstream of today's grounding line,
790 although they did not suggest that this was a Holocene GL position.

791 Similarly, in the Ross Sea exposure-age dating in the Trans-Antarctic Mountains (e.g. ref. 3,4,
792 43, 95) may be consistent with our conclusions, but cannot confirm or rule-out re-advance.
793 Geophysical observations have hinted at recent re-advance. Borehole temperatures have been
794 used to date the grounding and formation of Crary Ice Rise (CIR; Fig. 1b) to 1.5-1.0 kyr BP (ref.
795 58) and ice-penetrating radar surveys of Kamb Ice Stream indicates that the GL was upstream of
796 its current location during the last few centuries⁹. However, it is unclear if the latter observation
797 is evidence for a long-term large-scale re-advance, or for relatively-small-scale GL fluctuations.

798 In both sectors, it is unclear if these varied observations from diverse glacial environments
799 (outlet glaciers, ice streams, ice rises, nunataks), paint a consistent picture of the timing of retreat
800 and re-advance. Our work does not provide any detailed timing constraints; the timing of

801 simulated GL migration depends on uncertain bed topography and model parameters, and further
802 work is needed to extract timing information from our radiocarbon and radar observations. We
803 leave to future work the important task of unravelling a retreat-readvance chronology consistent
804 with all observations.

805 **Code Availability**

806 PISM code used in this study can be obtained from <https://doi.org/10.5281/zenodo.1199066>.
807 Results and plotting scripts are available from the authors on request. Scripts for processing and
808 plotting radar data are also available on request.

809 **Data Availability**

810 Ice-penetrating radar data can be obtained from the UK Polar Data Centre: <http://doi.org/99d>. A
811 simple MATLAB script for viewing the raw radar data is also provided at this link. The
812 radiocarbon data supporting the findings of this study are available in Extended Data Table 1.

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816 **Extended Data Captions**

817 **Extended Data Figure 1: Crevassing at Doake Ice Rumples. a**, Radarsat Antarctic Mapping
818 Project (RAMP)⁹⁶ image showing the surface expression of ice-shelf crevasses in synthetic
819 aperture radar data. Light areas indicate high backscatter from (near)surface reflectors interpreted
820 to be surface crevasses. Crevasses form over and immediately downstream of Doake Ice
821 Rumples. We hypothesize that crevasses once formed in a similar manner over the topographic
822 high beneath the northern tip of HIR. **b**, Close-up view of the crevasses (black box in **a** shows
823 location), whose spacing (100-300 m), orientation (perpendicular to the flow of the ice shelf) and
824 lateral extent (~10 km) are similar to the steeply-dipping reflectors discovered near the bed of the
825 northern tip of HIR (e.g. Extended Data Fig. 2g) in the region of a topographic high. Yellow
826 curves are flow lines computed from satellite-derived surface velocities³¹. Flow is from bottom
827 to top. Polar stereographic coordinates are in km. The present-day GL³² is in red.

828 **Extended Data Figure 2: Relic crevasses in Henry Ice Rise. a**, Radargram aligned
829 perpendicular to the divide ridge (inset shows location). One undulating isochrone is highlighted.
830 The colours show normalised elevation. **b** and **c**, close-up views of the regions indicated in **a** by
831 the boxes. In both close-up panels, diffractors (hyperbolic reflectors) are interpreted as
832 expressions of relic crevasses (data is unmigrated). The red vertical dashed line in **c** is the
833 present-day GL³². **d**, **e** and **f**, Radargrams aligned approximately perpendicular to northern relic
834 crevasses (**d** and **e** show migrated data). In **c** ($6 \leq x \leq 8$ km) and **f** ($0.3 \leq x \leq 1.4$ km) isochrones
835 intercepting the bed are evident. **g**, Three relic crevasses mapped across several radar lines over a
836 RAMP image⁹⁶. Inset shows an oblique, three-dimensional view of the features over an
837 interpolated surface showing the bed elevation z_b (Methods). Crevasse spacing in these areas
838 ranges between approximately 200 m and 600 m. The arrow indicates the view direction of the
839 oblique view.

840 **Extended Data Figure 3: Grounding-line retreat and lithospheric rebound.** Cross-sections
841 along transects through the Weddell (left) and Ross (right) Sea sectors, at 5 kyr intervals (for
842 transects see Fig. 3). Horizontal axis shows distance from the present-day GL. Vertical blue
843 dashed line shows position of maximum GL retreat. **a** and **b**, 15 kyr BP, with GL close to the
844 continental shelf edge. **c** and **d**, 10 kyr BP, GL retreat to approximately its minimum, most
845 retreated location. **e** and **f**, 5 kyr BP, both ice shelves have grounded on sub-ice-shelf bathymetric
846 highs due to seafloor uplift. **g** and **h**, Present day, the GL has re-advanced to approximately the
847 present-day configuration in response to the grounding of the ice shelf and uplift at the GL. The
848 Crary (CIR), Bungenstock (BIR) and Henry (HIR) ice rises are labelled in **g** and **h**. The Whillans
849 Ice Stream (WIS) and Subglacial Lake Whillans (SLW) sediment core locations are labelled in
850 **d**. Blue dotted lines show the observed present-day ice-sheet bed, ocean floor and ice surface³⁰,
851 remapped on to the 15 km grid of the ice-sheet model.

852 **Extended Data Figure 4: The drivers of re-advance and the impact of bed re-mapping. a**
853 **and b**, Results from four simulations (the reference simulation, and three additional experiments)
854 designed to examine the cause of re-advance in the **a**, Weddell and **b**, Ross Sea sectors
855 (Methods). The most inland GL location in the reference simulation around 10 kyr BP is in blue.
856 The colour map shows the flow buttressing number⁹⁷ at 9.5 kyr BP for the ‘No uplift, grounding
857 of ice rises’ experiment. The ice front position is in grey. Background images over the grounded
858 ice sheet are from MOA (ref. 34). **c**, Basal topography and bathymetry in the Weddell (GL in
859 red) according to a 1 km resolution dataset, constrained by geophysical observations (Bedmap 2;
860 ref. 30). **d**, Conservative remapping of these data to 15 km resolution. Remapping significantly
861 lowers the apparent maximum bed elevations beneath ice rises in the Weddell Sea Sector: 135 m
862 at Korff Ice Rise (KIR), 112 m at HIR, 36 m at Bungenstock Ice Rise (BIR). The present-day GL
863 is in red³⁰.

864 **Extended Data Figure 5: True and apparent ages of radiocarbon.** Eleven grey lines show the
865 exponential ^{14}C decay curves connecting the $^{14}\text{C}/^{12}\text{C}$ ratios (scale on the left-hand-side axis)
866 measured on AIO from our subglacial sediment samples to the apparent radiocarbon ages
867 calculated from these measurements. The latter calculation assumes that the initial $^{14}\text{C}/^{12}\text{C}$ ratios
868 in AIO was equal to the modern ratio in radiocarbon dating standards. As discussed in the text
869 and methods sections, organic matter in Antarctic glacial sediments frequently contains an
870 admixture of old ^{14}C -dead material^{44,45}. The record of oxygen isotopes in water ice from the
871 WAIS Divide ice core (green line with scale on the right-hand-side axis) provides climatic
872 context for the period between now and 35 kyr BP (ref. 98). Three key climatic periods are
873 labeled: WAIS LGM = Last Glacial Maximum for WAIS⁹⁹, ACR = Antarctic Cold Reversal, and
874 Holocene.

875 **Extended Data Figure 6: Model sensitivity to forcings.** Time series of GL migration
876 demonstrating model sensitivity in the Weddell (middle panels) and Ross (right panels) sea
877 sectors to different **a**, sea-level reconstructions^{70,79,80,81}, **b**, scalings of the sea-level forcing to
878 mimic self-gravitational effects, **c**, surface temperature forcings and **d**, accumulation forcings.
879 The constant LGM accumulation uses the EPICA Dome C core⁸⁴ and a scaling of 2% per degree.
880 Temperature and accumulation are expressed relative to the present-day. GL positions are
881 relative to present day position (vertical dashed line) along transects shown in Fig. 3. In all
882 simulations the GL is in its most advanced position, up to 1000 km beyond its present-day
883 position, before MWP1a (14.4 kyr BP, horizontal dotted line). During the Holocene the GL
884 retreats up to 500 km upstream of its current location and usually re-advances towards its
885 present-day position. Grey shading indicates spread of GL response and grey curves show the
886 mean of each sensitivity experiment. In each case the violet curve shows the reference
887 simulation. GL positions (based on marine and terrestrial geological evidence) from the RAISED

888 reconstruction with associated uncertainty are shown in black².

889 **Extended Data Figure 7: Model sensitivity to parameters.** Time series of GL migration
890 showing model sensitivity in the Weddell and Ross sea sectors to **a**, mantle viscosity μ , and the
891 flexural rigidity of the lithosphere, D , **b** and **c**, enhancement factors E_{SSA} and E_{SIA} , **d**, sliding law
892 exponent q , **e** till water decay rate T and till effective pressure fraction N , **f**, minimum till friction
893 angle and the method used to derived friction angle (Methods), **g** PICO ocean model parameters
894 for overturning strength C and heat exchange g and **h**, the dependence of calving rate on ice-
895 shelf spreading rate K (Extended Data Table 2). In each panel the violet curve shows the
896 reference simulation. GL positions (based on marine and terrestrial geological evidence) from
897 the RAISED reconstruction with associated uncertainty are shown in black².

898 **Extended Data Figure 8: Model sensitivity to spatial resolution.** The results of three
899 simulations using different grid resolutions: **a**, 15 km (reference simulation; identical to Fig. 3),
900 **b**, 10 km and **c**, 7 km. Due to computational limitations the two higher resolution simulations
901 only cover the last 35 kyr, so lack a higher resolution spin-up period, but display similar
902 Holocene retreat and re-advance driven by isostatic rebound to the reference simulation.
903 However, LGM extent and GL re-advance in the Weddell Sea are significantly smaller in the
904 higher resolution simulations. A full exploration of the resolution dependence of the model
905 requires using higher resolution during entire simulations for all ensemble members. This is
906 currently limited by computing resources. Background shading shows basal topography and
907 bathymetry³⁰.

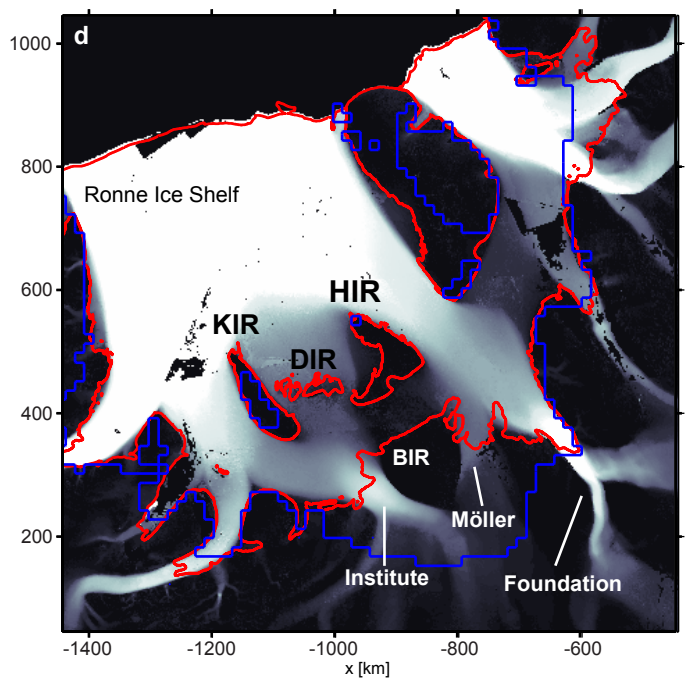
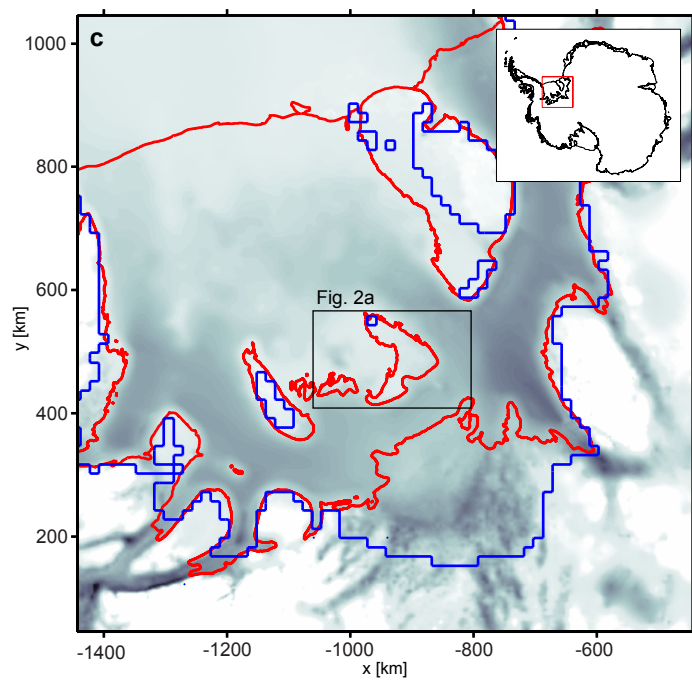
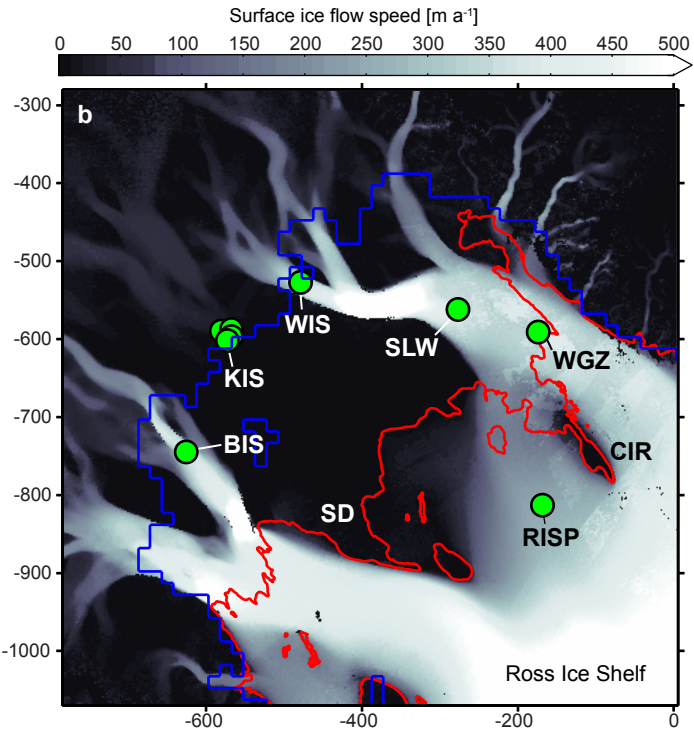
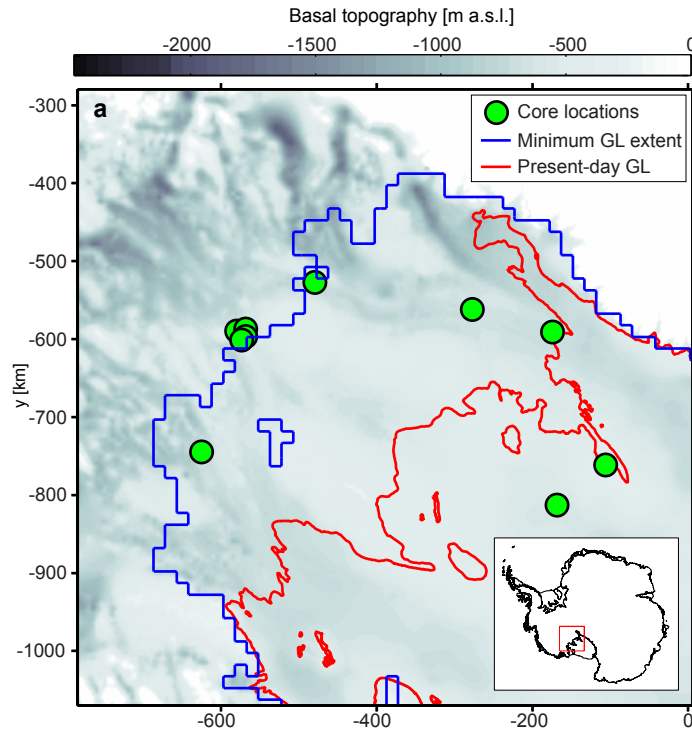
908 **Extended Data Table 1. Results of radiocarbon and $\delta^{13}\text{C}$ analyses of subglacial sediments.**
909 Carbon isotope results, including percent modern carbon, calculated age, analytical error and
910 independently measured $\delta^{13}\text{C}$. Low percent modern carbon relative to dominant ancient
911 (radiocarbon dead) carbon skews apparent ages older than the actual age of the marine
912 connection discussed here. The light $\delta^{13}\text{C}$ results also point to a significant old carbon source.

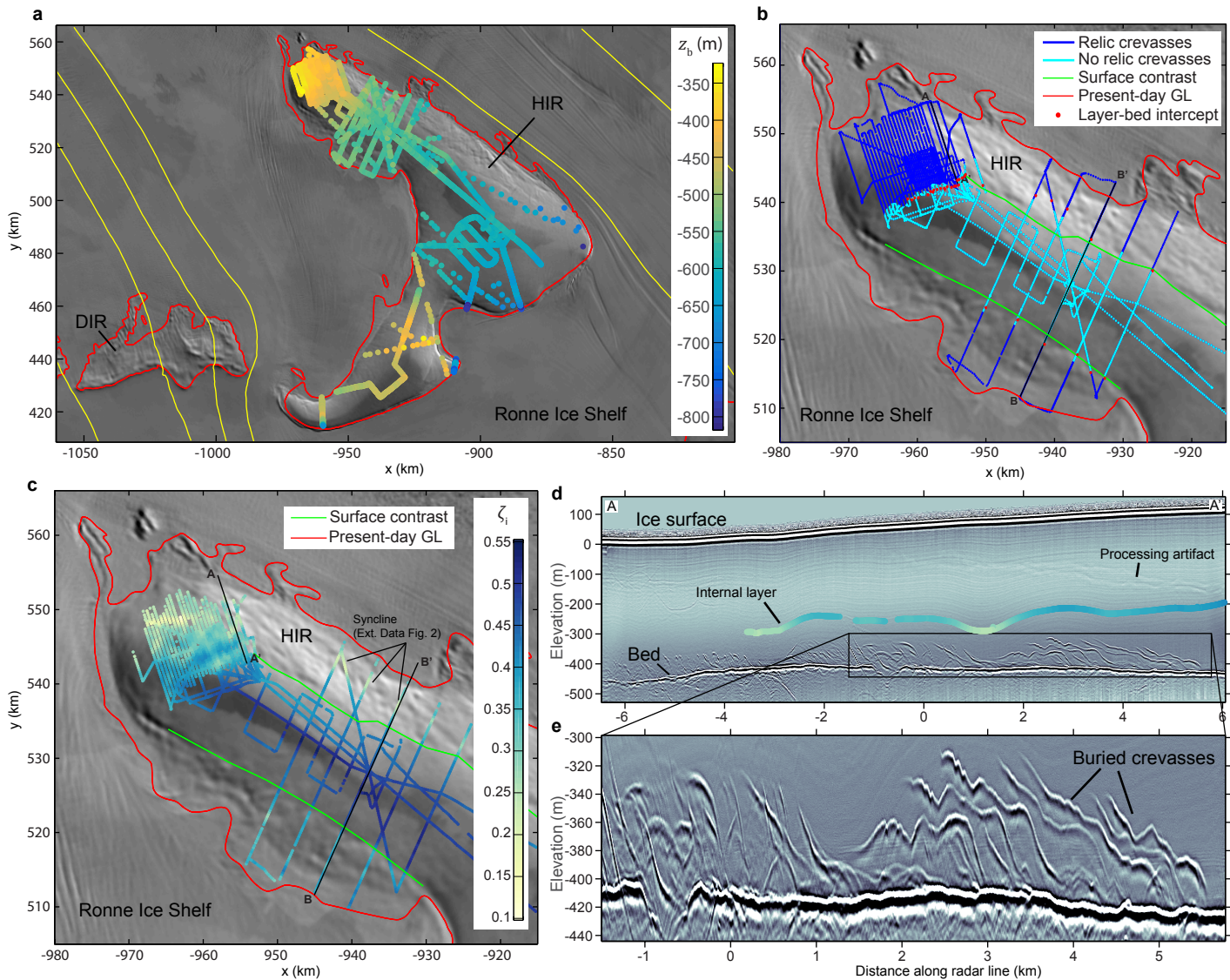
913 UpB is the upstream portion of the WIS.

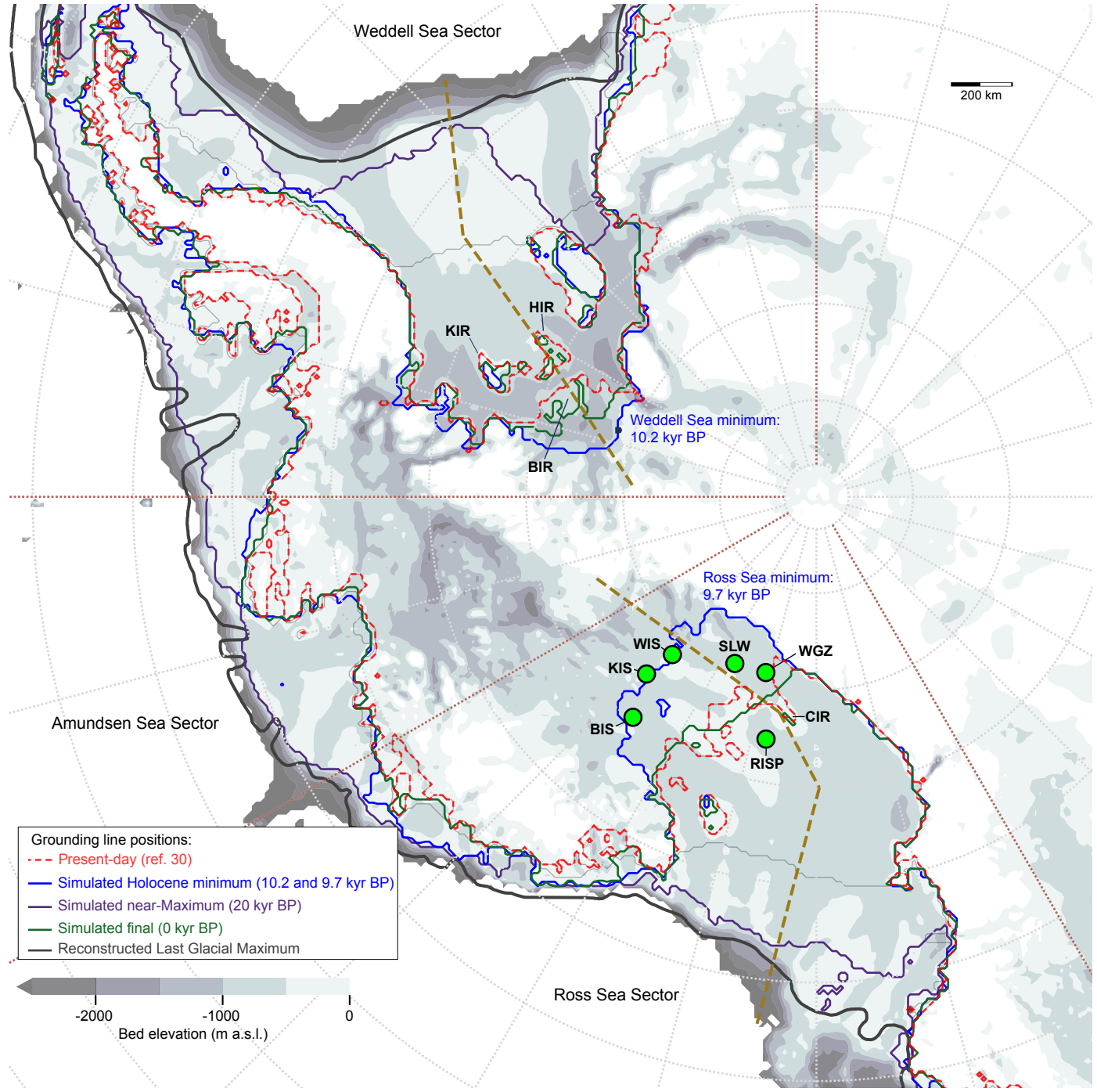
914 **Extended Data Table 2. Key model parameters with modelled retreat and re-advance.** Key
915 model parameters that have been varied as part of a sensitivity study of our ice-sheet model
916 (Methods). In each case the value used in the reference simulation is given as well as the range
917 over which the parameters were varied during the sensitivity study. Also provided is a summary
918 of the impact this parameter has on the model behavior in relation to the retreat of the GL past its
919 present-day location and subsequent re-advance. See Methods for a detailed discussion of model
920 sensitivities.

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Weddell Sea Sector

200 km

KIR

HIR

Weddell Sea minimum:
10.2 kyr BP

BIR

Ross Sea minimum:
9.7 kyr BP

WIS

SLW

WGZ

Amundsen Sea Sector

KIS

BIS

CIR

RISP

Ross Sea Sector

Grounding line positions:
- - - Present-day (ref. 30)
— Simulated Holocene minimum (10.2 and 9.7 kyr BP)
— Simulated near-Maximum (20 kyr BP)
— Simulated final (0 kyr BP)
— Reconstructed Last Glacial Maximum

-2000 -1000 0
Bed elevation (m a.s.l.)