



Rapid thinning of the Cordillera Darwin Icefield at the onset of Termination I

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ABSTRACT

Despite more than a century of research, the cause of the last ice-age termination remains uncertain. Here, we reconstruct the thinning history of the Cordillera Darwin Icefield, southernmost Chile, to track relative summer temperature change at the end of the ice age and to explore potential drivers of the warming. Eighteen ¹⁰Be exposure ages of erratics perched on glacially scoured bedrock indicate rapid surface lowering of at least 500 m elevation in the heart of the former icefield at some time between 18.8 and 16.9 ka at the onset of the termination. We infer that this drop in ice level reflects an increase in summer temperatures, which led to extensive glacier melt. We attribute the underlying cause to a poleward shift of the southern westerly winds, which placed the Cordillera Darwin Icefield in warmer air masses with temperatures incompatible with its LGM extent.

1. Introduction

What ended the last ice age? Traditionally, ice-age terminations, such as Termination I (~17.5–11.7 ka) are thought to have been forced by northern hemisphere summer solar insolation intensity (e.g., [Milankovitch, 1941](#); [Imbrie et al., 1993](#); [Raymo, 1997](#)). However, researchers as early as [Mercer \(1984\)](#) noted that this hypothesis cannot explain the broad global synchrony of terminations, because insolation is out of phase between the polar hemispheres. Thus, this view of insolation forcing requires propagation of the northern hemisphere signal to the entire globe. More recent work has looked for a cause in the inter-hemispheric phasing of millennial-scale changes during the termination. Hypotheses now hinge to a large degree on whether global climate was synchronous at these shorter timescales. For example, perceived

asynchronous climate behavior during Termination I (e.g., [Sowers and Bender, 1995](#)) has led some to invoke a bipolar seesaw (e.g., [Broecker, 1998](#)) as a critical driver, whereby shutdown of Atlantic Meridional Overturning Circulation (AMOC, [McManus et al., 2004](#)) caused warming of the southern hemisphere. Alternatively, those who favor globally synchronous climate commonly call upon atmospheric greenhouse gases to drive the end of the ice age (e.g., [Shakun et al., 2012](#)). Another possibility is that a latitudinal shift in the southern westerly winds (SWW), perhaps driven by southern hemisphere winter duration, influenced ocean heat storage and release, as well as atmospheric water vapor and carbon dioxide, causing globally synchronous climate change ([Denton et al., 2021](#)). Evaluating these hypotheses for the last termination requires accurate paleoclimate records from a variety of latitudes. Such information can show not only whether events are globally

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synchronous, but also whether the magnitude and rates of change are compatible with the proposed forcing mechanisms.

As a proxy for the timing and relative magnitude of summer temperature change during the last termination, we present here a new record of ice thinning in southernmost South America. Our chronologic data show a rapid reduction in surface elevation of the Cordillera Darwin Icefield at ~18.8–16.9 ka, at the start of the termination. We attribute this thinning to warming that accompanied a sudden southward shift in the SWW, which placed Cordillera Darwin in subtropical air masses more typical of interglacial times and not capable of sustaining the extensive LGM icefield.

2. Background

Cordillera Darwin (Fig. 1) is a west-east trending range near the southern tip of South America (54–55°S). The mountains rise from sea level to ~2400 m elevation and are covered by the Cordillera Darwin Icefield at present. The climate is maritime near the Pacific coast, but drier to the east (Tuhkanen, 1992). Glaciers descend to sea level in the center of the range, which is dissected heavily by fjords.

During the last glacial maximum (LGM), the present icefield expanded significantly to terminate on (or, in places, close to) the continental shelf (Coronato et al., 1999; Rabassa et al., 2000), although the exact LGM limit is uncertain in many places (Davies et al., 2020). Existing data suggest that the ice spread outward from mountain peaks and was influenced strongly by underlying topography. Ice flow was funneled through the major channels, such as Canal Beagle (Beagle Channel) south of the mountains and Canal Whiteside to the north (Fig. 1). North of the mountains, Cordillera Darwin outlet glaciers merged with eastward-flowing ice in the Estrecho de Magallanes (Straits of Magellan) and Bahía Inútil (Peltier et al., 2021; Huynh et al., 2024 and references therein; McCulloch et al., 2024). Cosmogenic exposure dates suggest that ice remained within the LGM moraine belt until ~18.2 ka (Lennon, 2014; Peltier et al., 2021) and retreated southward to the inner fjords before ~17 ka (Hall et al., 2013, 2019; Moreno et al., 2023; McCulloch et al., 2024, Fig. 2). This expanded icefield was

contiguous with the larger Patagonian ice sheet to the north, but maintained its own independent centers of outflow; separation of these ice masses is thought to have occurred at roughly 20–15 ka (Davies et al., 2020).

South of the range, information on former glacier extent and fluctuations is much more limited, given the remote nature of the region. At the LGM, an ice stream flowed eastward through the eastern half of Canal Beagle and terminated near the Atlantic Ocean (Rabassa et al., 2000). Near central Cordillera Darwin, Canal Beagle splits into two arms at Punta Divide (Fig. 1). West of this split, our own examination of subglacial erosional features indicates that LGM ice flow was to the west. These contrasting flow directions suggest the presence of a former ice divide somewhere to the east of Punta Divide, but its precise location and evolution through time remains unknown. Likewise, the exact position of the LGM terminus of the icefield along its southern and western margins also remains uncertain. For example, from an analysis of coastal sections, Hodgson et al. (2023) recently proposed a far-southern margin for the icefield on Isla Hermite (Fig. 1), beyond the LGM limit depicted in some reconstructions, but similar to the ice position at 35 ka suggested by Davies et al. (2020).

Chronology is likewise sparse south of the Cordillera Darwin summits. A handful of basal radiocarbon ages from bogs suggests minimum-limiting ages of 17.8–16.8 ka (Heusser, 1989a; McCulloch et al., 2020) for deglaciation of the eastern Canal Beagle (Fig. 2). Our prior minimum-limiting radiocarbon data from bogs located near the center of the former icefield indicate deglaciation of the western mountains before 14.8–14.4 ka (Hall et al., 2013), and Hodgson et al. (2023) obtained a single minimum-limiting radiocarbon age of 13.0 ka for deglaciation at the far southern tip of the icefield. It is unknown if any of these radiocarbon ages afford close-limiting ages.

3. Methods

To determine the timing of deglaciation and to assess thinning rates in the center of the icefield, we tracked recession along a vertical transect at Fiordo Pía (Fig. 3), south-central Cordillera Darwin, using ^{10}Be

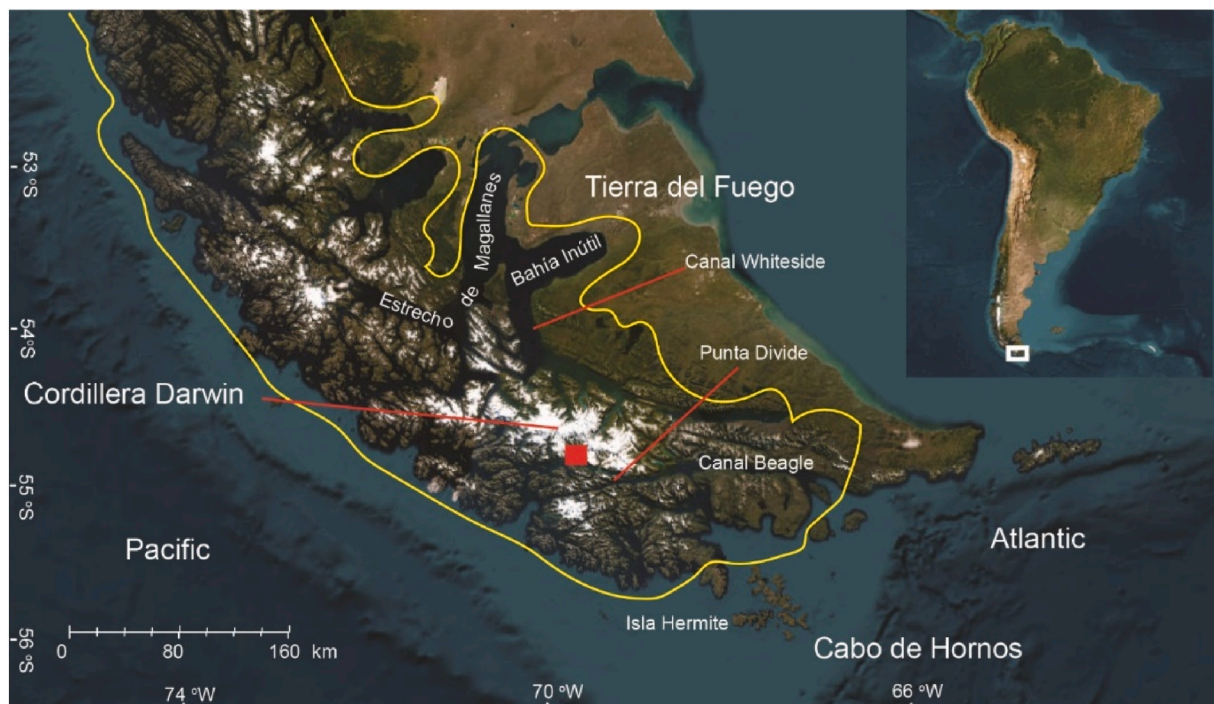


Fig. 1. Index map showing the location of the field area relative to the approximate LGM ice margin (yellow line; modified from Coronato et al., 1999) and major geographic features. The inset map of South America shows the location of the main image (white box). The Cordillera Darwin field area in the main image (red box) lies within the center of the former LGM icefield. Base map is from <https://experience.arcgis.com/experience/be61ce26335e4f02967071a6479e0dff>.

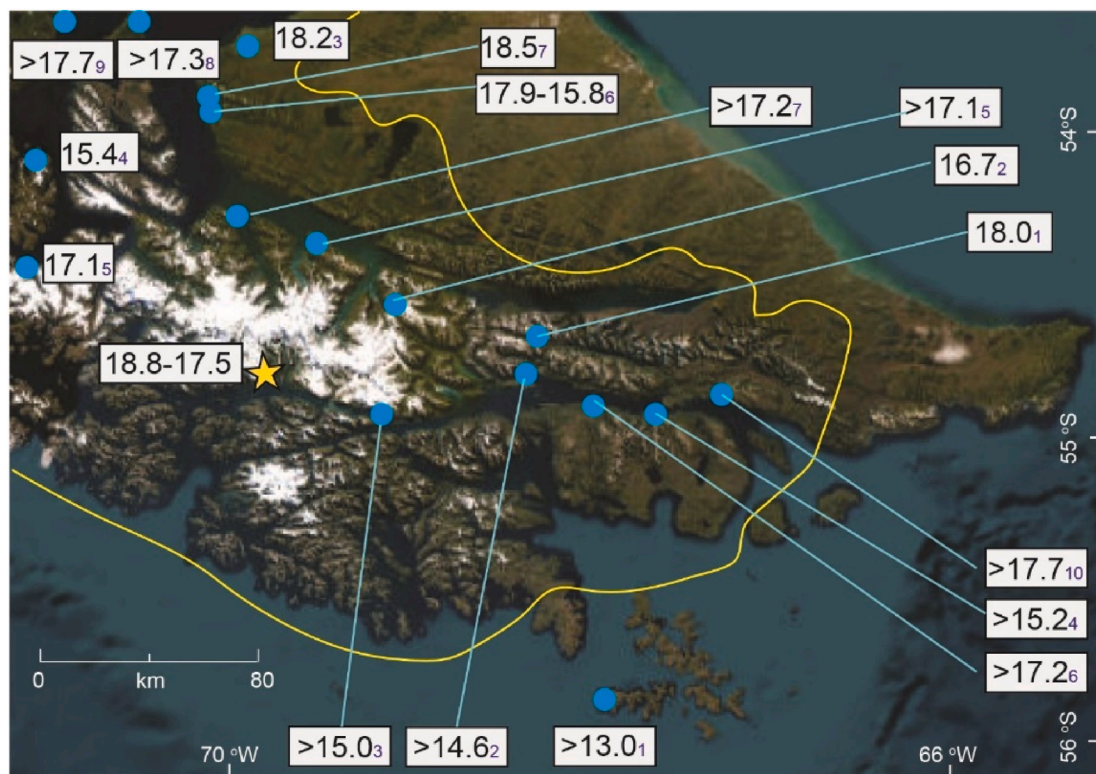


Fig. 2. Previously published constraining ages for deglaciation of the Cordillera Darwin Icefield from the approximate LGM position (marked by a yellow line, after Coronato et al., 1999). Samples include both exposure ages of glacial erratics and radiocarbon ages of organic materials, both in thousands of years. Exposure ages are keyed to Table S1 by the small number after the age. They date the timing of deglaciation. Minimum-limiting radiocarbon ages, distinguished from the exposure ages by the “>” symbol, are presented in (and keyed to) Table S2. The star shows the location of our present study and the approximate timing of the onset of thinning derived from the 95 % confidence interval in Fig. 6a.

surface exposure and radiocarbon dates. This sector lies in the heart of the former ice sheet and drains ice from the highest peaks. The transect extends from 611 to 114 m elevation along a bedrock ridge adjacent to the southwest arm of Fiordo Pía. The ridge descends southward toward Canal Beagle (Fig. 4). The area shows strong areal scouring and relatively little vegetation, consisting mainly of exposed bedrock and interspersed bogs. Erratics with common glacial molding and rare striations and polish are abundant (Fig. 5).

For exposure dating, we chose large, stable, granitic boulders commonly perched on bedrock (Fig. 5). The upper surface of each boulder was sampled using hammer and chisel or the drill and blast method (Kelly, 2003). Seventeen samples (with one additional duplicate) were processed at the University of Maine ($n = 8$) and Lamont-Doherty Earth Observatory ($n = 10$) cosmogenic isotope laboratories and show strong internal consistency. Methods consisted of purification of quartz with weak HF etches, followed by dissolution of quartz and extraction of beryllium using standard procedures (modified from Ditchburn and Whitehead, 1994). Samples were analyzed at Lawrence Livermore National Laboratory. We employed the v.3 calculator of Balco et al. (2008) with the Lago Argentino (Kaplan et al., 2011) production rate (with one outlier removed as recommended by those authors) and St scaling (Lal, 1991; Stone, 2000). As per standard procedures, all samples were corrected for topographic shielding. We did not make a correction for snow cover as these sites are highly exposed and wind-swept. We normalized the dates to 1950 for better comparison to radiocarbon data. We excluded one sample (PIA12-12) on the basis that its age is more than two standard deviations older than the next oldest sample. To reconstruct thinning rates, we employed the iceTEA vertical thinning tool of Jones et al. (2019). To set our results in a regional context, we also recalculated previously published data from the Estrecho de Magallanes with the same parameters (Table S1); these

dates may differ slightly from those given by the original authors.

To afford a complementary means of constraining deglaciation, we cored bogs along the same transect to obtain the oldest organic materials, which afford minimum-limiting ages for ice recession. We cleaned macrofossils with ultrapure water and sent them to the NOSAMS radiocarbon laboratory for processing. We converted results to calendar years using CALIB (Stuiver and Reimer, 1993) and the INTCAL20 dataset (Reimer et al., 2020). We considered, but did not use SHCal20 (Hogg et al., 2020), which is less well-constrained for this period. Atmospheric radiocarbon differences between the hemispheres (typically a few decades) are negligible when determining the timing of deglaciation.

4. Results

Eighteen ^{10}Be exposure ages of granitic boulders are 21.9–16.0 ka and constrain the deglacial history of this region (Table 1). After removal of the one old outlier, the data center between ~18–17 ka, with a mean of 17.5 ka (Figs. 3 and 6). The high-precision ^{10}Be ages lack a strong relationship to sample elevation, with ages at the top of the ridge being similar to those near the base. Using a linear least-squares regression model that employs a Monte Carlo simulation (Jones et al., 2019), we calculated likely ranges of thinning rates for the ice at this site of 0.52–3.66 m/yr (68 % confidence) to 0.32–19.89 m/yr (95 % confidence). This equates to ice lowering from the position of the highest sample (611 m) to within at least 100 m of present-day sea level in less than 1000 years, perhaps in as little as 150 years (at 68 % confidence). Modelled onset of thinning ranges from 18.8–17.5 ka (95 % confidence interval in Fig. 6a), and the entire 95 % confidence interval from the earliest onset of thinning to the latest possible completion ranges from 18.8–16.9 ka.

We cored 12 bogs along the same ridge. Sediment thickness reached

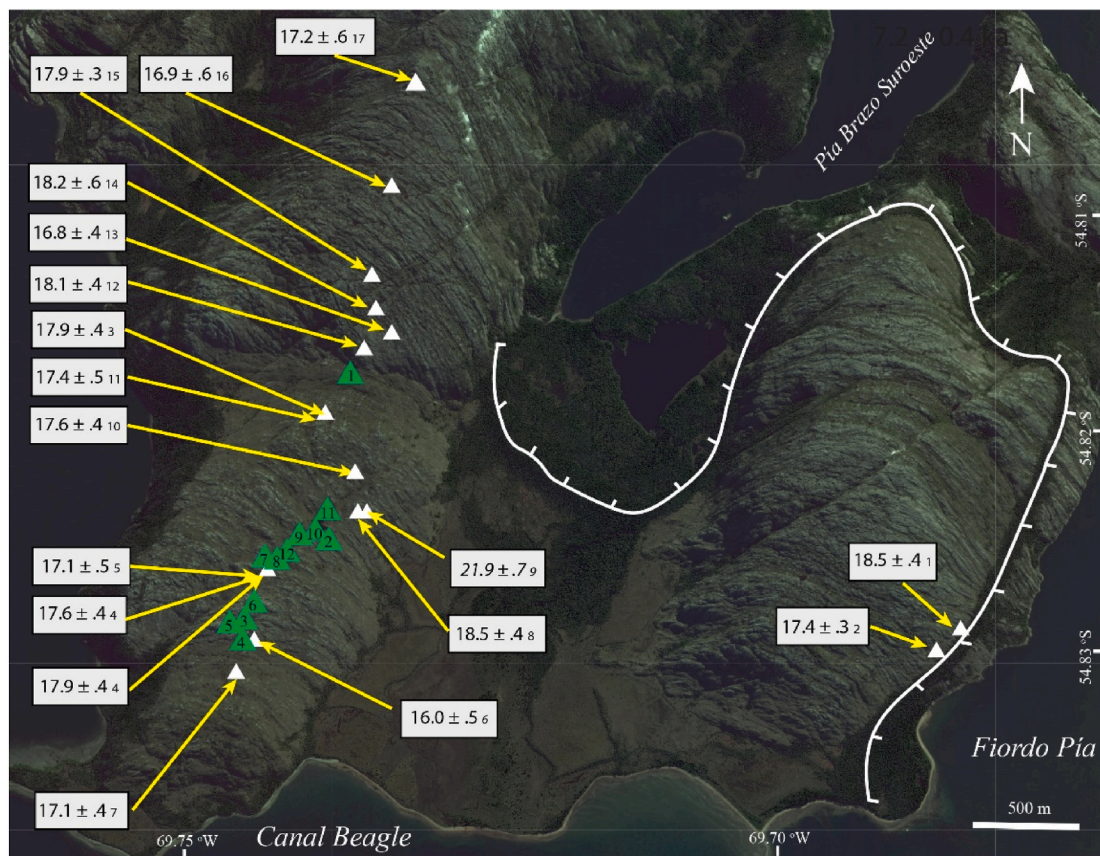


Fig. 3. The Pía field area showing areally scoured terrain and sample locations. Ridgelines rise from Canal Beagle (bottom) toward the crest of Cordillera Darwin (top). During deglaciation, ice thinned down these ridgelines toward Canal Beagle, which supported an ice stream at the time. White triangles mark the location of exposure age samples, with dates given in ka and keyed to Table 1 (small numbers after ages), which record the timing of this thinning. Green triangles show the location of core sites with minimum-limiting radiocarbon ages, with the numbers in the triangles keyed to Table 2. White line gives the limit of a mid-Holocene ice margin (our own unpublished data) from glaciers in Fiordo Pía for reference. Tick marks on the line delineate the ice-contact slope. Base image from Garmin Birdseye.

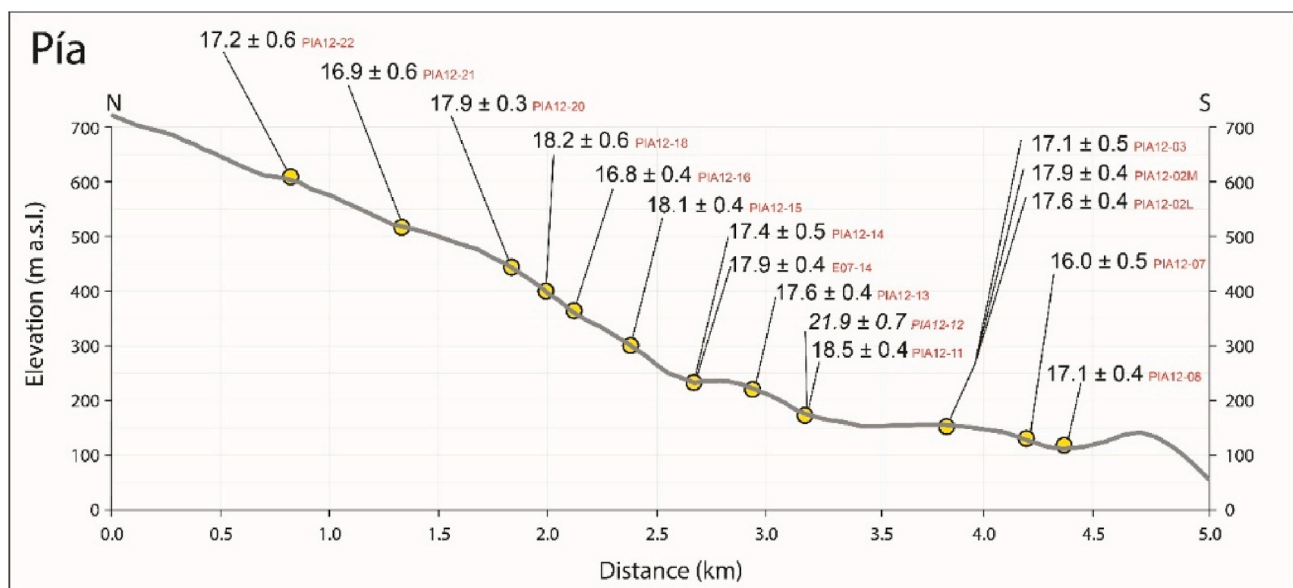


Fig. 4. Placement of exposure-age samples relative to topography along the main transect toward Canal Beagle (south). Ages are in thousands of years. Red numbers give sample names. Two samples on an adjacent ridge are not shown. Sample PIA12-12 was deemed an outlier and is shown in italics.

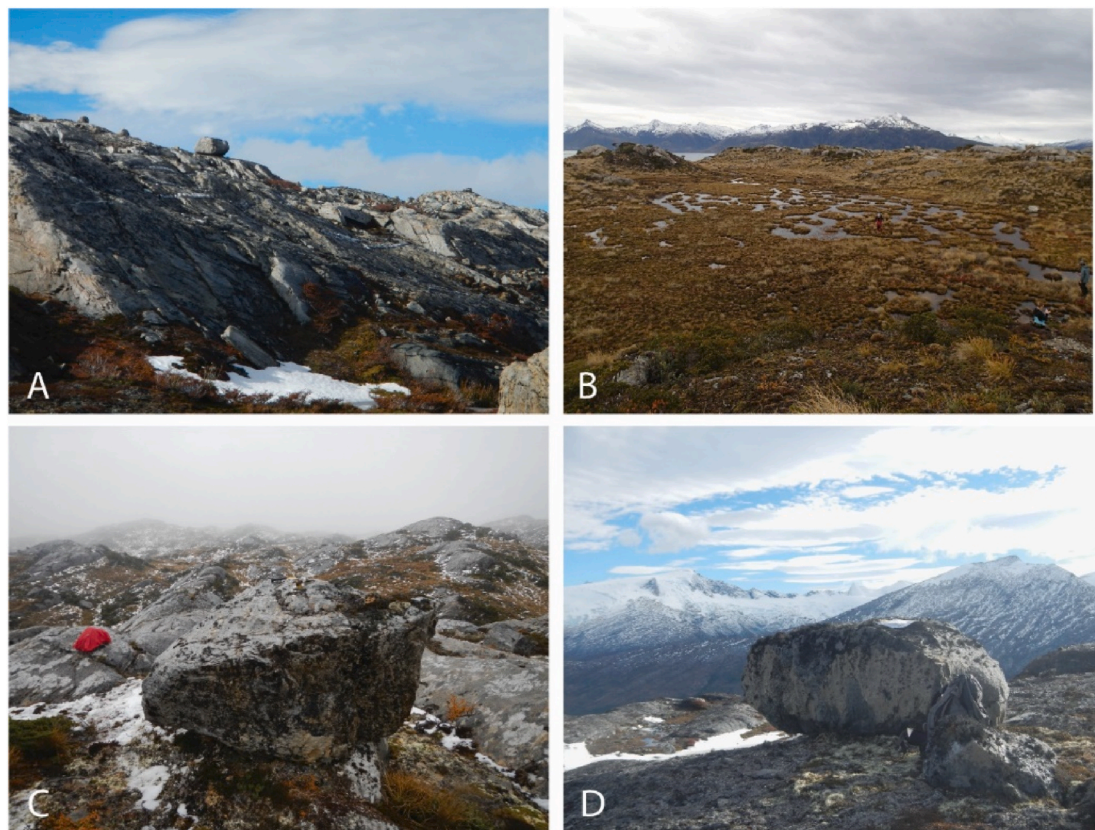


Fig. 5. View of terrain and sample sites. A. Perched erratics, including a large perched boulder approximately 1.5 m across, are common on the scoured bedrock. View is to the northeast; B. View to the southeast of the bog (people for scale) from which the PIA24-1 core was taken (green triangle 12 in Fig. 3). This core produced a basal radiocarbon age of 16.2 ± 0.2 ka; C) Sample from which PIA12-2 (exposure age sample 4 in Fig. 3) was taken, with backpack for scale; D) Sample from which PIA12-21 (exposure age sample 16 in Fig. 3) was collected. Boulder is roughly 2.5 m across, and view is to the west.

Table 1
Exposure-age data from this study.

Sample	Latitude	Longitude	Elevation (m)	Thickness (cm)	Shielding	[Be-10] at/g*10 ⁴	Error at/g*10 ³	Age (ka)	Error
¹ EXP06-10	−54.8281	−69.6864	157	5.58	0.9849	9.05	2.02	18.5	0.4
² EXP06-13	−54.8294	−69.6868	128	2.32	0.9793	8.47	1.67	17.4	0.3
³ E07-14	−54.8182	−69.7358	250	5.24	0.9953	9.70	1.97	17.9	0.4
⁴ PIA12-2M	−54.8256	−69.7402	157.75	2.35	0.9996	9.15	1.80	17.9	0.4
⁴ PIA12-2L	−54.8256	−69.7402	157.75	2.98	0.9996	8.95	1.79	17.6	0.4
⁵ PIA12-3	−54.8257	−69.7402	158.02	2.81	0.9996	8.69	2.70	17.1	0.5
⁶ PIA12-7	−54.8291	−69.7418	113.98	0.92	0.9987	7.91	2.41	16.0	0.5
⁷ PIA12-8	−54.8303	−69.7427	116.14	3.03	0.9884	8.27	1.83	17.1	0.4
⁸ PIA12-11	−54.8224	−69.7320	166.73	3.80	0.9990	9.43	1.85	18.5	0.4
⁹ PIA12-12	−54.8224	−69.7320	165.00	1.50	0.9889	11.12	3.68	21.9	0.7
¹⁰ PIA12-13	−54.8205	−69.7331	207.70	1.81	0.9967	9.46	2.26	17.6	0.4
¹¹ PIA12-14	−54.8181	−69.7358	240.73	5.20	0.9982	9.41	2.51	17.4	0.5
¹² PIA12-15	−54.8155	−69.7328	305.96	1.82	0.9898	10.57	2.13	18.1	0.4
¹³ PIA12-16	−54.8145	−69.7303	344.94	1.07	0.9934	10.31	2.34	16.8	0.4
¹⁴ PIA12-18	−54.8133	−69.7309	384.05	1.30	0.9886	11.45	3.71	18.2	0.6
¹⁵ PIA12-20	−54.8122	−69.7321	427.40	2.46	0.9934	11.71	2.15	17.9	0.3
¹⁶ PIA12-21	−54.8078	−69.7310	517.56	1.28	0.9997	12.24	4.00	16.9	0.6
¹⁷ PIA12-22	−54.8033	−69.7281	611.01	1.27	0.9993	13.50	4.84	17.2	0.6

All samples were calculated using a density of 2.7 g/cm^3 and are referenced to 07KNSTD (Nishiizumi et al., 2007).

Samples additionally were corrected by -56 yrs (2006 samples), -57 years (2007 samples), and -62 years (2012 samples) to normalize them to 1950 for comparison with radiocarbon data.

PIA12-2 was run twice, once at Maine (M) and once at Lamont (L).

Sample locations are keyed with superscripts to Fig. 3 and a statistical outlier is noted by italics.

more than 5 m where bogs occupy a fault zone but was ≤ 1.5 m at the highest elevation site, which displays only thin, poorly developed peat in a shallow basin. Most cores show peat overlying blue-gray clay thought to have formed during or immediately after deglaciation. Twenty-six radiocarbon dates of the lowest or near-lowest organic

materials (Table 2) are 10.5–16.6 ka, with most ($n = 21$) being between 15.5 and 16.6 ka. Some analyses were repeated to improve precision, as initial samples required small-sample processing that led to larger-than-normal errors. All are minimum-limiting ages for deglaciation.

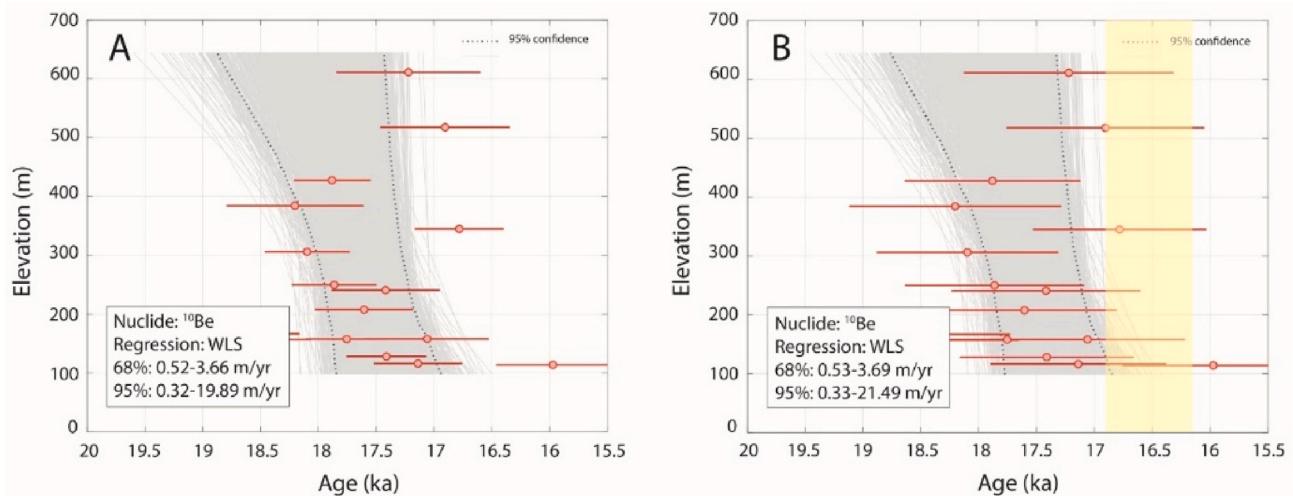


Fig. 6. Exposure ages (A = internal errors; B = external errors) plotted vs. elevation. Here, we used a weighted least squares regression script from the iceTEA toolkit (Jones et al., 2019) to derive probable ranges of thinning rates for the Cordillera Darwin Icefield at the Pía field site. Yellow band shows 2σ range of the oldest radiocarbon age for comparison.

Table 2

Radiocarbon data produced in this study.

Core	Depth (cm)	Lat.	Long.	Elev. (m)	Material	Lab #	$\delta^{13}\text{C}$	^{14}C yr BP	Error 1σ	Cal yr BP	Error 2σ
¹ BL07-15	150	-54.8176	-69.7350	244	Grasses, sedges	OS-61603	-25.1	9310	65	10,490	200
² BL07-16B	456	-54.8245	-69.7364		Peat	OS-64237	-21.6	12,350	120	14,510	450
³ BL12-1	242–243	-54.828	-69.7436	136	Moss	OS-96879	-20.4	13,600	110	16,450	380
³ BL12-1	242–243	-54.828	-69.7436	136	Moss	OS-120370	-20.2	13,400	40	16,140	150
⁴ BL12-2	347–347.5	-54.8292	-69.7433	106	Plant fragments	OS-96880	-22.4	13,450	110	16,200	340
⁴ BL12-2	347.5–348	-54.8292	-69.7433	106	Plant fragments	OS-120411	-23.7	13,250	40	15,910	150
⁵ BL12-3	242–244	-54.8285	-69.7441	121	Moss	OS-96881	-24.9	12,500	95	14,690	430
⁶ BL12-4	217.5–218	-54.8274	-69.7423	148	Plant, wood fragments	OS-96873	-21.1	12,000	90	13,910	170
⁷ BL12-5	391.5–392	-54.8255	-69.7414	145	Moss	OS-96882	-28.1	13,250	110	15,930	320
⁷ BL12-5	391.5–392	-54.8255	-69.7414	145	moss	OS-120412	-29.1	13,150	40	15,790	150
⁷ BL12-5	392.5–393	-54.8255	-69.7414	145	Moss	OS-96883	-29.6	13,050	110	15,620	330
⁷ BL12-5	392.5–393	-54.8255	-69.7414	145	Moss	OS-120413	-30.2	13,050	40	15,630	160
⁷ BL12-5	394.5–395	-54.8255	-69.7414	145	moss	OS-120414	-28.4	13,100	35	15,710	140
⁷ BL12-5	395–396	-54.8255	-69.7414	145	Plant fragments	OS-96884	-27.9	13,100	110	15,680	340
⁷ BL12-5	395–396	-54.8255	-69.7414	145	Plant fragments	OS-120415	-28.0	13,000	35	15,540	170
⁸ BL12-6	495	-54.825	-69.7401	146	Moss	OS-96886	-30.1	13,500	110	16,280	350
⁸ BL12-6	495	-54.825	-69.7401	146	Peat	OS-120153	-28.2	12,900	40	15,430	160
⁸ BL12-6	495	-54.825	-69.7401	146	Peat	OS-120221	-28.6	13,250	45	15,910	160
⁸ BL12-6	495	-54.825	-69.7401	146	Peat	OS-120154	-27.7	13,150	45	15,790	160
⁸ BL12-6	495	-54.825	-69.7401	146	Peat	OS-120180	-25.1	13,100	35	15,710	140
⁹ BL12-7	377–378	-54.8243	-69.7388	153	Wood fragments	OS-96888	-25.7	13,700	120	16,620	370
⁹ BL12-7	377–378	-54.8243	-69.7388	153	wood fragments	OS-120417	-26.8	13,450	40	16,190	150
¹⁰ BL12-8	418–419	-54.8241	-69.7382	153	Moss	OS-96889	-23.6	13,400	120	16,130	360
¹⁰ BL12-8	418–419	-54.8241	-69.7382	153	Moss	OS-120371	-25.8	13,200	35	15,850	140
¹¹ BL12-9	521.5	-54.8232	-69.7364	150	Sedge	OS-96890	-23.9	13,200	120	15,870	360
¹² PIA24-1B	468	-54.8250	-69.7399	143	Gyttja	OS-181803	n.a.	13,450	55	16,190	180

Calibrated probabilities <10 % are not shown. Superscripts in column one are keyed to the green triangles in Fig. 3.

5. Discussion

The exposure ages form a tightly constrained group that indicates deglaciation of this site occurred at some time between 18.8–16.9 ka (Fig. 6a), with a likely onset between 18.8–17.5 ka. The high internal consistency of the ages argues against any significant inherited nuclides or erosion, with the possible exception of the one excluded sample. In keeping with them being minimum-limiting ages, radiocarbon dates are younger than the exposure ages, with the oldest being 16.6 ± 0.4 ka of small wood fragments at 150 m elevation. This oldest radiocarbon age overlaps with the younger exposure ages, particularly when production rate errors are included (Fig. 6b).

Dates of erratics and the modelled thinning rates indicate that the ice surface level dropped to near present-day sea level rapidly (Fig. 6). Such

a rapid reduction in surface elevation must have been accompanied by horizontal ice recession from near the former LGM margin to the very center of Cordillera Darwin at that time (Fig. 7), suggesting that a large portion of the icefield may have disappeared. Erosional indicators, such as stoss and lee forms, show that ice from Fiordo Pía flowed westward onto the continental shelf at the LGM. There are no published chronologic data to record recession from the shelf to Fiordo Pía, although model reconstructions suggest (with low confidence) that minor recession had begun by ~20 ka (Davies et al., 2020, Fig. 7). Flow lines from Fiordo Pía to the modelled 20 ka limit (Davies et al., 2020) range from 75 to 130 km in length and give an estimate of the potential magnitude of horizontal ice recession associated with the vertical thinning we document in the center of Cordillera Darwin. Although onset of ice recession from the western continental shelf remains unconstrained by



Fig. 7. Regional context for the chronologic data from Fiordo Pía (yellow box). Red line gives the proposed 20 ka limit of the Cordillera Darwin Icefield from Davies et al. (2020). White lines give likely former flowlines (solid = confirmed by field observational data; dashed = potential flow lines). Base image from QFuego-Patagonia.

chronologic evidence, on the northeast side of the Cordillera Darwin Icefield, outlet glaciers remained at the LGM moraine belt until about 18.2 ka (Fig. 2). Exposure ages (Table S1) from the innermost LGM moraine at Punta Paulo on the Estrecho de Magallanes and at Bahía Inútil produce means of 18.2 ± 0.8 ka (Peltier et al., 2021) and 18.2 ± 0.5 ka (Lennon, 2014), respectively. A similar mean age, 18.5 ± 0.6 ka (McCulloch et al., 2024), comes from a site located just inboard. Minimum-limiting radiocarbon data along the same flowline indicate that ice had receded more than 100 km from these locations to the inner fjords by at least 17 ka (Hall et al., 2019; Table S2). These data suggest rapid horizontal retreat (as much as 80 % of the flowline) of the northeast sector of the ice sheet between ~18.2–17 ka.

Although these data for horizontal recession from the LGM position are confined to the northeast sector of the Cordillera Darwin Icefield on the opposite side of the mountains from our field site, there is no existing evidence elsewhere to suggest significant earlier ice recession in other sectors. For example, the oldest minimum-limiting radiocarbon ages from bogs along Canal Beagle just inboard of the LGM position in the eastern sector of the former icefield are 17.8–16.8 ka (e.g., Heusser, 1989a,b; 1998; McCulloch et al., 2020; Table S2). Thus, we tentatively infer that, just as in the northeast sector of the Cordillera Darwin Icefield, the ice margin on the western shelf also remained relatively close to its LGM position until ~18.2 ka. If this assumption is correct, this age, coupled with our data from Fiordo Pía, implies rapid ice recession of as much as 75–130 km into the center of the range at the very start of the termination to a position <15 km from present-day glaciers.

What caused the Cordillera Darwin Icefield to retreat is such a fashion? Temme et al. (2025) showed that over the last decades the icefield as a whole has responded primarily to climate change, although a small subset of individual tidewater glaciers also were responsive to marine forcing. Although glaciers can undergo accelerated retreat for

non-climatic reasons, we similarly favor climate change as the primary driver of retreat over the last glacial termination. Given that reconstructions show that the western icefield margin was almost entirely terrestrial at the end of the LGM (e.g., Davies et al., 2020), we do not consider marine mechanisms to have played any substantial role in causing ice recession. Bathymetric charts do indicate that a narrow channel of ocean water could have penetrated to Fiordo Pía during deglaciation. However, while calving may have contributed to some mass loss of this particular flowline, several factors argue against mechanical instability as a root cause for recession. First, Canal Beagle is relatively narrow (commonly <5 km across) and the passage from our field area to the LGM margin is winding and occupied by numerous islands that would have afforded robust pinning points, thus halting or slowing ice recession due to calving (Fig. 7). Rising sea level and/or warming ocean temperatures often are cited elsewhere as causes of deglaciation (e.g., Christiansen et al., 2016; Milillo et al., 2022). However, given 1) the small fraction of the ice margin that would have been in contact with the ocean, 2) the comparatively minor sea-level change between ~18–17 ka, and 3) the fact that reconstructed SSTs off western Chile do not show warming until ~16.5 ka (Haddam et al., 2018) after deglaciation was nearly complete, we do not attribute the underlying cause of deglaciation of Cordillera Darwin to marine mechanisms. This conclusion is supported by the fact that non-marine sectors of the icefield (e.g., the northeast and southeast sectors) appear to have undergone the same rapid recession at about the same time as this western sector (Fig. 2; Hall et al., 2013, 2019).

Proglacial lakes also can lead to rapid ice recession in some circumstances. McCulloch et al. (2024) proposed that a large lake occupied the channels that were exposed during retreat of the northeast sector of the ice sheet (e.g., Canal Whiteside, Bahía Inútil), although Moreno et al. (2023) showed that any such lake must have been restricted to <23 m

elevation after 17.3 ka in parts of Canal Whiteside. Whether any large lake existed south of the mountains remains to be confirmed. Bathymetry of Canal Beagle permits containment of a lake in the eastern portion of the channel prior to flooding by the sea after the Antarctic Cold Reversal (Bujalesky, 2011). However, there does not appear to be a sill that would dam a large lake in the western part of the channel between our field site and the LGM margin. Thus, we infer that rapid retreat in an ice-dammed lake did not significantly contribute to ice recession in this sector.

The fact that all sectors for which there are data appear to have undergone synchronous fast ice retreat favors atmospheric warming as a cause for ice recession over dynamical options. This suggests that this warming must have induced a highly negative mass balance on the icefield. However, atmospheric CO₂ (e.g., Shakun et al., 2012) is unlikely to have caused this warming, as it changed by < 10 ppm (Marcott et al., 2014) over the period of recession documented here. Likewise, we do not attribute this warming to a bipolar seesaw (Broecker, 1998) driven by AMOC, as deglaciation of Cordillera Darwin was essentially complete before overturning circulation is proposed to have shut down (McManus et al., 2004).

We propose instead that the primary cause of rapid warming of Cordillera Darwin was a sudden poleward shift of the SWW belt, which divides subpolar and subtropical air masses, to a latitude at or south of the icefield. Prior workers have suggested such a southerly movement accompanied deglaciation in South America (e.g., Anderson et al., 2009; Denton et al., 2010; Boex et al., 2013; Moreno et al., 2023). For example, Anderson et al. (2009) documented a distinct rise in opal production due to increased upwelling in the Southern Ocean east of Cordillera Darwin. As increased wind stress over the Drake Passage is thought to be a prime control on upwelling in this region (e.g., Toggweiler et al., 2006), these opal data have been interpreted as indicating a southward shift in the position of the SWW at the start of the last termination. Movement of the SWW to the vicinity of Cordillera Darwin at the onset of Termination I would have placed the icefield in relatively warm subtropical air masses incompatible with its LGM footprint. Given its extensive, unusually low-gradient outlet glaciers with relatively small high-elevation accumulation areas, this icefield may have been particularly susceptible to the rise in snow line that would have accompanied such a shift in the SWW. That this SWW migration was a jump rather than a gradual shift is supported further by the similarity in magnitude and timing of the warming between the Chilean Lake District (42° S; Denton et al., 1999; Moreno et al., 2015, 2025a, b) and Cordillera Darwin (54.8° S). For example, deglaciation in the Lake District had proceeded to the inner mountains no later than ~17 ka to allow time for the growth of the forest subsequently killed by the Lican ignimbrite (Moreno et al., 2015). Likewise, adjacent to the northeastern sector of the North Patagonian Icefield, Boex et al. (2013) documented ~1000 m of vertical thinning within the first millennium of the termination, beginning at ~18 ka. This rate of thinning is similar to the range we report here of 0.52–3.66 m/yr for the Pía region. Moreover, Huynh et al. (2024 and references therein) reviewed the deglacial history of the southern lobes of the South Patagonian Icefield (e.g., Seno Skyring) and ice in the Estrecho de Magallanes and also concluded that significant recession began at ~18 ka. This similarity in ages and rapidity of deglaciation between northern Patagonia (42°S) and our site (54.8°S) on the southern tip of South America reinforces the idea that this event was caused by widespread climate warming.

Studies elsewhere also have attributed warming at the onset of the termination to southward shift of the SWW. For example, Denton et al. (2021) proposed the Zealandia Switch mechanism, whereby the SWW drive the ocean heat release either north or south of Zealandia and jump rapidly between the two. Poleward jumps are linked in models to increased through-flow of warm water north of Australia, release of heat in the western tropical Pacific, and outgassing of CO₂ from the Southern Ocean, all contributing to the warming of the entire globe. Recently, Leger et al. (2023) espoused a similar view when examining the pre-LGM glacial

history of Patagonia. The underlying cause of such a poleward jump at the start of terminations is not known, but may relate to a proposed relationship between the mean annual position of the SWW and the duration of southern hemisphere winter (Denton et al., 2021).

Today, the SWW are moving south rapidly (e.g., Kushner et al., 2001; Fyfe et al., 2007; Cai et al., 2023). Understanding their role in the collapse of the Cordillera Darwin Icefield during Termination I gives insight into the fate of similar ice masses that may be influenced by the new southern wind position. We expect that subantarctic ice masses may decline quickly, similar to the Cordillera Darwin Icefield. However, the effect on the Antarctic ice sheet is less certain. A far-southern position of the SWW will influence the Antarctic ice mass through the effect on the polar easterlies, sea-ice extent, and intrusions of warm circumpolar deep water onto the shelves, as well as by steering atmospheric rivers toward the continent. Such rivers, and accompanying warm temperatures, lead to high accumulation (Simon et al., 2024) in the interior, but melting and ice-shelf instability in coastal regions (Wille et al., 2019, 2022). Thus, southward movement of the SWW is likely to lead to immediate, detrimental effects on ice in coastal regions, but (at least temporary) increase in interior ice elevations.

6. Conclusions

Eighteen exposure ages show that ice levels in the center of Cordillera Darwin receded from our highest sample location (611 m elevation) beginning at some time between 18.8–17.4 ka. Using a vertical transect of ages and a model of ice thinning, results suggest ~500 m of ice surface-level lowering in 1000–150 years. If, as shown elsewhere, the ice terminus stayed close to its LGM position along the Fiordo Pía flowline until at least ~18.2 ka, then our data also imply potential marginal retreat on the order of ~100 km over that same period, receding to a position <15 km from present-day glaciers. We attribute the underlying cause of the rapid ice recession to a rise in atmospheric temperatures that accompanied the onset of the termination. Our preferred explanation is that this was driven by a poleward shift of the SWW belt, which would have placed the Cordillera Darwin Icefield in warmer subtropical air masses and led to significant melting ablation.

Author contributions

Conception: Hall, Denton, Putnam, Russell.

Field work: Hall, Lowell, Soteres, Spoth-Ascencao, Miles, Thomas.

Lab work: Hall, Putnam, Schwarz.

Data Interpretation: Hall, Putnam, Denton, Lowell, Russell, Moreno, Schaefer.

Wrote Paper: Hall.

All authors read and edited the paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2025.109754>.

Data availability

All data and/or code is contained within the submission.

References

- Anderson, R., Ali, S., Bradtmiller, L., Nielsen, S., Fleisher, M., Anderson, B., Burckle, L., 2009. Wind-driven upwelling in the Southern Ocean and the deglacial rise in CO₂. *Science* 323, 1443–1448.
- Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J., 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from ¹⁰Be and ²⁶Al measurements. *Quat. Geochronol.* 3, 174–195.
- Boex, J., Fogwill, C., Harrison, S., Glasser, N., Hein, A., Schnabel, C., Xu, S., 2013. Rapid thinning of the late Pleistocene Patagonian ice sheet following migration of the southern Westerlies. *Sci. Rep.* 3. <https://doi.org/10.1038/srep02118>.
- Broecker, W.S., 1998. Paleocene circulation during the last deglaciation: a bipolar seesaw? *Paleoceanography* 13, 119–121.
- Bujalesky, G.G., 2011. The flood of the Beagle Valley (11,000 yr BP), Tierra del Fuego. *Annales Instituto de la Patagonia* 39, 5–21.
- Cai, W., Gao, L., Luo, Y., Li, X., Zheng, X., Zhang, X., Cheng, X., Jia, F., Purich, A., Santoso, A., Du, Y., Holland, D.M., Shi, J.-R., Xiang, B., Xie, S.-P., 2023. Southern Ocean warming and its climatic impacts. *Sci. Bull. (Taipei)* 68, 946–960.
- Christiansen, K., Bushuk, M., Dutrieux, P., Parizek, B., Joughin, I., Alley, R., Shean, D., Abrahamson, E.P., Anandakrishnan, S., Heywood, K., Kim, T.-W., Lee, S.H., Nicholls, K., Stanton, T., Truffer, M., Webber, B., Jenkins, A., Jacobs, S., Bindshadler, R., Holland, D., 2016. Sensitivity of Pine Island Glacier to observed ocean forcing. *Geophys. Res. Lett.* <https://doi.org/10.1002/2016GL070500>.
- Coronato, A., Salemme, M., Rabassa, J., 1999. Palaeoenvironmental conditions during the early peopling of southernmost South America (Late Glacial-Early Holocene, 14–8 ka B.P.). *Quat. Int.* 53/54, 77–92.
- Davies, B., Darvill, C., Lovell, H., Bendle, J., Dowdeswell, J., Fabel, D., Garcia, J.L., Geiger, A., Glasser, N., Georghiu, D., Harrison, S., Hein, A., Kaplan, M., Martin, J., Mendelova, M., Palmer, A., Pelt, M., Rodes, A., Sagredo, E., Smedley, R., Smellie, J., Thorndycraft, V., 2020. The evolution of the Patagonian Ice Sheet from 35 ka to the present day (PATICE). *Earth Sci. Rev.* 204, 103152.
- Denton, G.H., Lowell, T.V., Heusser, C.J., Moreno, P.I., Andersen, B.G., Heusser, L.E., Schlüchter, C., Marchant, D.R., 1999. Interhemispheric linkage of paleoclimate during the last glaciation. *Geogr. Ann.* 81A, 107–153.
- Denton, G., Anderson, R., Toggweiler, J.R., Edwards, R.L., Schaefer, J.M., Putnam, A.E., 2010. The last glacial termination. *Science* 328, 1652–1656.
- Denton, G.H., Putnam, A.E., Russell, J.L., Barrell, D.J.A., Schaefer, J.M., Kaplan, M.R., Strand, P.D., 2021. The Zealandia Switch: ice age climate shifts viewed from Southern Hemisphere moraines. *Quat. Sci. Rev.* 257, 1–28.
- Ditchburn, R.G., Whitehead, N.E., 1994. The separation of ¹⁰Be from silicates. Third Workshop of the South Pacific Environmental Radioactivity Association 4–7.
- Fyfe, J.C., Saenko, O.A., Zickfeld, K., Eby, M., Weaver, A.J., 2007. The role of poleward-intensifying winds on Southern Ocean warming. *J. Clim.* 20, 5391–5400.
- Haddam, N.A., Siani, G., Michel, E., Kaiser, J., Lamy, F., Duchamp-Alphonse, S., Heffer, J., Braconnot, J., Dewilde, F., Isgüder, G., Tisnerat-Laborde, N., Thil, F., Durand, N., Kissel, C., 2018. Changes in latitudinal sea surface temperature gradients along the Southern Chilean margin since the last glacial. *Quat. Sci. Rev.* 194, 62–76.
- Hall, B.L., Lowell, T.V., Bromley, G.R.M., Denton, G.H., Putnam, A.E., 2019. Holocene glacier fluctuations on the northern flank of Cordillera Darwin, southernmost South America. *Quat. Sci. Rev.* 222, 105904.
- Hall, B.L., Porter, C.T., Denton, G.H., Lowell, T.V., Bromley, G.R.M., 2013. Extensive recession of Cordillera Darwin glaciers in southernmost South America during Heinrich stadial 1. *Quat. Sci. Rev.* 62, 49–55.
- Heusser, C.J., 1989a. Climate and chronology of Antarctica and adjacent South America over the past 30,000 yr. *Paleogeogr. Palaeoclimatol. Palaeoecol.* 76, 31–37.
- Heusser, C.J., 1989b. Late Quaternary vegetation and climate of southern Tierra del Fuego. *Quaternary Research* 31, 396–406.
- Heusser, C.J., 1998. Deglacial paleoclimate of the American sector of the Southern Ocean: late Glacial–Holocene records from the latitude of Canal Beagle (55° S). *Argentine Tierra del Fuego. Paleogeogr. Palaeoclimatol. Palaeoecol.* 141, 277–301.
- Hodgson, D., Robets, D., Izaguirre, E., Perren, B., De Vleeschouwer, F., Davies, S., Bishop, T., McCulloch, R., Aravena, J.C., 2023. Southern limit of the Patagonian ice sheet. *Quat. Sci. Rev.* 321. <https://doi.org/10.1016/j.quascirev.2023.108346>.
- Hogg, A.G., Heaton, T.J., Hua, Q., Palmer, J.G., Turney, C.S.M., Southon, J., Bayliss, A., Blackwell, P.G., Boswijk, G., Bronk Ramsey, C., Pearson, C., Petchey, F., Reimer, P., Reimer, R., Wacker, L., 2020. SHCal20 southern hemisphere calibration, 0–55,000 cal years BP. *Radiocarbon* 62, 759–778.
- Huynh, C., Hein, A.S., McCulloch, R.D., Bingham, R.G., 2024. The last glacial cycle in southernmost Patagonia: a review. *Quat. Sci. Rev.* 344, 108972.
- Imbrie, J., Berger, A., Boyle, E., Clemens, S., Duffy, A., Howard, W., Kukla, G., Kutzbach, J., Martinson, D., McIntyre, A., Mix, A., Molino, B., Morley, J., Peterson, L., Pisias, N., Prell, W., Raymo, R., Shackleton, N., Toggweiler, R., 1993. On the structure and origin of major glacial cycles 2: the 100,000-year cycle. *Paleoceanography* 8, 699–736.
- Jones, R.S., Small, D., Cahill, N., Bentley, M., Whitehouse, P., 2019. iceTEA: tools for plotting and analyzing cosmogenic-nuclide surface-exposure data from former ice margins. *Quat. Geochronol.* 51, 72–86.
- Kaplan, M.R., Strelin, J.A., Schaefer, J.M., Denton, G.H., Finkel, R.C., Schwartz, R., Putnam, A.E., Vandergoes, M.J., Goehring, B.M., Travis, S.G., 2011. In situ cosmogenic ¹⁰Be production rate at Lago Argentino, Patagonia: implications for late-glacial climate chronology. *Earth Planet Sci. Lett.* 309, 21–32.
- Kelly, M., 2003. The Late Würmian Age in the western Swiss Alps – Last Glacial Maximum (LGM) ice-surface reconstruction and ¹⁰Be dating of Late-glacial features. PhD dissertation. University of Bern, p. 105.
- Kushner, P.J., Held, I.M., Delworth, T.L., 2001. Southern Hemisphere atmospheric circulation response to global warming. *J. Clim.* 14, 2238–2249.
- Lal, D., 1991. Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. *Earth Planet Sci. Lett.* 104, 424–439.
- Leger, T., Hein, A., Rodes, A., Bingham, R., Schimmelpennig, I., Fabel, D., Tapia, P., ASTER Team, 2023. A cosmogenic nuclide-derived chronology of pre-last glacial cycle glaciations during MIS 8 and MIS 6 in northern Patagonia. *Clim. Past* 19, 35–59.
- Lennon, J., 2014. ¹⁰Be surface-exposure Chronology of the Trés Hermanos and Rosa Irene Moraines near Bahía Inútil, Chilean Patagonia. MS Thesis. University of Maine, Orono, Maine, p. 66p.
- Marcott, S.A., Bauska, T.K., Buizert, C., Steig, E.J., Rosen, J.L., Cuffey, K.M., Fudge, T.J., Severinghaus, J.P., Ahn, J., Lak, M.L., McConnell, J.R., Sowers, T., Taylor, K.C., White, J.W.C., Brook, E.J., 2014. Centennial-scale changes in the global carbon cycle during the last deglaciation. *Nature*. <https://doi.org/10.1038/nature13799>.
- McCulloch, R.D., Blaikie, J., Jacob, B., Mansilla, C.A., Morello, F., De Pol-Holz, R., San Román, M., Tisdall, E., Torres, J., 2020. Late glacial and Holocene climate variability, southernmost Patagonia. *Quat. Sci. Rev.* 229, 106131.
- McCulloch, R., Bentley, M., Fabel, D., Fernandez-Navarro, H., Garcia, J.L., Hein, A., Huynh, C., Jamieson, S., Lira, M.P., Luthgens, C., Nield, G., San Roman, M., Tisdall, E., 2024. Resolving the paradox of conflicting glacial chronologies: reconstructing the pattern of deglaciation of the Magellan cordilleran ice dome (53–54° S) during the last glacial – interglacial transition. *Quat. Sci. Rev.* <https://doi.org/10.1016/j.quascirev.2024.108866>.
- McManus, J.F., Francois, R., Gherardi, J.M., Keigwin, L.D., Brown-Leger, S., 2004. Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature* 428, 834–837.
- Mercer, J.H., 1984. Simultaneous climatic change in both hemispheres and similar bipolar interglacial warming: evidence and implications. *Climate Processes and Climate Sensitivity* 29, 307–313.
- Milankovitch, M.M., 1941. Canon of Insolation and the Ice Age Problem.. Koniglich Serbische Akademie Boegrad Special Publication, p. 132.
- Milillo, P., Rignot, E., Rizzoli, P., Scheuchl, B., Mougnot, J., Bueso-Bello, J., Prats-Iraola, P., Dini, L., 2022. Rapid glacier retreat rates observed in West Antarctica. *Nat. Geosci.* 15. <https://doi.org/10.1038/s41561-021-00877-z>.
- Moreno, P., Henríquez, W., Villa-Martínez, R., 2025a. Environmental evolution of the Andes east of the North Patagonian Icefield since ~19.3 ka. *Quat. Sci. Rev.* 364, 109467.
- Moreno, P., Videla, J., Villa-Martínez, R., 2025b. Terrestrial ecosystem development since ~21 ka in the core of the central Patagonian Andes (~45° S). *Quat. Sci. Rev.* 109616 (in press).
- Moreno, P.I., Lambert, F., Hernandez, L., Villa-Martínez, R., 2023. Environmental evolution of Tierra Del Fuego (~54° S) since ice-free conditions and its zonal/hemispheric implications. *Quat. Sci. Rev.* 322, 108387.
- Moreno, P.I., Denton, G.H., Moreno, H., Lowell, T.V., Putnam, A.E., Kaplan, M.R., 2015. Radiocarbon chronology of the last glacial maximum and its termination in northwestern Patagonia. *Quat. Sci. Rev.* 122, 233–249.
- Nishiizumi, K., Imamura, M., Caffee, M.W., Southon, J.R., Finkely, R.C., McAninch, J., 2007. Absolute calibration of Be-10 AMS standards. *Nucl. Instrum. Methods Phys. Res., Sect. B* 258, 403–413.
- Peltier, C., Kaplan, M., Birkel, S., Soteres, R., Sagredo, E., Aravena, J.C., Araos, J., Moreno, P., Schwarz, R., Schaefer, J., 2021. The large MIS 4 and long MIS 2 glacier maxima on the southern tip of South America. *Quat. Sci. Rev.* 262, 106858.
- Rabassa, J., Coronato, A., Bujalesky, G., Roig, F., Salemme, M., Meglioli, A., Heusser, C., Gordillo, S., Borromei, A., Quatrocchio, M., 2000. Quaternary of Tierra del Fuego, southernmost South America: an updated review. *Quat. Int.* 68, 217–240.
- Raymo, M., 1997. The timing of major climate terminations. *Paleoceanography* 12, 577–585.
- Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kromer, B., Manning, S.W., Muscheler, R., Palmer, J.G., Pearson, C., van der Plicht, J., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S.M., Fogtmann-Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., Talamo, S., 2020. The IntCal20 northern hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62, 725–757.
- Shakun, J., Clark, P.U., He, F., Marcott, S.A., Mix, A.C., Liu, Z., Otto-Bleisner, B., Schmittner, A., Bard, E., 2012. Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation. *Nature* 484, 49–54.
- Simon, S., Turner, J., Thamban, M., Wille, J.D., Deb, P., 2024. Spatiotemporal variability of extreme precipitation events and associated atmospheric processes over Dronning Maud Land, East Antarctica. *JGR Atmospheres*. <https://doi.org/10.1029/2023JD038993>.
- Sowers, T., Bender, M., 1995. Climate records covering the last deglaciation. *Science* 269, 210–214.

- Stone, J.O., 2000. Air pressure and cosmogenic isotope production. *J. Geophys. Res. B* 105, 53–759.
- Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C database and revised CALIB radiocarbon calibration program. *Radiocarbon* 35, 215–230.
- Temme, F., Sommer, C., Schaefer, M., Jaña, R., Arigony-Neto, J., Gonzalez, I., Izagirre, E., Giesecke, R., Tetzner, D., Fürst, J., 2025. Climate's firm grip on glacier ablation in the Cordillera Darwin Icefield, Tierra del Fuego. *Nat. Commun.* 16. <https://doi.org/10.1038/s41467-025-57698-6>.
- Toggweiler, J.R., Russell, J.L., Carson, S.R., 2006. Midlatitude westerlies, atmospheric CO_2 , and climate change during the ice ages. *Paleoceanography* 21. <https://doi.org/10.1029/2005PA001154>.
- Tuhkanen, S., 1992. The climate of Tierra del Fuego from a vegetation geographical point of view and its ecoclimatic counterparts elsewhere. *Acta Bot. Fennica* 125, 4–17.
- Wille, J.D., Favier, V., Dufour, A., Gorodetskaya, I.V., Turner, J., Agosta, C., Codron, F., 2019. West Antarctic surface melt triggered by atmospheric rivers. *Nat. Geosci.* 12, 911–916.
- Wille, J.D., Favier, V., Jourdain, N.C., Kittel, C., Turton, J.V., Agosta, C., Gorodetskaya, R.V., Picard, G., Codron, F., Leroy-Dos Santos, C., Amory, C., Fettweis, X., Blanchet, J., Jomelli, V., Berchet, A., 2022. Intense atmospheric rivers can weaken ice shelf stability at the Antarctic Peninsula. *Commun. Earth Environ.* <https://doi.org/10.1038/s43247-022-00422-9>.