Glacier Fluctuations in the Northern Patagonian Andes (44°S) Imply Wind-Modulated Interhemispheric in Phase Paleoclimates During Termination 1

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Abstract

The Last Glacial Termination (T1) featured major changes in global circulation systems that led to a shift from glacial to interglacial climate. While polar ice cores attest to an antiphased thermal pattern at millennial timescales, recent well-dated moraine records from both hemispheres suggest in-phase fluctuations in glaciers through T1, which is inconsistent with the bipolar see-saw paradigm. Here, we present a glacier chronology based on 30 new ^{10}Be surface exposure ages from well-preserved moraines in the Lago Palena/General Vintter basin in northern Patagonia ($\sim 44^\circ\text{S}$). We find that local glacier lobe underwent profound retreat after 19.7 ± 0.7 ka. This recessional trend led to the individualization of the Cerro Riñón glacier by ~ 16.3 ka, which readvanced at 15.9 ± 0.7 ka during Heinrich Stadial 1; during the Antarctic Cold Reversal with successive maxima at 13.5 ± 0.6 , 13.1 ± 0.5 , and 13.1 ± 0.5 ka; and a minor culmination at 12.5 ± 0.4 ka during Younger Dryas time. We conclude that fluctuations of Patagonian glaciers during T1 were controlled primarily by climate anomalies brought by shifts on the Southern Westerly Winds (SWW) locus. We posit that the global covariation of mountain glaciers during T1 was linked to variations in atmospheric CO_2 promoted by the interplay of the SWW-Southern Ocean system at millennial timescales.

Full Text

The Last Glacial Termination (T1; $\sim 17.8\text{--}11.7$ ka) represents the largest, most abrupt climate change of the last glacial-interglacial cycle [1]. T1 featured the collapse of continental-scale ice sheets, a persistent rise in sea level and the concentration of atmospheric greenhouse gases, along with a millennial-scale sequence of climate changes that culminated with the onset of the current interglacial. Ice core data reveal a step like pattern of increasing atmospheric temperatures featuring a synchronous but antiphased trend at millennial timescale between the polar hemispheres [2, 3]. Recently developed precise mountain glacier chronologies in the mid-to-high latitudes of both hemispheres [4,5,6,7; see methods], however, are starting to reveal in-phase behavior, pointing to a globally consistent mountain glacier response to climate changes during T1. This pattern challenges the expected antiphased or out-of-phase response predicted by the bipolar seesaw paradigm. If replicated by detailed and precise glacial chronologies, this mismatch could reveal key insights about interhemispheric climate links mediated by some atmospheric component operative during glacial terminations.

Recently, Denton et al. [8] proposed that changes in the SWW are the critical missing link relating insolation, atmospheric greenhouse gas concentrations, atmospheric and ocean circulation, and glacier response at millennial timescale during glacial maxima and terminations. In their interaction with the SO, the SWW establish a coupled system that drives global ocean circulation, the atmospheric concentration of greenhouse gases, and high-latitude ocean productivity by enhancing upwelling of CO_2 -enriched and high-nutrient deep waters [9, 10]. The efficacy of the SWW-SO coupled system is dependent upon the wind stress imparted by the SWW on the surface of the SO south of the Drake Passage ($> 55^\circ\text{S}$). Hence, deciphering the geographical position and strength of the locus of the SWW are crucial for assessing global climate change during ice age terminations.

The SWW are the sole source of precipitation to the Pacific sector and Andean divide sectors of northern Patagonia (40°-44°S) [11]. This key aspect allows reconstructing past SWW behavior based on hydrologic balance variations preserved in sensitive stratigraphic records from the Chilean Lake District and the Chiloé archipelago (40–44°S). When analyzed in conjunction with records from southern Patagonia (50°-54°S), these records permit the identification of latitudinal shifts and intensity variations in the SWW at millennial-scale during the Last Glacial Maximum (LGM; ~35 – 18 ka) and T1 [12, 13]. However, few studies in northern Patagonia have examined in any detail glacier fluctuations following the onset of T1 [14, 15], limiting our understanding about the response of middle latitude austral glaciers and paleoclimate patterns and processes at continental, hemispheric, and global scales.

Mountain glaciers are sensitive to and provide a direct physical link to changing atmospheric conditions. For land-terminating glaciers in particular, moraines distal to present ice limits are unambiguous recorders that past climate changed. Thus, the anatomy of glacier fluctuations during T1 in the southern mid-latitudes not only offers empirical constraints on the interhemispheric synchrony of mountain glacier behavior, but also a means to examine the evolution of the SWW and associated paleoclimates. In this study, we present a detailed glacial geomorphologic map and a highly resolved ^{10}Be geochronology of the Lago Palena/General Vintter (LPGV) basin (~ 43.9°S; ~71.5°W) in northern Patagonia, to examine the timing and structure of glacier fluctuations during T1. This basin was covered by an eastward-flowing outlet lobe of the Patagonian Ice Sheet that was fed through several coalescing valleys during the LGM (Fig. 1) [16]. The core of our chronology comes from one of these tributary valleys located ~ 15 km from the southern shore of the lake, at the foot of Cerro Riñón (~ 1790 m asl). The Cerro Riñón valley (informal name) is carved into the North Patagonian batholith [17], which was the source of the abundant granitoid boulders found on the local landscape.

Results

Previous studies delineated multiple moraines alongside the eastern half of the LPGV, which have been tentatively assigned to the LGM [15, 16, 18, 19]. Our geomorphological map allows identification of at least six well-preserved, closely spaced and concentric moraine ridges, the innermost of which we name PV6 (Fig. 1). We obtained four ^{10}Be dates from boulders atop PV6, which yielded ages between 20.7 ± 0.4 and 18.9 ± 0.4 ka, with a mean of 19.7 ± 0.7 ka (Fig. 1, Table 1). Upstream from the PV moraines, within the Cerro Riñón tributary valley, we distinguish five well-preserved moraine groups (CR1 to CR5 from the outermost to the innermost). A single ^{10}Be date from a perched erratic boulder resting over polished bedrock outboard of the CR1 moraines, and ~ 30 m above the modern lake surface, affords an age of 16.3 ± 0.4 ka. The CR1 moraines lie ~ 300 m south from the lake shore and comprise a ~ 500 m long and ~ 10 m high main ridge connected to several minor ridges (Supplementary Fig. 2s). We obtained seven ^{10}Be dates that range from 16.6 ± 0.4 to 15.3 ± 0.4 ka, with a mean of 15.9 ± 0.5 ka. Directly inside CR1 we find two ridges that form the CR2 moraines, clearly distinguishable by their larger sizes (~ 700 m long and ~ 20 m high) and sharper appearance (Supplementary Fig. 2s). Six ^{10}Be dates from the largest and most continuous ridge yielded ages between 14.0 ± 0.2 to 13.1 ± 0.2 ka, with a mean of 13.5 ± 0.4 ka.

Immediately inboard, separated by a meltwater channel, we find the CR3 moraine that represents the most continuous (~ 1000 m long) and prominent (~ 30 m high) ice-marginal feature of the area. We obtained seven ^{10}Be dates that range in age from 13.5 ± 0.3 to 12.9 ± 0.3 ka, with a mean of 13.1 ± 0.4 ka. Approximately 200 m upstream from CR3, separated by an outwash plain, a group of several discontinuous ridges covered by dense vegetation form the CR4 moraine (Supplementary Fig. 2s). Two samples from the outermost moraine ridge of CR4 provide ages of 13.5 ± 0.3 and 12.9 ± 0.3 , with a mean of 13.1 ± 0.5 ka (the additional sample LV17-30 (10.6 ± 0.2 ka) was excluded as an outlier [20]) (Fig. 1, Table 1). CR5 comprises the innermost ice-marginal features, located ~ 500 m upstream from CR4, and consists of a ~ 400 m long group of latero-frontal moraine ridge fragments elevated ~ 20 m above the floor of the most extensive outwash plain in this valley. Two ^{10}Be dates collected from the outermost ridge yielded statistically identical ages of 12.5 ± 0.2 ka.

Discussion

Glacial geologic mapping and thirty new ^{10}Be ages (1 outlier) constitute the basis of a moraine chronology for the LPGV basin that captures in unprecedented detail the sequence of glacier/paleoclimatic events during T1 in northern Patagonia. Our data indicate that the LPGV glacier lobe abandoned the PV6 moraine sometime after 19.7 ± 0.7 ka. Considering the dispersion of the PV6 ages, and the significant number of undated ridges within this moraine belt, we interpret this date as a maximum-limiting age for the onset of major glacier withdrawal. The ice front then retreated more than 40% of its LGM length, prompting the detachment of the Cerro Riñón glacier shortly after 16.3 ± 0.4 ka. After this event, an advance of this tributary glacier culminated with the deposition of the CR1 moraine at 15.9 ± 0.5 ka. Subsequent advances deposited the statistically indistinguishable but geomorphologically distinct CR2 to CR4 moraines between 13.5 ± 0.4 and 13.1 ± 0.5 ka. Cerro Riñón glacier then underwent net recession, only interrupted by a stillstand that constructed CR5 at 12.5 ± 0.4 ka. No ice marginal features are evident up valley, suggesting irreversible glacier retreat to the headwalls after ~ 12.5 ka. The chronology for the Cerro Riñón glacier informs us, for the first time in northern Patagonia, the timing and structure of glacier fluctuations throughout the entirety of T1 within a single basin, and constrains four moraine deposition phases of similar magnitude (i.e., CR1-CR4) that culminated at ~ 15.9 ka during Heinrich Stadial 1 (HS1: ~ 17.8 – 14.7 ka) and between ~ 13.5 – 13.1 ka within the Antarctic Cold Reversal (ACR: ~ 14.7 – 12.7 ka), followed by an additional advance or stillstand of minor extent (i.e., CR5) at ~ 12.5 ka coeval with the Younger Dryas (YD: ~ 12.6 – 11.5 ka).

The Cerro Riñón glacier expanded and achieved its maximum extent during T1 by $\sim 15.9 \pm 0.5$ ka. This result differs from the majority of moraine-based records from southern South America dated so far, which document an apparent sustained and irreversible glacier recession during HS1. Notable exceptions are moraines of similar age observed along the eastern flank of the southern Patagonian Andes at the ^{10}Be dated Cerro Pintado moraine at Río Guanaco ($\sim 50^\circ\text{S}$) [21] and the ^{14}C -constrained Lago Pinto moraine at Última Esperanza ($\sim 50^\circ\text{S}$) [22]. Subsequent glacier activity in the Cerro Riñón valley represents the northernmost direct evidence for glacier advances during the ACR and gradual retreat

during the YD in Patagonia, expanding their known geographical footprint from 47.5° S to 43.9° S [23, 24, 25, 26]. The recent interpretation of an ACR maximum based on geomorphic analysis and lake sedimentary record of former Rosselot glacier [27], ~ 45 km directly west of Cerro Riñón, is consistent with our conclusions. The Patagonian findings indicate that ELA depressions at ~ 15.9 ka and during the ACR were similar in magnitude and were followed by a net ELA rise during the YD, accounting for modest glacier advances or standstills well within ACR limits. At similar latitude, but ~ 9000 km west of LPGV, several moraine records in New Zealand reflect synchronous glacier behavior: deep recession from the LGM limits was punctuated by deposition of the Prospect Hill moraines at ~ 15.9 ka in the Rakaia valley [28], which was followed by several ACR advances, and then subsequent YD recession was interrupted by minor stillstands in multiple valleys of the Southern Alps [29, 30, 31]. We propose that trans-Pacific coordinated glacier fluctuations at millennial timescales through T1 most likely involves zonally symmetric changes in the SWW and associated climate anomalies [23, 30].

We assess the representativity behavior of the Cerro Riñón glacier record with proxy evidence from lake sediment cores obtained in the Pacific sector of northern Patagonia, which afford valuable information for tracking the regional evolution of the SWW through the LGM and T1 [32, 33, 34]. Pollen records from the Chilean Lake District and Isla Grande de Chiloé [35] show a treeline depression of ~ 1000 m and presence of Magellanic Moorland communities during the LGM, attesting to cold and hyperhumid conditions brought by a northward shift of the SWW (Fig. 2). This was followed by rapid arboreal expansion, disappearance of Magellanic Moorland driven by deglacial warming and a southward shift of the SWW starting at ~ 17.8 ka. The interval between ~ 17.8–16.4 ka features a low lake-level stand, with peak abundance of the littoral macrophyte *Isoetes* (Fig. 2), signaling low SWW influence during the initial portion of T1. Discrete increases in precipitation occurred at ~ 16.4 ka and ~ 14.7 ka, as indicated by conspicuous increases in cold-tolerant hygrophilous conifers (*Fitzroya/Pilgerodendron* and *Podocarpus nubigena*, respectively). These changes suggest successive increments in SWW influence in northern Patagonia. The earliest of these increases lasted until ~ 15.9 ka, as the deglacial warming trend resumed and crossed a critical threshold that favored the diversification and densification of other thermophilous rainforest trees and vines at the expense of *Fitzroya/Pilgerodendron*. The most recent increase in conifers (*Podocarpus nubigena*) during T1 took place between ~ 14.7–12.6 ka, and was followed by enhanced fire activity, a lake-level decline, and decline in conifers after ~ 12.6 ka, which suggest a decline in precipitation related to a southward shift of the SWW. Wind-driven hydroclimate changes toward cold/wet conditions closely track glacier advances in the LPGV area. We therefore conclude that our record shows a coherent cryospheric response to significant SWW-modulated climate fluctuations during T1. Additionally, we note that the reservoir-age corrected paleoclimate records from marine core ODP1233 [36], collected offshore from northwestern Patagonia (Fig. 3), show a pattern consistent with our terrestrial-based chronology of climate change through T1.

Widespread glacier withdrawal in Patagonia [37] was contemporaneous with distinct atmCO₂ increments recorded at the beginning and end of T1, between ~ 18.1–16.3 ka and ~ 13–11.7 ka in the WAIS ice core [38], enhanced ocean ventilation inferred from a rise in opal flux recorded in the SO [9], and reduced $\delta^{13}\text{C}$

composition of atmCO₂ preserved in the EDC and TALDICE ice cores from Antarctica [39] (Fig. 3). Glacier advances or stillstands that stalled deep recession in northern Patagonia coincided with centennial-scale halts in the rising atmCO₂ trend followed by atmCO₂ plateaus between ~ 16.3–14.8 ka and ~ 14.8–13.0 ka [38], concomitant with decreased deep SO water ventilation [9] and minimum $\delta^{13}\text{C}$ composition of atmCO₂ from Antarctic ice cores [39] (Fig. 3).

Our collation of mid- and high-latitude paleoclimate data from the Southern Hemisphere suggests that variations in the strength/position of the SWW are the common denominator for hydroclimate changes and glacier mass balance variations in the temperate regions of South America and New Zealand, along with upwelling and ventilation of deep waters in the SO through T1. Overall, we note that negative mass balance driving glaciers recession from their LGM terminus in the LPGV basin was contemporaneous with negative anomalies in SWW influence in northwestern Patagonia [35] and sustained increase in atmCO₂ [38] coinciding with invigorated SO upwelling [9]. Collectively, these data indicate a poleward shift of the SWW early during T1 [9]. Subsequently, positive glacier mass balance episodes culminating at ~ 15.9 were concomitant with positive anomalies in SWW at ~ 44°S [35], a pause in the rising trend of atmCO₂ rapidly starting at 16.3 ka [38], and subdued increase in SO upwelling [9]. We interpret these correspondences as a concomitant widening of the SWW belt during the HS1. This was followed by enhanced positive glacier mass balance accounting for multiple readvances between ~ 13.5–13.1 ka coeval with positive anomalies of the SWW in northwestern Patagonia [35], and a stall in the rising of atmCO₂ trend [38] accompanied by attenuated degassing of the SO [9]. We interpret these data as increased SWW influence at ~ 44°S and diminished influence south of ~ 55°S, over the SO, implying a northward shift of the SWW belt. Finally, recurrent negative glacier mass balance prior to ~ 12.5 ka was coeval with negative anomalies in SWW influence in northwestern Patagonia [35], resumption of the atmCO₂ rising trend [38], and enhanced SO upwelling [9]. This correspondence suggests to us diminished SWW influence at ~ 44°S and stronger SWW influence south of ~ 51°S, implying a southward shift of the SWW belt during the YD.

The Cerro Riñón glacier chronology also shares similarities with mountain glacier chronologies from the mid and high northern latitudes [37] (Supplementary 3s). Those studies show glacier withdrawal from their LGM limits shortly after the onset of T1 at ~ 18.5 ka [39, 40], readvances between ~ 17 – 16 ka in multiple valleys of the European Alps [40, 41, 42] and between ~ 16.5–15.7 ka in western North America [43], broadly contemporaneous with the deposition of the CR1 moraine during HS1. A growing body of evidence indicates that glaciers readvanced between ~ 14.5–13.5 ka in the Norwegian Arctic [5], between ~ 14.3–12.8 ka in east Greenland [44], and between ~ 14.5–12.8 ka in western North America [45], coeval with the formation of the CR2-CR4 moraines during the ACR. Subsequent moraine formation events between ~ 12.8–12.3 ka in east Greenland [46], southern Alaska [6], and Scotland [7] occurred during the early YD, and several sites across the European Alps during the late YD [47, 48, 49, 50, 51]. These advances or standstills are indistinguishable in age, considering dating uncertainties, with the CR5 moraine, just before widespread and irreversible recession to the valley headwalls. We acknowledge that significant glacial activity during T1 occurred within the YD and few dates overlapping with the ACR have

been reported in the majority of northern hemisphere sites [37]. A large number of these glacier advances, however, culminated either early or late within the interval (Supplementary), indicating that glaciers were receding through much of the YD.

The pervasive interhemispheric synchrony in mountain glaciation during T1 lies in direct contrast to the largely antiphased polar ice core records (Fig. 3). Studies have attributed the severity of cooling in Greenland ice cores throughout HS1 and YD time to a seasonality switch related to episodes of extended sea ice cover in the North Atlantic region, skewing their isotopic records toward a predominantly winter temperature signal [52, 53]. Mountain glacier fluctuations, in contrast, respond primarily to summer temperatures which remained comparatively warm during key episodes of T1 as reflected by modelling experiments complemented with multiproxy records from Europe [54].

Our results and analysis show that the timing and structure of glacier fluctuations in the LPGV basin were coeval with climate events recorded in both the northern (i.e., HS1 and YD) and southern (i.e., ACR) hemispheres. From our interhemispheric comparison we interpret synchrony of mountain glaciers driven by a global climate signal during T1, challenging the expected antiphase behavior predicted from the bipolar seesaw paradigm. This finding favors an atmospheric mechanism for generating and globally propagating millennial-scale climate variability during T1. We conclude that high-to-middle latitude mountain glaciers fluctuated in phase during T1 partly in response to summer warming due to atmCO₂ concentrations brought by changes in the SWW-SO coupled system [4, 8].

Methods

Geomorphological mapping. Detailed geomorphological mapping of the moraine limits in Lago Palena/General Vintter basin was conducted based on satellite imagery (Sentinel 2), aerial photographs (GEOTEC 1:50,000) and digital elevation models (ALOS Palsar). The preliminary map was checked during two field campaigns (March, September 2017 and January 2020).

Rock samples collection. We collected 26 boulder samples for ¹⁰Be surface exposure dating from the Cerro Riñón moraines (CR complexes), in addition to one sample from a perched boulder (LV-17-42) located immediately outboard of the outermost moraine limit, and 4 boulder samples from the innermost moraine ridge along the eastern shore of Lago Palena/General Vintter (i.e., PV6). We aimed for large boulders to avoid potential effects of post-depositional movements or posterior exhumation. Samples were taken from the upper ~ 4 cm of the boulder surfaces using a drill and explosive charges, avoiding areas exhibiting clear signs of erosion, such as spalling or flaking. Elevation and geographic coordinates of each rock sample were recorded with a handheld GPS unit (WGS84). We measured topographic shielding using a handheld compass and a clinometer. Moraine ages are interpreted as representing the culmination of moraine construction, and, thus, cold episodes, whereas the perched-boulder age provides a minimum age for ice retreat from the sampling site.

Quartz separation and ^{10}Be isolation. Initial crushing and sieving of the rock samples was carried out at the Pontificia Universidad Católica de Chile and subsequent quartz and beryllium extraction at the Cosmogenic Nuclide Laboratory at Lamont-Doherty Earth Observatory following the protocol outlined in [55, 56]. $^{10}\text{Be}/^9\text{Be}$ ratios were measured at Lawrence Livermore National Laboratory Center for Accelerator Mass Spectrometry. Ratios were measured relative to the standard 07KNSTD with a $^{10}\text{Be}/^9\text{Be}$ ratio of 2.85×10^{-12} ([57]; ^{10}Be half-life = 1.36 Myr.). Analytical raw data are available in the supplementary material. Given relatively recent improvements described in [55, 56], the average analytical uncertainty is $\sim 2\%$, with almost half the analyses between 1.7% and 2.0%.

^{10}Be surface exposure ages. ^{10}Be ages were calculated based on methods incorporated in the CRONUS-Earth online exposure age calculator (v.3) [58], considering the time-dependent Lal/Stone [59, 60] scaling schemes and the regional Patagonian production rate ($\sim 50^\circ\text{S}$) [56], assuming zero erosion and a rock density of 2.65 g/cm^3 . We show in Table 1 that ^{10}Be ages are statistically identical (i.e., accuracy) using other scaling methods. In the text, we report individual ^{10}Be ages with 1σ analytical uncertainty and the standard error of the mean (SEM). For comparison with other proxy records, mean moraine ages include the propagation of the analytical uncertainty and that of the local production rate (3%) [56]. Similarly, for glacier ^{10}Be chronologies in New Zealand, we used a local production rate ($\sim 43.6^\circ\text{S}$) and the associated uncertainties include a 2% error [61].

Declarations

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Author contributions

R.L.S. and E.A.S. designed the study with conceptual contributions by all co-authors. R.L.S. performed geomorphological mapping and lab analysis. Fieldwork was conducted by R.L.S., E.A.S. and M.A.M. P.I.M. helped with palynological data curation and interpretation. S.A.R. discovered the study area. M.R.K. R.S. and J.M.S. participated on initial conceptualization and lab analysis. All the co-authors contributed to the formal analysis and interpretation of the results. R.L.S. wrote the initial draft of the paper and all the co-authors reviewed it.

Competing interests

The authors declare no competing interests.

Data availability

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Tables

Table 1. ^{10}Be ages from the Lago Palena/Vintter area calculated using the the non-time-dependent Lal/Stone scaling scheme (St; [56,57]) time-dependent Lal/Stone scaling (Lm; [56,57] and Lifton et al scaling (LSDn; [59]). Mean moraine ages are shown in bold with 1 outlier excluded (*), and are accompanied by the uncertainty (1 standard deviation [σ]/Standard Error of the Mean [SEM]) considering the propagated error (3%) of the production rate [53] for both.

	Id Sample	Age; St (ka)	Age; Lm (ka)	Age; LSDn (ka)
PV6	LVM17-19	19210 ± 400	18860 ± 390	19050 ± 400
	LVM17-20	21150 ± 400	20660 ± 390	20790 ± 390
	LVM17-21	19760 ± 570	19370 ± 560	19530 ± 560
	LVM17-23	20280 ± 580	19860 ± 570	20000 ± 570
	Mean ± σ/SEM	20100 ± 1030/730	19690 ± 970/700	19840 ± 950/700
CR1	LV17-15	16620 ± 310	16440 ± 310	16640 ± 310
	LV17-17	15640 ± 330	15510 ± 330	15690 ± 330
	LV17-18	16200 ± 310	16040 ± 310	16220 ± 310
	LV17-34	15550 ± 440	15420 ± 440	15630 ± 450
	LV17-35	15380 ± 350	15260 ± 350	15470 ± 360
	LV17-36	16750 ± 440	16560 ± 440	16770 ± 440
	LV17-41	15980 ± 310	15830 ± 300	16040 ± 310
	Mean ± σ/SEM	16020 ± 720/520	15860 ± 690/510	16070 ± 700/520
CR2	LV17-20	13000 ± 310	13070 ± 310	13270 ± 320
	LV17-21	14000 ± 240	13980 ± 240	14170 ± 240
	LV17-23	13660 ± 260	13670 ± 260	13880 ± 260
	LV17-24	13710 ± 320	13720 ± 320	13930 ± 320
	LV17-25	13210 ± 250	13260 ± 260	13500 ± 260
	LV17-27	13060 ± 250	13120 ± 250	13370 ± 250
	Mean ± σ/SEM	13440 ± 570/430	13470 ± 550/430	13690 ± 550/440
CR3	LV17-03	13500 ± 260	13530 ± 260	13760 ± 260
	LV17-04	13070 ± 290	13130 ± 290	13370 ± 300
	LV17-05	12830 ± 330	12910 ± 340	13150 ± 340
	LV17-06	12780 ± 250	12870 ± 260	13090 ± 260
	LV17-07	13070 ± 290	13130 ± 290	13330 ± 300
	LV17-08	12910 ± 310	12990 ± 310	13180 ± 310
	LV17-12	12880 ± 240	12970 ± 240	13160 ± 250
	Mean ± σ/SEM	13010 ± 460/400	13070 ± 450/400	13290 ± 460/410

CR4	LV17-29	12800 ± 260	12890 ± 270	13110 ± 270
	LV17-30*	10480 ± 240	10720 ± 250	11010 ± 250
	LV17-37	13330 ± 270	13360 ± 270	13590 ± 270
	Mean ± σ/SEM	13060 ± 540/470	13130 ± 520/460	13350 ± 520/470
CR 5	LV17-38	12340 ± 240	12460 ± 240	12700 ± 240
	LV17-39	12420 ± 230	12540 ± 250	12770 ± 240
	Mean ± σ/SEM	12380 ± 380/370	12500 ± 380/380	12730 ± 390/380
Perched boulder	LV17-42	16420 ± 430	16250 ± 420	16470 ± 430

Figures

Figure 1

Glacial geomorphology and chronology of the a) Lago Palena/General Vintter ice lobe with ^{10}Be ages ($n = 4$) obtained from the innermost moraine ridge (PV6) and b) the Cerro Riñón valley glacier with ^{10}Be ages ($n = 26$) obtained from CR1-CR5 moraine complexes and the additional perched boulder. On top of the boxes the mean moraine age accompanied by 1 standard error of the mean including a 3% propagated production rate error (Table 1). Individual ages are presented along with internal uncertainty and sample

ID. One age in red italics is considered an outlier. Inset maps with the location of sites mentioned in the text. Black dots correspond with glacial chronologies from RG: Río Guanaco; SUE: Seno Última Esperanza. Red dots correspond to paleovegetation reconstruction. LL: Lago Lepué. CP: Canal de la Puntilla. TH: Turbera Huelmo. Green dot is the location of ODP1233. White outlines represent Northern (NPI) and Southern (SPI) Patagonian Icefields and Cordillera Darwin Icefield (CDI).

Figure 2

Glacier chronology of the Lago Palena/General Vintter basin and selected species from the Canal de la Puntilla and Turbera Huelmo in the Chilean Lake District [12] and Lago Lepu pollen record in Isla Grande de Chilo [36]. Blue bars highlight cold/wet interval and yellow bars demote warm/dry periods within T1.

Figure 3

Paleoclimate proxies spanning T1. a) Records from the North Greenland Ice Core Project: $\delta^{18}\text{O}$ [3]; winter temperatures in purple [60]; summer temperatures in yellow [60]. b) Glacier length of the Lago Palena/General Vintter ice lobe (this study). Yellow triangles are bracketing radiocarbon ages for the final glacial advance (100 % length) of the LGM in the Chilean Lake District [15]. c) Glacier-derived temperatures from Rakaia Valley, New Zealand [29,30]. d) Planktonic $\delta^{18}\text{O}$ from marine core ODP-1233 [27]. e) Opal flux from marine core TN057-13PC [9]. f) Integrated $\delta^{13}\text{C}$ from TALDICE and EPICA Dome C (EDC) [14]. g) Records from the central West Antarctica Ice Core (WAIS): CO_2 in light blue and $\delta^{18}\text{O}$ in red. Blue bars highlight cold/wet interval and yellow bars demote warm/dry periods inferred from palinological analyses.

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