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Holocene History of Río Tranquilo Glacier, Monte San Lorenzo (47°S), Central Patagonia

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The causes underlying Holocene glacier fluctuations remain elusive, despite decades of research efforts. Cosmogenic nuclide dating has allowed systematic study and thus improved knowledge of glacier-climate dynamics during this time frame, in part by filling in geographical gaps in both hemispheres. Here we present a new comprehensive Holocene moraine chronology from Mt. San Lorenzo (47°S) in central Patagonia, Southern Hemisphere. Twenty-four new ^{10}Be ages, together with three published ages, indicate that the Río Tranquilo glacier approached its Holocene maximum position sometime, or possibly on multiple occasions, between 9,860 ± 180 and 6,730 ± 130 years. This event(s) was followed by a sequence of slightly smaller advances at 5,750 ± 220, 4,290 ± 100 (?), 3,490 ± 140, 1,440 ± 60, between 670 ± 20 and 430 ± 20, and at 390 ± 10 years ago. The Tranquilo record documents centennial to millennial-scale glacier advances throughout the Holocene, and is consistent with recent glacier chronologies from central and southern Patagonia. This pattern correlates well with that of multiple moraine-building events with slightly decreasing net extent, as is observed at other sites in the Southern Hemisphere (i.e., Patagonia, New Zealand and Antarctic Peninsula) throughout the early, middle and late Holocene. This is in stark contrast to the typical Holocene mountain glacier pattern in the Northern Hemisphere, as documented in the European Alps, Scandinavia and Canada, where small glaciers in the early-to-mid Holocene gave way to more-extensive glacier advances during the late Holocene, culminating in the Little Ice Age expansion. We posit that this past asymmetry between the Southern and Northern hemisphere glacier patterns is due to natural forcing that has been recently overwhelmed by anthropogenic greenhouse gas driven warming, which is causing interhemispherically synchronized glacier retreat unprecedented during the Holocene.

Keywords: Patagonia, Holocene, glacier fluctuations, ^{10}Be dating, Southern Annular Mode, Neoglaciation, Paleoclimate, South America

INTRODUCTION

Following an early Holocene glacier minimum, most of the glacierised areas around the world experienced a phase of renewed glacier advances, a phenomenon commonly known as Neoglaciation (Porter and Denton 1967). Since their recognition by the middle of the last century, numerous studies have attempted to decipher the causes underlying these glacier fluctuations (e.g., Grove 2004) by comparing the sequence and temporal phasing of advances in disparate regions of the world with terrestrial or extraterrestrial climate-forcing mechanisms (e.g., Denton and Karlen 1973; Bond et al., 2001; Denton and Broecker 2008). Such an understanding is crucial, as it may provide key insights into the mechanisms governing abrupt climate changes and any corresponding cryospheric response. However, further advances in these efforts have been limited by the lack of a well-distributed global network of high-resolution glacier chronologies.

In the case of Patagonia (South America between 40° and 54°S), several chronological models of Holocene glacier fluctuations have been proposed (Mercer 1982; Clapperton and Sugden 1988; Aniya 1995; Aniya 2013). These models—relaying predominantly on radiocarbon dating—differ significantly from each other and more recent studies, and make difficult any effort to understand the recent glacial history of southern South America. The apparent differences between chronological models can be attributed to: i) the reliance on minimum (maximum)-limiting ages, which tend to underestimate (overestimate) the true age of the landforms; ii) the incompleteness of the chronologies due to the limited availability of datable organic matter to conduct radiocarbon analysis; and iii) the fragmentary nature of the surficial glacial record (i.e., due to erosional censoring typical for glaciers, few sites are able to preserve the evidence of every glacier advance that occurred in the area) (Glasser et al., 2005; Strelin et al., 2011; Reynhout et al., 2019). As a consequence, significant gaps remain in our knowledge of centennial- and millennial-scale glacier responses under natural climate variability.

Advances in surface exposure dating techniques, involving both sample processing (e.g., low process blanks) and AMS measurements, have opened new horizons for the development of high-resolution Holocene glacier chronologies based on the analysis of low ^{10}Be/^{9}Be ratios (Schaefer et al., 2009) (e.g., ~10^{14-15} in **Table 1**). These improvements, combined with the establishment of a Patagonian ^{10}Be production rate (Kaplan et al., 2011), have recently allowed the emergence of a new generation of comprehensive moraine chronologies from southern South America spanning much or all of the Holocene (i.e., Strelin et al., 2014; Kaplan et al., 2016; Reynhout et al., 2019; García et al., 2020). These ^{10}Be chronologies have been for the most part, developed within a narrow latitudinal band at around 49–51°S in southern Patagonia, and they indicate that in this locale glaciers underwent a series of progressively less extensive advances throughout most of the Holocene.

TABLE 1 | Geographical and analytical data for samples from the Río Tranquilo valley.

Sample	CAMS #	Latitude (°)	Longitude (°)	Elevation (m a.s.l.)	Thickness (cm)	Shielding	Quartz wt (g)	^{9}Be carrier (mg)	^{10}Be/^{9}Be (10^{-14})	^{10}Be (10^{4} atoms g^{-1})
PC13-01-13	BE49281	−47.5314	−72.3897	1,350	1.4	0.9821	30.0566	0.1015	7.3287 ± 0.2415	1.6801 ± 0.056
PC13-01-14	BE46329	−47.5305	−72.3905	1,332	1.5	0.9750	39.1895	0.1821	5.6108 ± 0.1270	1.7743 ± 0.041
PC13-01-18	BE49279	−47.5263	−72.3921	1,258	2.3	0.9815	60.0041	0.1806	2.3305 ± 0.0880	0.4702 ± 0.018
PC13-01-19 *	BE38777	−47.5258	−72.3904	1,236	2.4	0.9770	15.1244	0.1825	10.1541 ± 0.1921	8.4684 ± 0.16
PC13-01-23	BE46458	−47.5135	−72.3935	968	2.2	0.9590	41.0145	0.1819	1.1336 ± 0.0522	0.2949 ± 0.015
PC13-01-24	BE46459	−47.5129	−72.3927	938	2.0	0.9660	62.6149	0.1811	1.7508 ± 0.1107	0.3149 ± 0.02
PC14-01-33	BE46336	−47.5228	−72.3893	1,181	1.4	0.9820	10.0743	0.1822	5.9373 ± 0.1491	7.2577 ± 0.184
PC14-01-34	BE46337	−47.5215	−72.3885	1,157	1.7	0.9840	10.029	0.1812	7.2295 ± 0.2159	8.8565 ± 0.266
PC14-01-35	BE49286	−47.5195	−72.3875	1,107	1.9	0.9840	15.159	0.1808	12.2390 ± 0.2279	10.0182 ± 0.187
RTV16-01-03	BE49287	−47.5232	−72.3895	1,194	1.5	0.9799	15.0128	0.1814	8.7750 ± 0.1633	7.2613 ± 0.136
RTV16-01-04	BE46330	−47.5262	−72.3916	1,253	1.6	0.9660	40.4318	0.1818	15.8400 ± 0.2939	4.8823 ± 0.091
RTV16-01-05	BE49284	−47.5279	−72.3917	1,315	1.8	0.9783	20.8781	0.1813	7.3116 ± 0.1491	4.3415 ± 0.089
RTV16-01-06	BE49285	−47.5280	−72.3917	1,303	3.6	0.9865	21.8359	0.1830	7.4771 ± 0.1482	4.2861 ± 0.085
RTV16-01-07	BE49280	−47.5294	−72.3912	1,335	2.0	0.9845	37.7023	0.1802	5.4173 ± 0.1123	1.7647 ± 0.037
RTV16-01-08	BE49288	−47.5282	−72.3912	1,313	2.1	0.9863	15.0778	0.1815	8.7084 ± 0.1704	7.1787 ± 0.141
RTV16-01-09	BE46453	−47.5279	−72.3921	1,301	2.0	0.9840	70.7804	0.1825	4.2715 ± 0.1105	0.7277 ± 0.019
RTV16-01-10	BE46454	−47.5276	−72.3921	1,287	1.4	0.9090	38.1763	0.1821	1.8539 ± 0.1002	0.5534 ± 0.031
RTV16-01-12	BE46455	−47.5270	−72.3922	1,272	3.1	0.9870	70.4651	0.1835	2.6276 ± 0.1020	0.4409 ± 0.017
RTV16-01-13	BE46331	−47.5224	−72.3901	1,166	1.5	0.9800	43.1031	0.1824	12.6946 ± 0.2356	3.6789 ± 0.069
RTV16-01-15	BE46332	−47.5186	−72.3996	1,149	1.7	0.9860	27.8859	0.1821	7.6896 ± 0.1595	3.4278 ± 0.072
RTV16-01-16	BE49282	−47.5179	−72.3988	1,136	1.9	0.9876	20.0446	0.1019	9.5665 ± 0.2737	3.3145 ± 0.095
RTV16-01-17	BE46333	−47.5172	−72.3981	1,112	2.2	0.9830	45.2772	0.1813	12.2140 ± 0.2267	3.3486 ± 0.062
RTV16-01-18	BE46334	−47.5170	−72.3981	1,112	1.7	0.9780	15.0336	0.1818	5.2897 ± 0.1187	4.3137 ± 0.098
RTV16-01-19	BE46457	−47.5143	−72.3947	1,012	2.9	0.9810	64.0671	0.1805	1.7906 ± 0.0705	0.3143 ± 0.013

AMS ratios presented as boron-corrected values measured against the 07KNSTD standard material with a reported ^{10}Be/^{9}Be value of 2.85 × 10^{-12} (Nishiizumi et al., 2007; ^{10}Be half-life = 1.36 Myr). 1σ analytical or internal AMS uncertainties are shown. Rock density = 2.65 g/cm^{3}. Carrier concentrations used are 1,037 ppm (*) and 1,030 ppm for all others. We processed procedural blanks associated with each sample set, and their total ^{10}Be ranged from ~6,600 to ~26,000 atoms; these were subtracted respectively from sample concentrations.

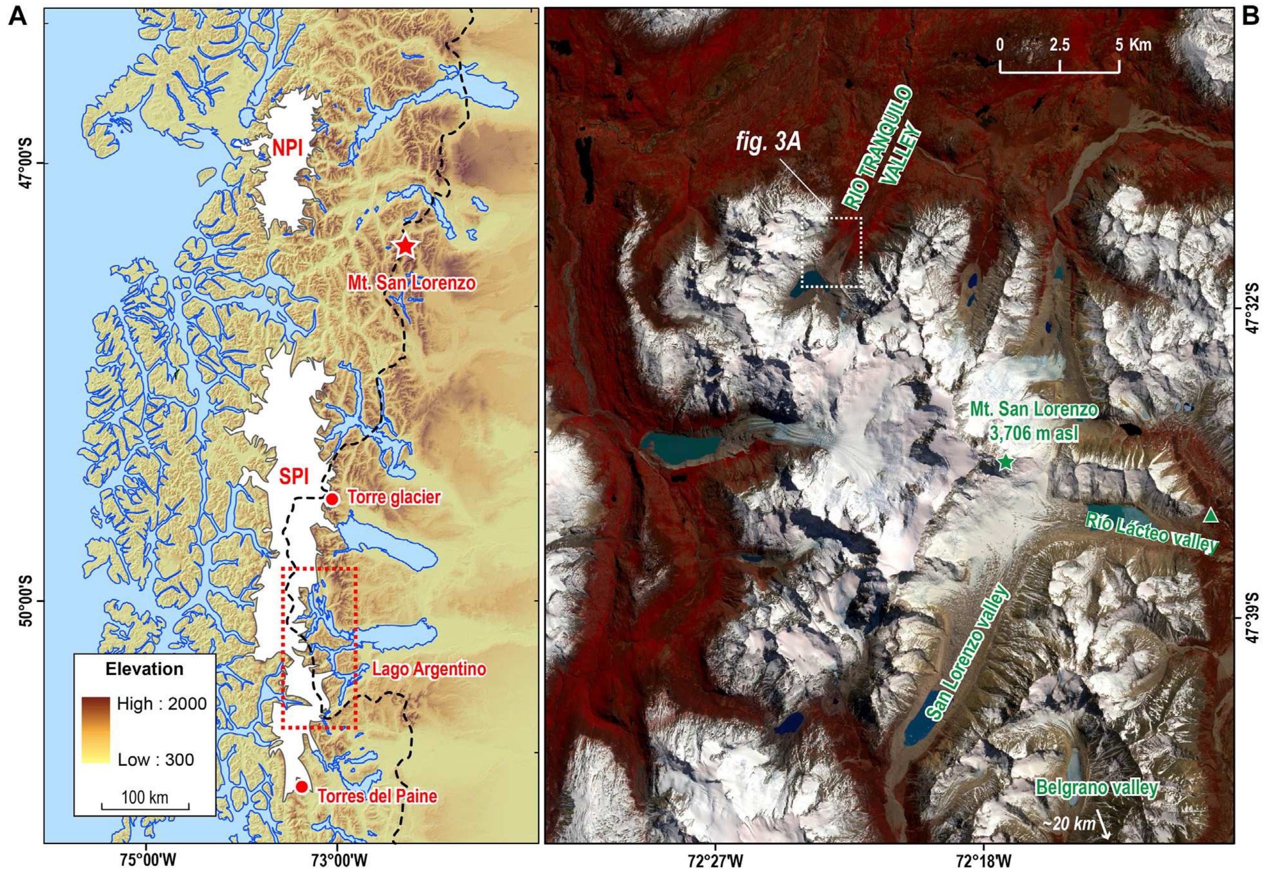

FIGURE 1 | Geographic setting of this and prior studies. **(A)** Regional overview of the Patagonian Icefields and surrounding area. ALOS PALSAR composition (m asl) NPI, Northern Patagonian Icefield; SPI, Southern Patagonia Icefield. **(B)** Río Tranquilo valley, Mt. San Lorenzo. Sentinel 2 false color image (Infrared, 2016) showing the entire San Lorenzo massif and all the glaciers draining from its headwalls. Green star indicates Mt. San Lorenzo summit. Green triangle shows the approximated location of the available Holocene radiocarbon date (Mercer, 1968). Other sites discussed in the text are also shown.

Recently published glacier chronologies, moreover, show promising consistency with pollen-inferred changes in the intensity of the Southern Westerly Winds (SWW) (Moreno et al., 2018). Modern SWW intensity is positively correlated with annual precipitation, and negatively correlated with summer temperatures throughout western Patagonia (see Figures 5, 8 in Garreaud et al., 2013). Accordingly, strong westerlies are associated with the cold and wet conditions ideal for glacier expansion; weaker westerlies, on the other hand, are associated with warmer and drier conditions, promoting glacier withdrawal. Based on the apparent relationship with past Westerlies behavior, it has been hypothesized that Holocene glacier fluctuations in southern Patagonia were paced by centennial-scale temperature and precipitation anomalies associated with changes in the SWW intensity (Moreno et al., 2018; Reynhout et al., 2019). To test and validate this hypothesis across the whole of Patagonia requires expanding the spatial network of study sites, to assess the regional representativeness of emerging ^{10}Be chronologies.

Here, we set out to refine the structure and timing of Holocene glacier fluctuations of southern South America by developing a new comprehensive ^{10}Be moraine chronology in the Río Tranquilo valley, on the northern flank of Mt. San Lorenzo (47°35′ S; 72°19′ W). Located roughly in central Patagonia, Mt. San Lorenzo is located to the east of a tectonic depression that breaks the Andes (and separates the Patagonian Ice Fields), and despite being more than 160 km from the Pacific Ocean, it is the first major orographic barrier to the moisture-laden SWW (Mendelová et al., 2020b). Consequently, Mt. San Lorenzo is ideally located to track the position of the Westerlies and assess their role in pacing Holocene glacier fluctuations in Patagonia (Moreno et al., 2018; Reynhout et al., 2019).

STUDY AREA

Mt. San Lorenzo (47°35′S, 72° 21′W) is an isolated granodiorite massif astride the border between Chile and Argentina, 80 km to the east of the topographic divide of the Andes (**Figure 1**). Mt. San Lorenzo exhibits a transitional maritime to continental climate, with a wide annual thermal amplitude and a narrow range of mean monthly precipitation (Falaschi et al., 2019). At

TABLE 2 | All the new ^{10}Be were ages calculated using CRONUS v. 3 (Balco et al., 2008) and are reported with 1σ internal (analytical) error.

Sample	St		Lm		LSDn	
	Age	±1σ	Age	±1σ	Age	±1σ
PC13-01-13	1,330	40	**1,370**	**50**	1,310	40
PC13-01-14	1,440	30	**1,480**	**30**	1,420	30
PC13-01-18	400	20	**460**	**20**	480	20
PC13-01-19	7,460	140	**7,600**	**140**	7,490	140
PC13-01-23	330	20	**380**	**20**	400	20
PC13-01-24	360	20	**400**	**30**	430	30
PC14-01-33	6,590	170	**6,770**	**170**	6,760	170
PC14-01-34	8,200	250	**8,370**	**250**	8,290	250
PC14-01-35	9,680	180	**9,860**	**180**	9,790	180
RTV16-01-03	6,540	120	**6,730**	**130**	6,720	130
RTV16-01-04	4,260	80	**4,390**	**80**	4,370	80
RTV16-01-05	3,570	70	**3,730**	**80**	3,700	80
RTV16-01-06	3,570	70	**3,740**	**80**	3,710	70
RTV16-01-07	1,420	30	**1,460**	**30**	1,400	30
RTV16-01-08	5,870	120	**6,090**	**120**	6,050	120
RTV16-01-09	600	20	**670**	**20**	670	20
RTV16-01-10	500	30	**560**	**30**	570	30
RTV16-01-12	380	20	**430**	**20**	450	20
RTV16-01-13	3,390	60	**3,540**	**70**	3,530	70
RTV16-01-15	3,190	70	**3,320**	**70**	3,300	70
RTV16-01-16	3,110	90	**3,240**	**90**	3,230	90
RTV16-01-17	3,230	60	**3,360**	**60**	3,350	60
RTV16-01-18	4,160	100	**4,290**	**100**	4,300	100
RTV16-01-19	330	10	**380**	**20**	410	20

"St" is the non-time-dependent scaling from the Lal (1991)/(Stone et al., 2000) scheme; "Lm" is the time dependent version of Lal (1991)/(Stone et al., 2000); LSDn is the time dependent version of Lifton et al. (2014). We use the "Lm" scaling scheme (in bold letters), but this choice does not change our conclusions given the overlap at 1σ. All ages calculated using a^{10} Be production rate measured at Lago Argentino, south Patagonia (50°S) (Kaplan et al., 2011).

3,706 m a.s.l., Mt. San Lorenzo is one of the most extensively glacierized mountains in the region, with an ice-covered area of ca. 139 km^2. For the years 2005/2008, Falaschi et al. (2013) estimated the snowline to be ~1,700–1,750 m a.s.l. on the western sector of the massif and ~1,800 m asl on the eastern side. This study focuses on the Rio Tranquilo valley, a north-south oriented valley on the northern flank of Mt. San Lorenzo. The headwall of this valley is home to 16 small glaciers <5 km^2 which collectively cover an estimated area of 15 km^2 (Falaschi et al., 2013).

PREVIOUS STUDIES

Nearly all studies that have reconstructed the extent and timing of glacier events on Mt. San Lorenzo have focused on the last glacial-interglacial transition (Wenzens 2005; Glasser et al., 2012; Horta et al., 2017; Davies et al., 2018; Sagredo et al., 2018; Martin et al., 2019; Mendelová et al., 2020a; Mendelová et al., 2020b). Among these studies, Sagredo et al. (2018) addressed the deglacial history specifically of the Tranquilo valley, where they identified major glacier advances during the Antarctic Cold Reversal (ACR; 13,680 ± 460 and 13,490 ± 430 years), followed by a minor stabilization during the Younger Dryas (YD; sometime in between 12,330 ± 410 and 11,460 ± 390 years). These findings are consistent with Mendelová et al. (2020a), who found glacier advances at 13,100 ± 600 and 12,400 ± 300 to the east, in the Belgrano area.

Studies regarding the Holocene glacier history of Mt. San Lorenzo are scarcer, and the available information mostly comprises minimum ^{14}C ages, and other bracketing estimates produced by dendrochronology and lichenometry. Mercer (1968) obtained a minimum age of 5,210 ± 344 cal year BP for the most extensive Holocene glacier advance of the Río Lácteo glacier (**Figure 1**), based on a radiocarbon date of a tree stump buried in a moraine-dammed lagoon. This chronology was extended by Garibotti and Villalba (2017) who estimated the ages of the entire moraine sequence of the Río Lácteo valley using lichenometry, identifying glacier advances at 5,250 ± 360 years, 2,180 ± 50 years, 1,490 ± 20 years, and two advances during the last hundred years. Using the same approach, Garibotti and Villalba (2017) identified advances of the San Lorenzo glacier at 5,750 ± 430 years, 3,880 ± 180 years, 2,470 ± 70 years, as well as several glacier advances/stabilizations during the last few hundreds of years.

In the Tranquilo valley, using dendrochronology, Aravena (2007) dated a group of moraines in the upper section of the valley. Based on the oldest tree growing atop the ridges, he concluded that the entire sequence of moraines was deposited around or before AD 1670. However, the author also acknowledged the possibility that these moraines could be much older, arguing that their age estimate may be limited by the maximum biological ages that can be attained by *Nothofagus pumilio* (targeted species). Later on, Sagredo et al. (2017) partially confirmed this hypothesis by obtaining three coherent ^{10}Be ages of 5,450 ± 100 years, 5,640 ± 110 years and 5,800 ± 150 years (recalculated here) from a single ridge in the middle of the same moraine sequence study by Aravena (2007).

MATERIALS AND METHODS

To constrain the age of former Holocene glacier fluctuations in the Tranquilo valley, we mapped and directly dated seven moraine crests using ^{10}Be surface exposure dating. Detailed geomorphological mapping built upon previous work by Sagredo et al. (2018). In addition to field observations, we used analyses of satellite imagery from Google Earth (2021 Cnes/SPOT, ~15 m spatial resolution), aerial photographs (GEOTEC 1:70,000) and digital elevation models (ALOS Palsar). For exposure dating, we collected samples (~1 kg) from boulders embedded in or resting on stable positions atop the moraine ridges in the upper section of the Tranquilo valley. We selected tall boulders (preferably >1 m) that did not show evidence of post-depositional movement, surface erosion, or exhumation. Samples were taken from the upper ~5 cm of the boulder surface using a hammer and chisel, and the blast method of Kelly (2003). We recorded topographic skylines, as well as surficial strike and dip measurements, using a handheld transit and clinometer. We measured the coordinates and altitude of

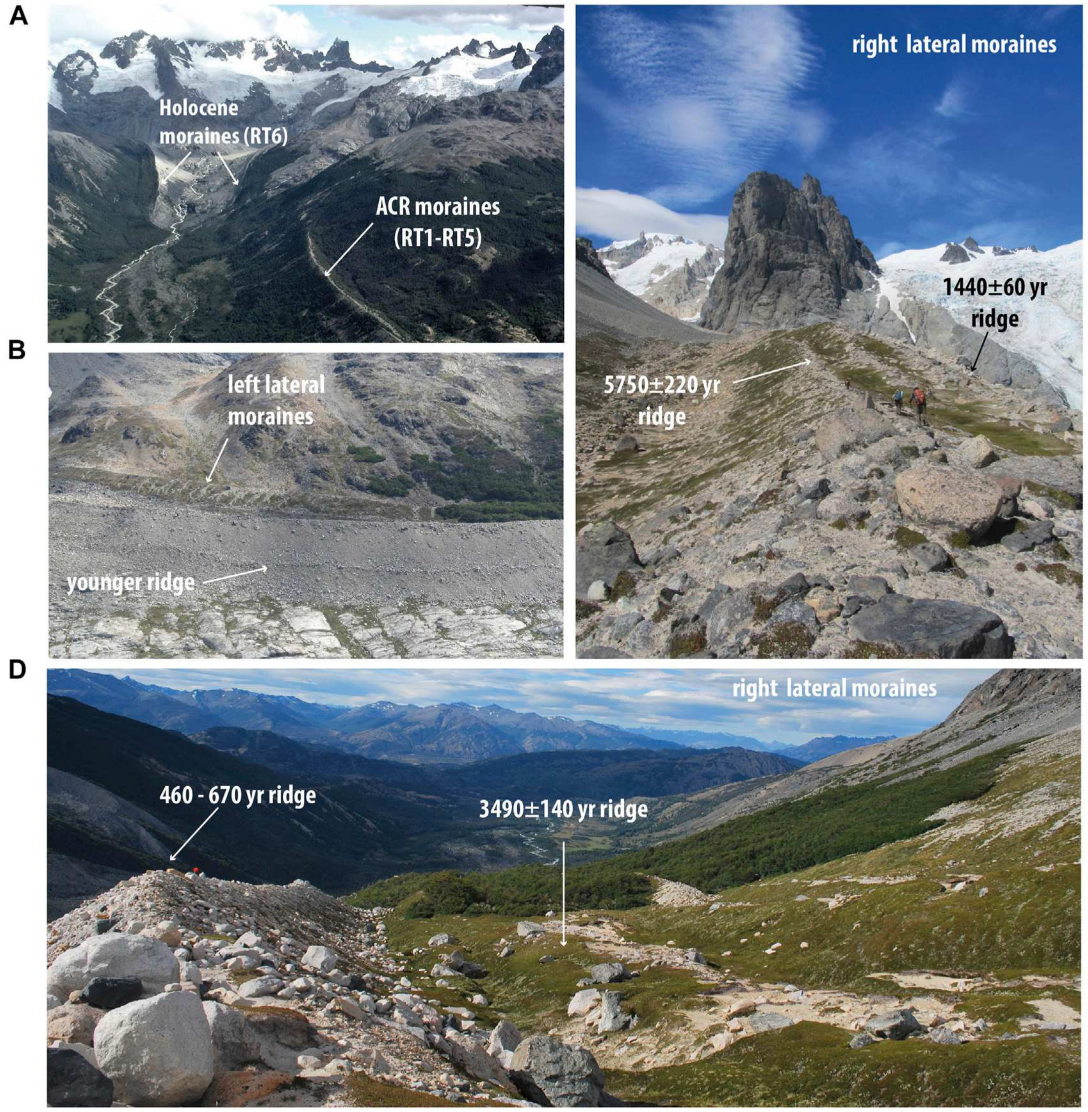

FIGURE 2 | Photographs of the moraines and settings in the Río Tranquilo valley. **(A)** Late glacial (RT1-RT5) and Holocene (RT6) moraines. Note the difference in the magnitude between the glacier advances (Photo: Horacio Parraguez). **(B)** Left lateral moraines. Along the proximal slope it is possible to find remnants of younger recessional ridges. **(C)** Right lateral moraines (facing upstream). In this sector, the ~3,500 years ridge was over-printed by the younger moraine. **(D)** Right lateral moraines (facing downstream). Note the difference in appearance between the younger and older ridges.

samples using a handheld commercial GPS (WGS84) with an assumed uncertainty of <10 m. **Table 1** provides geographical and analytical data of the samples. Quartz isolation and beryllium extraction were performed at the Cosmogenic Nuclide Laboratory at the Lamont-Doherty Earth Observatory (LDEO), Columbia University (NY, United States), following Schaefer et al. (2009). ^{10}Be/Be isotope ratios were measured at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory (CAMS LLNL). We used version 3 of the CRONUS-Earth online calculator (Balco et al., 2008), along with a regional nuclide production rate developed at Lago Argentino, Patagonia (50°S; Kaplan et al., 2011), assuming zero erosion. Ages discussed here are based on the time dependent version of Stone/Lal's scaling protocol scheme (Lm) (Lal 1991; Stone 2000); however, the choice of scheme does not impact our main conclusions (**Table 2**). We report individual ^{10}Be ages with 1σ analytical uncertainty. We calculate the arithmetic mean ages for moraines and present them with the standard error of the mean and a 3% propagated production rate error (Peltier et al., 2021). Given the sampled boulders were sitting atop the moraines, we assume they were likely deposited at the end of moraine construction episodes; therefore, we interpret the ^{10}Be dates as most likely representing close minimum ages for the culmination of a glacier advance. ^{10}Be ages from previous studies were recalculated following the same procedures as above. Previously published radiocarbon ages were recalibrated (cal yr BP) using the SHCal 20 curve (Hogg et al., 2020) in OxCal v. 4.4 (Ramsey 2009).

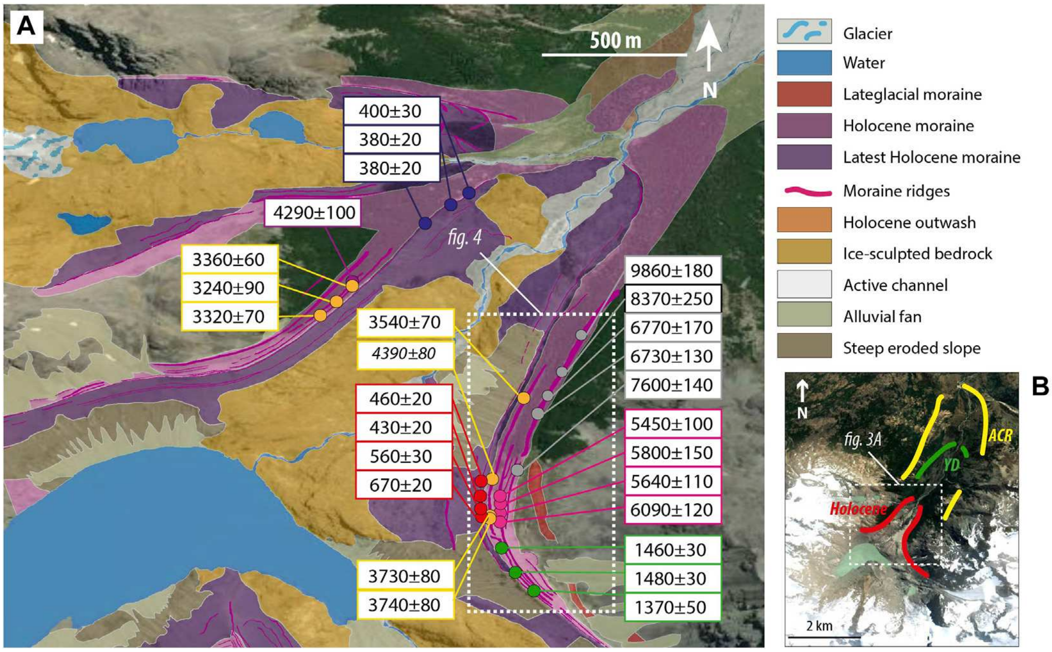

FIGURE 3 | (A) Glacial geomorphologic map of the Río Tranquilo valley with new ^{10}Be ages. Circles with the same color correspond to samples on the same moraine ridge or on correlated ridges on opposite sides of the valley. Individual ^{10}Be ages are provided with 1σ analytical uncertainty **(Table 2)**. One outlier is shown in italics. **(B)** Relative position of the Antarctic Cold Reversal (RT1-4 margins), Younger Dryas (RT5 margin) and Holocene margins (RT6) (Sagredo et al. 2017).

RESULTS

Sagredo et al. (2018) mapped and dated five late-glacial moraines (dubbed RT1-RT5) in the lower reaches of the Tranquilo valley. Upstream, on both sides of the valley, between five and seven well-defined lateral moraine crests were identified (RT6 moraines) (**Figure 2**). RT6 moraine ridges crosscut each other in multiple places documenting readvances of the glacier front (**Figures 3**, **4**). Given the frontal sections of all of the RT6 moraines are not preserved, we cannot precisely determine the maximum glacier extent during these events; however, based on the geometry and slope of the lateral ridges, we infer that the Río Tranquilo glacier reached an extent of between 6 and 7 km from the headwall. Poorly-preserved moraine/glacial drift was found beyond (i.e., distal) RT6, while inward (proximal) of RT6 remnants of small, degraded ridges are occasionally preserved (Sagredo et al., 2017) (**Figure 2**). To avoid error associated with post-depositional disturbances of these poorly-preserved landforms, our chronology focuses on the relatively intact RT6 moraine ridges. Here, we present 24 new ages, which constrain the history of glacier advances in the Tranquilo valley during the Holocene (**Figures 3**, **4**; **Table 2**). Hereafter, when referring to the right (left) moraine or side of the valley, we always mean the true-right (true-left); in other words, the location is identified in relation to an observer looking in the direction of the ice-flow (i.e., down-valley).

Right Lateral Moraines

The outermost RT6 ridge forms a continuous, well-defined ridge rising over 30 m in height downvalley. It gradually loses topographic relief upvalley before it disappears under the inner moraines (**Figure 3**). We collected five samples from boulders along the outermost RT6 ridge crest, yielding ^{10}Be ages of 6,730 ± 130, 6,770 ± 170, 7,600 ± 140, 8,370 ± 250, and 9,860 ± 180 years.

The next prominent moraine as you move inward corresponds to the same ridges previously dated by Sagredo et al. (2017) (*Previous Studies*). A new sample collected from this ridge yielded an age of 6,090 ± 120 years, which is statistically indistinguishable from the existing ages. Our new date, combined with the ages in Sagredo et al. (2017) results in a mean age of 5,750 ± 220 years.

Immediately inward, we found a 5–10 m in high, sharp-crested moraine ridge that can be traced continuously for almost 1 km. We collected four samples from this ridge. Three of them yielded coherent ages of 3,540 ± 70, 3,730 ± 80 and 3,740 ± 80 years (mean of 3,670 ± 130 years). The fourth sample (RTV16-01–04) affords an age of 4,390 ± 80 years, which is excluded from the moraine mean age because it does not overlap with the three ages at 2σ.

In the upper section of the right lateral system (**Figures 3**, **4**), the ~3,700 years ridge has been destroyed by a glacier advance that deposited a small (2-m high) ridge that can be traced to the proximity of the present glacier margin. Three samples collected from boulders atop this ~2-m high ridge provide ages of 1,370 ± 50, 1,460 ± 30 and 1,480 ± 30 years, with a mean age of 1,440 ± 60 years.

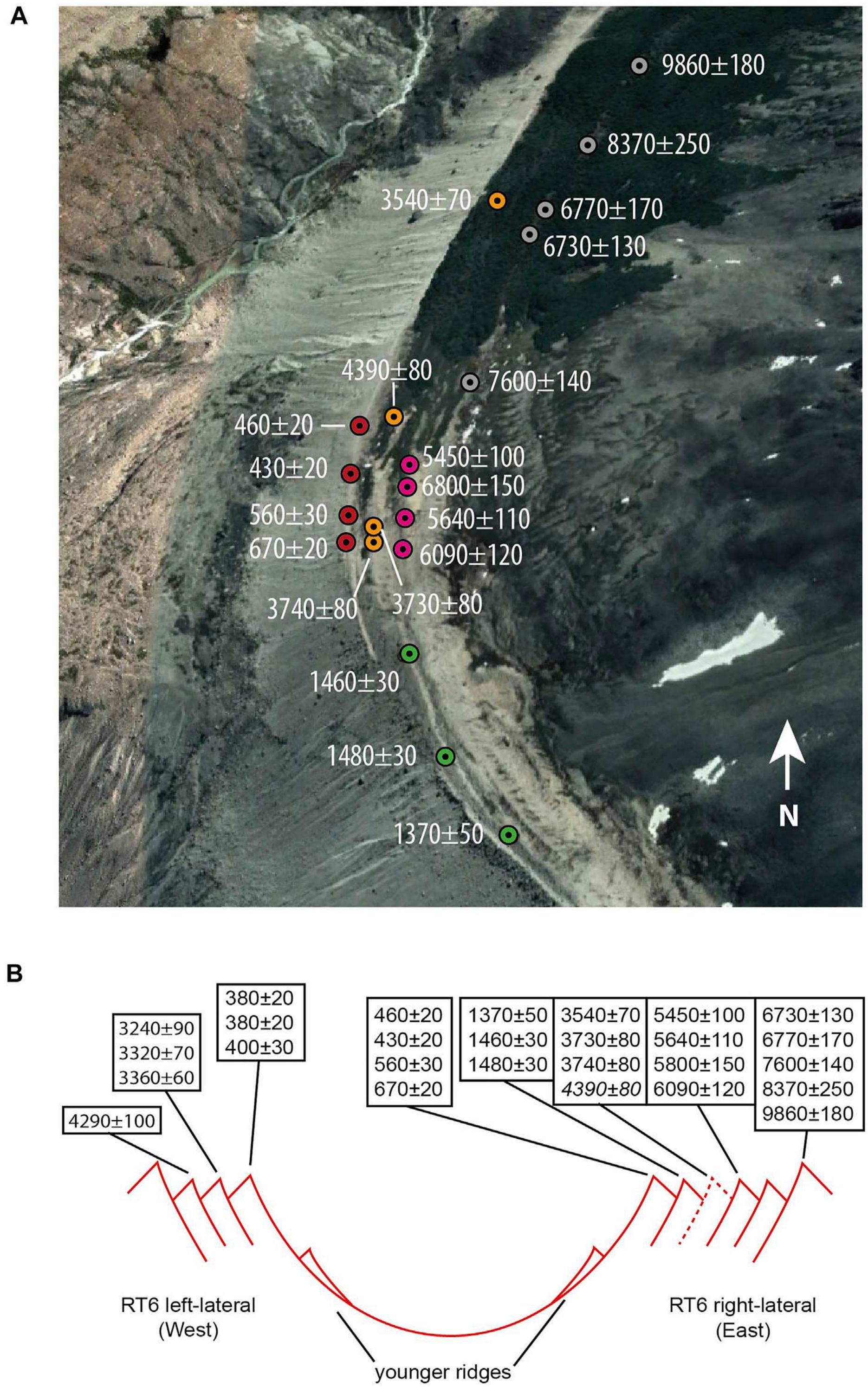

FIGURE 4 | Glacier chronology of Río Tranquilo glacier. **(A)** ^{10}Be ages obtained from the right lateral moraines (oblique perspective) on Google Earth image. **(B)** Schematic cross section of the valley. Notice that the ~3,700 years ridge was destroyed by the ~1,440 years advance in the upper right side of the valley (as represented by the dotted line) (Sagredo et al., 2017).

Finally, the innermost RT6 moraines correspond to a very sharp ridge (**Figure 2**) with a steep postglacially modified proximal slope that reaches the bottom of the valley. Four samples collected on this moraine yield ages ranging from 430 ± 20 to 670 ± 20 years with a mean age of 530 ± 60 years.

Left Lateral Moraines

We did not find any boulders from which to collect suitable samples for surface exposure dating on the two outermost ridges of the moraine suite on the left side of the valley. The outermost moraine dated from this area corresponds to the third-outermost crest, which rises ~10 m above the surrounding topography and is intermittently continuous over about 1 km. A single boulder on this ridge yielded an age of 4,290 ± 100 years.

Immediately inward, we collected three samples from a continuous ~1 km long sharp ridge, which provided ages of 3,240 ± 90, 3,320 ± 70 and 3,360 ± 60 years (mean: 3,310 ± 110 years). Finally, three samples from the steep innermost ridge provided statistically indistinguishable ages of 380 ± 20, 380 ± 20 and 400 ± 30 years (mean: 390 ± 10 years).

DISCUSSION

The glacier chronology at Río Tranquilo shows a clear pattern of multiple progressively less-extensive advances through the Holocene. We found evidence that the Tranquilo glacier reached its maximum extent sometime - or possibly at multiple occasions - during the first half of the Holocene between 9,860 ± 180 and 6,730 ± 130 years (n = 4). Our data suggest that during this Holocene glacier maximum, the Río Tranquilo ice lobe was 30–40% smaller (less extensive) than during the ACR accounting for slight uncertainties in frontal positions. Next, Tranquilo glacier readvanced around 5,750 ± 220 years (n = 4) and 3,490 ± 140 years (n = 6). The later advance is recorded and dated on both sides of the valley by moraines with statistically indistinguishable ages of 3,670 ± 130 (right lateral) and 3,310 ± 110 years (left lateral). A single date from a left lateral ridge outside this landform suggests that Tranquilo glacier may have experienced another glacier advance in between the two advances described above, at around 4,290 ± 100 years; notably, this age is statistically indistinguishable from RTV16-01-04 (4,390 ± 80 years), which was considered an outlier specifically on the ~3,700 years moraine (right lateral side of the valley). The next advance recorded in the area is dated to 1,440 ± 60 years (n = 3). Over the last millennium, we infer that the Tranquilo glacier advanced and lingered in an extended position between 670 ± 20 and 430 ± 20 years (n = 4) and underwent a final major advance ~390 ± 10 years (n = 3). After, the Tranquilo glacier retreated towards the headwall, depositing the minor ridges in the process. Continuing retreat ultimately separated the Río Tranquilo glacier into smaller ice bodies, as observed at present.

The Río Tranquilo valley provides a comprehensive chronology of the glacier history of Mt. San Lorenzo and the adjacent areas. Despite methodological differences, the new ^{10}Be chronology of Holocene glacier advances from Tranquilo valley is consistent with published chronologies (**Figure 1**) from the Río Lácteo (Mercer 1968; Garibotti and Villalba 2017: radiocarbon dating and lichenometry, respectively) and San Lorenzo valleys (Garibotti and Villalba 2017: lichenometry). The Tranquilo chronology encompasses most of the events recorded in these adjacent valleys, except for the glacier advances constrained by a minimum date of 2,470–2,180 years and another during the last 200 years. Additionally, the Tranquilo chronology captures an early Holocene glacier advance not recorded in these other valleys. We speculate that these differences may reflect the strengths and limitations of different dating approaches (cf., cosmogenic dating compared with lichenometry). However, immediately to the south of Mt. San Lorenzo, Wenzens 2005) identified at least three moraine ridges and based on ^{14}C minimum-limiting ages from kettles he inferred they were deposited sometime between 9,620 ± 120 and 7,500 ± 80 cal year BP. It is unclear if the southern glaciers of Mt. San Lorenzo were tributaries of the lobe that deposited those moraines, but interestingly the inferred timeframe for their deposition overlaps with the possible deposition (n = 2 ^{10}Be ages) of the outermost moraine in Río Tranquilo valley.

At a regional level, there are remarkable similarities between the Holocene record at Mt. San Lorenzo and other ^{10}Be (and ^{14}C)-based chronologies to the south (**Figure 5**). Records from southwestern Patagonia show evidence for early Holocene advances that coincide with the range of ages captured by the outermost RT6 moraine. At Lago Argentino (49.8°–50.7°S), based on stratigraphic evidence, Strelin et al. (2014) ^{14}C dated a glacier advance between 7,740 and 7,220 cal year BP in the Agassiz Este valley, which was less extensive than the subsequent maximum Holocene limits after 7 ka; at Torre valley (49.3°S), Reynhout et al. (2019) dated two outermost limits to 9,620 ± 340 and 6,790 ± 210 years. Although the Tranquilo record does not allow us to pinpoint the exact timing of the early Holocene events, we suggest that, collectively, these three sites offer mounting evidence to suggest that expanded glaciers were commonplace in Patagonia during the first half of the epoch. At Tranquilo and the Glacier Torre sites, the early to mid-Holocene expansions represent the Holocene glacier maximum. At Lago Argentino, on the other hand, the maximum Holocene frontal (cf., lateral) limits were reached after 7 ka and by 6 ka.

During the middle Holocene, the Tranquilo record features glacier expansions at 5,750 ± 220, 3,490 ± 140 and 1,440 ± 60 years; within uncertainties, these events may be consistent with an advance at nearby Lago Colonia (47.3°S) at 5,055 ± 190 years (Nimick et al., 2016), and they are statistically indistinguishable from those at Lago Argentino at 5,970 ± 110 and 1,380 ± 50 years (Kaplan et al., 2016), and at Torre valley at 6,030 ± 230 years (Reynhout et al., 2019). Moreover, at Lago Argentino, three ^{10}Be ages of 5,500 ± 200 (n = 2) and 5,700 ± 200 years on different crests within the maximum ~6 ka Holocene limits (e.g., at Frias valley) overlap with ages in the Tranquilo record. An additional glacier advance, preliminary dated at ~4,300 years at Tranquilo valley, is consistent with

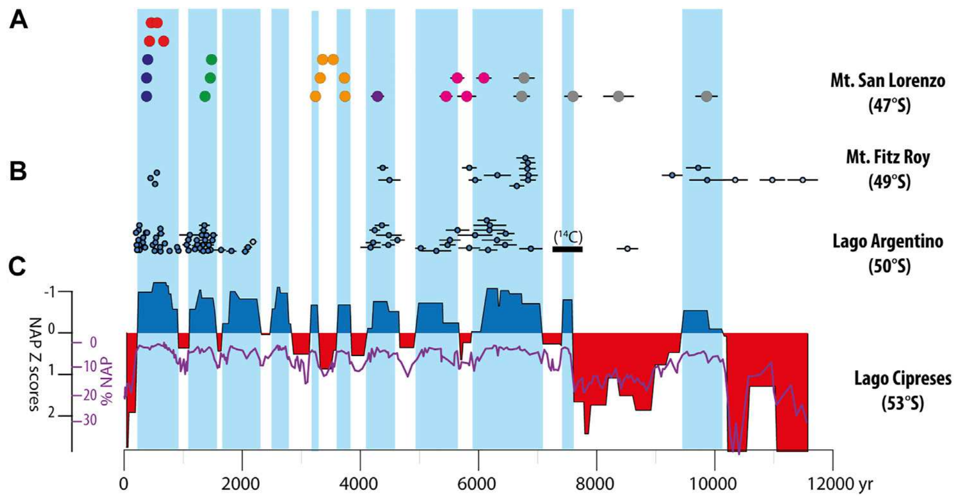

FIGURE 5 | Holocene glacier ^{10}Be chronologies from Patagonia. **(A)** Individual ages (±1σ) on moraine ridges in the Río Tranquillo valley; circles with the same color correspond to samples on the same moraine ridge, including correlated crests between right and left laterals on either side of the valley (same color as in **Figures 3**,**4**). For samples <4,000 years, the error is smaller than the symbol. Events are found between 9,860 ± 180 and 6,730 ± 130, at 5,750 ± 220, 4,290 ± 100 (?), 3,490 ± 140, 1,440 ± 60, between 670 ± 20 and 430 ± 20 and finally at 390 ± 10 years **(B)** Individual ages (±1σ) on moraine ridges in the Torre valley (Reynhout et al., 2019) and Lago Argentino basin (Strelin et al., 2014; Kaplan et al., 2016). Also, we show a glacier advance between 7.7 and 7.2 ka, detected with ^{14}C dating of wood in a stratigraphic section (Strelin et al., 2014) but not with ^{10}Be ages for the moraine record. **(C)** Cold and wet (blue) and warm and dry periods (red) as shown by regime shift detection analysis of non-arboreal pollen (NAP) record from Lago Cipreses at 51°S (Moreno et al., 2018). Negative (positive) values correspond to periods of strong (weak) and northward (southward) displaced SWW. We also included the percent of NAP (purple line). To facilitate comparisons with the glacier records, we included **blue vertical shading** representing the cold and wet periods.

the 4,440 ± 180 years advance at Lago Argentino and the 4,440 ± 140 years advance at Torre valley.

On the other hand, Lago Argentino also preserves advances at ~2,100–2000 and ~1,200–1,000 years that are not present in the chronology at Tranquilo valley, although undated moraine fragments in our study area may reflect these events. We also note that the Río Tranquilo record contains a prominent glacier advance at 3,490 ± 140 years (n = 6) not found in the chronologies at either Lago Argentino or Glacier Torre; however, evidence of this advance has been inferred elsewhere in Southern Patagonia (Wenzens 1999) and Tierra del Fuego (Kuylenstierna et al., 1996; Strelin et al., 2008; Hall et al., 2019). Future efforts will help define better similarities and potential differences between the glacier histories of central and Southern Patagonia.

Finally, during the last millennium, Tranquilo glacier underwent advances between 670 ± 20 and 430 ± 20 years, and at 390 ± 10 years. Statistically indistinguishable ^{10}Be-dated glacier advances have been documented in other sites in Patagonia: Lago Argentino basin (630–480 and 350 ± 20 years BP; Kaplan et al., 2016), Torre valley (510 ± 40 years; Reynhout et al., 2019), and Torres del Paine (51.2°S) (<600 ± 70 years BP and 340 ± 20 years BP; García et al., 2020). We acknowledge that younger glacier advances have been also documented at Lago Argentino (240 ± 10 years) and Torres del Paine (<190 years); we presume that these events correspond to the undated and poorly preserved ridges/drift inward of RT6 (**Figure 2**). Overall, we posit that our findings at Rio Tranquilo are strongly consistent with the onset and timing of expanded glaciers on the southern side of the SPI over the last 1,000 years.

The chronology of glacier fluctuations at the Río Tranquilo valley correlates well with changes in the strength of the SWW, as reconstructed in the pollen record at Lago Cipreses (51°S), in southern Patagonia (**Figure 5**) (Moreno et al., 2018). Thus, glacier advances at Río Tranquilo occurred during inferred periods of SWW maximum strength, which are associated with negative anomalies of temperature and positive anomalies of precipitations throughout western Patagonia (Moreno et al., 2018). The lower latitudinal position of Tranquilo relative to other sites demands that westerlies must have been stronger across the entirety of southern Patagonia reaching towards the central sector. We suggest that even during the early Holocene, relatively brief northward excursions of the SWW from their modern core at 52°S could have interrupted the overall warm conditions that characterized this time slice (Moreno and León 2003; Moreno et al., 2018), triggering what were likely the most extensive alpine glacier advances of the epoch.

Thus, our findings at 47°S support the hypothesis that Holocene glacier variability was modulated by shifts in intensity and location of the westerly winds throughout Patagonia. To drive glacier advances, these changes in SWW strength must have persisted over at least the decadal/centennial time scale. Moreno et al. (2018) proposed that centennial-scale climate variability, resembling that of the Southern Annular mode (SAM) (Moreno et al., 2018), the main mode of atmospheric variability in the mid- and high-latitudes of the Southern Hemisphere (Marshall 2003), could result in changes in mean SWW circulation over Patagonia. Therefore, we posit that centennial-scale paleo-SAM-like variations provide a mechanism by which SWW circulation excursions could be sustained for long enough to drive glacier advances over the Holocene in central Patagonia.

We infer that the Río Tranquilo record captures much of the centennial/millennial Holocene glacier variability observed throughout Patagonia. It captures glacier advances coeval with those recorded by both small mountain glaciers and major outlet glaciers of the larger Southern Patagonian Icefield. The new comprehensive Holocene chronology confirms the idea that Patagonia exhibited progressively less extensive glacier advances throughout most of the Holocene (Reynhout et al., 2019). In addition, the maximum Holocene glacier extent in southern South America likely occurred sometime during the early part of the epoch. Such patterns appear robust generally south of (at least) 47°S, the location of San Lorenzo, although recently published glacier chronologies from Cordillera Darwin (55°S) suggests that the scenario may be different in the southernmost tip of the continent (e.g., Menouno et al., 2013; Hall et al., 2019; Reynhout et al., 2021).

Finally, the observed high-resolution pattern of multiple moraine building events with slightly decreasing net extent throughout the early, mid- and late Holocene, appears to be one of the most distinctive signatures of glacier behavior in the southern Hemisphere. This pattern has not only been recognized in the southern mid-latitudes including New Zealand (e.g., Putnam et al., 2012; Kaplan et al., 2013; Dowling et al., 2021), but also around the Antarctic Peninsula, at 64°S (Kaplan et al., 2020). Recently, Bakke et al. (2021) documented a trend of gradually smaller glaciers traceable back to the ACR on the island of South Georgia (54.2°S). Collectively, the pattern of generally smaller expansions in the southern latitudes contrasts with the general pattern observed in the Northern Hemisphere, where glaciers reached their maximum extent in the late Holocene (e.g., Grove, 2004; Holzhauser et al., 2005; Schimmelpfennig et al., 2014, 2021; Luckman et al., 2017; Wittmeier et al., 2020; Braumann et al., 2020, 2021). This long-term, asymmetrical Holocene glacier pattern between Hemispheres seems at odds with the global glacier response during the last decades, when anthropogenic warming has overwhelmed the natural forcing (IPCC, 2021) and appears to be driving inter-hemispherically synchronized and accelerating glacier retreat.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

ES, SR, JA, MK, and JS contributed to conception and design of the study, and analysis of the results. ES, SR, JA, PA, MK, and BL conducted field mapping and sample collection. SR, PA, and RS conducted laboratory work. ES, MK, and SR wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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