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# Holocene glacier history of the Lago Argentino basin, Southern Patagonian Icefield

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ABSTRACT

We present new geomorphic, stratigraphic, and chronologic data for Holocene glacier fluctuations in the Lago Argentino basin on the eastern side of the southern Patagonian Andes. Chronologic control is based on $^{14}C$ and surface-exposure $^{10}Be$ dating. After the Lateglacial maximum at 13,000 cal yrs BP, the large ice lobes that filled the eastern reaches of Lago Argentino retreated and separated into individual outlet glaciers; this recession was interrupted only by a stillstand or minor readvance at 12,200 cal yrs BP. The eight largest of these individual outlet glaciers are, from north to south: Upsala, Agassiz, Onelli, Spegazzini, Mayo, Ameghino, Perito Moreno, and Grande (formerly Frías). Holocene recession of Upsala Glacier exposed Brazo Cristina more than 10,115 ± 100 cal yrs BP, and reached inboard of the Holocene moraines in Agassiz Este Valley by 9205 ± 85 cal yrs BP; ice remained in an inboard position until 7730 ± 50 cal yrs BP. Several subsequent glacier readvances are well documented for the Upsala and Frías glaciers. The Upsala Glacier readvanced at least seven times, the first being a relatively minor expansion – documented only in stratigraphic sections – between 7730 ± 50 and 7210 ± 45 cal yrs BP. The most extensive Holocene advances of Upsala Glacier resulted in the deposition of the Pearson 1 moraines and related landforms, which are divided into three systems. The Pearson 1a advance occurred about 6000–5000 cal yrs BP and was followed by the slightly less-extensive Pearson 1b and 1c advances dated to 2500–2000 and 1500–1100 cal yrs BP, respectively. Subsequent advances of Upsala Glacier resulted in deposition of the Pearson 2 moraines and corresponding landforms, also separated into three systems, Pearson 2a, 2b, and 2c, constructed respectively at ~700, >400, and <300 cal yrs BP to the early 20th century. Similar advances are also recorded by moraine systems in front of Grande Glacier and herein separated into the Frías 1 and Frías 2a, 2b, and 2c. The Onelli and Ameghino glacier valleys also preserve older Holocene moraines. In the Agassiz, Spegazzini, and Mayo valleys, ice of the late-Holocene advances appears to have overridden landforms equivalent in age to Pearson 1. Perito Moreno Glacier is an extreme case in which ice of historical (Pearson 2c) advances overrode all older Holocene moraines. Based on the distribution and number of moraines preserved, we infer that the response to climate differed among the Lago Argentino outlet glaciers during the Holocene. This led us to examine the effects of climatic and non-climatic factors on individual glaciers. As a consequence, we detected an important effect of the valley geometry (hypsometry) on the timing and magnitude of glacier response to climate change. These results indicate that caution is needed in correlating moraines among glacier forefields without firm morpho-stratigraphic and age control. Finally, we note important similarities and differences between the overall moraine chronology in the Lago Argentino basin and that in other areas of southern South America and elsewhere in the Southern Hemisphere.



## 1. Introduction

Little is known regarding the Holocene glacial history of the southern Patagonian Andes, despite the fact that glacial morphostratigraphy affords an important paleoclimate proxy. The reasons

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for this lack of knowledge include the difficulties associated with accessing the upper reaches of the cordilleran valleys, the inland arms of lakes, and the fjords, as well as insufficient dating of glacial landforms. As a result, information on the Holocene glacier history of this region is spatially and temporally fragmented (e.g., Glasser et al., 2004). Yet, the southern part of the South American continent is considered uniquely positioned to record fluctuations in mid-to-high-latitude climate systems, including connections with Antarctica (Villalba, 2007). In turn, detailed and well-dated evidence of past climates in southern Patagonia can aid an understanding of regional versus hemispheric patterns of glacier changes (Schaefer et al., 2009; Kirkbride and Winkler, 2012). Comparison of such records with those in the Northern Hemisphere (e.g. Davis et al., 2009), can also reveal climate forcings and global teleconnections.

The Lago Argentino basin was selected as a prime location to refine Holocene glacial history, and thus knowledge of paleoclimate in the southern Patagonian Andes, because of well-preserved glaciogenic landforms and stratigraphic exposures (Mercer, 1965). The basin is now nourished by large, temperate, outlet glaciers, with catchment areas located on the 140-km-long, east-facing side of the Southern Patagonian Icefield (SPI) (Fig. 1).

We present a new record of Holocene fluctuations of the main outlet glaciers on the east side of the SPI that drained into the Lago Argentino basin. Our approach is based on geomorphology, glacial stratigraphy, and a twofold chronologic method that includes radiocarbon ($^{14}$C) dating of organic material in glaciogenic exposures and peat cores, together with cosmogenic surface-exposure $^{10}$Be dating of boulders rooted in moraines. We present a morphometric analysis of the main valleys of the Lago Argentino basin, which allows us to infer the origin of the differing responses of glaciers to past Holocene and ongoing climate variability.

Finally, the new chronologic data allow us to discuss and place into context previous and new attempts to define Holocene and Neoglacial advances in the Patagonian Andes (Mercer, 1976; Clapperton and Sugden, 1988; Aniya and Sato, 1995) and compare them with results from elsewhere in the Southern Hemisphere.

## 2. Previous work

Feruglio (1944) first described and mapped what he considered to be young historic moraines in the Lago Argentino basin close to the present-day Upsala Glacier. In a subsequent comprehensive study, Mercer (1965, 1968, 1976) assigned the moraines in the Lago Argentino basin to three Holocene glacier advances. For the oldest Neoglacial moraines, Mercer (1976) obtained a minimum-limiting $^{14}$C age of >3680 ± 165 cal yrs BP, derived from wood from a paleo channel that cut through the outer moraines located between Brazo Sur and Lago Frías (Fig. 1). Mercer (1965) constrained the second-most-extensive Neoglacial advance, which resulted in deposition of the Pearson 1 moraines in front of Upsala Glacier, with maximum- and minimum-limiting $^{14}$C ages of 2255 ± 120 cal yrs BP and 1890 ± 130 cal yrs BP, respectively. Mercer (1965, 1976) also described the younger, well-preserved Pearson 2 moraines (Fig. 1), deposited by Upsala Glacier north of Brazo Norte, and their equivalents in Lago Frías sector, south of Brazo Sur, assigning them, based on dendrochronology, to the same time as the Northern Hemisphere Little Ice Age (LIA).

In a subsequent study, Malagnino and Strelin (1992) provided a detailed geomorphological map of glacial landforms in the northern arms of Lago Argentino, including Mercer's (1965) Pearson moraines and related landforms. They further subdivided Mercer's (1965) Pearson 1 moraines into three systems with associated outwash plains: Pearson 1a, 1b, and 1c (from older to younger) and a fourth, recessional moraine system 1d without associated outwash plains. Likewise, they also divided Mercer's (1965) Pearson 2 moraines and related landforms into three systems: 2a, 2b and 2c. In addition, discontinuous recessional moraine ridges north of Brazo Norte were assigned a post-Pearson-2 age (Malagnino and Strelin, 1992). No new $^{14}$C dates were provided by these authors, but minimum-limiting ages of 280 yrs BP and 190 yrs BP were established by tree-ring chronologies for the Pearson 2a advance and Pearson 2c recession, respectively (ages recalculated to the year A.D. 2013). Malagnino and Strelin (1992) also described, for the first time, the Herminita moraines located in the southern sector of Península Herminita. Aniya and Sato (1995) assigned Herminita moraines to the second-oldest Neoglacial advance (~2340–2120 cal yrs BP), and Mercer's (1965) Pearson 1 moraines to the third-oldest Neoglacial advance (~1220–1190 cal yrs BP). However, Strelin et al. (2011) recently established that the Herminita moraines are Lateglacial in age and this paper documents the Pearson 1 moraines as being middle-Holocene in age.

Other studies have been carried out in the forefields of the Onelli and Ameghino glaciers (Nichols and Miller, 1951; Mercer, 1965; Aniya, 1996). Most of these efforts were focused on moraines considered by these authors to be Younger Dryas to LIA in age (for more detail see below "5.6. Other glacier valleys"). Finally, Strelin et al. (2011) discussed the Lateglacial record from landforms near the entrance to the Lago Argentino inland arms, specifically related to the Puerto Bandera moraines. They also presented ages for the Herminita moraines and for early-Holocene recession.

## 3. Physical setting and vegetation

Lago Argentino is the sixth largest lake in South America and the second largest in Patagonia, after Lago Buenos Aires-General Carreras. Lago Argentino is fed by meltwater derived from the SPI. The drainage basin is about 8100 km$^2$ in area. The catchment area of the basin extends north-south for 140 km, between 49° 30′W and 50° 45′S along the eastern side of the SPI, and reaches a mean elevation of 1500–2000 m (a.s.l.). The highest peak is Cerro Agassiz at 3180 m (a.s.l.). Several inland arms of Lago Argentino extend into the mountain ranges of Cordillera Patagónica, following deeply entrenched transversal and longitudinal, structurally controlled, glacier valleys.

The geology of this segment of the Cordillera comprises an old Gondwanian metamorphic terrain, rifted, partially filled, and accreted with Jurassic marine-to-continental acidic volcaniclastic rocks (sinrift), Lower Cretaceous ophiolites, volcanic arc andesites, deep-marine volcaniclastic rocks (marginal basin), and Upper-Cretaceous-to-Cenozoic marine-to-continental sedimentary rocks (foreland basin). During several Late-Cretaceous-to-Cenozoic Andean orogenic phases, this complex was uplifted, folded, thrust, and injected by plutonic -mostly granitic- rocks.

Eight large outlet glaciers now flow into the Lago Argentino basin (Fig. 1). Upsala Glacier is the largest outlet glacier of the SPI, and the third largest in South America. It reaches 50 km in length and 840 km$^2$ in total drainage area. Upsala Glacier has an accumulation area of ~600 km$^2$ that rises to ~3000 m a.s.l. at the valley heads. The equilibrium line altitude (ELA) is estimated to be ~1050 m a.s.l. (Casassa et al., 2002). The western part of the Upsala Glacier tongue descends southwards, reaching a calving front at Brazo Upsala (Lago Argentino, 185 m a.s.l.). The eastern front of Upsala Glacier calves in a newly formed "Lago Guillermo" at ~300 m (a.s.l.). Both fronts have recently undergone rapid recession, retreating ~6 km in the last 40 years (relative to April, 2009).

The climate at Lago Argentino is driven by the mid-latitude westerly wind regime of the southern Patagonian Andes, with frequent passage of subpolar cyclones. Pervasive cloudiness (more than 70% daily cover) and orographically controlled annual

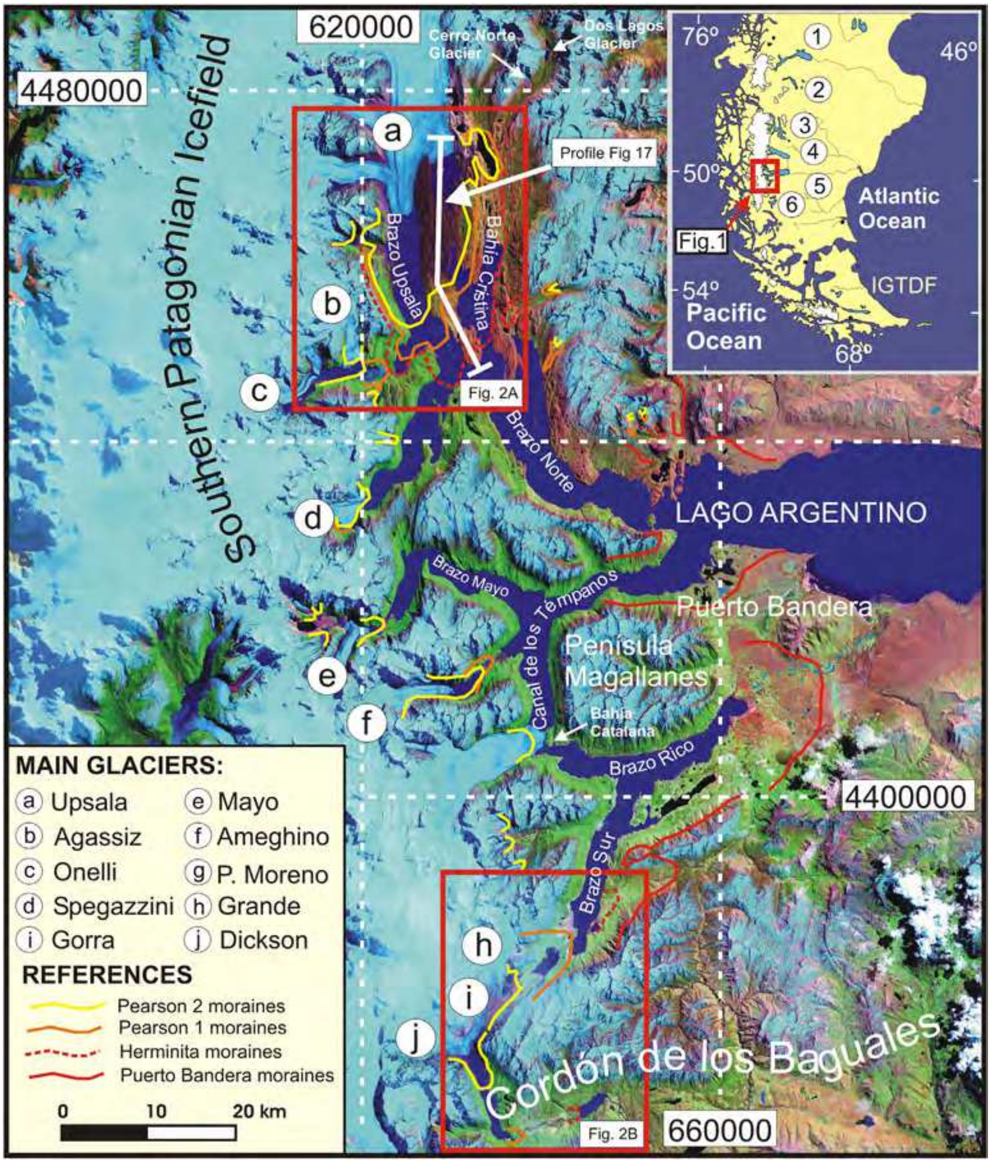


**Fig. 1.** Lateglacial and Holocene moraines in the Lago Argentino basin. The studied sectors in the northern arms of the lake and near Lago Frías (red frames) are shown in more detail in Fig. 2A and B. The moraines are designated according to type locality (see references). Inset shows reference locations for: 1) Lago Buenos Aires-General Carreras, 2) Lago Pueyrredón-Cochrane, 3) Lago San Martín-O'Higgins, 4) Lago Viedma, 5) Río Santa Cruz, 6) Torres del Paine, and IGTF Isla Grande de Tierra del Fuego. For better interpretation of all the figures, the reader is referred to the colored on-line version of this article.

precipitation, which ranges from 2000 to 7000 mm, characterize the western Pacific mountain facade (Carrasco et al., 2002). On the high part of the Cordillera, annual snowfall peaks at ~10,000 mm water equivalent, nourishing the SPI (DGA, 1987). Markedly drier air masses reach the eastern foothills of the Cordillera, resulting in an annual precipitation of only 200 mm at El Calafate (Argentine Servicio Meteorológico Nacional). The westerlies become stronger during the summer due to the southward shift of the Subtropical Anticyclone and the consequent steepening of the latitudinal pressure gradient. On both sides of the Cordillera the mean annual air temperature is ~6 °C, with higher (lower) seasonal and daily amplitude on the eastern (western) more-continental (oceanic) side (Carrasco et al., 2002). Under the prevailing oceanic, cold climate conditions, the ELA of the glaciers on the western side of the SPI is 800–1000 m (a.s.l.). The ELA rises to ~1300 m a.s.l. on the drier eastern slope (Casassa et al., 2002). For glaciers on the western side of the Andes, both temperature and precipitation regulate mass balance, especially on short timescales, with an additional important calving ablation component for tidewater glaciers in fiords; on the eastern slope of the Cordillera, a temperature-dependent mass balance largely controls the glacier regime (Warren and Sugden, 1993; Casassa et al., 2002). In recent decades, general regional climate warming and accelerated calving of glacier fronts are considered to be responsible for marked ice recession on both sides of the SPI (Rignot et al., 2003; Glasser et al., 2011).

The vegetation is also constrained by the steep west–east climate gradient. On the western and wetter side of the icefield, the ELA intersects wetlands (patches of peat bogs), and Nothofagus rainforest characterized by evergreen *Nothofagus betuloides*, deciduous *Nothofagus pumilio*, *and Nothofagus antarctica*. On the eastern side of the icefield, the tree line is located well below the ELA, allowing development of an Andean tundra biome. Prevailing deciduous forest of *N. pumilio and N. Antarctica* occur at lower elevation on this eastern and drier side. East of 72° 45′ W, where the inland arms of the lake merge into the main body of Lago Argentino, an abrupt transition to the Patagonian steppe coincides with a marked drop in precipitation (Feruglio, 1944).

## 4. Methodology

Five sectors of the Lago Argentino basin (Fig. 2A, B) were selected for stratigraphic survey, peat-bog coring and sampling, and sample collection for cosmogenic exposure $^{10}$Be dating. The recently deglaciated areas in front of Upsala Glacier and the former Frías Glacier were examined through satellite images, aerial photographs, and field surveys. Topographic data were obtained from the Argentine Instituto Geográfico Nacional (IGN) 1:100,000 cartography and SRTM NASA 3D.

Stratigraphic profiles were developed for glaciogenic Holocene exposures, with descriptions of texture, fabric, composition, sedimentary structures, and stratigraphic relationships. These parameters are used to determine sedimentary processes (mostly glaciogenic) and to establish past glacier behavior. Three of the exposures provided wood for $^{14}$C dating.

Peat cores were obtained from bogs and spillways associated with moraine ridges. The cores were logged for stratigraphy and subsampled for intercalated and basal organic material for $^{14}$C dating. The samples comprised twigs, wood, bark, seeds, sedge and plant remains picked out from bulk peat inclusions, soil horizons, and organic layers. The samples were collected between A.D. 2005 and 2010 and, except for two processed at University of California at Irvine, were dated by AMS in National Ocean Science Accelerator Mass Spectrometry Facility (NOSAMS) at the Woods Hole Oceanographic Institution. Mean $\pm 1\sigma$ calendar ages were determined for $^{14}$C data using OxCal 4.2 software (Bronk Ramsay, 2013) with the Southern Hemisphere atmospheric curve (SHCal04, McCormac et al., 2004). In the main text we present only calendar ages. The complete data, including the original $^{14}$C ages, are presented in tables in the Supplementary Material (SM).

Boulders on or rooted in the crests of moraine ridges were sampled for $^{10}$Be measurement. We excluded boulders with obvious signs of erosion, such as spallation or surface fragmentation, and generally those less than 75 cm in height above the adjacent moraine surface. Samples were removed from the top surfaces of boulders with either a hammer and chisel or with a drill. Details of sample collection, laboratory preparation, and measurement are presented in Schaefer et al. (2009), in Kaplan et al. (2011; i.e., specific to Patagonia), and in the SM. We use the Southern Hemisphere middle-latitude production rate obtained by Putnam et al. (2010) and Kaplan et al. (2011), which are statistically identical within $1\sigma$. The latter rate was derived within the field area, on Península Herminita (Fig. 1), minimizing systematic $^{10}$Be uncertainties in this study. Moreover, although ages are presented with the scaling scheme of Stone (2000), different schemes agree within 5% at this latitude and low altitude. Hence, use of different scaling schemes does not affect the conclusions of this paper. We employed the methods incorporated in the CRONUS-Earth online exposure-age calculator version 2.2, except that we followed those changes described in Putnam et al. (2010). All ages are calculated assuming zero erosion. Individual $^{10}$Be ages are shown and

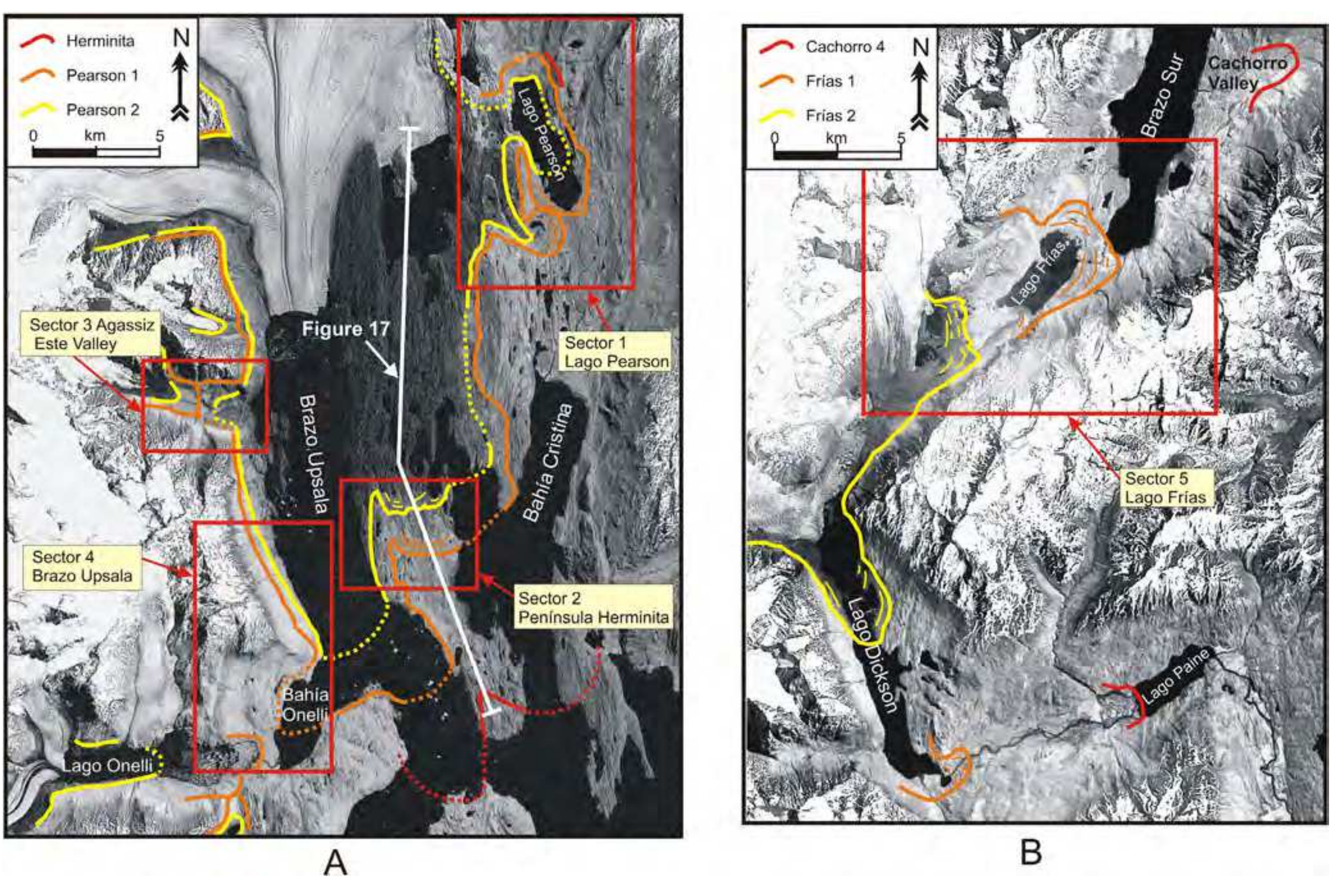


**Fig. 2.** The studied sectors: **"A"** is located in the northern arms of Lago Argentino and shows the two former land-grounded portions of Upsala Glacier in Lago Pearson (Sector 1 and Fig. 3), Península Herminita (Sector 2 and Fig. 7), the deglaciated area of Agassiz Este Glacier, a former tributary of Upsala Glacier (Sector 3 and Fig. 9), and the southwest Brazo Upsala lateral moraines (Sector 4 and Fig. 11). **"B"** shows the moraines located south of Brazo Sur, Lago Frías, and Lago Dickson, deposited by Dickson Glacier and the recently disappeared Frías Glacier (Sector 5 and Fig. 13).

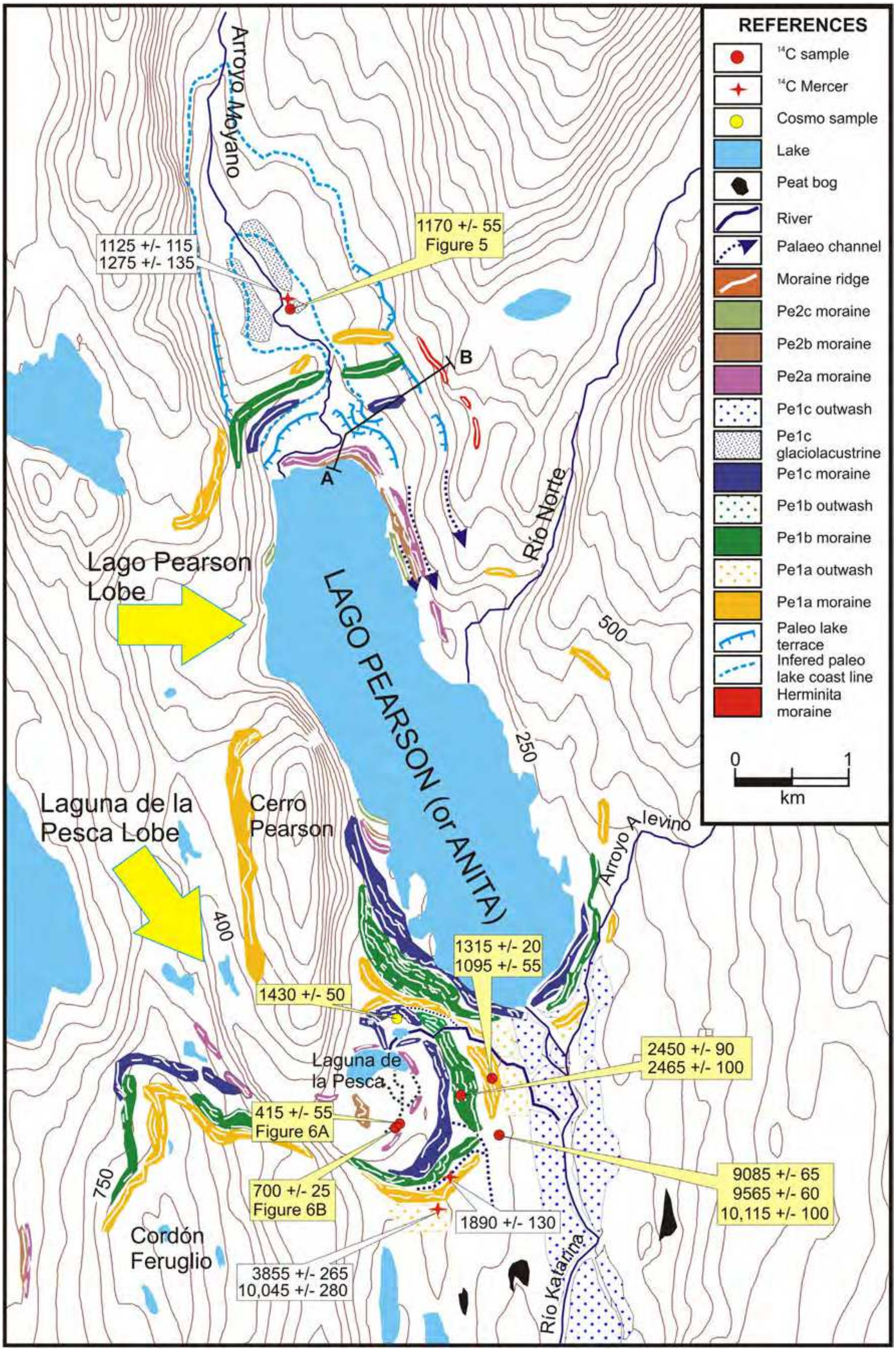


**Fig. 3.** Glacial geomorphology near Lago Pearson (Sector 1 in Fig. 2A) and location of the stratigraphic profiles and dated samples. See colored map in the on-line version of this paper.

discussed with analytical errors only. See SM for tables and details of $^{10}$Be ages.

Cumulative-percentage hypsometric curves were constructed to determine the Holocene topographic control on the climate response of the eight main outlet glaciers of the Lago Argentino basin (Fig. 16A, B).

## 5. Description of sectors

### 5.1. Sector 1: Lago Pearson

Lago Pearson is located in a structurally controlled depression separated from the east margin of the Upsala Glacier tongue by Cordón Feruglio and its northern extension, Cerro Pearson. Mercer (1965) visited this sector in A.D. 1963 and reconstructed how, during the Pearson 1 and Pearson 2 glacier advances, the Upsala Glacier overran Cordón Feruglio and Cerro Pearson in two places, generating northern and southern lobes, herein named Lago Pearson and Laguna de la Pesca lobes, respectively. On the eastern slope of the Arroyo Moyano valley, a lateral moraine ridge is identified that probably antedates the Pearson 1 moraine (Fig. 3). This 500-m-long and as-much-as-4-m-high moraine ridge descends northward from 420 to 400 m a.s.l. (220–200 m above the present-day Lago Pearson lake level, a.p.l.). This lateral moraine is tentatively correlated with the Lateglacial Herminita event (Strelin et al., 2011) (Fig. 2A).

The deglaciation in Sector 1 (Fig. 2A) antedated the age of plant colonization obtained from a sediment core to the base of a bog located just outboard of the Laguna de la Pesca Lobe. This age indicates extensive withdrawal of Upsala Glacier, close to the present-day ice front, prior to 10,115 ± 100 cal years. Two additional basal peat samples in the same bog afford dates of 9565 ± 65 and 9085 ± 65 cal yrs BP for post-Lateglacial recession. These ages agree with that in Mercer and Ager (1983), who obtained an age of 10,045 ± 280 cal yrs BP for the lowest peat in a bog in the Upper Río Katarina valley (Fig. 3).

Detailed mapping of the Holocene landforms allows us to divide the outer Pearson 1 moraines into three closely spaced systems and corresponding outwash plains (1a, 1b, and 1c). Likewise, we separate the inner Pearson 2 moraine into three systems (2a, 2b, and 2c). During the three Pearson 1 advances, the glacier dammed a lake, whose surface reached to as much as 360 m a.s.l. (~160 m a.p.l.), and constructed a large moraine at the entrance to Arroyo Moyano valley (Figs. 3 and 4, Photograph 1 in SM). During the Pearson 1a glacier advance, the southern margin of the Lago Pearson Lobe shared terminal moraines with the northern margin of the Laguna de la Pesca Lobe that enclosed Cerro Pearson (Fig. 3). Such merging of the two lobes did not occur during the Pearson 1b and 1c advances, when the two lobes were separated by meltwater channels. The best outline of the three Pearson 1 glacier systems can be reconstructed on the eastern side of the Río Katarina valley. Here, three moraine belts, each with several ridges as much as 8 m in relief, are separated by narrow outwash plains and meltwater channels. Unfortunately this area lacks peat deposits and therefore a $^{14}$C chronology could not be established.

A slightly different Pearson 1 moraine configuration was generated by the southern Laguna de la Pesca Lobe. Numerous ponds were dammed by the moraine and structural ridges. It seems, however, that wind deflation and/or meltwater channel erosion affected these ponds, as they afford ages for plant colonization that are younger than expected. For example, basal organics from peat bogs between Pearson 1a moraines are as much as 1315 ± 20 and 1095 ± 55 cal yrs old, i.e. >1000 yrs younger than plant colonization inboard of the Pearson 1b moraine ridges dated to 2450 ± 90 and 2465 ± 100 cal yrs BP (Fig. 3). A single $^{10}$Be age on an inboard Pearson 1c moraine deposited by the Laguna de la Pesca Lobe is 1430 ± 50 yrs BP.

Numerous shorelines carved into the northern Arroyo Moyano moraine demonstrate that during Pearson 1a, 1b, and 1c glacier advances, this stacked, composite moraine was covered several times by a proglacial lake. The highest and best-outlined lake terrace was preserved, more than 50 m wide and 2 km long, at 360 m a.s.l. (160 m a.p.l., Photograph 1 in SM). After the glacier abandoned the Pearson 1c (Arroyo Moyano) moraine, this highest lake level was never achieved again. A well-developed, 260 m a.s.l. (60 m a.p.l.) lake terrace reaches to within 30 m of the crest of the Pearson 1c (Arroyo Moyano) moraine. This lower terrace can be traced up-valley and through the spillway gap of the Arroyo Moyano moraine, where it is connected with an expanded lake terrace. About 500 m north of the Arroyo Moyano moraine, river erosion entrenched the lake terrace located 260 m a.s.l. (15 m above the alluvial plain), exposing more than 6 m of glaciolacustrine clay and silty rhythmites that are covered by about 2.0 m of glaciofluvial sand and gravel (Fig. 5). About 6 m below the top of the terrace, varved sediments incorporate wood dated to 1170 ± 55 cal yrs BP. Mercer (1976) obtained similar dates of 1275 ± 135 and 1125 ± 115 cal yrs BP for wood collected 4–5 m below the top of this same terrace. It follows from these dates, the landforms, and the exposed rhythmites that a proglacial lake was persistently dammed at least from 1275 to 1125 cal yrs BP, prior to formation of the prominent lake terrace at 260 m (a.s.l.).

During the Pearson 2 glacier advances, the Lago Pearson Lobe reached only to the northern shore of the lake, where it deposited two well-preserved moraine ridges as much as 10 m high (Pearson 2a and 2b, Photograph 1 in SM). These moraines are comprised largely of volcanic pyroclastic acidic blocks, as much as 4 m high, with a gravelly, silt-to-clay matrix. During these glacier advances the present-day Lago Pearson was divided into two lakes. A higher (northern) proglacial lake was dammed several times between the Arroyo Moyano moraine and the receding Lago Pearson Lobe. Thus several lower lake terraces were sculpted on the ice-facing side of the Arroyo Moyano moraine. The highest of these terraces reaches 245 and the lowest 210 m a.s.l. (45 and 10 m a.p.l.) (Figs. 3 and 4). The spillway of this lake was probably located close to where the present-day Río Norte flows into Lago Pearson. Discharge from the lower (southern) proglacial lake was regulated by the Katarina River spillway. The reconstruction of the proglacial lakes dammed by the Lago Pearson Lobe demonstrates that the Pearson 2 moraines along the northern shore of the present-day lake were submerged, whereas the southern continuation of the moraines, which allow us to separate a third Pearson 2c moraine system, was deposited subaerially.

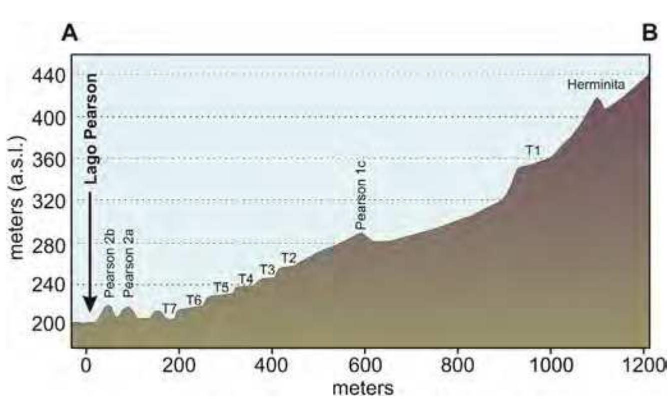


**Fig. 4.** Lake terraces formed during the different glacier pulses blocking the Moyano River north of Lago Pearson. See location of topographic profile in Fig. 3.

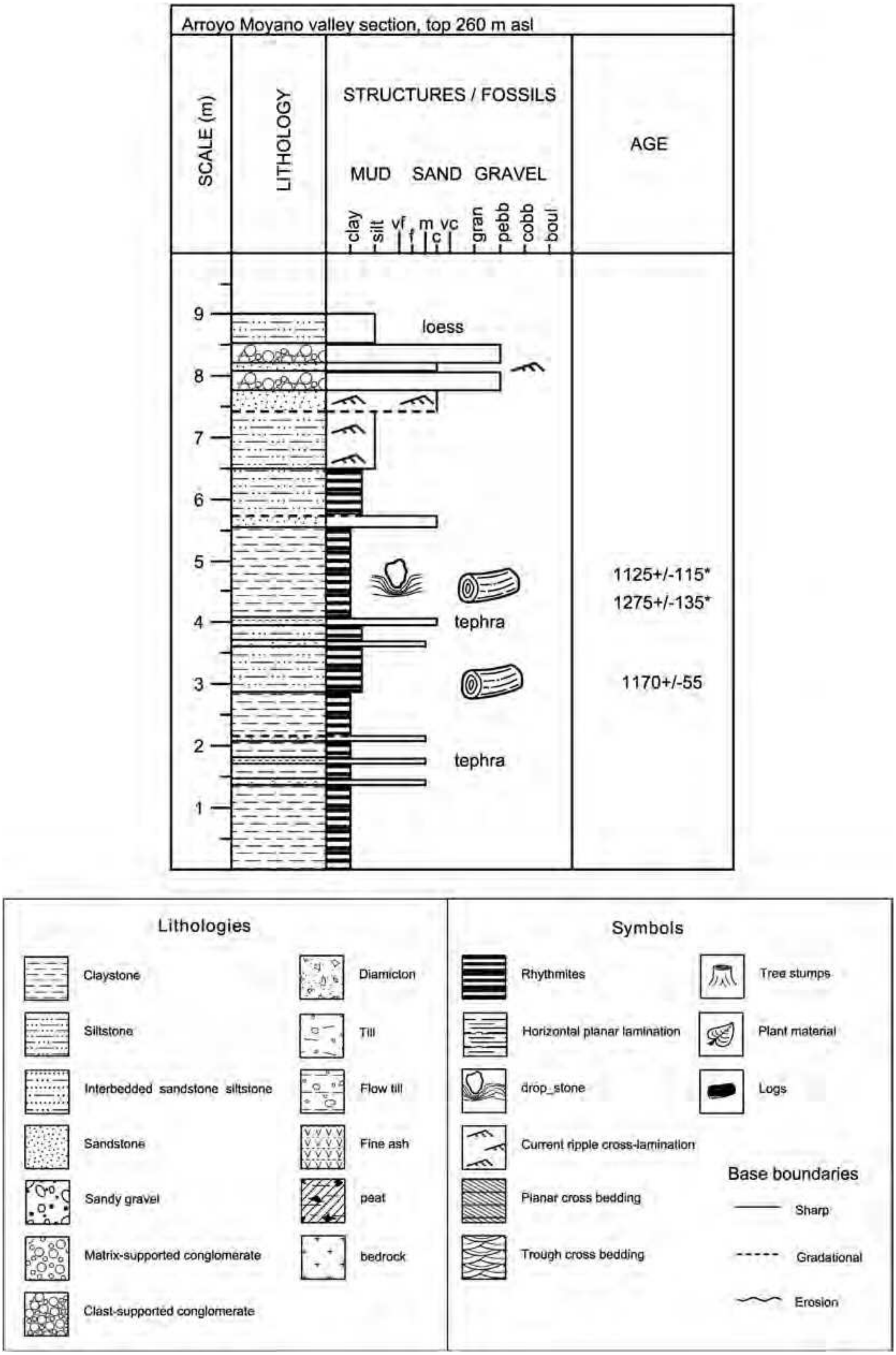


**Fig. 5.** Outcrop of glaciolacustrine and glaciofluvial deposits in Arroyo Moyano valley. Profile location in Fig. 3 and profile description in the SM. Below are given the lithologies and symbols used in all the profiles.

For the Laguna de la Pesca Lobe, only Pearson 2a and 2b moraine systems are recognized. Based on the stratigraphy and $^{14}C$ dates of two peat bogs (Fig. 6A, B) cored in the glaciofluvial plain located between the moraines, some inferences about the ages of both moraines can be attained. One of the cores demonstrates that plant colonization was initiated between the two moraine systems about 700 ± 25 cal yrs BP, thus providing a minimum-limiting age for the Pearson 2a system. The second peat bog, also cored in a depression

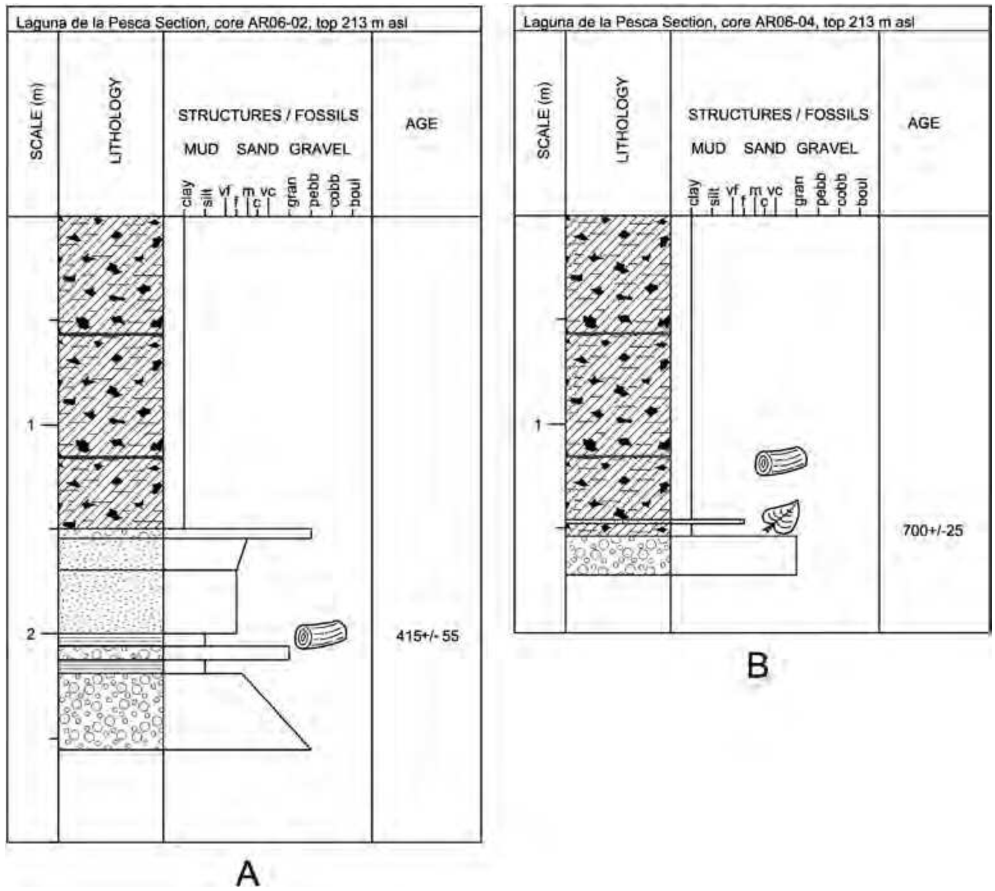


**Fig. 6.** Peat bog profiles in Laguna de la Pesca; profile locations in Fig. 3 and profile descriptions in the SM.

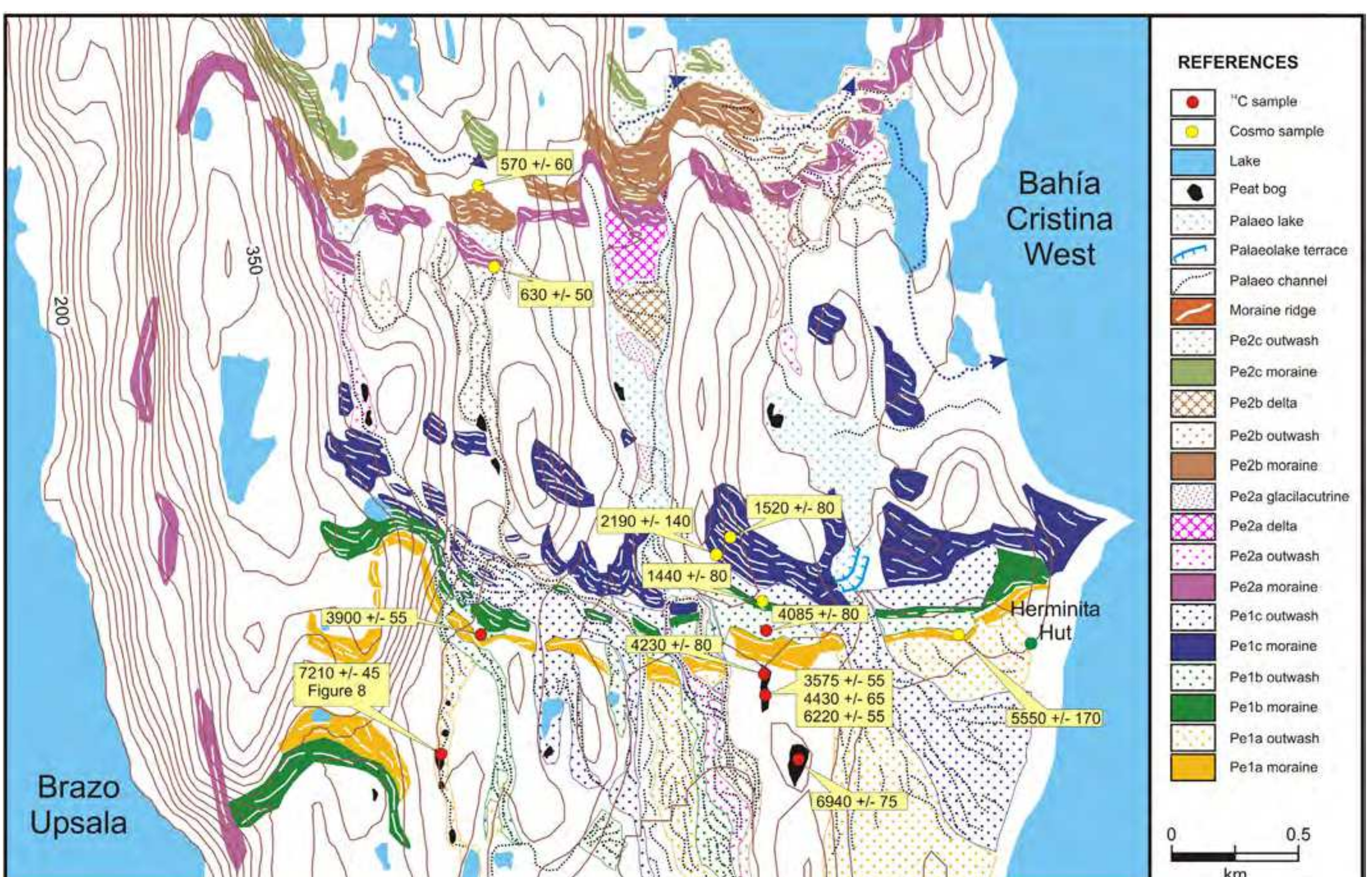


**Fig. 7.** Glacial geomorphology of Península Herminita (Sector 2 in Fig. 2A).

between the moraines, affords a minimum-limiting age of 415 ± 55 cal yrs BP for the Pearson 2a system. This age was obtained on material from a 5-cm-thick organic layer covered by a 0.5-m-thick inversely graded sandy-to-gravelly sequence, topped by 1.5 m of continuous peat. The inversely graded sandy-gravelly sequence is linked to the Pearson 2b outwash deposit; accordingly, the 415 ± 55 cal yrs BP age probably represents a maximum-limiting value for the Pearson 2b moraine system.

### 5.2. Sector 2 Península Herminita

Península Herminita contains structurally controlled, south–north oriented ridges and valleys, and it separates Brazo Upsala from Bahía Cristina (Fig. 2A). About 1.6 km from the southern tip of the Peninsula, the hilly (as much as 340 m a.s.l. of relief, 155 m above Lago Argentino level, a.l.a.) landscape is crossed by the interlobate Herminita moraine, dated to 12,220 ± 110 cal yrs BP (Fig. 2A; Strelin et al., 2011). Boulders rooted in this $^{14}$C-dated moraine were used to derive the $^{10}$Be production rate given in Kaplan et al. (2011).

Farther north, five south–north trending ridges separate four troughs (or small valleys). These structurally controlled features are crossed by three west–east trending Pearson 1 (1a, 1b, and 1c) and three similarly trending Pearson 2 (2a, 2b, and 2c) moraine systems (Fig. 7). A land-terminating glacier that generated outwash deposits (Photograph 2 in SM) is associated with most of the moraine groups. The Pearson 1 outwash deposits largely accumulated in flat and open topography that prevails in the south-central part of the Península, whereas the Pearson 2 outwash and some glaciolacustrine deposits were largely channelized in the south–north oriented valleys (Figs. 2A and 7, Photograph 4 in SM).

The Pearson 1a system, the oldest, comprises a double-ridged moraine. Erratics are mainly of a sandstone/mudstone composition, and some exhibit quartz veins. Erratics of volcanic acidic and rhyodacitic composition are also found. The few small exposures in the moraines reveal a gray silty matrix, which incorporates faceted and striated angular blocks and gravel of pelitic and sandstone composition. Several ponds and peat bogs occur on the land surface outboard of the Pearson 1a moraines. One of these bogs provides the oldest minimum-limiting age of 7210 ± 45 cal yrs for the 6.5-km recession from the position of the Herminita moraine. Other younger $^{14}$C ages of 7085 ± 70, 6940 ± 75, and 6220 ± 55 cal yrs BP also afford minimum-limiting values for the post-Herminita deglaciation (Fig. 7). According to the plant-colonization ages derived from peat bogs located just inboard of the Pearson 1a moraine system, these moraines were deposited more than 4085 ± 75 cal yrs BP (Fig. 7). A $^{10}$Be age from a boulder rooted in the Pearson 1a moraine ridge is 5550 ± 170 yrs BP old, consistent with the $^{14}$C data.

The stratigraphy in a core obtained from a Pearson 1a meltwater channel, in the westernmost part of the Peninsula, allows us to infer the timing of fluctuations of Upsala Glacier (Fig. 8). The glacier front was near the core site sometime before 7210 ± 45 cal yrs BP, between 5875 ± 75 and 5475 ± 80 cal yrs BP, and after 1500 ± 65 cal yrs BP. After construction of the Pearson 1a moraines, the glacier receded, with meltwater generating spillways and proglacial lakes within the north-south trending, structurally controlled valleys. These spillways entrenched the abandoned Pearson 1a moraines and outwash plains that extend south of the hilly landscape.

During Pearson 1b time, a multiple-ridged moraine system (at least 4 crests) formed <100 m behind the inboard Pearson 1a moraine. The 1b moraines mirror the older ones in their trend across Península Herminita, and were associated with new meltwater channels and outwash deposits at the former ice fronts

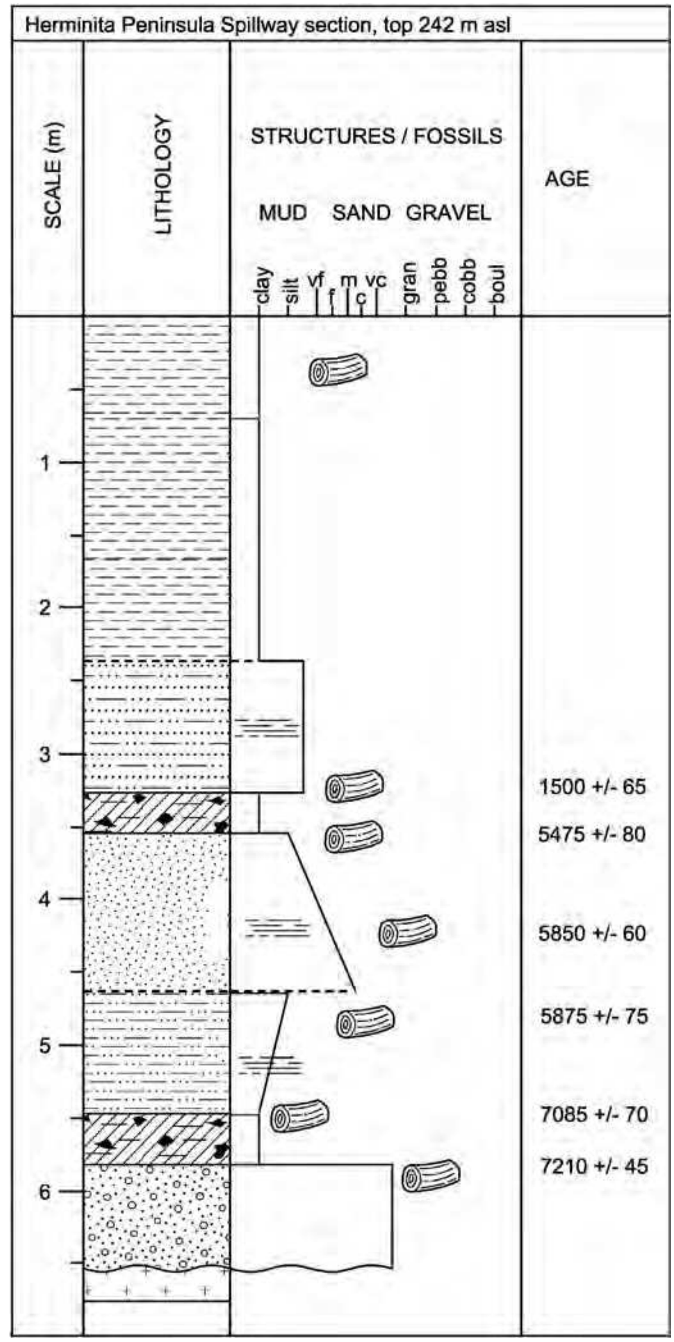


**Fig. 8.** Profile of the peat bog that brackets different Holocene glacier advances on Península Herminita. Profile location is shown in Fig. 7, and detailed description is in the SM.

(Photograph 2 in SM). Only one $^{10}$Be age of 1440 ± 80 yrs is available for the moraine chronology (Fig. 7). The glacier recession was associated with the formation of proglacial lakes and spillways. The spillways extend to the southern plains of Península Herminita, entrenching older moraine and outwash landforms.

During Pearson 1c time, a conspicuous, multiple-ridged moraine system (at least 8 crests) formed in and at the mouths of the valleys in the southern lowlands (Fig. 7). Additional recessional moraines, distinguished as Pearson 1d by Malagnino and Strelin (1992) but herein considered Pearson 1c, are confined to the valleys. A $^{10}$Be age for the outermost Pearson 1c moraine is 2190 ± 140 yrs BP, whereas one for the fifth inner Pearson 1c moraine is 1520 ± 80 yrs BP (Photograph

3 in SM). The outwash plain connected to the 1c moraines is the largest and best preserved in the Pearson moraine system. During retreat of glacier fronts from the inner Pearson 1c recessional moraines, the four north-south trending valleys were dammed several times by ice, generating ephemeral proglacial lakes. Spillways of these lakes drained southward, entrenching the older moraines and outwash plains. As glacier recession continued, the northern entrance of the valleys opened and the proglacial lakes drained largely to the north.

During Pearson 2a, Upsala Glacier blocked the northern entrances of the structurally controlled valleys, damming proglacial lakes and generating deltas and braided outwash plains (Fig. 7, Photograph 4 in SM). Tree-ring counts in a mature forest growing in wind-protected areas indicate a minimum-limiting age of more than 300 yrs BP for recession from the inner Pearson 2a position (Malagnino and Strelin, 1992). This minimum age accords with a $^{10}$Be age of 630 ± 50 yrs BP from the outermost, and hence oldest, Pearson 2a moraine.

During Pearson 2b, a multiple-ridged moraine system was built close behind the 2a moraines. Analogous to the previous glacier advance, meltwaters were channeled into the structural valleys, generating outwash plains and temporary proglacial lakes. Almost all the outwash plains and glaciolacustrine spillways indicate meltwater drainage to the south. Only the easternmost frontal lobe did not drain its meltwaters to the south, discharging them directly to the east into Bahía Cristina West. A $^{10}$Be age on a boulder from one of the innermost Pearson 2b moraines ridges is 570 ± 60 yrs BP.

Pearson 2c meltwater channels did not reach the entrances of the south–north trending valleys, and meltwater drained directly into the western branch of Bahía Cristina. Ring counts of immature trees, growing inboard of these moraines, afford a minimum-limiting colonization age of 170 yrs BP relative to A.D. 2012 (Malagnino and Strelin, 1992).

Finally, after the last Pearson 2c glacial advance, the ice receded rapidly, with only a few stillstands marked by small moraines ~4 km north of the primary belt (Malagnino and Strelin, 1992). The glacier front in the year A.D. 2010 was >15 km behind the Pearson 2c belt and it was still receding in A.D. 2014.

### 5.3. Sector 3: Agassiz Este Valley

Agassiz Este Valley is also known as Vega de las Vacas (IGN map). The most prominent landform in this valley is a large shared moraine generated by the confluence of Agassiz Este Glacier and a westward-flowing lobe of Upsala Glacier (Fig. 9). The complex history of this site involves bulky moraines and several proglacial lake deposits. Despite the complexity, it is possible to provide a model of Holocene landscape evolution, mainly because of well-preserved moraines and terraces and, perhaps most important, stratigraphic sections exposed in a gully excavated by the Agassiz Este River through the shared moraine (see Photograph 5 in SM).

The oldest stratigraphic unit revealed in Agassiz Este is related to post-Lateglacial deglaciation that promoted slope instability. Specifically, a landslide occurred on the right (south) slope, depositing a diamicton that extended into the central part of the valley. The chaotic fabric of this matrix-poor diamicton includes angular boulders, wood fragments, and remains of tree trunks. The oldest $^{14}$C ages obtained on tree fragments incorporated in the diamicton (Fig. 10A) indicate that the glaciers (Agassiz Este and the westward-flowing Upsala lobe) receded close to their present-day limits, inboard of the Holocene moraines, prior to 9205 ± 85 cal yrs BP, and remained there at least until 9040 ± 120 cal yrs BP, a maximum-limiting age for the landslide deposit.

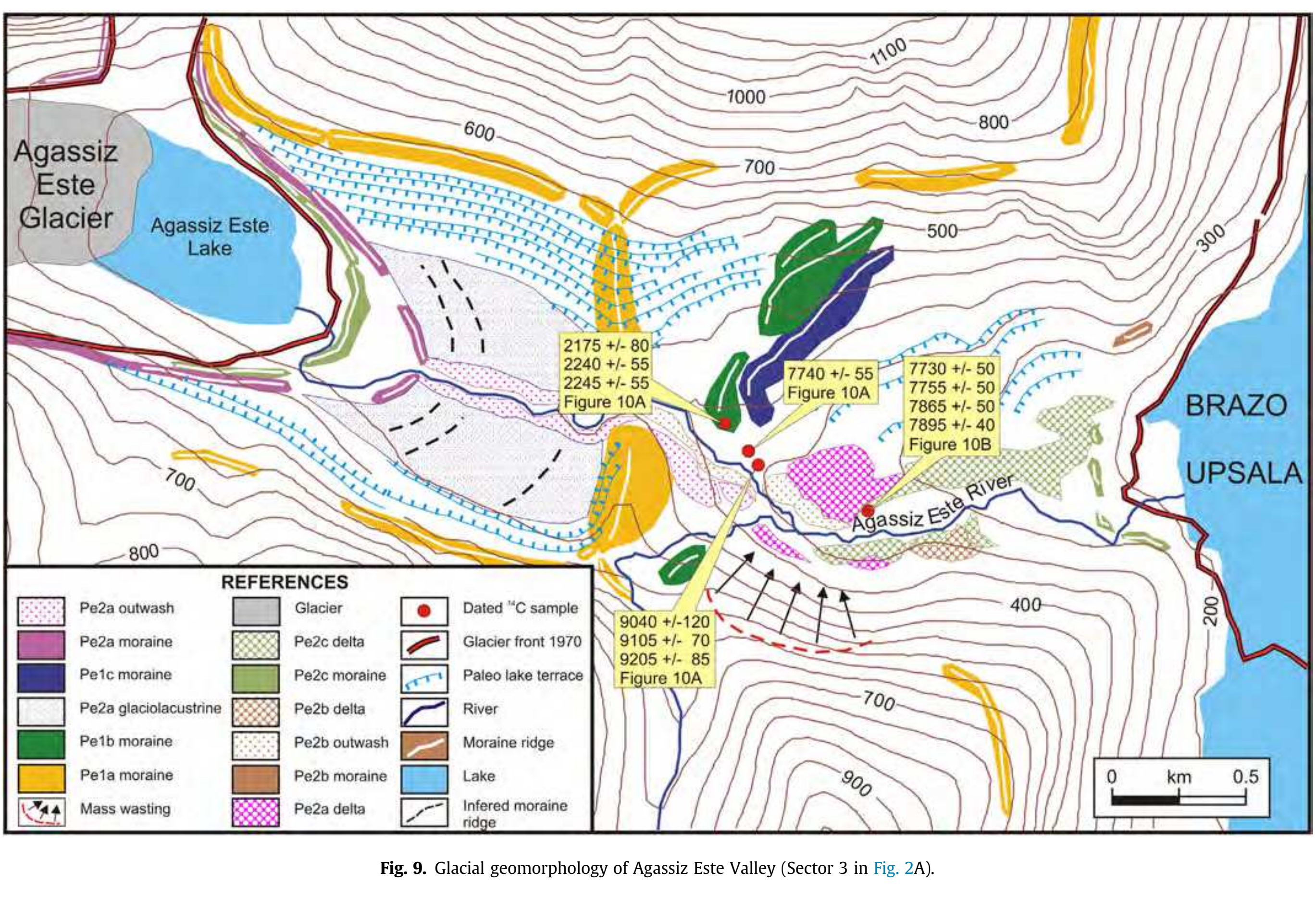


**Fig. 9.** Glacial geomorphology of Agassiz Este Valley (Sector 3 in Fig. 2A).

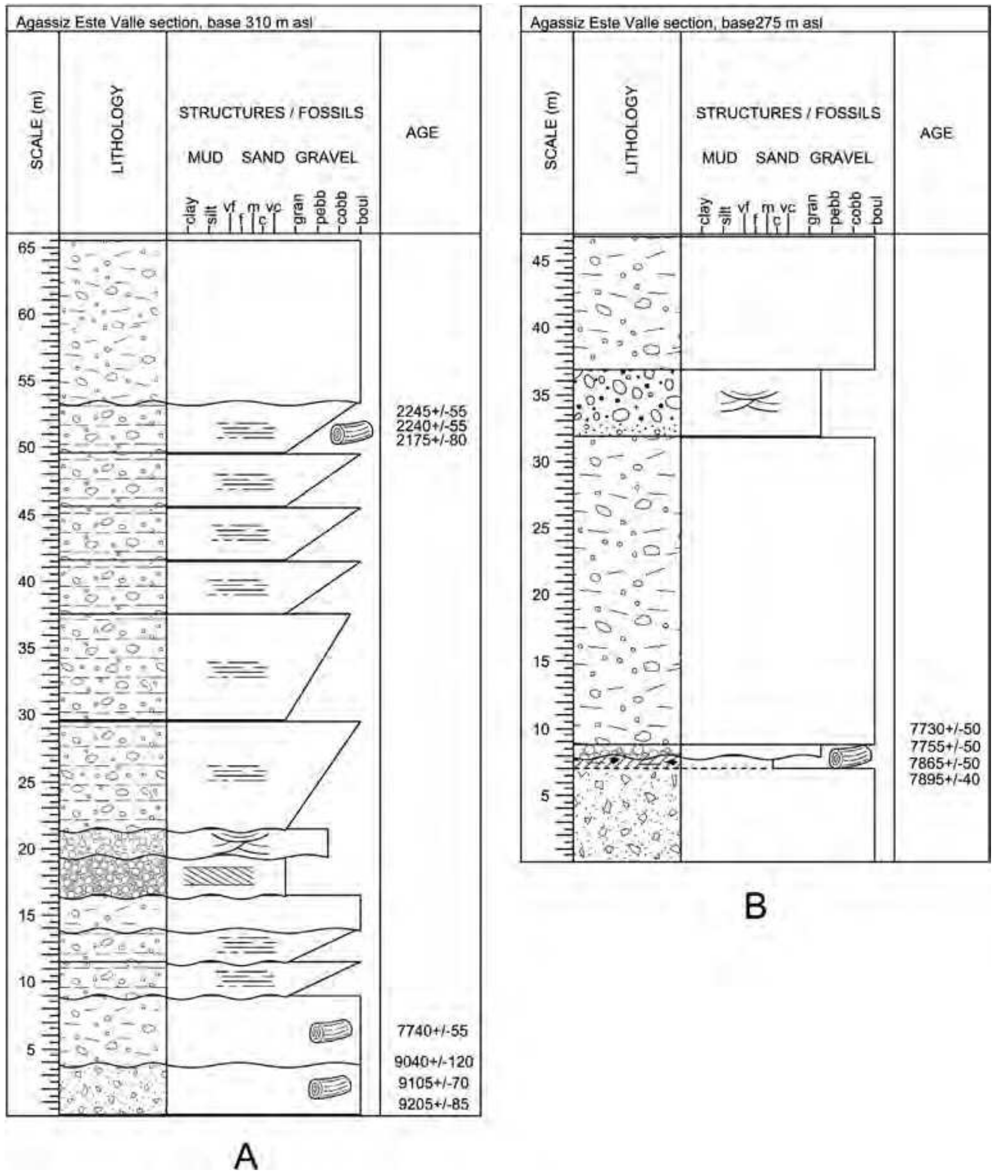


**Fig. 10.** Profiles of exposures in the gully of Agassiz Este River. The base of profile A reaches ca 310 m a.s.l. and the base of profile B ca 275 m (a.s.l.). Profile locations are shown in Fig. 9. See also Photograph 5 and an additional profile description in the SM.

Forest colonization occurred after deposition of the diamicton, as indicated by the existence of abundant tree trunks incorporated in the overlying paleosoil and glaciofluvial deposits (Fig. 10B). The tree trunks remaining from this forest are as old as 8095 cal yrs BP (bark $^{14}C$ age of 7895 $\pm$ 40 cal yrs BP plus ~200 annual tree rings). Thus, the warm postglacial period with a mature forest lasted at least until 8095 cal yrs BP. Covering the glaciofluvial material is a lodgment till as much as 25 m thick. As inferred from the age of a tree trunk in the paleosoil and glaciofluvial deposit, a glacier advance occurred soon after 7730 $\pm$ 50 cal yrs BP. The resulting lodgment till, located deep inside the Agassiz Este Valley, documents a glacier advance that is recognized only from deposits in stratigraphic section, and not from surface morphology anywhere in the Lago Argentino basin.

Moraines allow the identification of three subsequent glacier advances in Agassiz Este, which we correlate with the three Pearson 1 moraine systems (Malagnino and Strelin, 1992). A proglacial lake with a surface elevation of as much as 520 m a.s.l. (335 m a.l.a.) was ice dammed during the Pearson 1a glacier advance, leading to the deposition of flow tills and glaciolacustrine deltaic sediments by both of the coalescent glacier lobes. Similar stratigraphic and morphological conditions were replicated during the subsequent Pearson 1b advance. But in this case, a flow till sequence as much as 40 m thick, deposited from the westward-flowing lobe of Upsala Glacier (Fig. 10A, Photograph 5 in SM), includes tree trunks as much as 10 cm in diameter; from the wood, we obtained a maximum-limiting age of 2175 $\pm$ 80 cal yrs BP for accumulation of the flow and upper lodgment tills. The upper lodgment till is connected with the surface morphology of the Pearson 1b frontal moraine deposited by the westward-flowing Upsala Glacier lobe. Construction of the Pearson 1c moraine followed a similar evolution as during both the 1a and 1b advances, increasing the bulk of the composite moraine. The corresponding Pearson 1b and 1c moraines deposited by the Agassiz Este Glacier were likely reworked during the different lake-damming stages and are therefore difficult to recognize (Fig. 9). According to the incipient and well-developed lake terraces recognized on the valley slopes, the “unified proglacial lake” reached its last highstand of 520 m a.s.l. (335 m a.l.a.) during the Pearson 1c glacier advance.

Two late-Holocene moraine systems, both correlated with Pearson 2 moraines, were recognized very close to the southeastern shore of a small Agassiz Este proglacial lake (Fig. 9). There is no sign of flooding by proglacial lakes during Pearson 2 time on this western and higher side of the shared moraine. During the Pearson 2 glacier expansion, small proglacial lakes were dammed as much as 320 m a.s.l. (135 m a.l.a.) on the eastern side of Agassiz Este valley, facing Brazo Upsala. No Pearson 2a moraines were identified on this side of the valley, but some younger moraine fragments (Pearson 2c) are preserved on top of a rocky shoulder located at the entrance of the Agassiz Este Valley. These moraine remnants and three segmented delta deposits (Fig. 9) allow the reconstruction of three complete lake transgressional cycles in Agassiz Este. We assume that the proglacial lake highstands and delta formation reflect the Pearson 2 glacier advances, as proposed by Malagnino and Strelin (1992).

### 5.4. Sector 4: Brazo Upsala

Pearson 1 and 2 moraines are well represented along both sides of Brazo Upsala (Fig. 2A). A detailed survey of both right-lateral moraine groups was undertaken along the slope on the western side of Brazo Upsala (Fig. 11). The Pearson 1 and 2 moraines, which are as much as 6 m high, are covered with erratics

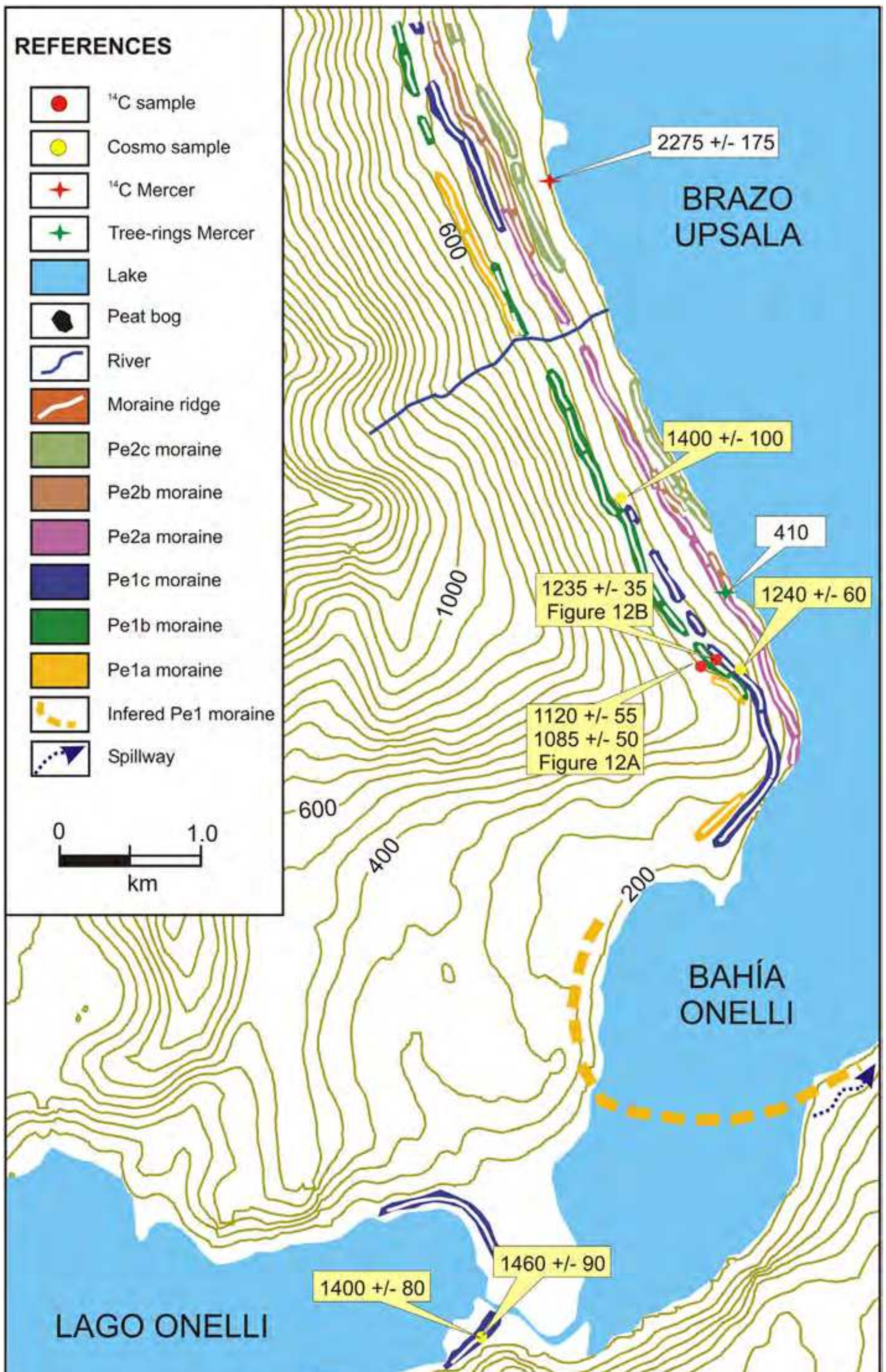


**Fig. 11.** Geomorphological map of the western slope of Brazo Upsala showing the Pearson 1 and 2 moraine groups (Sector 4, Fig. 2A).

similar to those on other moraines, except for the addition of Andean granite boulders. Some till exposures occur close to lake level, where waves undercut the moraines. In one of these exposures, at 190 m a.s.l. (5 m a.l.a.), Mercer (1965) described a 6-m-high profile with an unconformity separating two different tills. He obtained a date of 2275 ± 175 cal yrs BP on a log in the lower till (Fig. 11) and assigned this age as a maximum-limiting value for the Pearson 1 moraine. Mercer (1965) estimated an approximate minimum-limiting age for Pearson 2 moraines based on tree-ring counts. Using an ecesis of 50 yrs, he determined a minimum-limiting age of ~410 yrs BP (A.D. 1600) for the outer part of this moraine, and of ~240 yrs BP (A.D. 1770) for post-Pearson 2 recession.

Peat bogs in former spillways and lacustrine deposits yielded the primary material used to date the Pearson 1 moraines (Fig. 11, Photograph 6 in SM). Wood-and-bark fragments collected from the base of 0.70 m of thinly layered lacustrine silt and sand (Fig. 12A) yield dates of 1120 ± 55 and 1085 ± 50 cal yrs BP, indicating plant colonization after recession from Pearson 1c landforms. A second peat bog (Fig. 12B), located between Pearson 1b and 1c moraines (Fig. 11), reveals two fluvial-lacustrine sequences of 2.0 m thickness, covered by 1.5 m of red fibrous peat. The lowermost peat provided an age of 1235 ± 35 cal yrs BP for abandonment and plant colonization of the post-Pearson 1c spillway. Moreover, two $^{10}$Be ages of 1240 ± 60 and 1400 ± 95 yrs BP were obtained on the inner Pearson 1c moraine, in good agreement with the $^{14}$C ages (Fig. 11).

During the Pearson 1 advance, both sides of Bahía Onelli were blocked several times by the Brazo Upsala Glacier Lobe, damming a proglacial lake, which is documented by rhythmites resting on outwash deposits (Mercer, 1965). During this expansion, the Onelli Glacier built two frontal moraine ridges; $^{10}$Be ages of 1460 ± 90 and 1400 ± 80 yrs BP are used to assign them to Pearson 1c. We found Mercer's (1965) glacier-transgressive sequence, exposed in a 5-m-high outcrop in the Lago Onelli spillway. Also, terraced kame deposits, probably related to former spillways of the ice-dammed proglacial lake, are preserved on the southeastern slope of Bahía Onelli (Fig. 11). They reach as much as 20 m a.l.a. (205 m a.s.l.).

Along Brazo Upsala, about 100–150 m below the topographic position of Pearson 1 lateral moraines, another closely attached lateral moraine group is mapped (Fig. 11). These mapped moraines are correlated to the Pearson 2 left (east) lateral and frontal moraines deposited on Península Herminita. During the Pearson 2a and 2b glacier advances, the frontal margin in western Brazo Upsala reached the pinning point just north of Bahía Onelli (Fig. 11), whereas during Pearson 2c the front was located 2 km up-valley of this locality. As mentioned above, Mercer (1965) derived a tree-ring count minimum-limiting age of ~410 yrs BP (A.D. 1600) for the outer Pearson 2a moraine, and ~240 yrs BP (A.D. 1770) for the abandonment of the moraines inboard of the Pearson 2c moraine.

### 5.5. Sector 5: Lago Frías

Strelin et al. (2011) discussed the Lateglacial recession in this sector, which occurred prior to 12,270 ± 100 cal yrs BP. Here, we focus on two well-defined moraine groups named Frías 1 and 2. The older of these two systems is located on the spit of land separating Brazo Sur from the northern shore of Lago Frías, and the youngest is located ~2 km to the southwest of the southern shore of Lago Frías. The Frías 1 moraines were deposited by the former Frías Glacier Lobe fed by a northeast-flowing lobe of the Dickson Glacier and by the northern Gorra and Grande tributary glaciers. Subsequently, the Frías 2 moraines were largely deposited during an advance of Grande Glacier (Figs. 2B, 13).

Mercer (1976) provided a minimum-limiting age of 3680 ± 165 cal yrs for Frías 1, obtained from a piece of wood from the lower 0.10 m of a 1.50-m-thick organic layer in a “former watercourse” crossing the outer Frías moraines (Fig. 13). $^{10}$Be ages on rhyodacitic boulders resting on the surface of the outer Frías 1 moraines are 6330 ± 260 and 5680 ± 200 cal yrs BP, consistent with Mercer's (1976) minimum-limiting age.

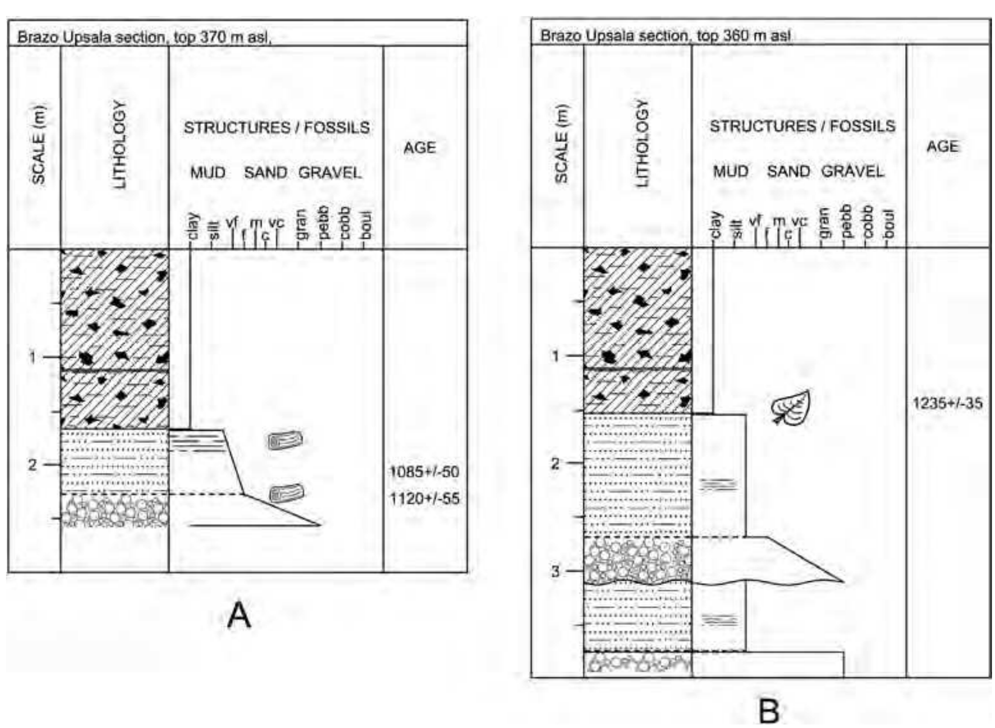


**Fig. 12.** Peat bogs cored on the western side of Brazo Upsala (A) between Pearson 1a and 1b lateral moraines and (B) between Pearson 1b and 1c lateral moraine. Profile locations in Fig. 11. Also see profile descriptions and Photograph 6 in the SM.

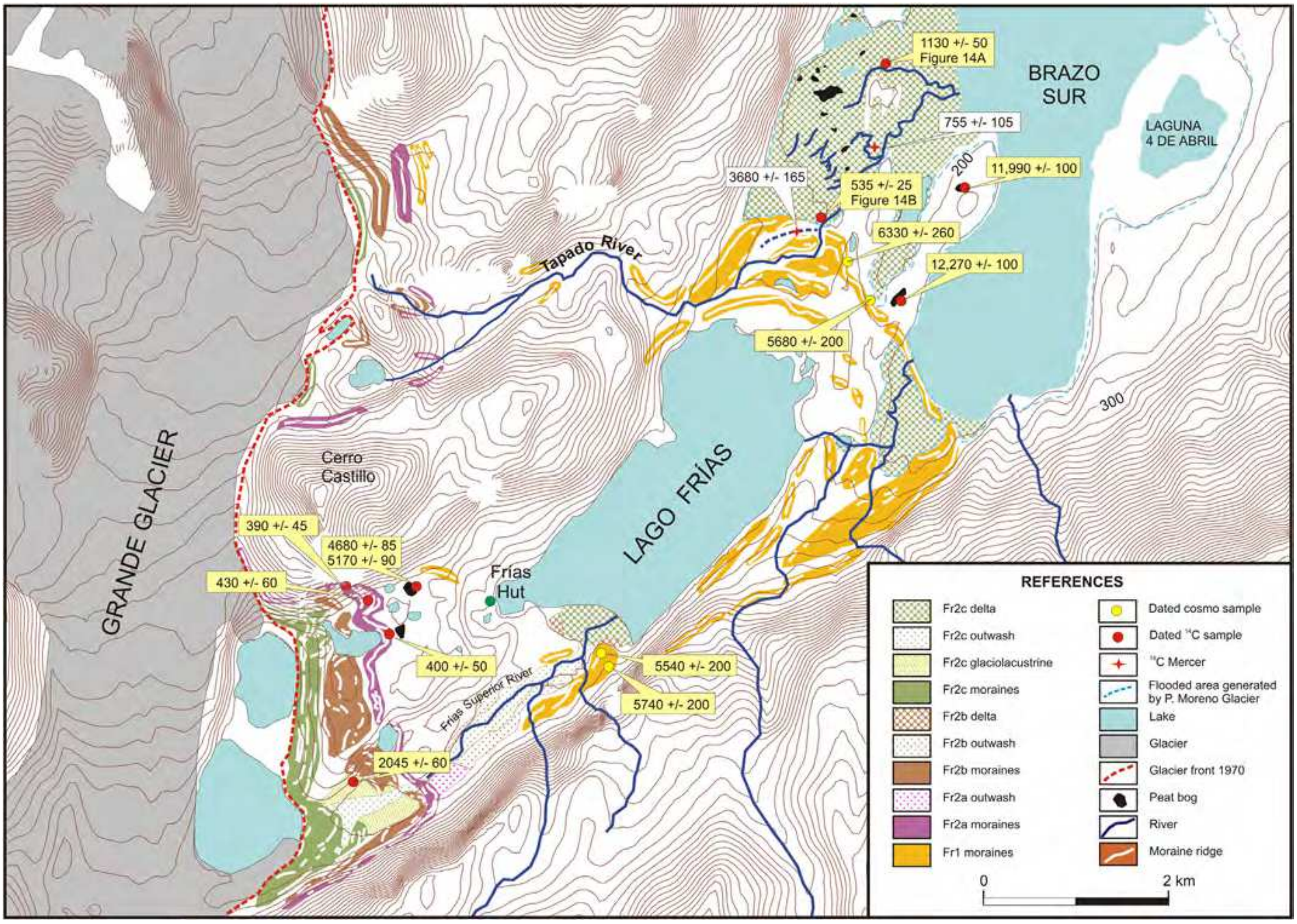


**Fig. 13.** Glacial geomorphology of Lago Frías (Sector 5 in Fig. 2A).

Analogous to the Pearson 1 moraine morphology in front of Upsala Glacier, the Frías 1 moraines cover an extended area. However, no outwash plains or delta deposits could be assigned to the Frías 1 moraine systems, possibly because they were covered and reworked by the Tapado River. We obtained statistically indistinguishable $^{10}$Be ages of 5540 $\pm$ 200 and 5740 $\pm$ 200 yrs BP for erratics rooted in two inner moraine ridges located south of Lago Frías and assigned them to Frías 1 (Fig. 13). These ages are also supported by a minimum-limiting $^{14}$C date of 5170 $\pm$ 90 cal yrs BP, obtained on basal peat ~1 km west of the Frías Hut, just outboard of the Frías 2 moraines (Fig. 13).

Mercer (1968) described the Frías 2 moraine group as being composed of three main moraine ridges, all located within 1 km of the glacier front as it existed in A.D. 1966, the year of his investigation. Herein, we also separate the Frías 2 moraines into three moraine systems, each with multiple ridges (Frías 2a, 2b, 2c). The three moraine systems could be related to corresponding outwash plains in the Frías Superior River valley, and to two delta deposits (Frías 2b, 2c) located at the mouth of Frías Superior River where it empties into Lago Frías (Fig. 13). The outer and therefore older Frías 2a and 2b systems are partially forested in wind-sheltered sites, whereas the inner Frías 2c is bare and appears to be of recent historical age. A piece of wood incorporated in the lodgment till of the Frías 2a left-lateral moraine affords a maximum-limiting $^{14}$C age of 390 $\pm$ 25 cal yrs BP (Fig. 13, Photograph 7 in SM). Pieces of wood were also sampled from hollows between boulders on the moraine surface and provide minimum-limiting ages of 430 $\pm$ 60 and 400 $\pm$ 50 cal yrs BP for the moraine. These values agree with those of Mercer (1968), who estimated a minimum-limiting age of 300 yrs BP for the same moraine system (recalculated to A.D. 2012, allowing for a 100 yrs ecesis). The Frías 2b moraine system is colonized by an immature forest that is 150 yrs younger than that on Frías 2a (Mercer, 1968), and accordingly this moraine is assigned an age of ~250 yrs BP. Judging by Mercer's (1968) description and by an aerial photograph taken in A.D. 1970 (IGN), Frías 2c is a 100-to-50-yr-old moraine system.

In the upper part of the Frías Superior River valley, a 1.80-m-long and 0.30-m-wide tree trunk protruded from the gravels of Frías 2c glaciofluvial and lacustrine deposits. The trunk, with partially preserved roots and bark, afforded a $^{14}$C age of 2045 $\pm$ 60 cal yrs BP. It follows from its position inboard of the Frías 2b moraine system, and far distance from the valley slopes, that this tree was killed during a glacier advance <2250 cal yrs BP (considering additional ~200 tree rings), and later transported to the final position in the last ~200 years by the Frías 2b advance.

Additional, but indirect, information about former Frías, Grande, and Perito Moreno glacier fluctuations can be determined by studying the stratigraphy of a delta located immediately north of the Frías 1 moraine system (Fig. 13). This delta is controlled by the level of Brazo Sur, which in turn is regulated by fluctuations of Perito Moreno Glacier (damming the southern

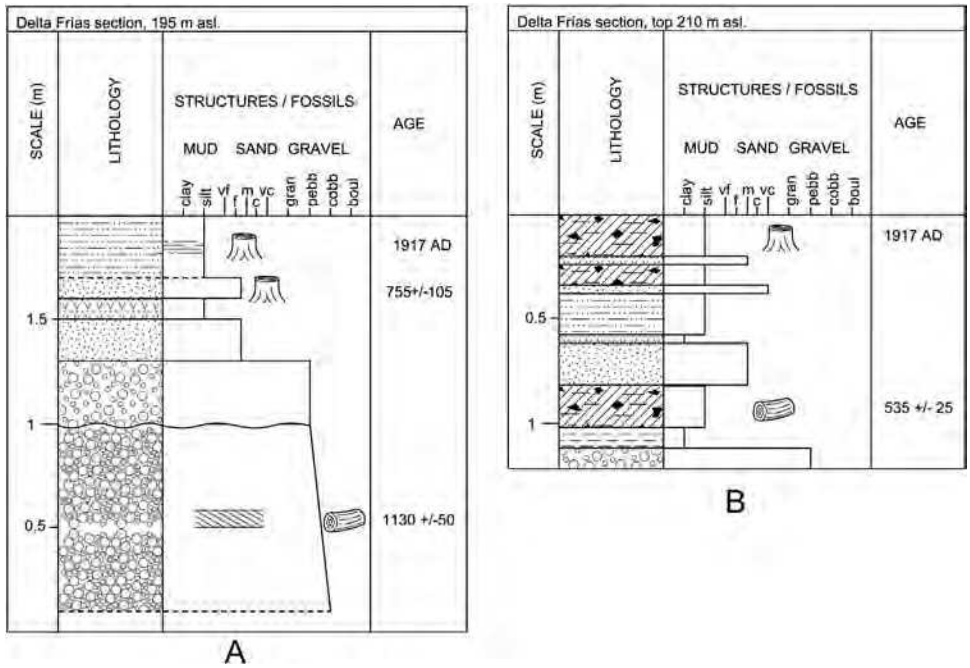


**Fig. 14.** (A) Frías Inferior delta section The top of the exposure reaches 195 m a.s.l., about 10 m above the Brazo Sur lowstand, (B) Peat bog cored close to the mouth of Tapado River, 210 m a.s.l, 5 m below the Brazo Sur highstand. Profile locations in Fig. 13 and profile description in the SM.

arms of Lago Argentino) and the Brazo Rico spillway (25 m above the present-day level of Lago Argentino). During Frías 1 time, sediment supply to the delta was provided mainly by meltwater generated at the glacier front. During Frías 2 time, the sediment supply was mainly from the Tapado River, which in turn was fed by melt from the Grande Glacier (Tapado Norte and Tapado Sur lobes, Fig. 13). A river incision into the delta, 2 km downstream of the Frías 1 moraines, exposes evidence of a lake-level lowstand followed by a rise of lake level recorded by a transgressive sedimentary sequence (Fig. 14A). Bark sampled from one of the trunks incorporated in, but not rooted in, the lower iron-oxide-cemented gravelly fluvial layer dates to 1130 ± 50 cal yrs BP, providing a maximum-limiting age for the Brazo Sur lowstand and therefore glacier withdrawal. These glacifluvial gravels are covered by a 0.4-m-thick layer of fine-sand-to-clay lacustrine sediments, with stumps in growth position. About 1 km south of this exposure, an age of 755 ± 105 cal yrs BP was obtained by Mercer and Ager (1983) for similar rooted stumps, buried beneath 3 m of lacustrine sandy clay (Fig. 14A), providing a close maximum age of a Brazo Sur lowstand. Thus, both ages, 1130 ± 50 and 755 ± 105 cal yrs BP, bracket a lowstand of Brazo Sur, and thus recession of Perito Moreno Glacier. The subsequent lake highstand indicates renewed damming of the southern branches of Lago Argentino by Perito Moreno Glacier. The coeval high glaciolacustrine sedimentation rate, described by Mercer and Ager (1983), was probably connected with the glacier advance and associated high sediment input into the delta by Tapado River. Last, the rooted trunks at the top of the profile (Fig. 14A) were killed during the historical flooding of Brazo Sur and Brazo Rico in the year A.D. 1917. Based on ring counts from trees killed by this historical flooding (Strelin and Malagnino, unpublished), a previous lowstand prevailed for about 200 years.

Additional indirect data concerning late-Holocene glacier fluctuations are obtained from the stratigraphy of a peat core from an abandoned channel of the Tapado River (Figs. 13, 14B) incised ~5 m below (210 m a.s.l.) the highest flood level of Brazo Sur (215 m a.s.l.). Wood included in a lower peat layer (Fig. 14B) dates to 520 ± 15 cal yrs BP, affording a maximum-limiting age for the overlying sand-and-clay lacustrine sediments deposited during a Brazo Rico highstand, and thus blockage of the southern lake arm by Perito Moreno Glacier. Accordingly, this glacier advance is correlated with the Frías 2a advance in the Frías Superior river valley, about 390 cal yrs BP.

A notable observation is, that during the 20th century, the Perito Moreno Glacier advanced and fluctuated near its maximum Holocene position, whereas the Grande Glacier retreated markedly (also see Section 6). A glacial lake formed during recession of the Grande Glacier, and only recently drained into Lago Dickson (Fig. 2B). This changed the drainage from the Atlantic to the Pacific Ocean, with a northern shift of the entire continental watershed in this area.

### 5.6. Other glacier valleys

In the context of the data presented so far, it is also pertinent to discuss glacial morphology recognized near other outlet glaciers in the Lago Argentino drainage area. Near Lago Onelli (Fig. 2A), it was possible to identify a southward-flowing Pearson 1 glacier lobe that blocked the northern Cerro Heim tributary glacier. Also near Lago Onelli, approximately 4 km up-valley of the Pearson 1 frontal moraine, the position of a Pearson 2 fresh-water calving front was reconstructed for Onelli Glacier. At this site a steep descending lateral moraine allowed the placement of the former glacier front. A photograph presented by Feruglio (1944) shows that a receding front of Onelli Glacier occupied this position in A.D. 1931. Since that time the lake-calving front has receded markedly, particularly in the last 40 years, reaching in April 2006 a position 4.5 km inboard (west) of the Pearson 2 position.

Agassiz Glacier (Figs. 1, 2A) has lost only ~20 m in ice thickness at its terminus since its last major late-Holocene expansion, which is documented by a well-preserved, partly-vegetated-to-bare lateral moraine. The terminus of the Spegazzini Glacier (Fig. 1) is near a dense mature forest that is separated from the present-day (April 2006) ice margin only by a less-vegetated-to-bare, <30-m-high trimline. According to Feruglio (1944) and to our own observations, Spegazzini Glacier is located only about 200 m from the outer vegetated Holocene moraine. Feruglio (1944) presented a photograph taken in the summer of A.D. 1919 that shows the calving front of Spegazzini Glacier to have been much closer to its outer lateral Holocene moraine ridges, compared with the position in A.D. 2006.

Mayo Glacier (Fig. 1) is located just south of the narrowest sector of the SPI. In February 2005 the eastern portion of the Mayo Glacier front was situated approximately 2.0 km from an immature forest-covered moraine ridge and about 1.5 km from a seedling-covered moraine ridge. The outer vegetated moraine remains undated, but based on the immature forest cover it is assigned to one of the youngest of the Holocene advances. Small tree trunks incorporated in the seedling-covered-to-bare inner moraine provide $^{14}C$ ages of 102 ± 73 and 90 ± 60 cal yrs BP (Strelin, unpublished), thus representing a minor glacier advance in the late 19th century.

Studies focused on the Ameghino Valley (Fig. 1) have documented four Holocene advances (Nichols and Miller, 1951; Aniya, 1996). The first advance was proposed to be as old as the Younger Dryas stadial (~12,000 cal yrs BP in age), which was followed by three middle-to-late-Holocene fluctuations. The youngest prominent double-ridged moraine belt, which encloses the eastern shore of Lago Ameghino, was deposited by an oscillating glacier front between 330 ± 110 cal yrs BP (Aniya, 1996) and A.D. 1880 (Nichols and Miller, 1951). Since the field work of Nichols and Miller (1951) in A.D. 1949, the glacier has receded rapidly, generating a 5-km-long proglacial lake (November, 2010).

In the early 20th century, Perito Moreno Glacier (Fig. 1) reached its most advanced position since Lateglacial time, probably overriding older moraine ridges (Strelin et al., 2011). Since then, the glacier has remained in a steady state, losing a few meters of ice thickness at the terminus in the last decade. Nevertheless, several relatively minor Holocene fluctuations are inferred based on the stratigraphic evidence presented above, namely flooding and delta construction in Brazo Rico and Brazo Sur (see above "Sector 5: Lago Frías").

The Cerro Norte Glacier (Fig. 1), northwest of Lago Pearson, shows an interesting pattern of glacial response to climate change. Here the earliest advance was clearly not the largest (Mercer, 1965). Remnants of an older moraine are buried by a younger moraine. Deposits of a marsh generated by the last advance, incorporate a tree dated to 395 ± 80 cal yrs BP (Mercer, 1965). This evidence indicates that a Pearson-2-equivalent glacier advance overrode moraines that are probably Pearson 1 in age.

## 6. Glacier response to climate change

It is widely accepted that glacier oscillations indicate regional-to-global climatic change (Leclercq and Oerlemans, 2011; WGMS, 2011). However, in the Lago Argentino area, neighboring glaciers, under similar climates, appear to show differences in their frontal (length) fluctuations, causing difficulties in the interpretation of historical (short-term) and geological (long-term) climate changes. Four of the larger glaciers, Upsala, Onelli, Ameghino, and Grande (former Frías) underwent considerable retreat, leaving behind numerous middle-to-late-Holocene moraine systems. Three other glaciers, Agassiz, Spegazzini and Mayo, have retreated slowly, and remain close to their maximum late-Holocene positions; and one, Perito Moreno, reached its maximum Neoglacial position in the beginning of the last century (Mercer, 1976), since then oscillating near this advanced position (Figs. 1, 15).

One explanation for this discrepancy is that changes in "local climate factors" affected mass balance, but according to Furbish and

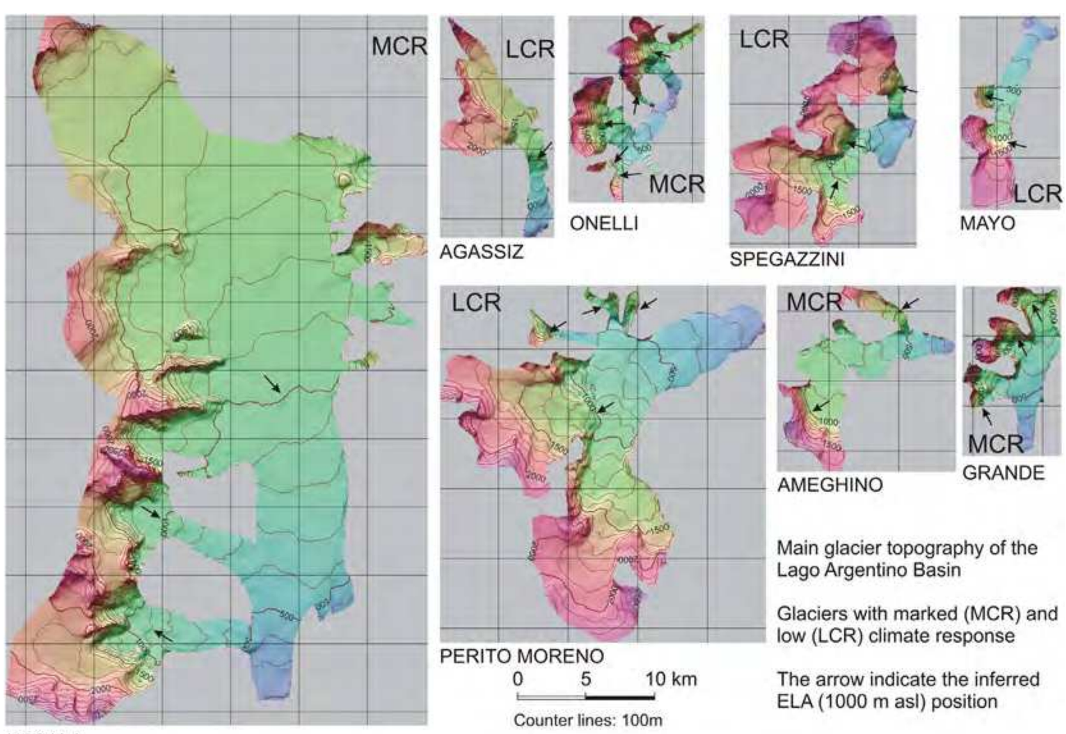


**Fig. 15.** The eight main outlet glaciers of the Lago Argentino basin, showing their topography and ELA position as indicated by the arrow in each panel. Glaciers with marked climate response (MCR) and low climate response (LCR) are indicated.

Andrews (1984) these factors should only cause minor discrepancies, mainly in the short term. These authors considered that much of the differential response that obscured the climatic effect was linked to varying glacier "flow dynamics" and glacier "geometry".

Because of scarcity of data, little can be said about the "flow dynamics" that may have affected the climate response of the main Lago Argentino outlet-glaciers. During the middle and late Holocene, most of these glacier termini (excluding the west Upsala, Spegazzini and Perito Moreno) were grounded and land facing. At present, the eight main Lago Argentino outlet glaciers terminate, at least partly, in proglacial lakes, and thus calving is an important control on their frontal dynamics, complicating the interpretation of their response to climate change. On the other hand, at least in late-Holocene time, pinning points may have been important in stabilizing the termini of four of the more-stable glaciers: Agassiz, Spegazzini, Mayo, and Perito Moreno.

Another factor to be considered in explaining different behaviors is valley "geometry", i.e. the areal distribution of glaciers with regard to their surface elevations. Mercer (1965) first mentioned that the "… low gradient Upsala Glacier may respond to climate fluctuations differently from a short, steep glacier…" Mercer (1965) considered that for glaciers such as Upsala, a small oscillation of the ELA can result in large changes of the accumulation and ablation areas.

Here, we examine this issue of glacier geometry by using cumulative-percentage hypsometric curves (Fig. 16). In these curves, elevation intervals (of 20–30 m equidistance) are plotted against the cumulative percentage area. The glaciated area distribution is plotted in percent, in order to standardize the different glacier sizes, whereas the elevation intervals are plotted using their absolute value. This procedure allows the areal distribution of glaciers to be compared with their ELA fluctuations.

As a first approach, we consider a mean ELA of $1000 \pm 100$ m for the present-day Lago Argentino catchment area (Table 1). A plot of the mean ELA in Fig. 16A and B shows that the equilibrium lines intersect the hypsometric curve of the first group of glaciers at places where a small elevation change affects a large surface area (Fig. 16A). This is why the termini of these glaciers have a marked climate (temperature) response (MCR in Fig. 15). In contrast, in the second group (Fig. 16B), the equilibrium lines intersect glacier surfaces at places where a large elevation change affects only a small surface area, resulting in a smaller response of the termini to climate change (LCR; Fig. 15).

Due to glacier-surface geometry, among other factors, it follows that Upsala, Onelli, Ameghino, and Grande (former Frías) glaciers: i) show a marked climate response; ii) provide numerous Holocene moraine systems; and iii) at present, are retreating markedly due to recent warming. Conversely, Agassiz, Spegazzini, Mayo, and Perito Moreno glaciers: i) provide the lowest climate response; ii) are in near steady state, overriding previous moraines and remaining close to their maximum late-Holocene position, and; iii) at present, are only retreating slightly, as they are attached to pinning points.

By taking into account the influence of surface hypsometry, we consider Upsala, Onelli, Ameghino, and Grande (former Frías) glaciers to be appropriate proxies for the study of climate-driven Holocene glacier fluctuations in the Lago Argentino basin. The climatically less-responsive Agassiz, Spegazzini, Mayo, and Perito Moreno glaciers underwent minor fluctuations during the Holocene, with Holocene moraines overridden by late-Holocene advances or, in the case of Perito Moreno Glacier, overridden during historical advances.

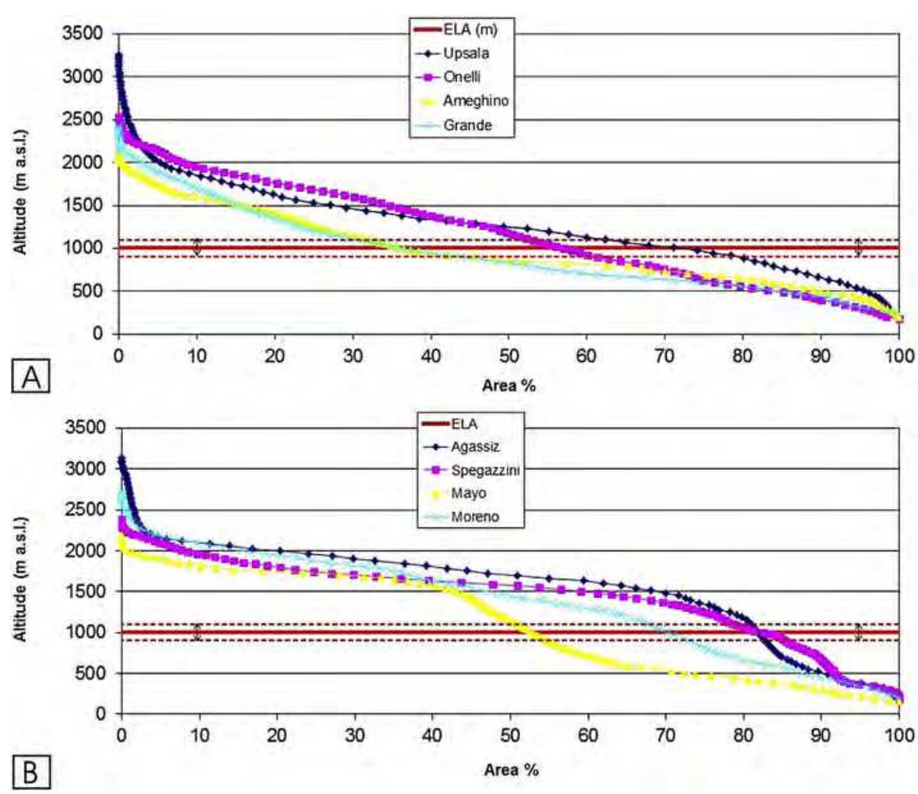


**Fig. 16.** Hypsometric curves of (A) glaciers with marked climate response (MCR, Fig. 15) such as Upsala, Onelli, Ameghino, and Grande (former Frías), and (B) glaciers with low climate response (LCR, Fig. 15), such as Agassiz, Spegazzini, Mayo, and Perito Moreno. The continuous straight (red in the on-line version) line indicates the mean ELA, and the arrows and dashed lines indicate the elevational deviation of this value (Table 1).

**Table 1**
Area, equilibrium line altitude (ELA), and accumulation area ratio (AAR) of the eight main Lago Argentino outlet glaciers. The areas were measured in the satellite image mosaic (Mosaic ID S-18-45_loc and S-18-50_loc), file format MrSid, platform Landsat, sensor TM from the years A.D. 1999–2002. ELA and AAR were communicated by Gino Casassa.

| Glaciar | Upsala | Agassiz | Onelli | Spegazzini | Mayo | Ameghino | Moreno | Grande |
|---|---|---|---|---|---|---|---|---|
| Area ($km^2$) | 841 | 46 | 53 | 109 | 35 | 55 | 243 | 42 |
| ELA (m a.s.l.) | 1050 | 1380 | 1070 | 1010 | 1090 | 840 | 1150 | 870 |
| AAR | 0.74 | 0.75 | 0.68 | 0.87 | 0.58 | 0.64 | 0.71 | 0.53 |

## 7. Glacial history

Based on the observations presented above, we provide the following history of outlet glacier fluctuations in the Lago Argentino basin during the Holocene (Fig. 17).

### *7.1. Deglaciation at 12,220–7730 cal yrs BP*

After the Puerto Bandera Lateglacial advance, which culminated close to 13,000 cal yrs BP, Lago Argentino outlet glaciers underwent recession deep into the cordillera by 12,660 ± 70 cal yrs BP (Strelin et al., 2011). The only readvance recognized during this pronounced glacier withdrawal resulted in the construction of the Herminita moraines about 12,220 ± 110 cal yrs BP (Strelin et al., 2011). In some locations elsewhere around Lago Argentino, moraines are mapped that may correlate with the Herminita event (Fig. 2A, B). For example, south of Brazo Sur plants colonized a peat bog 12,270 ± 100 cal yrs BP (Fig. 13), providing close minimum-limiting age for the Cachorro IV moraines (Lovecchio et al., 2008). The "E-moraines", recognized east of Lago Paine (Marden and Clapperton, 1995), may correspond with the Herminita and Cachorro IV moraines (Fig. 2B).

This pronounced retreat continued well into the early Holocene. Plant colonization of peat bogs located immediately south of Lago Pearson, just outboard of the outermost Holocene moraines, are dated to 10,115 ± 100 cal yrs BP (Fig. 3). The full extent of this deep recession into the cordillera is best detected in Agassiz Este Valley (Fig. 9). Reworked wood in a landslide deposit, 2 km from the present-day Agassiz Este glacier front, indicates that this valley was forested and ice extent was similar to, or perhaps even less than, today from prior to 9205 ± 85 until at least 9040 ± 120 cal yrs BP. Subsequently, trees dated from 8095 ± 40 until 7730 ± 50 cal yrs BP, were killed by a glacier advance, indicating the decay of the warm climate.

### *7.2. Glacial advance at 7730–7210 cal yrs BP*

As indicated above, evidence for an early-Holocene glacier advance was detected on Península Herminita and in Agassiz Este Valley (Figs. 7 and 9). A peat bog cored on the western side of Península Herminita (Fig. 8) affords evidence of a glacial advance prior to 7210 ± 45 cal yrs BP. In Agassiz Este Valley, further evidence indicates that, after forest colonization, the glaciers advanced soon after 7730 ± 50 cal yrs BP (Fig. 10A, B). Of particular importance is that the early-Holocene advance, in both locations, was less extensive than the middle-Holocene advance, and hence the early advance is not recorded by geomorphological features on the land surface (Fig. 17).

### *7.3. Glacial advance at 6000–5000 cal yrs BP*

In Península Herminita (Fig. 7), minimum-limiting $^{14}C$ ages of 4085 ± 75 and 3900 ± 55 cal yrs BP are consistent with a $^{10}Be$ age of 5550 ± 170 yrs BP for construction of Pearson 1a moraines. A middle-Holocene glacier advance between 5875 ± 75 and 5850 ± 65 cal yrs BP is also supported by the stratigraphy and dates from the spillway core on the westernmost side of the peninsula (see Fig. 8).

In Agassiz Este Valley (Fig. 9), the Pearson 1a moraines were constructed during the first stages of formation of the complex shared moraine. Along the western valley slope of Brazo Upsala (Fig. 11), the Pearson 1c moraines appear to partially cover the older 1a and 1b moraines.

In Brazo Sur (Fig. 13), we attempted to recognize different Frías 1 moraine systems (cf., Pearson 1a, 1b, 1c). But neither outwash nor glaciolacustrine deposits show the existence of more than one major glacier advance. $^{10}Be$ ages indicate that the Frías Glacier was in an advanced state about 6000 cal yrs BP. Moraines south of Lago Frías also yield middle-Holocene $^{10}Be$ ages of 5740 ± 200 and 5540 ± 200 yrs BP for recessional phases. All these ages fit well with the plant-colonization minimum-limiting $^{14}C$ age of 5170 ± 90 cal yrs BP obtained for Frías 1 recession (Fig. 13). These dates are much older than Mercer's (1976) proposed minimum-limiting age of 3680 ± 165 cal yrs BP for the outer Frías moraines.

### *7.4. Glacial advance at 2500–2000 cal yrs BP*

In the Lago Pearson sector, south of the Laguna de la Pesca Lobe (Fig. 3), plant-colonization $^{14}C$ ages of 2465 ± 100 and 2450 ± 90 cal yrs BP place a minimum-limiting age on glacier

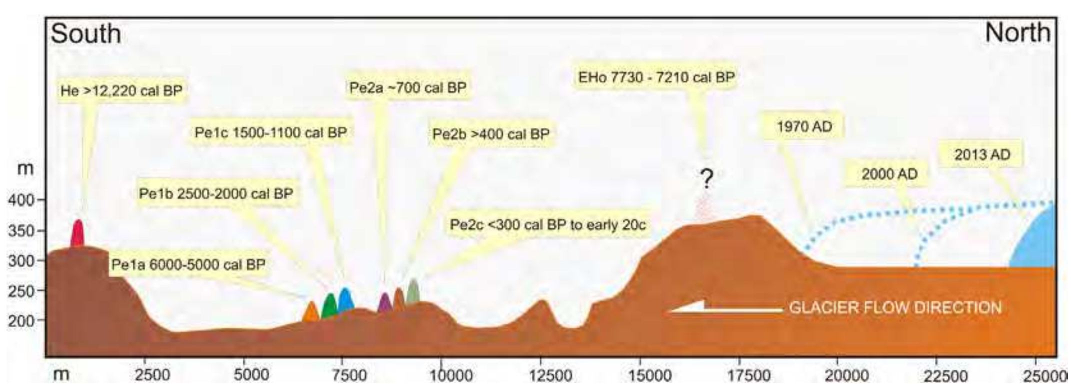


**Fig. 17.** Lateglacial and Holocene frontal moraine positions on Península Herminita. See profile position in Fig. 1. The early-Holocene (EHo) moraine is situated at an uncertain distance behind the Pearson 1 and 2 moraine groups, based on the stratigraphic interpretations in Agassiz Este Valley.

recession behind this locality. Close to this site, Mercer (1965) obtained a $^{14}C$ age of 1890 ± 130 cal yrs BP and used it to bracket the glacier recession behind the outermost Pearson 1 moraine. However, Mercer (1965) did not have the evidence to consider the possibility of other glacier fluctuations such as Pearson 1b and 1c (i.e., prior to Pearson 2).

In Agassiz Este Valley (Fig. 9) a thick, glacier-transgressive sedimentary sequence that incorporate tree trunks provides a close maximum-limiting age of 2175 ± 80 cal yrs BP for the final construction of the Pearson 1b moraine (Fig. 10B). On the western valley slope of Brazo Upsala (Fig. 11), Mercer (1965) employed an age of 2275 ± 175 cal yrs BP for a log from the lower till as a maximum-limiting value for Pearson 1. Following our interpretations in Agassiz Este Valley, in Brazo Upsala this log was incorporated in the Pearson 1b lodgment till and later buried by Pearson 1c and/or Pearson 2 moraines.

In Brazo Sur a 0.3-m-diameter tree trunk incorporated in late Frías 2 glaciolacustrine sediment and dated to 2045 ± 60 cal yrs BP is a possible indicator of an overridden and reworked Frías 1b (Pearson 1b equivalent) moraine.

We also note that on Península Herminita (Fig. 7) the $^{10}Be$ age of 1440 ± 80 cal yrs BP from the Pearson 1b moraine is in conflict with the minimum $^{14}C$ ages obtained for this event in the Lago Pearson sector and hence is probably too young.

### 7.5. Glacier advance at 1500–1100 cal yrs BP

Chronological data from several sites help constrain the age of Pearson 1c. Wood included in the rhythmites along Arroyo Moyano (Figs. 3–5) indicate that the valley was dammed by the northern sector of the Lago Pearson Lobe between 1275 ± 135 and 1125 ± 115 cal yrs BP. In addition, an erratic block deposited by the Laguna de la Pesca Lobe afforded a $^{10}Be$ age of 1430 ± 50 cal yrs BP for the Pearson 1c moraine.

On Península Herminita (Fig. 7), $^{10}Be$ ages of 1520 ± 80 and 2190 ± 140 yrs BP were obtained for boulders on Pearson 1c moraine crests. Although the first of these two ages is consistent with the $^{14}C$ data, the second age may reflect previously acquired $^{10}Be$.

In Brazo Upsala (Fig. 11), lateral moraines provide $^{10}Be$ ages of 1240 ± 60 and 1400 ± 100 cal yrs BP. The lateral moraines are close together and ice of the Pearson 1c advance seems to have partially overridden previously deposited moraines. These $^{10}Be$ ages agree with the minimum-limiting basal $^{14}C$ ages of 1235 ± 35, 1120 ± 55, and 1085 ± 50 cal yrs BP, from peat bogs on the valley-facing side of the Pearson 1c moraines, just to the southwest of Brazo Upsala.

Two $^{10}Be$ ages from the moraines deposited by the Onelli Glacier (Fig. 11) are consistent with deposition during Pearson 1c at 1400 ± 80 and 1460 ± 90 yrs BP.

Aniya (1996) assumed a middle-to-late-Holocene age for moraines near Ameghino Glacier (Fig. 1). Although these moraines are also inferred by us to be middle-Holocene in age, they remain undated.

Finally, a possible Pearson 1c moraine was dated by Mercer (1965) near the Dos Lagos Glacier in the Río Norte valley (Fig. 1). Mercer (1965) interpreted that ice from an advance of Cerro Norte Glacier overran a tree dated to 1455 ± 100 cal yrs BP. This age is in close agreement with the $^{14}C$ chronology of the ice-damming of Arroyo Moyano valley and also with the $^{10}Be$ age for the Pearson 1c moraine deposited south of Lago Pearson by the Laguna de la Pesca Lobe.

### 7.6. Glacial advance ~700 cal yrs BP

As revealed in a core from a peat bog at Laguna de la Pesca (Fig. 3), plant colonization behind Pearson 2a moraines was initiated ~700 ± 25 cal yrs BP (Fig. 6B).

On Península Herminita (Fig. 7), an erratic from a Pearson 2a moraine affords a $^{10}Be$ age of 630 ± 50 yrs BP.

In Agassiz Este Valley (Fig. 9), the presence of a glacially dammed lake linked to the Pearson 2a glacier advance is inferred from a well-developed terraced beach and delta deposit (Malagnino and Strelin, 1992). Moreover, to the south of Agassiz Este, along the western valley slope of Brazo Upsala (Fig. 11), Mercer (1965) postulated that trees colonized the outer Pearson 2 moraine slope at A.D. 1600 (410 cal yrs BP considering an ecesis of 50 years). Based on this limiting age, we infer that the landform might correspond to the oldest Pearson 2a moraine system.

### 7.7. Glacier advance >400 cal yrs BP

After the Pearson 2a event, the Lago Pearson Lobe (Fig. 3) receded and the Moyano Valley paleo-lake probably reached close to the present-date lake level. Subsequently, both the Lago Pearson and the Laguna de la Pesca glacier lobes readvanced to a position just inboard of the Pearson 2a position. From dates of cored peat bogs, close to Laguna de la Pesca (Fig. 6A), we infer a maximum-limiting age of 415 ± 55 cal yrs BP for this advance.

During the Pearson 2b event on Península Herminita (Fig. 7), the Upsala Glacier advanced, producing a moraine arrangement similar to that of Pearson 2a. An erratic from a distal Pearson 2b moraine ridge provided a $^{10}Be$ age of 570 ± 60 yrs BP.

In Agassiz Este Valley (Fig. 9), we infer that relicts of a delta and elevated shorelines reflect damming during Pearson 2b. Immediately south, along the slope of the valley on the western side of Brazo Upsala, stacked lateral moraines, dated to 410 yrs BP (minimum-limiting age) by tree-ring counts (Mercer, 1965), might also correlate with this late-Holocene glacier advance (Fig. 11).

### 7.8. Glacier advance <300 cal yrs BP to early 20 century

During the youngest advance of Upsala Glacier, Lago Pearson (Fig. 3) was split by the glacier lobe, with a higher lake dammed north of the lobe (surface ~10 m higher than that of the present-day lake). A single moraine ridge, resulting from this advance and assigned to Pearson 2c, is confined to the northeast and southwest coasts of Lago Pearson. According to Mercer (1965), growth rings of trees growing between this moraine and the lake indicate that Upsala Glacier constructed this landform early in the 19th century.

On Península Herminita (Fig. 7), after a minor recession, the Upsala Glacier readvanced, depositing multiple-ridged Pearson 2c moraines just north of the entrance to the structurally controlled valleys. The meltwater channels did not reach the level of the valleys, and therefore drained to the east, and then to the south into Bahía Cristina West. Minimum-limiting ages of 190 yrs BP (recalculated to A.D. 2012) were established by tree-ring chronologies for the Pearson 2c recession (Malagnino and Strelin, 1992).

In Agassiz Este Valley (Fig. 11), and the western side of Brazo Upsala, a sparsely vegetated inboard moraine ridge indicates the approximate position of the last stable Pearson 2c glacier front.

Late-Holocene moraines equivalent to Pearson 2c were also detected and dated upvalley of Cañón Cerro Norte (Fig. 1). Mercer (1965, field work undertaken in 1963) described a mature-forest-covered moraine constructed by the Cerro Norte tributary glacier, subsequently cut by a moraine without surface trees. The younger treeless moraine crosses the valley and generated a marsh that drowned a tree; a date of 390 ± 85 cal yrs BP from the tree affords a maximum-limiting age for deposition of the moraine.

None of the three Frías 2 moraine systems (Mercer, 1968; this study) is completely forested and only the distal slope of the outer moraine shows mature trees in a closed-canopy forest. A close maximum-limiting age of ~400 cal yrs BP was obtained from three logs embedded in the outer Frías 2a moraines. A minimum-limiting age of 300 yrs BP was obtained by Mercer (1968) based on tree-ring counts derived from trees on the surface of the same moraine (recalculated to A.D. 2012).

The remaining two Frías moraines are much less forested. Mercer (1968) provided minimum-limiting ages from tree-ring counts of 250 and 100 yrs respectively. Taken at face value, the late Holocene Frías 2 moraines are not equivalent to the Pearson 2a, 2b, and 2c moraine systems of Upsala Glacier. The Frías 2a advance most likely correlates with the Pearson 2c advance of Upsala Glacier. At Frías 2a event, ice probably overrode the older Holocene moraines including Pearson 1b and 1c equivalents.

### 7.9. *Frías delta area*

Evidence for glacier advances equivalent to Pearson 2a (<1130 ± 50 >755 ± 105 cal yrs BP) and 2b and/or 2c (<520 ± 15 cal years BP) were identified in this delta environment. A $^{14}$C age of 1130 ± 50 cal yrs BP (Figs. 13, 14) indicates retreat of Perito Moreno Glacier and the consequent lack of damming of Brazo Sur and Brazo Rico. A second $^{14}$C age of 755 ± 105 cal yrs BP provides a maximum-limiting age for flooding of Brazo Sur and is therefore linked to an advance of Perito Moreno Glacier during a Pearson-2a-equivalent glacier expansion. North of Frías 1, close to where the Tapado River empties into Brazo Sur, a highstand (i.e., Perito Moreno advances) occurred <520 ± 15 cal years BP (based on a basal peat age). Finally, a rooted tree that remains in the upper silty sediment layer, records a historical advance of Perito Moreno Glacier since A.D. 1917.

## 8. Regional and hemispheric Holocene glacier advances

Various Holocene glacial chronologies have been proposed for the southern Patagonian Andes. A synthesis of data from Mercer (1976, 1982), Clapperton and Sugden (1988), Aniya and Sato (1995), and those obtained in the current study are presented in Fig. 18.

The record proposed here for Holocene glacier fluctuations in the Lago Argentino basin matches well with the records produced by Mercer (1976) and Clapperton and Sugden (1988) but differs from the record of Aniya and Sato (1995). The main difference lies in the fact that Aniya and Sato (1995) replaced the first Neoglacial event at 6000–5000 cal yrs BP with a later event at ~3800 cal yrs BP. Aniya (2013) recently reviewed the Holocene chronology of both Patagonian Ice Fields, including an older

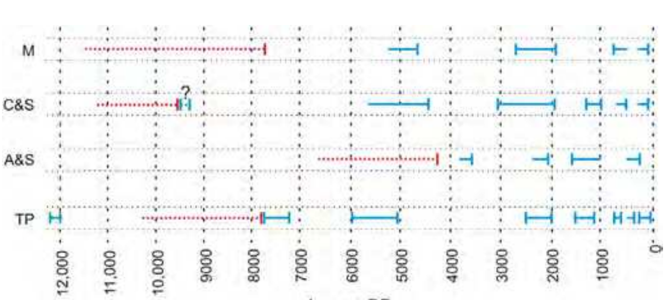


**Fig. 18.** **M**: Mercer (1976, 1982), **C&S**: Clapperton and Sugden (1988), **A&S**: Aniya and Sato (1995), and **TP**: this paper. Closed (blue in the on-line version) segments indicate well-bracketed glacier advances, dashed (red in the on-line version) segments indicate glacier recession.

advance during middle-Holocene time. Aniya and Sato's (1995) second Neoglacial advance, assumed to have resulted in construction of the Herminita moraines about 2300–2120 cal yrs BP, conflicts with the ages obtained by Mercer (1965) and also with the new $^{14}$C and $^{10}$Be ages obtained directly on the Herminita moraines themselves (Kaplan et al., 2011; Strelin et al., 2011). In some areas, we infer that differences between records may be due to climate more or less responsive glaciers, as we explain in Section 6; in some cases, the most extensive Holocene glacier advances recorded by moraines occurred between the 17th and 19th centuries (cf., Masiokas et al., 2009).

At Fachinal, on the southern side of Lago Buenos Aires-Lago General Carrera (46°S) (Fig. 1, inset), cosmogenic dating reveals glacier advances in middle-to-early-Holocene time (~7 ± 1 and >10 ka; Douglass et al., 2005 recalculated with the production rate in Kaplan et al., 2011). In Torres del Paine (Fig. 1, inset), located immediately south of Lago Argentino, proxy data derived from cores in peat bogs point to periods of glacier recession at 4100–2900, 2300–1300, and 1000–570 cal yrs BP (Moreno et al., 2009). In the Lago Dickson area, a close maximum-limiting age of 520 ± 35 cal yrs BP was obtained from a tree killed in the course of the latest glacier advance (Strelin, unpublished data). Moreover, in the same area, Marden and Clapperton (1995) inferred several glacier advances during the last few hundred years, based on a tree-ring chronology of moraine formation.

In Tierra del Fuego, a preliminary moraine chronology shows at least four Holocene glacier advances at >3300, ~1200, ~620, and 350 cal yrs BP to mid-20th century (Strelin et al., 2008). In addition, Strelin et al. (2008) noted an outboard moraine that may date to middle-or-early-Holocene time, or possibly even Lateglacial time.

On James Ross Island, Strelin et al. (2006) provided ages for three moraines of 7300–7100, 5700–4900, and <4100 cal yrs BP. In addition, there are three younger ice-cored moraines that remain undated (Strelin et al., 2006), located close to present-day glacier fronts, which are tentatively assigned to the late Holocene. Late Holocene deposits also have been identified in the South Shetland Islands, including a possible advance over the last 500–600 years (John and Sugden, 1971; Clapperton and Sugden, 1988; Hall, 2007; Simms et al., 2012).

Of particular interest, there is a notable difference between the Southern Alps of New Zealand, on the western side of the South Pacific Ocean (Schaefer et al., 2009; Putnam et al., 2010; Kirkbride and Winkler, 2012; Kaplan et al., 2013), and the Lago Argentino basin, on the eastern side, with regard to early Holocene glacial history. Our $^{14}$C and stratigraphic data indicate that glaciers near Lago Argentino were well retracted during this time. In contrast, in New Zealand's Southern Alps, early Holocene moraines were well outboard of present-day glacier termini. Thereafter, in both places, glacier events are recorded in the middle-Holocene and also within the last 600 years.

Future work will refine our knowledge of the events discussed here and the correlations with other regions in the Southern Hemisphere, as well as those in the Northern Hemisphere. For example, Mercer and Ager (1983) hypothesized that glacier expansions occurred at similar times between the hemispheres, including in the middle Holocene, but the relative magnitudes may have been different between areas.

## 9. Conclusions

a) Geomorphology, stratigraphy, and $^{14}$C and $^{10}$Be dating in the Lago Argentino area allow past climate events to be recognized. These events are recorded by glaciers with marked climate responses.

b) After the last Lateglacial minor readvance at 12,220 cal yrs BP, marked glacier recession occurred in the early Holocene either to, or even inboard of, present-day glacier termini.
c) Subsequently, glaciers advanced to maxima at 7700–7200, 6000–5000, 2500–2000, 1500–1100, ~700, >400, and <300 cal yrs BP.
d) During the Holocene, outlet glaciers in the Lago Argentino basin exhibited different frontal response to a similar climate signal. We assume this difference is mainly related to how ELA changes in the context of the glacier valley geometry (hypsometry). Future work will refine our chronology, providing an assessment of this assumption.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2014.06.026.

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