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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