Quaternary Science Reviews 133 (2016) 130–146

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

# Late Quaternary evolution of Lago Castor (Chile, 45.6°S): Timing of the deglaciation in northern Patagonia and evolution of the southern westerlies during the last 17 kyr

Maarten Van Daele [a, *], Sébastien Bertrand [a], Inka Meyer [a], Jasper Moernaut [b], Willem Vandoorne [a], Giuseppe Siani [c], Niels Tanghe [a], Zakaria Ghazoui [a, d], Mario Pino [b], Roberto Urrutia [e], Marc De Batist [a]

[a] Renard Centre of Marine Geology, Ghent University, Krijgslaan 281, S8, Gent, Belgium
[b] Instituto de Ciencias de la Tierra, Universidad Austral de Chile, Casilla 567, Valdivia, Chile
[c] GEOPS, UMR 8148 Université de Paris – Sud 11, Bâtiment 504, Orsay, France
[d] IsTerre, Institut des Sciences de la Terre, Université Joseph Fourier, BP 53 38041 Grenoble, France
[e] Centro EULA, Universidad de Concepción, Casilla 160-C, Concepción, Chile

A R T I C L E I N F O

*Article history:*
Received 25 August 2015
Received in revised form
22 December 2015
Accepted 23 December 2015
Available online 5 January 2016

*Keywords:*
Deglaciation
Patagonia
Westerlies
Seismic reflection
Sediment drift

A B S T R A C T

Even though Patagonia is ideally located to study climate of the southern mid-latitudes, many questions on the late Quaternary climate evolution remain unresolved. The timing of maximum glacier extent is still uncertain in vast areas, and the postglacial evolution of the Southern Westerly Wind Belt (SWWB) remains highly debated. Here, we study the sedimentary infill of a glacigenic lake (Lago Castor; 45.6°S, 71.8°W) located at the leeside of the Andes in Chilean Patagonia to i) reconstruct the deglacial evolution of the eastern flank of the Patagonian Ice Sheet (PIS), and ii) discuss postglacial changes in wind strength at a critical location where westerly wind records are critically lacking. A dense grid of high-resolution reflection-seismic data was used to reconstruct the large-scale infill history of the lake, and a radiocarbon dated sediment core penetrating all lacustrine seismic units, was retrieved. Results indicate that the deglaciation of the lake basin and its catchment occurred no later than ~28 cal kyr BP (i.e. an early LGM), but possibly even already after MIS 4. Afterwards, the Lago Castor area was covered by a large proglacial lake that drained – possibly through an outburst flood – when the PIS outlet glaciers retreated to a critical location. Subsequently, very dry conditions caused the lake to desiccate, as evidenced by an unconformity visible on the seismic profiles and in the sediment core. This dry period likely resulted from the increased orographic effect of the PIS-covered Andes, accompanied by weaker westerlies. From ~20 kyr BP onwards, the combination of a shrinking PIS and a southward shift of the SWWB resulted in increased precipitation, which caused the lake level to rise. After ~17 cal kyr BP, lake sedimentation was more directly influenced by the southern westerlies, with the formation of sediment drifts resulting from strong bottom current during periods of intense westerly winds. Our results suggest a progressive increase in wind strength at 46°S from 11.2 to 4.5 cal kyr BP, which supports the hypothesis that the SWWB broadened during the early and middle Holocene.



## 1. Introduction

Patagonia is ideally located to reconstruct the late Quaternary climate evolution of the southern mid-latitudes (e.g., Fogwill et al., 2015; Moreno et al., 2015). Yet, very few records exist that cover both the deglaciation and the postglacial period and many questions still remain regarding ice sheet retreat dynamics and the evolution of climate conditions across the region. It is now well known that during glacial periods the current North and South Patagonian Ice Fields were connected and formed one large Patagonian Ice Sheet (PIS) (Caldenius, 1932; Glasser et al., 2008). The exact extension of the PIS during the Last Glacial Maximum (LGM), especially between 43°S and 46°S, is however still under debate

* Corresponding author.
*E-mail address:* maarten.vandaele@ugent.be (M. Van Daele).

http://dx.doi.org/10.1016/j.quascirev.2015.12.021
0277-3791/

(Kaplan et al., 2004; Singer et al., 2004; Kaplan et al., 2005; Wenzens, 2006; Glasser et al., 2008). In addition, recent studies suggest that the timing of maximum extent of the Patagonian glaciers was not coeval with the global LGM at 23–19 cal kyr BP, but instead occurred during an early LGM, around 28 kyr BP (Sugden et al., 2005; Vandergoes et al., 2005; Glasser et al., 2008 and references therein; Fogwill et al., 2015). The exact timing of maximum extension of the PIS and its subsequent retreat remains, however, still under discussion, as the existing, mostly pollen-based, records from Patagonia rarely provide adequate information on the deglaciation rate and mode, mostly due to the lack of vegetation (sensitivity) during and immediately after the deglaciation (e.g., Markgraf et al., 2007; de Porras et al., 2012; Villa-Martínez et al., 2012; de Porras et al., 2014).

Another frequently debated topic in Patagonia is the postglacial evolution of the southern westerly wind belt (SWWB). It is generally accepted that between glacial and interglacial periods, the core of the SWWB latitudinally migrates by up to 10° in latitude, with a more equatorward position (~42°S) under cold glacial conditions, and a more poleward position (~52°S) during warm interglacials (Toggweiler et al., 2006; Ho et al., 2012; Kohfeld et al., 2013; Lamy et al., 2014). For the Holocene, two contradicting hypotheses have been put forward. Moreno et al. (2010) argue that the entire wind belt weakened during the early Holocene and strengthened afterwards, while Lamy et al. (2010) claim that the Holocene variations of the southern westerlies are caused by a contraction of the SWWB at the start of the Holocene followed by an expansion of the wind belt starting as early as 11 cal kyr BP. Resolving such issues is of crucial importance to understand global climate, especially since the southern westerlies influence atmospheric $CO_2$ concentrations through the ventilation of the southern ocean (Toggweiler et al., 2006).

Studying carefully selected sedimentary records that span the complete deglacial and post-glacial to Holocene time window may help in providing answers to these outstanding questions. Large, glacigenic lakes are known to hold such sedimentary records, and seismic-reflection studies of the basin morphology and sediment stratigraphy in such lakes can be used to reconstruct the deglacial history (e.g., Van Rensbergen et al., 1998; Heirman et al., 2011; Pinson et al., 2013; Ndiaye et al., 2014), especially when combined with sediment cores that can be absolutely dated. Lacustrine seismic-reflection and sediment core studies have also proven to be useful for studying wind intensity variations. Gilli et al. (2005), Anselmetti et al. (2009) and Heirman et al. (2012), for example, demonstrated that lacustrine sediment drifts were formed by the southern westerlies, and that they can be used to reconstruct paleowind intensity. Such a direct wind proxy is extremely valuable in Patagonia since most of the existing SWWB records are based on the positive relation between wind and precipitation (e.g., Lamy et al., 2010; Moreno et al., 2010), which may have changed through time, especially at the leeside of the Andes (Kilian and Lamy, 2012).

Here, we present results from a multiproxy reflection-seismic and sedimentological study of Lago Castor. Lago Castor (45.6°S, 71.8°W) is located on the leeside of the Andes in Chilean Patagonia and currently occupies one of the depressions that were carved during Quaternary glacier advances. According to Caldenius (1932), the lake was entirely covered by PIS outlet glaciers during the LGM. However, no landforms were dated in this area and recent geomorphological observations (Glasser et al., 2008) question whether the Lago Castor area was actually glaciated during the LGM. Its sedimentary infill was thus believed to contain a record potentially extending well into the Late Pleistocene. Finally, Lago Castor is also located in the suggested postglacial pathway of the SWWB.

The goal of this study is to reconstruct the deglacial and postglacial history of the lake and to contribute to a better understanding of the postglacial evolution of the SWWB, in a region were westerly wind reconstructions are crucially lacking.

## 2. Regional setting

### 2.1. Site description

Lago Castor (45.6°S; 71.8°W; 699 m asl) is located near the Chile-Argentina border on the leeside of the Patagonian Andes (Fig. 1b). The lake has a surface area of 4.5 km$^2$ and a relatively small catchment area of 21 km$^2$. It is located at an elevation of ~700 m and it is surrounded by hills that reach ~1030 m (i.e., ~330 m above lake level). Most of the lake watershed is vegetated by 'temperate deciduous forested scrubland of *Nothofagus antarctica* and *Berberis microphylla*' (Luebert and Pliscoff, 2006). Apart from some creeks, the lake has no major inflow. The outflow of the lake is located in its southwestern extremity. It drains towards Lago Pollux, and eventually to the Pacific Ocean through Aysén fjord (Fig. 1b), and thus drains towards the West even though it is located on the eastern flank of the Andes. Present-day precipitation around the lake is positively correlated to westerly wind speed (Fig. 1a), and changes in precipitation intensity over Lago Castor are therefore mostly related to the intensity of the southern westerlies. The lake has a maximum depth of 52 m (Urrutia et al., 2002), however, prior to this study, the lake bathymetry was largely unknown (Elbert et al., 2013). In December 2009, the lake was stratified (this study; thermocline at ~10 m), but in January 2009 it was mixed (Elbert et al., 2013). Hence, there is at present no consistent summer stratification – probably as a result of the strong westerlies – while during winter it is probably mostly mixed.

### 2.2. Geological setting

The lake catchment consists mainly of Cretaceous volcanic rocks (pyroclasts, rhyolites, dacites, andesites and basalts), as well as some intrusive and subvolcanic diorites, mainly in the western part. In the northwestern and northeastern part of the catchment the bedrock is covered by patches of Quaternary glacial deposits (De la Cruz et al., 2003). The entire lake watershed is blanketed by ~1 m thick postglacial volcanic ash soils (Gut, 2008; Vandekerkhove et al., 2016).

Lago Castor is also located at the latitude of the southern part of the Andean Southern Volcanic Zone (SVZ). The nearest active volcanoes are Cay, Macá and Hudson (Fig. 1b) (Naranjo and Stern, 1998, 2004). Hudson Volcano (45.9°S; 73.0°W) is the southernmost volcano of the SVZ and has caused some of the most explosive eruptions (e.g., H1 and H2 at 8.50–8.01 and 4.09–3.61 cal kyr BP, respectively, both with an estimated Volcanic Explosivity Index of 6) during the Holocene (Naranjo and Stern, 1998; Stern and Weller, 2012). The H2 tephra has a thickness of 5–10 cm in the study area, while H1 was deposited more towards the south (Fig. 1b) and was not encountered in the sedimentary records of small Chilean and Argentinian lakes in the vicinity of Lago Castor (Weller et al., 2015). Based on these lake records, Weller et al. (2014) recently described a large late-glacial eruption of Hudson volcano (Ho) at 17.44–17.30 cal kyr BP. The thicknesses of the Ho deposits in those lakes indicate that the Ho eruption was larger than any of the known post-glacial eruptions of Hudson Volcano. Stern et al. (2015) obtained an estimated age of ~18.82 cal kyr BP for a Hudson deposit in the Cisnes river valley, and interpreted it to be Ho.