Abstract: The Northern Patagonia Icefield (NPI) is the primary glaciated terrain worldwide at its latitude (46.5–47.5°S), and constraining its glacial history provides unique information for reconstructing Southern Hemisphere paleoclimates. The Colonia Glacier is the largest outlet glacier draining the eastern NPI. Ages were determined using dendrochronology, lichenometry, radiocarbon, cosmogenic 10Be and optically stimulated luminescence. Dated moraines in the Colonia valley defined advances at 13.2 ± 0.95, 11.0 ± 0.47 and 4.96 ± 0.21 ka, with the last being the first constraint on the onset of Neoglacialization for the eastern NPI from a directly dated landform. Dating in the tributary Cachet valley, which contains an ice-dammed lake during periods of Colonia Glacier expansion, define an advance at ca. 2.95 ± 0.21 ka, periods of advancement at 810 ± 49 cal a BP and 245 ± 13 cal a BP, and retreat during the intervening periods. Recent Colonia Glacier thinning, which began in the late 1800s, opened a lower-elevation outlet channel for Lago Cachet Dos in ca. 1960. Our data provide the most comprehensive set of Latest Pleistocene and Holocene ages for a single NPI outlet glacier and expand previously developed NPI glacial chronologies. Copyright © 2016 John Wiley & Sons, Ltd.

Keywords: Colonia Glacier; cosmogenic nuclides; glacial lake outburst flood; radiocarbon; Lago Cachet Dos.

Introduction

The Northern and Southern Patagonia Icefields (Fig. 1) form the largest continental ice mass in the world outside of Antarctica and Greenland (Loriaux and Casassa, 2013) and occupy the only terrain (except for very southern New Zealand) glaciated at their latitude during the Late Pleistocene and Holocene. Changes in the volume and extent of these icefields are tied closely to changes in climate (Glasser and Holocene, 2013). Changes in the volume and extent of these icefields are tied closely to changes in climate (Glasser and Holocene, 2013). Other important and unique temporal information on past climatic changes in the Southern Hemisphere. More generally, this void limits our understanding of Southern Hemisphere glacial history and our ability to corroborate reconstructed temperature records.

The Colonia valley (Figs 1 and 2) on the eastern side of the NPI contains glacial features that date back ca. 13 ka and thus provide an important constraint on Patagonia Icefield glacial history for the period between the LGM and the late 1800s. The Colonia Glacier, with an ice area of 288 km² in 2001, is the fifth largest of 24 main outlet glaciers (Fig. 1) draining the NPI (Rivera et al., 2001). Because it is the largest outlet glacier on the east side of the NPI and drains the central part of the icefield, the Colonia Glacier is probably a sensitive proxy of icefield changes. Glacial landforms in the valley have been mapped in the field (Tanaka, 1980; Harrison and Winchester, 2000) and from visible satellite imagery (Glasser et al., 2009, 2012), but dating has been restricted to landforms younger than ca. 150 years (Harrison and Winchester, 2000).

The rapid retreat of NPI outlet glaciers during the past century (Harrison et al., 2007; Davies and Glasser, 2012) has increased the area of proglacial lakes surrounding the NPI (Loriaux and Casassa, 2013) and, more importantly, the frequency of catastrophic glacial lake outburst floods (GLOFs) (Harrison et al., 2006; Dussaillant et al., 2010). Most of the known GLOFs originating from the NPI during the past century have occurred in the Colonia valley (Tanaka, 1980; Friesen et al., 2015). GLOFs result from the sudden and catastrophic drainage of supraglacial or proglacial lakes and present a significant hazard to human populations and infrastructure (Richardson and Reynolds, 2000). Thus, understanding the history and mechanisms of the GLOFs in the Colonia valley has both local and global implications. A better resolved chronology of Colonia Glacier advance and retreat is essential to future studies of Colonia valley GLOFs.

Studies in the Colonia valley were undertaken to identify glacial landforms and deposits and to collect data and samples suitable for improved constraint on the post-LGM glacial history of the NPI. Field studies focused on moraines...
in the Colonia valley proper (Fig. 2) and deposits and landforms in the tributary Cachet valley containing Lago Cachet Dos (Fig. 3), a lake currently dammed by the Colonia Glacier.

**Description of study area**

The Colonia valley extends east and north-east from the NPI to the Rio Baker (Fig. 1). The eastern 19-km reach of the valley is drained by the Río de la Colonia (henceforth abbreviated to Río Colonia), a braided glacial outwash river with a wide (≤3 km), largely unvegetated floodplain composed of fluvo-glacial sediment. The center reach of the valley contains Lago Colonia, an 8-km-long moraine-dammed lake (Fig. 4A). The 5-km reach upstream of the lake contains a sparsely vegetated outwash plain with the eroded remains of moraines (Fig. 4B) formed during the past ca. 150 years (Harrison and Winchester, 2000) and a proglacial lake at the terminus of the Colonia Glacier (Fig. 5G). The Colonia Glacier extends north-west 18 km from its terminus (elevation of ca. 200 m) to the base of an icefall (elevation of ca. 950 m), where this outlet glacier flows from the NPI.

The Colonia Glacier today and in the past created ice-dammed lakes in two valleys tributary to the Colonia valley. Both lakes have been intermittent through time depending on the position of the Colonia Glacier and its effectiveness as a dam. GLOFs are (or were) a feature of both ice-dammed lakes (Tanaka, 1980; Dussaillant et al., 2010). One of these ice-dammed lakes is the current Lago Cachet Dos in the Cachet valley (Fig. 2). The second lake formed in the Arco valley on the south side of the Colonia valley (Fig. 5G) when the Colonia Glacier abutted the north flank of Cerro Colonia. This paleo Lago Arco existed during much of the 20th century and was larger than the present-day moraine-dammed Lago Arco shown in Fig. 2 (Tanaka, 1980). GLOFs from paleo Lago Arco occurred from before 1930 to 1968 (Tanaka, 1980), while GLOFs from Lago Cachet Dos started in 2008 (Dussaillant et al., 2010). Our field studies included the Cachet valley because determining previous fluctuations in the size and
extent of Lago Cachet Dos provides one way to constrain the chronology of Colonia Glacier advance and retreat.

**Methods**

Field studies were conducted during austral summers 2011/12 and 2012/13. Sample sites were located using a hand-held GPS with stated accuracy of <15 m using Universal Transverse Mercator projection, zone18S World Geodetic System of 1984 (WGS84). Dendrochronology and lichenometry ages are reported as calendar ages. Terrestrial cosmogenic nuclide (10Be) and optically stimulated luminescence (OSL) ages are reported as calendar years before publication date. Radiocarbon ages are reported as calendar-calibrated years before present (BP, with present = 1950) calculated from the conventional radiocarbon age, the SHCAL13 database (Hogg et al., 2013), and the 1-sigma error band.

Dendrochronological ages (Table 1) were determined from cores collected from live trees using an increment borer. Cores were mounted in the laboratory, and tree rings were counted using a stereoscopic microscope. Missing rings for cores not containing the tree center were estimated using the methodology of Duncan (1989). The growth rate for each tree for the section below coring height and ecesis were assumed to be 11.7 cm a⁻¹ and 26 a, respectively, based on previous work in the Colonia valley (Winchester and Harrison, 2000).

Lichenometric ages (Table 1) were determined at six sites near a cored live tree. The longest diameter of 3–5 of the largest individual lichens (*Placopsis perrugosa*) on boulders at each site were measured (Fig. 5E). A lichen growth rate of 4.7 mm a⁻¹ (which incorporates the colonization period) was assumed based on previous work in the Colonia valley (Winchester and Harrison, 2000). The mean age for the three largest lichens at each live-tree site was used for the site.

10Be surface-exposure ages (Table 2) were determined for samples collected from the top of upward-facing surfaces of boulders (with a b-axis >1 m where possible) on lightly vegetated moraine crests using hammer and chisel (Fig. 4C) according to techniques from Gosse and Phillips (2001). Some boulders had a thin layer of moss or lichen, which was removed before sampling. Topographic shielding was estimated from skyline measurements made with an Abney level. Physical preparation, quartz purification, dissolution and conversion into beryllium oxide, and 10Be analyses were performed by the Purdue Rare Isotope Measurement Laboratory (West Lafayette, IN, USA). All 10Be/9Be ratios were measured against the revised ICN standard of Nishiizumi et al. (2007), which assumes a half-life of
1.36 Ma. The $^{10}\text{Be}/^{9}\text{Be}$ ratio ($2.84 \times 10^{-15} \pm 0.57 \times 10^{-15}$) of the processing blank prepared with the samples was subtracted from the $^{10}\text{Be}/^{9}\text{Be}$ ratios of the samples. $^{10}\text{Be}$ exposure ages were calculated with the CRONUS-Earth calculator (Balco et al., 2008) using a quartz density of 2.73 g cm$^{-3}$, topographic shielding listed in Table 2, the Dunai time-dependent scaling scheme and production rates from Lago Argentino in Patagonia (Kaplan et al., 2011). We applied no corrections for erosion rate or snow shielding (Gosse and Phillips, 2001), and these assumptions should not affect our conclusions. Similarly, use of alternative scaling schemes (Balco et al., 2008) resulted in age differences of <3% and therefore would not affect our conclusions. To facilitate comparisons, we recalculated the ages reported by Glasser et al. (2012) for nearby sites (Fig. 1) using the same scaling scheme, production rates and erosion rate listed above.

Figure 3. Satellite image of Cachet valley showing trimlines, deltaic deposits and sampling sites. Ages shown in parentheses are from either dendrochronology or dendrochronology/lichenometry (Table 1). Trimlines and 2007 Lago Cachet Dos boundary are from Friesen et al. (2015). Elevation of lacustrine trimline is ca. 500 m. Image produced from DigitalGlobe WorldView-2 data collected on 13 February 2014, 12 days after a GLOF emptied Lago Cachet Dos.
Table 1. Ages for live trees and lichens sampled on the east side of Lago Cachet Dos in October 2011. The age of individual trees (Nothofagus sp.) and the mean age of the three largest lichens (Placopsis perrugosa) at each site are reported.

| Sample number | Latitude (°S) | Longitude (°W) | Elevation (m) | Tree diameter (cm) | Tree species | Tree Age (AD) | Lichen Age (AD) |
|---------------|---------------|----------------|----------------|-------------------|--------------|---------------|-----------------|
| Ltree1        | 47.12101      | 73.28293       | 497            | *                 | coigue†      | 1945          | –               |
| Ltree 2       | 47.14917      | 73.25912       | 421            | 30                | coigue       | 1957          | –               |
| Ltree 3       | 47.14896      | 73.25845       | 463            | 29                | coigue       | 1948          | –               |
| Ltree 4       | 47.14861      | 73.25761       | 492            | 29                | coigue       | 1950          | –               |
| Ltree 6       | 47.17070      | 73.25750       | 432            | 15                | coigue       | 1964          | 1965            |
| Ltree 7       | 47.17048      | 73.25708       | 453            | 27                | coigue       | 1963          | 1957            |
| Ltree 8       | 47.17049      | 73.25687       | 459            | 25                | coigue       | 1957          | –               |
| Ltree 10      | 47.17785      | 73.25252       | 440            | 17                | lenga        | 1955          | 1960            |
| Ltree 11      | 47.17679      | 73.25439       | 478            | 14                | lenga        | 1948          | 1963            |
| Ltree 13      | 47.18653      | 73.25117       | 452            | 18                | coigue       | 1959          | 1958            |
| Ltree 14      | 47.18657      | 73.24949       | 479            | 18                | nirre§       | 1953          | –               |
| Ltree 16      | 47.19241      | 73.24306       | 486            | 15                | nirre        | 1947          | –               |
| Ltree 17      | 47.19448      | 73.24134       | 479            | 21                | coigue       | 1964          | –               |

†Nothofagus betuloides.
‡Nothofagus pumilio.
§Nothofagus antarctica.

Burial ages based on optical dating (Table 3) were determined for sediment samples collected in 5-cm-diameter by 15-cm-long PVC core tubes inserted horizontally into shaded and freshly excavated vertical surfaces. Quartz and potassium feldspar grains (180–250 μm) were analysed by single aliquot regeneration (Murray and Wintle, 2000, 2003) using continuous-wave OSL and continuous-wave infrared stimulated luminescence (IRSL), respectively. Luminescence data were subject to community standard quality-control tests including the recycling-ratio and dose-recovery tests (Rhodes, 2011). Additional information on OSL dating is given in supplementary Appendix S1.

Radiocarbon ages (Table 4) were determined for samples of outer tree rings collected using a handsaw from eight in situ dead trees exposed on the Cachet valley floor during post-GLOF periods. In addition, one sample was collected from the center of one of the trees and another from a paleo-soil excavated beneath an in situ tree. Radiocarbon analyses were performed by Beta Analytical (Miami, FL, USA) using gas proportional counting for tree-ring samples and accelerator mass spectrometry for the soil sample. Samples were pre-treated using sequential acid/alkali/acid washes. Calendar-calibrated ages were calculated using OxCal 4.2.4 software (Bronk Ramsey, 2009) and SHCAL13 database (Hogg et al., 2013).

Results

Glacial landforms and deposits

Cerro Colonia lateral moraine

A lateral moraine on the northern flank of Cerro Colonia (Figs 2 and 5G) probably records the confinement of large glaciers descending the Arco and Colonia valleys. The moraine is ca. 300 m long, 40 m wide and 10 m high. The rounded moraine crest slopes down valley and ranges in elevation between ca. 910 and 930 m, far above the modern Colonia Glacier terminus at ca. 200 m. Sparse rounded boulders on or near the crest have diameters of ca. 1 m and are composed of fine- to coarse-grained granite or gneiss (Fig. 5H).

Lago Colonia terminal moraine and outwash terraces

The Lago Colonia terminal moraine that dams Lago Colonia (Figs 2 and 4A) was first identified by Tanaka (1980), who named it Colonia Moraine No. 1 and estimated it to be 2.8 km long, 1.5 km wide and as much as 85 m in height above Lago Colonia. The moraine crest ranges in elevation between ca. 190 and 210 m. Numerous granitic boulders 2–5 m in length litter the moraine surface (Fig. 4C). Based on observation of the expansive north-facing slope cut through the moraine by the Río Colonia (Fig. 4E), the moraine is underlain by massive diamicton. Several outwash terraces, which are at successively lower elevations and underlain primarily by coarse-grained gravel and sand, extend downstream from the moraine (Figs 2 and 4E). OSL samples were collected from a loess deposit of silt and fine-to-coarse sand near the top of the moraine (Fig. 4D) and from a medium sand lens near the top of the uppermost terrace (Fig. 4F).

Río Claro lateral moraine

The lateral moraine at the mouth of the Río Claro valley (Figs 2 and 4G) was first identified by Tanaka (1980), who named it Colonia Moraine No. 2. The moraine is ca. 200 m high, and its crest, which is more rounded than the crest of the Lago Colonia terminal moraine, ranges in elevation between ca. 350 and 380 m. Semi-rounded granitic boulders on the moraine crest are as large as 2 m in diameter (Fig. 4H).
advances and retreats. A lower outlet at the south-east corner of the lake (Fig. 3) limits the lake’s maximum level to an elevation of ca. 420 m. A trimline at an elevation of ca. 500 m on both sides of the Colonia valley (Figs 3 and 5C) is demarcated by a dense and mature forest above the trimline and an immature and openly spaced forest of smaller diameter trees below the trimline (Friesen et al., 2015). The lateral extent and horizontal nature of this trimline indicate that it was formed during a high stand of Lago Cachet Dos and that, at that time, the lake extended from the Colonia Glacier to the modern boundary of Lago Cachet Uno. Downstream and near the south-east corner of Lago Cachet Dos, this lacustrine trimline extends to an abandoned upper outlet channel (ca. 500 m) that controlled the former 500-m level of Lago Cachet Dos. Near the south-west end of the lake, the lacustrine trimline grades into a glacial trimline that extends to the west up the Colonia valley (Figs 2 and 3). In the upper Cachet valley, the lacustrine trimline grades into another glacial trimline (Fig. 3), which rises up-valley on both sides of Lago Cachet Uno (Friesen et al., 2015). Based on
Before the onset of GLOFs in 2008, the Cachet valley between Lago Cachet Uno and the Colonia Glacier contained a flat valley floor and the braid plain of the Río Cachet over its upstream half while Lago Cachet Dos, at its 420-m level, filled the downstream half (Friesen et al., 2015). Large-scale age-dating of similar trimlines in and near the Arco valley (Fig. 5G; Harrison and Winchester, 2000), these glacial trimlines probably demarcate the maximum late-1800s extent and thickness of the Colonia and Cachet Glaciers, respectively.

Before the onset of GLOFs in 2008, the Cachet valley between Lago Cachet Uno and the Colonia Glacier contained a flat valley floor and the braid plain of the Río Cachet over its upstream half while Lago Cachet Dos, at its 420-m level, filled the downstream half (Friesen et al., 2015). Large-scale
Table 2. 10Be surface-exposure ages calculated using the CRONUS-Earth webcalculator (Balco et al., 2008) for boulders sampled in March 2013.

| Sample no. | Latitude (°S) | Longitude (°W) | Elevation (m) | Sample thickness (cm) | Topo-graphic shielding | Quartz sample mass (g) | 10Be/9Be (x 10^−15) | 10Be (10^5 atoms g^−1) | 10Be exposure age†‡ (a) | Internal uncertainty§ (a) | External uncertainty¶ (a) |
|------------|---------------|----------------|---------------|-----------------------|------------------------|-----------------------|-----------------------|-------------------------|-------------------------|--------------------------|--------------------------|
| LCM5       | 47.34680      | 73.12182       | 189           | 1                     | 0.9852                 | 134.097               | 2.6255                 | 187.49 ± 4.90          | 0.242                   | 5130                     | 140                      | 220                      |
| LCM6       | 47.34743      | 73.12151       | 212           | 1                     | 0.9824                 | 37.797                | 0.26319               | 50.81 ± 3.10           | 0.223                   | 4650                     | 310                      | 340                      |
| LCM7       | 47.34809      | 73.12068       | 206           | 1                     | 0.9813                 | 124.976               | 0.26607               | 170.20 ± 5.62          | 0.238                   | 4990                     | 170                      | 240                      |
| LCM8       | 47.34545      | 73.11213       | 194           | 1                     | 0.9911                 | 42.799                | 0.26618               | 60.93 ± 3.67           | 0.241                   | 5060                     | 320                      | 370                      |
| LCM9       | 47.34680      | 73.12182       | 189           | 1                     | 0.9852                 | 134.097               | 2.6255                 | 187.49 ± 4.90          | 0.242                   | 5130                     | 140                      | 220                      |
| LCM10      | 47.34743      | 73.12151       | 212           | 1                     | 0.9824                 | 37.797                | 0.26319               | 50.81 ± 3.10           | 0.223                   | 4650                     | 310                      | 340                      |
| LCM11      | 47.34809      | 73.12068       | 206           | 1                     | 0.9813                 | 124.976               | 0.26607               | 170.20 ± 5.62          | 0.238                   | 4990                     | 170                      | 240                      |
| LCM12      | 47.34545      | 73.11213       | 194           | 1                     | 0.9911                 | 42.799                | 0.26618               | 60.93 ± 3.67           | 0.241                   | 5060                     | 320                      | 370                      |

10Be isotope ratios normalized to 10Be standards prepared by Nishiizumi et al. (2007).
†A blank value of 10Be/9Be = 2.84 × 10^−15 ± 0.57 × 10^−15 used to correct for background.
‡ Using 0 mm ka^−1 steady-state erosion, time-dependent scaling scheme (Dunai, 2001) and Kaplan et al. (2011) production rate in the CRONUS-Earth calculator (Wrapper script 2.2; Main calculator 2.1; constants 2.2.1; muons 1.1). The mean ± one standard deviation of ages for all samples is shown for each site.
§ One sigma analytical uncertainty.
¶ One sigma analytical uncertainty plus the uncertainty of the production rate.
erosion of the Cachet valley floor during and after each of the 15 GLOFs that occurred in 2008–2014 removed a substantial volume of sediment from the valley floor (Friesen et al., 2015). This erosion exposed the stratigraphy of the valley fill (e.g., Fig. 5A) and unearthed hundreds of in situ, upright trees (Fig. 5C, D) that presumably grew on the valley floor during an episode of delta formation in a paleo Lago Cachet Dos. IRSL analyses obtained using high-purity germanium gamma spectrometry. Errors obtained with calibration standards.

### Table 3. Single aliquot regeneration quartz OSL and potassium feldspar IRSL data and ages for samples collected in March 2012.

| Sample number | OSL1 | OSL5 | OSL6 |
|---------------|------|------|------|
| **Sample description** | Deltaic sand from Lago Cachet Dos lakebed | Loess from near top of Lago Colonia terminal moraine | Fluvial sand from near top of highest outwash terrace downstream of Lago Colonia terminal moraine |
| **Latitude (ºS)** | 47.15723 | 47.34314 | 47.34218 |
| **Longitude (ºW)** | 73.25925 | 73.10860 | 73.10301 |
| **Elevation (m)** | 423 | 187 | 127 |
| **Water content (%)** | 3.33 ± 0.07 | 2.75 ± 0.06 | 2.28 ± 0.05 |
| **U (ppm)** | 1.21 ± 0.16 | 2.58 ± 0.28 | 1.88 ± 0.28 |
| **Th (ppm)** | 6.54 ± 0.37 | 12.3 ± 0.61 | 11.2 ± 0.40 |
| **Cosmic dose (Gy/kg)** | 0.18 ± 0.01 | 0.17 ± 0.01 | 0.18 ± 0.01 |
| **Total dose rate (Gy/ka)** | 3.97 ± 0.11 | 5.74 ± 0.19 | 4.56 ± 0.13 |
| **Equivalent dose (Gy)** | 11.7 ± 0.75E4 | 27.0 ± 1.1E3 | 12.7 ± 1.5E3 |
| **n** | 9 (37)F | 12 (46)F | 10 (35)F |
| **Scatter (%)** | 42E1 | 92E1 | 122E1 |
| **Age (ka)** | 2.950 ± 210E3 | 4.700 ± 230E3 | 2.790 ± 140E3 |

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1Field moisture, with figures in parentheses indicating the complete sample saturation percentage. Dose rate calculated using 50% of the saturated moisture [i.e. 3 (15) = 15 × 0.50 = 7.5].

2Analyses obtained using high-purity germanium gamma spectrometry. Errors obtained with calibration standards.

3Cosmic doses and attenuation with depth were calculated using the methods of Prescott and Hutton (1994).

4Number of replicated equivalent dose (D_e) estimates used to calculate the overall D_e. Figures in parentheses indicate total number of measurements used for the minimum age model of RadialPlotter and a sigma-b value of 0.2 (Vermeesch, 2014; Galbraith, 2010).

5Obtained from RadialPlotter (Vermeesch, 2014). Samples with values >35% are considered to be poorly bleached.

6Dose rate and age for 180–250µm grains using single aliquot regeneration (Murray and Wintle, 2000, 2003). Exponential fit used on equivalent dose; errors to one sigma.

7Equivalent dose measurements obtained using continuous wave OSL (Murray and Wintle, 2000) on quartz grains.

8Equivalent dose measurements obtained using continuous-wave on potassium feldspar grains as post-IR IRSL.

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### Table 4. Radiocarbon ages for wood and soil samples collected in October 2011 or February 2012. Data for samples Tree 10 to Tree 1 are shown in downstream-to-upstream order in the Cachet valley. Tree samples were collected from outer rings except sample Tree 10B, which was collected from the center of Tree 10.

| Sample no. | Lab. no.       | Latitude (°S) | Longitude (°W) | Conventional radiocarbon age\(^*\) (\(^{14}\)C a BP) | 2-sigma calendar calibrated age\(^*\) | Mean age\(^*\) (cal a BP) |
|------------|----------------|---------------|----------------|---------------------------------|---------------------------------|---------------------|
| Soil11     | Beta-323914    | 47.15896      | 73.26090       | 1130 ± 30 BP                     | AD 890–1020                     | 995 ± 38             |
| Tree11     | Beta-323917    | 47.15896      | 73.26090       | 920 ± 30 BP                      | AD 1045–1090                    | 790 ± 47             |
| Tree18     | Beta-388185    | 47.15860      | 73.26083       | 950 ± 30 BP                      | AD 1040–1210                    | 830 ± 50             |
| Tree10B    | Beta-323916    | 47.16277      | 73.25856       | 400 ± 30 BP                      | AD 1450–1630                    | 410 ± 55             |
| Tree10     | Beta-323915    | 47.16277      | 73.25856       | 120 ± 30 BP                      | AD 1695–1725                    | 240 ± 12¥            |
| Tree15     | Beta-323920    | 47.15463      | 73.26070       | 90 ± 30 BP                       | AD 1695–1725                    | 240 ± 10§            |
| Tree14     | Beta-323919    | 47.15031      | 73.26047       | 190 ± 30 BP                      | AD 1665–1815                    | –§                   |
| Tree13     | Beta-323918    | 47.14608      | 73.26327       | 170 ± 30 BP                      | AD 1670–1745                    | 245 ± 19§            |
| Tree6      | Beta-309533    | 47.13951      | 73.26810       | 90 ± 30 BP                       | AD 1695–1725                    | 240 ± 10§            |
| Tree1      | Beta-309531    | 47.13400      | 73.27161       | 210 ± 30 BP                      | AD 1650–1710                    | 270 ± 13§            |

\(^*\)Radiocarbon years before present with ‘present’ = 1950. The conventional radiocarbon age represents the measured radiocarbon age corrected for isotopic fractionation calculated using the measured \(^{13}\)C/\(^{12}\)C ratio.

\(^\dagger\)Calculated using OxCal 4.2.4 software (Bronk Ramsey, 2009) and SHCAL13 database (Hogg et al., 2013) from the conventional radiocarbon age.

\(^\dagger\)Mean age calculated for only the earliest calendar-calibrated age range.

\(\dagger\)Mean age not calculated.

calibrated ages (AD 1650–1950, or 0–300 cal a BP). Owing to this age overlap and the large spatial spread of the sampled trees along much of the longitudinal axis of the Cachet valley (Fig. 3), these trees were probably killed nearly simultaneously by inundation when Lago Cachet Dos last formed, probably as the Colonia Glacier thickened en route to its late-1800s maximum. The possible age of these trees can be narrowed to the earliest part of the 1650–1950 period by assuming that Lago Cachet Dos was probably created >100 years before the late-1800s maximum. This assumption is reasonable considering that the lake has continued to exist >100 years after the late-1800s maximum even in the face of substantial post-late-1800s retreat of the Colonia Glacier (Harrison and Winchester, 2000; Davies and Glasser, 2012). Five of the six trees have a distinct calibrated age range before 1750 (>100 years before the late-1800s maximum); the mean of these ranges (245 ± 13 cal a BP) is considered the most plausible age for the formation of Lago Cachet Dos.

**Dendrochronology and lichenometry ages for Lago Cachet Dos trimline**

The age of the lacustrine trimline that encircles much of Lago Cachet Dos at an elevation of ca. 500 m was bracketed from its appearance in aerial photographs and estimated using dendrochronology and lichenometry. The 500-m lake was at this trimline elevation in 1945, based on a map compiled by Lliboutry (1998, fig. 27) from aerial photographs. By 1975, Lago Cachet Dos had lowered to the 420-m level (Fig. 2) based on the 1: 50,000 Cordón Soler quadrangle (published in 1982 by the Instituto Geográfico Militar de Chile and based on 1975 aerial photographs). Based on our dendrochronological and lichenometric ages, the lake level dropped to its current 420-m position in ca. 1960. Tree-ring cores from 13 live trees located below the lacustrine trimline provided ages between 1945 and 1964, with a mean of 1955 (Table 1). Ages based on the mean of the three largest lichens at the five live-tree sites where lichens were measured ranged from 1957 to 1965, with a mean of 1961 (Table 1).

**Discussion**

**Chronology of Colonia Glacier advance and retreat**

During the LGM, the Colonia Glacier filled the Colonia valley, coalesced with other NPI outlet glaciers, flowed eastward and formed moraine systems in Argentina (Kaplan et al., 2004; Singer et al., 2004). The LGM occurred at 27–25 ka with subsequent advances at 23–22, 20–18 and ca. 18–17 ka; rapid deglaciation from the LGM moraines began after 18–17 ka (Hein et al., 2010; Boex et al., 2013). During deglaciation but while the Río Baker’s path to the Pacific Ocean was still dammed by the retreating outlet glaciers, paleo lakes formed with surface elevations of ca. 489–512 m and later at ca. 375–397 m near the Nef and Colonia valleys; the Río Baker finally drained to the Pacific Ocean at ca. 12.8 ka (Turner et al., 2005).

The earliest evidence for a post-LGM ice position of the Colonia Glacier is the Cerro Colonia lateral moraine high on
the north flank of this mountain. Dated to 13.2 ± 0.95 ka (Table 2), this moraine records the most extensive Colonia Glacier position that has been found within the Colonia valley proper and the position held just before the initiation of westward Río Baker drainage at ca. 12.8 ka (Turner et al., 2005). The Río Claro lateral moraine also records a distant downvalley advance or perhaps stabilization during post-LGM retreat of the Colonia Glacier at 11.0 ± 0.47 ka. No terminal moraine associated with either the Cerro Colonia or the Río Claro lateral moraines has been identified, but the moraine mounds at Lago Esmeralda (site LE, Fig. 1) dated by $^{10}$Be at 12.0 ± 0.75 ka (Glasser et al., 2012) may indicate an approximately contemporaneous downstream limit.

Although we found no evidence for early Holocene activity for the Colonia Glacier, evidence for advance and retreat during the Neoglacial (Porter and Denton, 1967) is relatively abundant. In the early Neoglacial, the Colonia Glacier advanced and created the terminal moraine at Lago Colonia at 4.96 ± 0.21 ka. The IRSL age (4.70 ± 0.23 ka, sample OS5L, Table 3) for the loess from the top of the Lago Colonia terminal moraine is a minimum age for formation of this moraine and is consistent with the $^{10}$Be age.

Information on more recent Colonia Glacier activity comes from the Cachet valley, which has a multi-million-year record of alternating periods of the valley either containing a lake during periods of an advanced and thickened Colonia Glacier or being forested during periods of stable fluvial drainage, probably when the glacier was smaller than it is today. The oldest deltaic-sand sample (OSL1, Table 3) indicates a Colonia Glacier advance that created a paleo Lago Cachet Dos at or before 2.95 ± 0.21 ka. No terminal moraine associated with this advance has been identified. However, the fluvial sand from the upper outwash terrace of the Lago Colonia terminal moraine (2.79 ± 0.34 ka, sample OSL6, Table 3) also dates to this period and suggests that the Colonia Glacier may have readvanced as far down valley as this moraine. Sometime after 2.95 ± 0.21 ka, but before 995 ± 38 cal a BP, the glacier retreated and the paleo Lago Cachet Dos disappeared, allowing soil development (sample Soil11) on the valley floor. However, the lake may have been re-dammed at 810 ± 49 cal a BP (mean of ages for outer-ring samples from Tree 18 and Tree 11, Table 4) assuming these two trees were killed by inundation. If a paleo Lago Cachet Dos did form at 810 ± 49 cal a BP, it had disappeared by 410 ± 55 cal a BP based on the radiocarbon sample from the center of Tree 10, and the valley floor was again forested.

At 245 ± 13 cal a BP (Fig. 5C), thickening of the Colonia Glacier dammed the Cachet valley forming a lake, presumably with a water level of ca. 420 m controlled by the current outlet channel for Lago Cachet Dos. Sometime later but probably before the late-1800s maximum, continued advance of the Colonia Glacier into the Cachet valley sealed the lower outlet channel. This event allowed the lake level to rise to the elevation of the upper outlet channel at ca. 500 m. This continued advance of the Colonia Glacier reached a maximum, recorded by glacial trimlines (Fig. 5G) and remnants of a terminal moraine (Fig. 4B) ca. 5 km downstream from the current terminus, dated to 1850–1880 (Harrison and Winchester, 2000). Between the late-1800s maximum and 1996, the Colonia Glacier terminus retreated ca. 1.5 km (Harrison and Winchester, 2000; Fig. 2). Only small and isolated remnants of the late-1800s terminal moraine and post-late-1800s recessional moraines remain downstream of the current Colonia Glacier terminus, probably because of erosion by numerous GLOFs during the past century from the Arco and Cachet valleys. GLOFs from the Arco valley stopped occurring in 1968 presumably because retreat of the Colonia Glacier away from the northern flank of Cerro Colonia removed the dam.

By ca. 1960, retreat of the Colonia Glacier from the Cachet valley uncovered the lower outlet channel for Lago Cachet Dos at ca. 420 m, and the lake abandoned its previous 500-m level. Between 1966 and 2013, the Colonia Glacier terminus retreated another ca. 1.5 km, and the individual proglacial lakes in the Arco and Colonia valleys (Fig. 5G) joined to form a single larger proglacial lake in 2014 (Fig. 2). GLOFs from Lago Cachet Dos started in 2008 probably due to thinning and weakening of the Colonia Glacier, thus allowing the lake to drain catastrophically via meltwater channel(s) within or beneath the 8-km terminal reach of the glacier (Dussaillant et al., 2010).
Advances of outlet glaciers draining the Northern Patagonia Icefield. Patagonia Icefield Neoglacial advances (hatched areas) are from Aniya (2013) and advances from Strelin et al. (2014) for the Lago Argentino area on the eastern side of the Southern Patagonia Icefield (horizontal grey bars) are shown for comparison. Ages derived from $^{14}$C (triangles), $^{10}$Be (circles), OSL (diamonds), dendrochronology or lichenometry (squares), or sedimentological and geochemical analysis of fjord sediment (dashed horizontal line). Colored symbols are for moraines. Open symbols are for other indicators of ice position. One-sigma error band is shown by a solid horizontal line (which is within the size of symbols for $^{14}$C ages). Plotted $^{14}$C ages were recalculated using OxCal 4.2.4 software (Brong Ramsey, 2009) and SHCAL13 database (Hogg et al., 2013) from original data reported in 14C a BP. Plotted $^{10}$Be ages were recalculated using CRONUS-Earth calculator (Balco et al., 2008), production rates from Kaplan et al. (2011), and no erosion. Data references: San Rafael Glacier (Winchester and Harrison, 1996; Harrison et al., 2012), Gualas Glacier (Harrison and Winchester, 1998; Bertrand et al., 2012), Exploradores Glacier (Glasser et al., 2007; Aniya et al., 2007), Leones Glacier (Harrison et al., 2008; Glasser et al., 2012), Soler Glacier (Sweda, 1987; Aniya and Naruse, 1999; Glasser et al., 2002, 20122012), Nef Glacier (Winchester et al., 2001; Glasser et al., 2012) and Colonia Glacier (Harrison and Winchester, 2000; this study).

dated at 5.7 ± 0.6 ka (Harrison et al., 2012) and the Colonia Glacier dated at 4.96 ± 0.21 ka (Table 2) and 4.70 ± 0.23 ka (Table 3). No other glacial features on either side of the NPI have been dated to this period. Their timing coincides with the Strelin et al. (2014) age for an SPI advance at 5000–6000 cal a BP and is similar to the Aniya (2013) age for Neoglacial I (5130–4430 cal a BP, Table 5).

The record compiled to date for the main part of the Neoglacial (Fig. 6) does not indicate broad regional patterns for NPI and vicinity. The oldest advances include the terminal moraine in the Leones valley dated to ca. 3.3–2.4 ka by Harrison et al. (2008) and deltaic sediment in the Cachet valley indicating a Colonia Glacier advance at ca. 2.95 ± 0.21 ka (Table 3). These events broadly coincide with advances dated to 2500–2000 cal a BP for the SPI (Strelin et al., 2014) and the Aniya (2013) age for Neoglacial III (2770–1910 cal a BP, Table 5). Similarly, reported ages for advances in a few eastside NPI valleys coincide with SPI advances dated to 1500–1100 and ca. 700 cal a BP (Strelin et al., 2014) and the Aniya (2013) age for Neoglacial IV (1450–750 cal a BP, Table 5). These advances of the NPI are recorded by moraines dated at 814–657 cal a BP for the Exploradores Glacier (Aniya et al., 2007), 1210 cal a BP (Aniya and Naruse, 1999) and 721–507 cal a BP (Glasser et al., 2002) for the Soler Glacier, and before 580 cal a BP for the Nef Glacier (Winchester et al., 2001). In addition, radiocarbon data indicate possible inundation of trees in the Cachet valley caused by an advancing Colonia Glacier at 810 ± 49 cal a BP (Table 2). Lastly, sedimentological and geochemical analysis of fjord sediment indicates three advance/retreat cycles of the Gualas Glacier at 4180–850 cal a BP (Bertrand et al., 2012).

The best documented regional advance of NPI outlet glaciers occurred at 350–50 cal a BP (Aniya, 2013; Strelin et al., 2014), a period commonly referred to as the Little Ice Age. Although advances early in this period have been reported for several SPI outlet glaciers (Strelin et al., 2014), only our 245 ± 13 cal a BP radiocarbon age indicating an advancing Colonia Glacier provides similar temporal evidence. Conversely, contemporaneous advances to late-1800s maximum positions are a common feature of almost all studied NPI outlet glaciers: seven shown in Fig. 6 and five others listed in Masiokas et al. (2009). After the late-1800s, retreat of and volume loss from all NPI outlet glaciers has been comparable (Rivera et al., 2007; Masiokas et al., 2009; Davies and Glasser, 2012).

**Conclusion**

The post-LGM glacial history of the NPI has become better known over the past 30 years owing to the many field expeditions that have studied some, but not all, of the outlet glaciers draining the NPI. Our study adds to this growing body of information by providing ages covering ca. 13 ka for the Colonia valley, where glacial history before the late-1800s maximum had not been well known. The glacial record for the Colonia valley developed during our study is the most complete post-LGM record for any of the NPI outlet glaciers and is particularly important because the Colonia Glacier is the largest outlet glacier draining the eastside NPI.

Possible advances of the Colonia Glacier were recognized at 13.2 ± 0.95, 11.0 ± 0.47 and 4.96 ± 0.21 ka based on $^{10}$Be ages for moraines, and 2.95 ± 0.21 ka based on an OSL age for deposition of deltaic sediment in an ice-dammed lake in the tributary Cachet valley. In addition, minimum ages (810 ± 49 and 245 ± 13 cal a BP) were established for the start of the advances leading to maximum positions during Neoglacial IV and V, respectively, based on radiocarbon dates for trees presumed killed by creation of the ice-dammed lake in the Cachet valley. Overall, this study supports and provides additional definition of the developing history of post-LGM glacial events associated with the NPI.

**Supporting Information**

Additional supporting information may be found in the online version of this article.

The following appendix is available within the Wiley Online Library.

**Appendix S1.** Supplementary information on luminescence dating.

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Abbreviations. GLOF, glacial lake outburst flood; IRS, infrared stimulated luminescence; LGM, Last Glacial Maximum; NPI, Northern Patagonia Icefield; OSL, optically stimulated luminescence; SPI, Southern Patagonia Icefield.

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