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Glaciar León, Chilean Patagonia: late-Holocene chronology and geomorphology

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Abstract: Glaciar León is a temperate, grounded outlet of the eastern North Patagonian Icefield (NPI). It terminates at an active calving margin in Lago Leones, a 10 km long proglacial lake. We take a multidisciplinary approach to its description and use ASTER imagery and clast sedimentology to describe the geomorphology of the glacier and its associated moraines. We date periods of glacier retreat over the last 2500 years using a combination of lichenometric, dendrochronological, cosmogenic and optically stimulated luminescence techniques and show that the glacier receded from a large terminal moraine complex some 2500 years ago and underwent further significant recession from nineteenth-century moraine limits. The moraine dates indicate varying retreat rates, in conjunction with significant downwasting. The bathymetry of Lago Leones is characterized by distinct ridges interpreted as moraine ridges that dissect the lake into several basins, with water depths reaching 360 m. The fluctuations of Glaciar León appear to have been controlled by the interplay between climatic forcing and calving dynamics.

Key words: Geomorphology, 'Little Ice Age', Patagonia, glacier fluctuations, calving dynamics, late Holocene, chronology, Chile.

Introduction

The Patagonian Icefields (46°30′–51°30′S) are the largest low-latitude ice masses in the world, and are critically located with respect to Southern Hemisphere atmospheric and oceanic climatic systems (Mercer, 1982; Casassa *et al.*, 2002; Harrison, 2004). Together, they cover 17 200 km^2, and are nourished by annual precipitation of 6000–8000 mm (Escobar *et al.*, 1992; Warren and Aniya, 1999). The North Patagonian Icefield (NPI) is drained by about 21 large valley glaciers, some 13 of which calve into proglacial lakes (Aniya, 2001). Most of these ice-contact lakes have formed in conjunction with recent glacier retreat from 'Little Ice Age' (LIA) terminal moraines into glacially overdeepened troughs, initiating calving at formerly land-based termini. Calving has therefore become increasingly important to the mass balance and dynamics of the icefield (Warren and Aniya, 1999). Given the large numbers of calving termini around the Patagonian icefields, and given that topographic effects and glacier dynamics may significantly affect the terminus variations of calving glaciers (eg, Vieli *et al.*, 2001), the glacio-climatic record may have been significantly modulated by glacio-dynamic effects at many sites. As yet, however, chronological controls are insufficient to test the synchrony or asynchrony of glacier fluctuations across both icefields or in different sectors of each icefield.

It also remains uncertain whether there have been east–west contrasts in the timing of glacier fluctuations in response to precipitation and temperature gradients (Warren and Sugden, 1993; Hulton *et al.*, 1994; Aniya *et al.*, 1997; Harrison and Winchester, 2000). These gradients, which are steep today, were probably much steeper at times of icefield expansion in the past, enhancing

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aridity on the eastern flank of the NPI (Sugden *et al.*, 2002; Turner, 2003). Furthermore, the extent to which teleconnections exist between the timing and nature of environmental changes in southern South America and those in the Northern Hemisphere remains contentious (Bennett *et al.*, 2000; Luckman and Villalba 2001; Glasser *et al.* 2006). Western Patagonia is a key area for testing hypotheses of global climate change (Moreno, 2002; Glasser *et al.*, 2004), but a much fuller picture of the Patagonian glacial chronology is required if these regional, interhemispheric and global questions are to be resolved and this paper contributes to this debate. However, there remain uncertainties in the development of Holocene glacier chronologies in Patagonia. Most dating studies of late-Holocene and earlier glacier fluctuations have concentrated on the use of radiocarbon dating of organic material within moraine belts and these are known to have uncertainties relating to the time required for dateable material to accumulate, especially in the rain-shadow zone to the east of the icefields. Dating of nineteenth-century glacier fluctuations has employed dendrochronology and lichenometry (eg, Winchester and Harrison 1996; Harrison and Winchester 2000; Koch and Kilian, 2005; Harrison *et al.* 2007). In this paper, and for the first time in Patagonia, we use a combination of dating techniques to provide a more secure chronological framework for the geomorphological evolution of a major outlet glacier of the Patagonian icefield during the late Holocene. Our study site is Glaciar León and its proglacial environs on the eastern flank of the NPI.

Site description

Glaciar León (46°46′S, 73°13′W) is one of eight major outlet glaciers draining the eastern side of the NPI (Figure 1). It is 11.4 km long, with an ice surface area of 44.5 km^2 (Aniya, 1988). It descends from an icefield accumulation area at a maximum elevation of 3000 m a.s.l. and the equilibrium line lies at 1350 m a.s.l., indicating an accumulation area ratio of 0.67 (Aniya, 1988). Its three tributaries join below icefalls at ~750 m a.s.l. to form a single glacier that terminates in Lago Leones at 303 m a.s.l. The entire surface of Glaciar León from the icefall to the terminus, with surface gradients of 15°, comprises heavily crevassed ice and is largely debris-free, other than a medial/lateral moraine that divides the north and central tributaries. The steep gradient of the glacier's lower terminus, and the fact that part of the 1.5 km wide ice cliff has lost contact with the lake, indicates that any significant further recession would involve retreat out of the lake and the cessation of calving (Haresign and Warren, 2005). Lago Leones, 10 km long and some 2.5 km wide, has formed since the glacier margin withdrew from the 135 m high terminal moraine that now forms the northeastern margin of the lake. More recent glacier recession is shown by small moraines within 3 km of the present glacier terminus.

Methods

Geomorphology and sedimentology

The glacial geomorphology of the area surrounding Lago Leones was mapped using a combination of field mapping over three field seasons (2001–2004) and by visual interpretation of Terra ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) satellite images. The images were radiometrically and geometrically corrected based upon the orbital parameters supplied by the USGS, allowing a horizontal error in the order of one pixel size (15 m for ASTER and 30 m for Landsat ETM+). Features mapped include terminal moraines, glacio-fluvial outwash, glacier trimlines and ice-scoured bedrock.

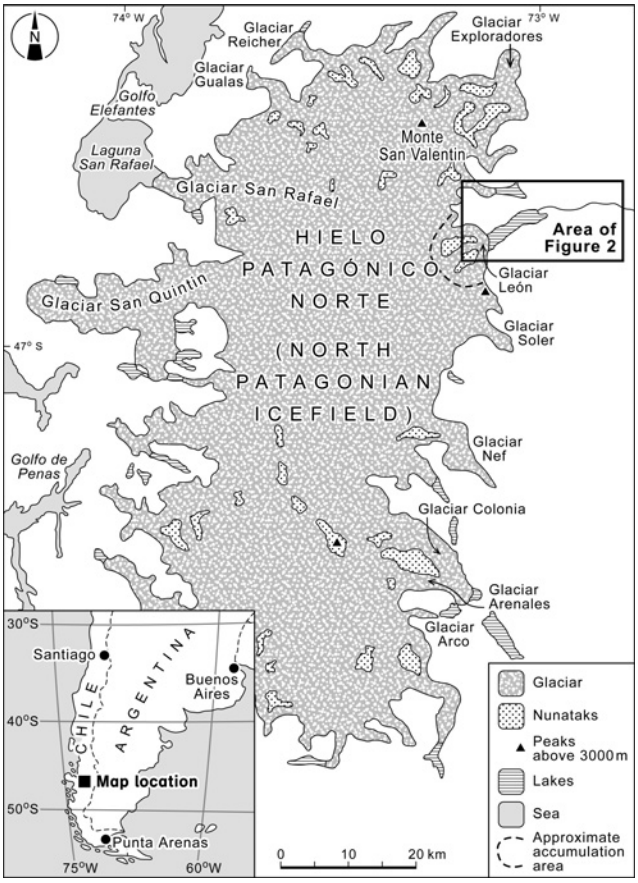

Figure 1 Map of the North Patagonian Icefield (Hielo Patagónico Norte), showing the main outlet glaciers and the location of the study area

Sediments exposed in sections on the terminal moraines were described in the field according to texture, particle size and clast-shape analyses. Poorly sorted sediments were classified in the field on the basis of a modification of the Moncrieff (1989) classification (Glasser and Hambrey, 2002). Clast morphology was analysed for samples of 50 clasts, including clast roundness on a modified Powers (1953) scale and the measurement of a, b and c axes for clast shape. These data were analysed using the approach of Benn and Ballantyne (1994) in which the RA index (% of angular and very angular clasts) is plotted against the C_{40} index (% of clasts with c/a axial ratio ≤ 0.4) on a co-variant plot. This method has been shown to provide good discrimination between glacial facies (Bennett *et al.*, 1997). Clast lithological analysis is based on field identification of hand specimens.

Lake bathymetry

Lake bathymetry was mapped in 2001 using a Lowrance LMS-350A echo-sounder with integral GPS. A total of 475 individual depth soundings were made every 100–200 m along intersecting transects across the lake, providing a detailed sampling network (Haresign, 2004). A greater density of soundings was acquired in the ice-proximal zone, providing a higher resolution picture of the bathymetric topography of the zone over which the glacier has retreated in historic time. Safety considerations prohibited close approach to the ice front, but estimates of water depth at the ice front were obtained by extrapolating from nine long-transects in the ice-proximal area, which were continued to within ~150 m of the calving cliff. A greater density of soundings was also made around the area of the lake near the island (near the northern shore of Lago Leones), where the lake-side geometry hinted at the presence of a ridge-like feature.

Dating the terminal moraine complex

Dating of the large moraine complex forming the eastern edge of Lago Leones was undertaken using Optically Stimulated Luminescence dating of quartz extracted from fine sediment and cosmogenic isotope dating on large boulders on the moraine surface.

Optically stimulated luminescence (OSL) dating

Samples of sand-sized material from the moraine complex were dated using optically stimulated luminescence (OSL) measurements on quartz. Five samples were collected for OSL dating in 2000, with analysis being undertaken at the University of Oxford, and a further two collected in 2003 for analysis at the University of Wales Aberystwyth.

Of the five samples collected in 2000 for OSL dating of sand-sized quartz grains refined from these samples, only one provided successful results (Winchester *et al.*, 2005). Of the four unsuccessful samples, luminescence emissions from two of the samples were too weak to be measured reliably whilst the other two gave effectively saturated (infinite age) signals (these four samples having been taken from the lake's southern margin where lateral moraines containing sandy units are also developed). The remaining, successful, sample (CH3b) was taken from the proximal flank of the Leones terminal moraine where a small landslide exposed finely laminated well-sorted sands and gravels (interpreted as glacio-lacustrine deposits) capped by a diamicton. The sample was taken at a height of 100 m above lake level, 8 m below the moraine crest at this point and 0.9 m below a boulder marking the base of the overlying diamicton.

For luminescence measurements at the University of Oxford, aliquots of refined quartz (approximately 200 grains in each case, from the size range 125–180 µm) were mounted on aluminium discs. A Risø reader (TL-DA-15), as described in Bøtter-Jensen *et al.* (2000), was used for irradiation (with a calibrated ^{90}Sr β-source), preheating (details below) and luminescence measurement (optical stimulation was with blue [470Δ 20 nm] light). Quartz purity was assessed using IR (830 nm) stimulation. Estimates of the total absorbed radiation dose (D_e) were made using the Single-Aliquot Regenerative-dose (SAR) method (Wintle and Murray, 2006), with preheating for 10 s at 220°C or 260°C for regeneration doses (PH_1) and at 220°C (for 10 s) following the 5 Gy test dose (PH_2). No significant differences in D_e results from the two PH_1 conditions, nor correlation between the zero-dose point and D_e value were observed; hence results from both preheat conditions were included in final analysis. Other relevant information is given in Table 1. A significant degree of skewness and overdispersion was observed in the measured distribution of D_e values (Table 1), indicative of incomplete and heterogeneous signal resetting of the sampled grains prior to deposition. The 'Minimum-age' statistical model of Galbraith *et al.* (1999) was applied (following Bailey and Arnold, 2006; and Arnold *et al.*, 2008) to obtain the best estimate of the mean burial dose since deposition.

In the light of this experience, in 2003 a further two samples (Aber79/LEG1 and Aber79/LEG4) were taken from sections in well-sorted sands and silts dug into the crest of the terminal moraine. These underwent OSL analysis based on measurements of single sand-sized grains of quartz at the University of Wales Aberystwyth, in order to isolate only the grains that were reset at the time of deposition (Duller, 2004). The samples came from the edge of a small meltwater channel that cuts through the moraine crest. Quartz grains from 180–211 µm diameter were isolated and measurements made on 2900 single grains of quartz from sample Aber79/LEG1 and 1700 grains of Aber79/LEG4. Only a small proportion (0.6% and 1.6%, respectively) of these grains yielded measurable OSL signals. A SAR procedure was used, similar to that for sample CH3b, except the preheat temperature (PH_1) was 220°C and the cutheat (PH_2) 160°C. Single grain analysis permits the luminescence properties of each grain to be inspected, and those with undesirable properties can be rejected. These rejection criteria were applied as described in Duller (2006) and resulted in valid equivalent dose values from 18 and 26 grains for the two samples, respectively.

As expected on the basis of the distribution of D_e values found for CH3b (Figure 2), the two samples collected in 2003 also showed evidence for incomplete bleaching at deposition, and hence the single grain data were analysed using both the minimum age and finite mixture models (Duller, 2006) that seek to identify

Table 1 Luminescence measurements were made on samples taken from the terminal moraine and measured in Oxford (CH3b) and Aberystwyth (LEG1 and LEG4)

Dosimetry	Sample		
	Ox/CH3b	Aber79/LEG1	Aber79/LEG4
U (ppm)	2.04 ± 0.02	2.22 ± 0.26	1.35 ± 0.18
Th (ppm)	6.24 ± 0.08	7.17 ± 0.86	4.97 ± 0.59
K (%)	2.14 ± 0.10	1.87 ± 0.06	1.50 ± 0.05
Cosmic dose (Gy/ka)	0.14 ± 0.05	0.17 ± 0.02	0.20 ± 0.02
Water content	0.05 ± 0.03	0.10 ± 0.05	0.10 ± 0.05
Dose-rate (Gy/ka)	2.97 ± 0.16	2.66 ± 0.11	2.05 ± 0.09
Recycling ratio	0.96 ± 0.02	*	*
Zero-point ratio	0.04 ± 0.01	*	*
N	16	2900 (18)	1700 (26)
*D*c (Gy)	7.6 ± 0.2	6.4 ± 1.2	6.8 ± 1.8
Age (ka)	2.6 ± 0.2	2.4 ± 0.5	3.3 ± 0.9

* For the two samples analysed in Aberystwyth, only those grains whose recycling ratio was within 10% of unity within errors, and whose recuperation was less than 5% were included.

Dosimetry is based on ICP-MS for the sample from Oxford and beta and alpha counting for the sample in Aberystwyth. The number of *D*c measurement (*N*) is given. For the sample measured in Oxford *N* is the number of aliquots measured, while for the two samples in Aberystwyth the first value is the number of individual sand-sized grains measured, and the figure in brackets is the number of grains for which a reliable estimate of *D*c could be obtained.

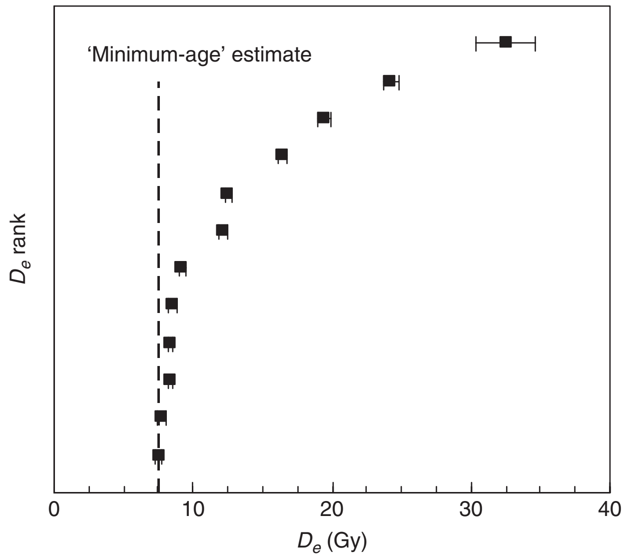

Figure 2 D_e values for sample CH3b from the Lago Leones terminal moraine. Values have been ranked to aid visual comparison. Values above 40 Gy were omitted from this plot. The minimum-age D_e estimate (Galbraith *et al.*, 1999) is indicated

Table 2 Results from the cosmogenic dating of large boulders on the terminal moraine

Sample no.	Latitude	Longitude	Altitude	Thickness	Shielding	^{10}Be atoms/g $SiO_2 \times 10^3$	Exposure age (yr) upper limit
Leg1	46.720	73.104	362	7	0.993	6.25 ± 1.44	≤1160
Leg2	46.721	73.104	360	4.5	0.993	1.28 ± 3.09	≤650
Leg3	46.730	73.095	328	5	0.995	5.31 ± 2.36	≤1180

the appropriate depositional event. For these two samples, the results were very similar using both analytical methods, but following the work of Rodnight *et al*. (2006) the results from the finite mixture model were used as these have generally been found to be more reproducible than those from the minimum age model.

Cosmogenic isotope dating

Samples for cosmogenic nuclide analysis on the moraine were taken from the upper surfaces of flat-topped erratic boulders following the sampling guidelines of Gosse and Phillips (2001). The boulders LEG 1 and LEG 2 were located on the distal side within 1–5 m of the crest of the moraine; LEG 3 was located on a lower part of the moraine ridge near the lake outflow. Each boulder was larger than 1.5 m (b axis) and care was taken to avoid boulders on uneven or unstable surfaces, which may have moved since deposition. Angles were measured to the horizon using an Abney level at 5° intervals to account for topographic shielding. Rock samples were crushed and sieved to a grain size less than 0.6 mm. Quartz was isolated by selective chemical dissolution with weak HF using a shaker table and hot ultrasonic bath (Kohl and Nishiizumi, 1992). The quartz mineral separates were further enriched using a Frantz magnetic separator. After addition of ^{9}Be carrier, the quartz was dissolved with concentrated HF. We used anion and cation exchange and selective pH controlled precipitations (Ochs and Ivy-Ochs, 1997) to separate and purify Be. ^{10}Be/^{9}Be along with appropriate standards and blanks were measured by accelerator mass spectrometry at the PSI/ETH tandem facility in Zurich (Kubik *et al*., 1998). For the background correction to the measured ratios, we have used a long-term average chemistry blank value of $1.48 \pm 0.17 \times 10^{-14}$ for the ^{9}Be carrier used in this study (Alfa Aesa). Surface exposure ages were calculated using a sea level, high latitude ^{10}Be production rate of 5.1 ± 0.3 atoms per gram SiO_2 per year, with a contribution from muons of 2.2% (Stone, 2000). Scaling to the sample latitude (geographic) and altitude were also carried out following Stone (2000). Corrections for past changes in the orientation and intensity of the Earth's magnetic field have been estimated using the spreadsheets provided by Pigati and Lifton (2004) and the latitude and longitude of the sampling site. This correction amounts to a lowering of the production rate of approximately 6% for the time period of 1000 to 1500 yr ago. AMS measurement errors are at the 1σ level, including the statistical (counting) error and the error resulting from the normalization to the standards and blanks. Exposure age errors include the production rate errors given in Table 2, but do not include errors resulting from latitude and altitude scaling.

Dendrochronology and lichenometry

Lichenometry and dendrochronology were used to provide minimum dating estimates on recent moraine surfaces. Both colonization and growth rates given for lichens and trees are necessarily tentative since few precisely dated surfaces exist in the Leones valley. However, the growth rate of the sections can be considered reliable and these support the estimated rates for small trees. Estimates for larger, older trees are rather more questionable since these trees will have started to grow under a different climatic regime. Further details of how lichen growth rates and colonization are calculated and a discussion of the problems using lichenometry and dendrochronology in an area almost totally lacking surfaces of known date are given in Winchester and Harrison (2000) and Winchester *et al.* (2001). Apart from measurement error introduced by irregularities in rock surface, lichen dating estimates may also be affected by differences in colonization and growth rates caused by microhabitat variations including aspect, exposure, rock type, colour and mineral composition, temperature, water relations and competitive state.

Dendrochronology

The dendrochronological dates for glacier recession were obtained using a 5 mm increment borer to take 40 cores from largest *Nothofagus nitida* and *Podocarpus nubigenus* trees growing on moraines, valley-sides and outwash plain, and in the ancient forest fragments on the distal side of the terminal moraine. After mounting and finely sanding the cores, ring measurement and counting was carried out with a Lintab measuring system and TSAP software. Dating estimates were based on annular ring counts added to colonization estimates and tree age below core height (Table 3).

The problem for geomorphologists interested in dating tree colonization and growth on recently exposed surfaces is that a core only gives tree age above the core; age below it must be added. In addition, a tree may take many years to colonize a freshly exposed surface. *N. nitida* age below core height in the local environments was obtained by sectioning four small seedlings just above their root collars. Their annual growth rates were calculated by dividing seedling height by ring count, giving an average rate of 9.2 cm/yr. Estimates of growth rate were also obtained from three small trees that were cored rather than sectioned: assuming that the growth rate for the height above core would be approximately the same as that below the core, an average rate was obtained for the cores of 12.4 cm/yr. The sectioned trees showed the slowest growth rate of 2.4 cm/yr on the peninsula and the highest rates, 17.6 and 17.8 cm/yr, on the flat Rio Leones outwash plain, the top of the northern terminal moraine and in a valley distal to the most recently formed moraine near the ice front on the south shore of Lago Leones. The coniferous species, *P. nubigenus*, showed an average growth rate of 4.7 cm/yr in the understorey of the dense ancient forest on the distal flank of the terminal moraine, most likely because of suppression; a higher rate of 11 cm/yr, was estimated for a large individual on the edge of the forest. This species and *N. nitida* trees in the forest were not included in the analysis since the forest has been unaffected by glacier ice for a very long time and the trees within it will all have been subject to normal succession processes.

Tree colonization estimates were based on the difference between tree age and surface dates provided by measured lichen age, with estimates varying widely from 7 years on distal slopes near the glacier, 42 to 48 in relatively sheltered positions and 57 years on the proximal side of the peninsula (see Figure 3). These values are supported by Sweda (1987) who found colonization values of 24 to 50 years in the neighbouring Soler Glacier valley.

Lichenometry

Lichenometric dates for exposure of recently deglaciated surfaces are dependent on size/age correlations (Innes, 1985) and addition

Table 3 Key lichen diameters (mm) and dates (based on a growth rate 4.7 mm/yr, with 2.5 yr added for colonization) providing colonization delays for trees in the different sampling locations

Location	Lichens		Tree colonization				
	Diam. (mm)	Date	Delay (yr)	Date	Rings (yr)	Growth rate (cm/yr)	Core ID (tree ht m)
Ancient forest floor distal side terminal moraine	–		Succession	1942	41	4.3	Sect. 1 (1. 75 m)
			Succession	1977	22	5.2	Sect. 2 (14 m)
			Succession	1744	255	19.7	Core A6/7 (25 m)
Peninsula 3.5 km ice front proximal flank	611	1867	57	1924	75	2.4	Sect. 3 (1.80)
			Succession	1957	42	9.7	Core C4/7 (4 m)
Calafate, tarn 5 m below distal crest moraine	280	1937	46	1983	16	8.7	Sect. 4 (1. 4 m)
Calafate summit moraine and proximal flank	340	1924	48	1972	23	11.2	Core A6/16 (3 m)
			Succession	1979	19	16.4	Core A5/16 (1. 8 m)
50 m E ice front roche moutonée distal side	240	1945	42	1987	12	8.2	Sect. 5 (1 m)
Lago S shore valley stream side	203	1954	7	1961	38	17. 8	Core A8/10 (6.7 m)
Rockfall S shore Lago and forest fragment	97	1976 event date?	7	1917	75	15.3	Core A11/10 (14 m)
Rio Leones outwash plain			Fire or grazing control	1991	8	17.6	Sect. 6 (1. 41 m)
Terminal moraine summit and tree, top of N moraine	664	1855 Unaffected by glacier	Succession	1951	48	17.6	Core C1/12 (8. 5 m)

Species: *Podocarpus nubigenus* not included in the analysis.
All other tree cores and sections, *Nothofagus nitida*.
Key tree ages and dates on total ring numbers above and below core and growth rate to core height or of trees under 1.8 m tall. Differences between lichen and tree dates provide colonization delay for trees on freshly exposed surfaces. The material was collected in February 2000, thus ages are calculated as from 1999.

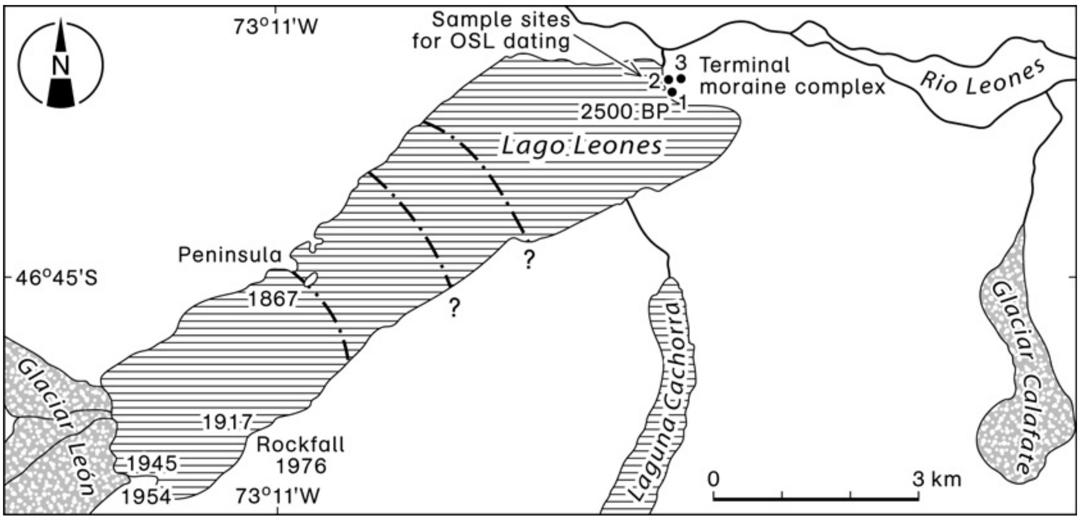

Figure 3 Dated surfaces in the Lago Leones area from OSL, cosmogenic nuclide dating, lichenometry and dendrochronology. Location of samples for OSL dating is shown: 1, Ox/CH3b; 2, Aber79/LEG1; 3, Aber79/LEG4

of a delay before colonization (ecesis). Longest axis measurements were made of 90 largest *Placopsis perrugosa,* bodies (thalli), the most common rock-inhabiting lichen species in the area, using a flexible tape accurate to ±1 mm. Extensive searches for specimens having near-circular thalli were made over selected landforms (see Figure 3) on as many boulders as possible. Dates were based on a cumulative linear growth rate of 4.7 mm/yr and an ecesis value of 2.5 yr derived from studies on the wet west side of the icefield at Laguna San Rafael and for the much drier east side in the Colonia and Arco valleys (Winchester and Harrison, 1994, 2000).

Results

Geomorphology and sedimentology

Three distinct sediment–landform associations occur in the Leones valley: (1) the large moraine that dams Lago Leones, (2) extensive tracts of ice-scoured bedrock, sometimes draped by a thin sediment cover and (3) the contemporary sandur on the valley floor (Figure 4).

Lago Leones moraine

The contemporary Lago Leones is dammed by a 135 m high, sharp crested moraine, approximately 10 km from the contemporary ice

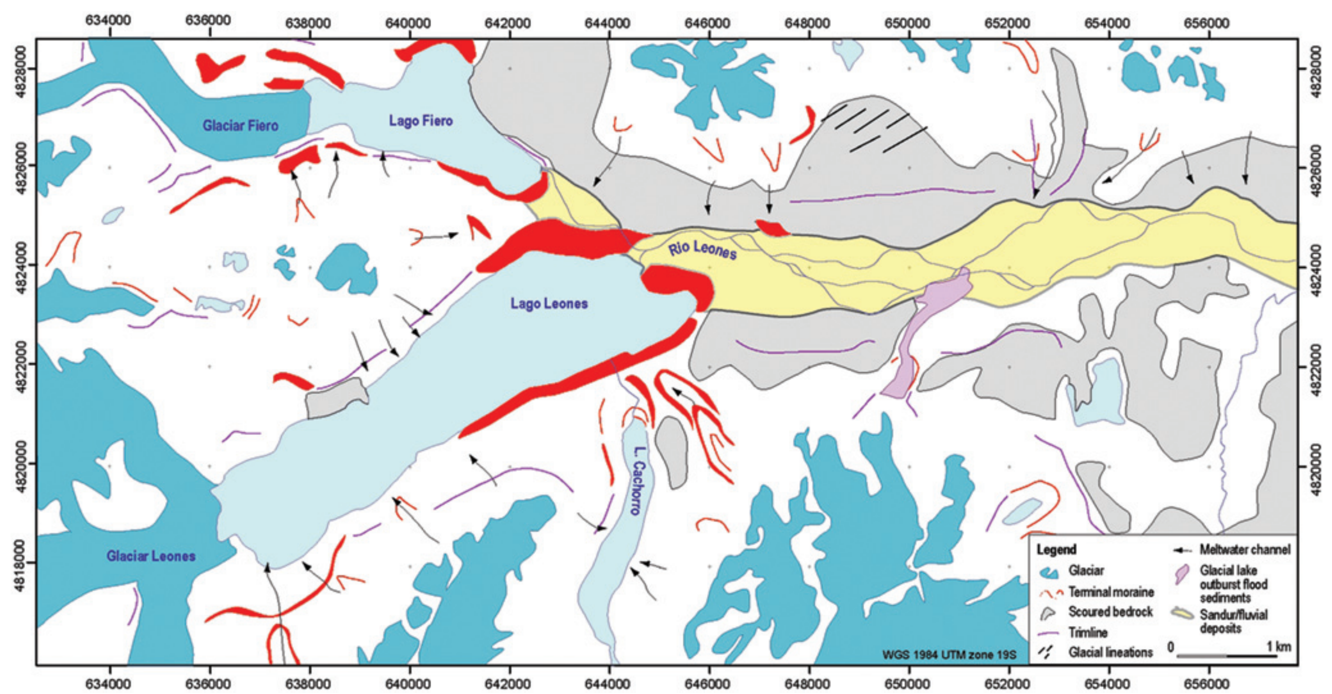

Figure 4 Geomorphological map derived from ASTER imagery showing Glaciar Leon, Lago Leones and surrounding area

front. The moraine is composed primarily of sandy boulder gravel and sandy gravel, with boulders of up to 5 m (b-axis) on its surface. The sandy boulder gravel, although texturally variable, is typically a massive boulder gravel in a sand matrix. The following proportions are typical: gravel (60%), sand (30%) and mud (10%). Clast distribution within this facies is variable, with clasts occurring either in clusters or in contact with one another. Typical gravel-sized clast roundness distribution in samples of 50 is angular (14%), subangular (38%), subrounded (42%) and rounded (6%). The sandy gravel facies is a moderately well sorted unit, consisting of gravel (70%) and sand (30%). Typical gravel-sized clast roundness distribution in samples of 50 is subangular (32%), subrounded (46%) and rounded (22%). The sandy boulder gravel is a result of the mixing by glaciotectonic processes, slumping and stream sorting of different parent populations (basal glacial, supraglacial and glaciofluvial sediments) at the glacier margin (Glasser and Hambrey, 2002). The sandy gravel facies is interpreted as a reworked glaciofluvial deposit on the basis of its sorting, clast roundness and the absence of striated and faceted clasts.

Ice-scoured bedrock terrain

Large exposures of ice-scoured bedrock occur along the sides of the Leones Valley. This undulating bedrock surface is draped in places by a thin (*c.* 0.5–2 m thick, but locally thicker in places) layer of sandy gravel, sandy boulder gravel or diamicton. The sandy gravel and sandy boulder gravel are texturally similar to the sedimentary facies present in the Lago Leones moraine, described above. The diamicton is a massive, clast-rich silty diamicton, comprising gravel (50%), sand (40%) and mud (10%). The gravel-sized clasts in samples of 50 are typically subrounded (66%) and subangular (32%), with few angular clasts (2%). Striated and faceted clasts are common, with up to 26% striated clasts and 32% faceted clasts in samples of 50. The presence of large areas of ice-scoured bedrock along the valley sides and its patchy cover of glacigenic sediments indicates sustained vigorous ice flow by a temperate glacier in the main valley.

Sandur plain

An extensive sandur (glaciofluvial outwash plain), fed by meltwater streams draining Glacier León when the ice front was located at the Lago Leones moraine is present on the floor of the Leones Valley. The sandur is composed of rounded gravel, sandy gravel and sand. Clast shapes in these facies are characterized by very low RA (per cent of angular and very angular clasts) and low C_{40} (per cent of clasts with c/a axial ratio ≤ 0.4) indices. Typical gravel-sized clast roundness in samples of 50 is subangular (14%), subrounded (50%), rounded (32%) and well-rounded (4%). No striated or facetted clasts are found in these facies.

Lake bathymetry

The bathymetric results (Figure 5a,b) show that the lake reaches depths of over 350 m in places. Large, distinct ridges rising nearly 200 m from the lake floor can be seen at 3.5, 5.5 and 7 km from the glacier. These are interpreted to be moraine ridges, the subaerial continuations of which have been almost completely reworked by slope processes on the steeply sloping valley sides. At the ice front, water depths average 65 m. The lake floor descends steeply away from the glacier, reaching a depth of 360 m in the westernmost basin of Lago Leones, the maximum depth recorded in the lake. No bedrock crops out at the lake's outlet.

Late-Holocene glacier fluctuations

OSL dates were derived from the two independent sets of samples collected in 2000 and 2003. The D_e obtained for sample CH3b was 7.57 ± 0.17 Gy, and the environmental dose rate (D'), calculated using U, Th and K concentrations obtained from ICP-MS (Bailey *et al.*, 2003), along with the contribution from cosmic dose calculated according to Prescott and Hutton (1994), was 2.97 ± 0.16 Gy/ka. This yields an age of 2.6 ± 0.2 ka (see Table 1).

The results of the samples from Aber79/LEG1 and Aber79/LEG4 produced D_e values of 6.4 ± 1.2 Gy and 6.8 ± 1.8 Gy, respectively. Combined with dose rates determined from a combination of thick source alpha counting and beta counting, this gives ages of 2.4 ± 0.5 ka and 3.3 ± 0.9 ka, very similar to that determined for the sample using multiple grain data. On the basis of the OSL results, we can therefore say with some confidence that the moraine complex was emplaced by about 2.5 ka.

^{10}Be surface exposure ages for samples Leg1, Leg2, and Leg3 on the lower part of the moraine damming Lago Leones are listed

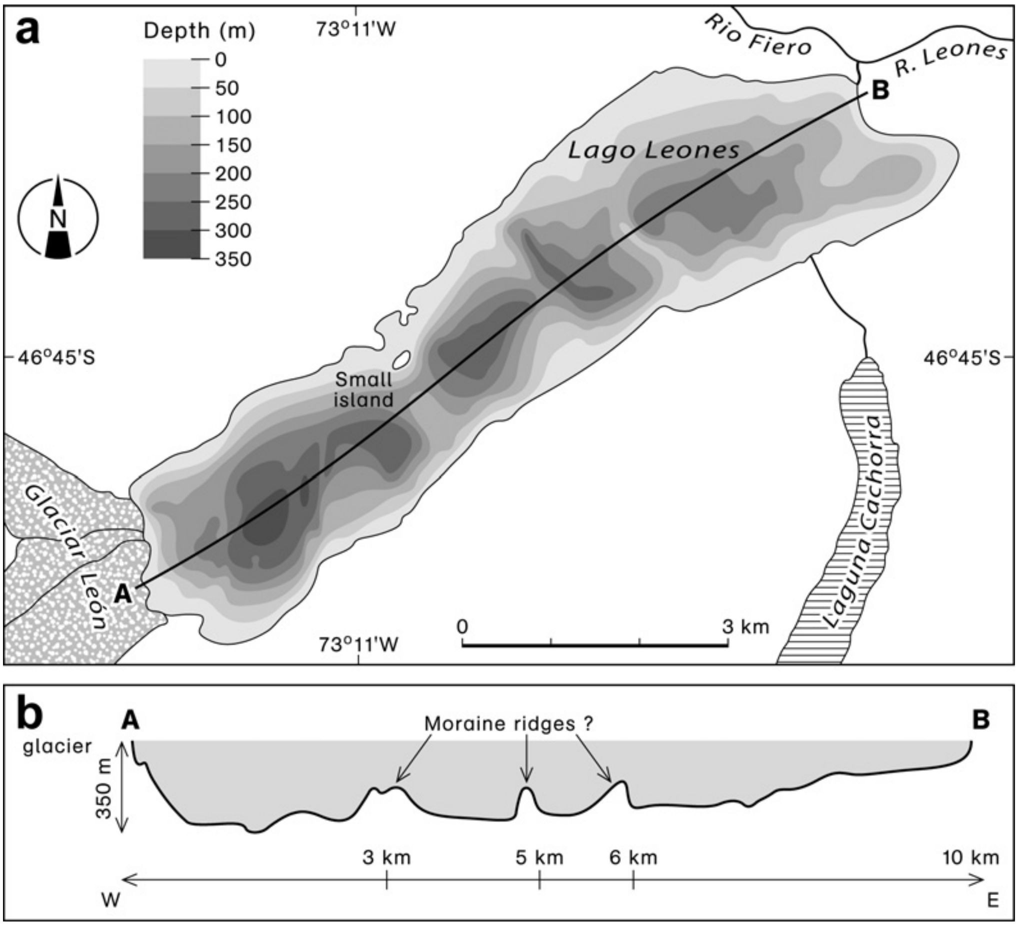

Figure 5 Lago Leones and the terminus of Glaciar León showing the results of the bathymetric survey (a) with the inferred subaqueous moraines indicated (b). Map based on 1:100 000 series of the Chilean Instituto Geográfico Militar, Sheets 162 and 278, and 1974 aerial photographs, updated to show the terminus position in November 2002

in Table 2. Because the measured ratios were on the order of but no more than double the blank value, we have calculated the age as an upper age limit by taking the measured atoms per gram SiO_2 and the upper error bar. This yields ages of 1160 yr, 650 yr and 1180 yr for Leg1, Leg2 and Leg3, respectively. As the ages include the upper error limit no errors are given. We stress that these are maximum exposure ages based on measured ^{10}Be concentrations. As with all moraine boulder ages the possibility that the sampled surface was covered by sediment or vegetation, or shifted in orientation during all or part of the exposure is difficult to rule out. Thus for timing of construction of the moraine these may be considered to be minimum ages.

Nineteenth- and twentieth-century fluctuations

Results of the dendrochronological and lichenometric dating are given in Figure 3 and Table 3. The dendrochronological date of 1867 from a tree growing on moraine deposits on the northern lakeshore peninsula locates the 'Little Ice Age' maximum while glacier thinning and retreat in the second half of the nineteenth and early twentieth centuries is suggested by dates on the southern lake shore within the LIA limit.

Discussion

The OSL and cosmogenic dates clustered around 1.1–2.5 ka for the terminal moraine complex at the end of Lago Leones indicate that the glacier retreated from this moraine sometime before that date and therefore that a lake (of variable size) has probably existed in the current lake basin for several millennia (Winchester *et al*., 2005). These dates also suggest that moraine formation occurred over a considerable period of time, and this is supported by the large size, extent and topographic complexity of the moraine system. The glacio-climatic and glaciological significance of this date is that it represents a minimum age, first, for the significant Holocene advance that constructed the major moraine itself and, second, a maximum age for the transition from non-calving to calving following retreat from this moraine. No dates are available for the two large moraines between the lake-end moraine and the LIA maximum revealed by the bathymetric survey (Figure 3a,b), but they must represent stillstands or readvances during Neoglacial time. It is tempting to equate the Lago Leones moraines with Clapperton and Sugden's (1988) scheme of four Neoglacial advances (at *c*. 3.6 ka, *c*. 2.3 ka, *c*. 1.4 ka and the LIA). Although correlation remains speculative at present, with this scheme the cosmogenic and OSL dates from the lake-end moraine would then represent the second and third period of advance, respectively, although the possibility remains that the moraine complex may have developed in response to repeated advances. Neoglacial glacier advances in Patagonia did not begin until some time after 6000 ^{14}C yr BP, coincident with a strong cooling episode at this time. Holocene glacier advances can be assigned to one of three time periods following a 'Mercer-type' chronology, or one of four time periods following an 'Aniya-type' chronology. The 'Mercer-type' chronology has glacier advances between 4700 and 4200 ^{14}C yr BP, 2700 and 2000 ^{14}C yr BP and during the LIA (Mercer, 1976). The 'Aniya-type' chronology has glacier advances at 3600 and 2300 ^{14}C yr BP, between 1600 and 1400 ^{14}C yr BP and during the LIA (Aniya, 1995). These chronologies are best regarded as broad regional trends, since there are dated examples of glacier advances in Patagonia outside these time periods (Glasser *et al*., 2004).

Both Mercer- and Aniya-type chronologies are based largely on radiocarbon-dated records, many of which are minimal dates, and from calving glaciers that may react to climate in a non-linear fashion. Indeed, contrasting histories have been obtained for the behaviour of land-terminating glaciers within relatively short distances of each other. The validity and uncritical use of such chronologies in inter-hemispheric comparative studies is therefore questionable.

However, unlike most other sites around the NPI, the onset of lake formation at Lago Leones (and hence calving) did not take place in historic time and the dating evidence presented here implies that the glacier has had a calving terminus throughout much of Neoglacial time. If so, the dynamics of Glaciar León will have been sensitive to topographic geometry throughout the late Holocene. The glacier could therefore have been expected to exhibit a pulsed response to climate change as it jumped between topographically defined points of stability – pinning points – in the lake basin (cf. Vieli *et al*., 2002; Warren, 2004). The geomorphological evidence supports such a scenario. The most stable location of all is at the northeastern end of the lake where the glacier could maintain a non-calving terminus. Here, the substantial dimensions of the lake-bounding terminal moraine attest to an extended stillstand (or stillstands). Once the terminus retreated into deep water, rapid calving retreat would have ensued through each of the lake's four basins, punctuated by topo-climatic stillstands at relatively shallower and/or narrower locations.

The likely maximum position reached by Glaciar León during the LIA is marked by a small till-covered bedrock peninsula extending from the northern shore of Lago Leones some 3.5 km from the ice front. Glacier retreat from this location has been dated by dendrochronology to 1867, providing a minimum date for the maximum LIA advance in this valley. The timing of this here is closely similar to that for other NPI outlet glaciers. On the east side of the NPI, retreat of the Colonia, Arenales and Arco glaciers began in the late 1870s to early 1880s (Harrison and Winchester, 2000), Glaciar Nef retreated from a LIA maximum position around 1860–1870 (Winchester *et al.*, 2001), and an LIA maximum at Glaciar Soler was reached some time between 1600 and 1900 (Glasser *et al.*, 2002). On the west side of the NPI, retreat from LIA maxima began in the 1870s at Gualas, Reicher, San Rafael and San Quintin glaciers (Winchester and Harrison, 1996; Harrison and Winchester, 1998). The data from Lago Leones thus strengthen the argument made by Harrison and Winchester (2000) and Harrison *et al.* (2007) that retreat at the end of the LIA was largely synchronous at sites on both flanks of the icefield.

Thinning and retreat of Glaciar León in the second half of the nineteenth and twentieth centuries is shown by dates on the southern lake shore within the LIA limit (Figure 3). A reconnaissance map of the NPI based on 1945 aerial photographs (Lliboutry, 1956) shows the terminus only ~ 300 m in advance of its position in 1991 (Aniya, 2001) indicating that most of the post-LIA retreat took place during the first half of the twentieth century. Between 1994 and 1999, there was a readvance of ~ 190 m, followed by retreat of ~ 100 m from 1999 to 2000, in common with the other eastern side NPI glaciers (Aniya, 2001). In the late twentieth century synchronous glacier behaviour across the NPI was less apparent owing to the increasing influence of calving dynamics and topographic controls as glaciers retreated into overdeepened troughs and experienced rapid calving retreats (Warren and Aniya, 1999; Harrison *et al.*, 2001). The post-LIA behaviour of Glaciar León illustrates the sensitivity of calving glaciers to the topographic geometry of their valleys. Both the LIA and present locations of the terminus are topographic pinning points, providing the glacier terminus with a greater measure of stability relative to the deeper, wider parts of the lake. Available chronological evidence and the apparent absence of moraines suggest that retreat through the 360 m deep intervening basin was rapid and largely uninterrupted. Conversely, the present location is so stable that the terminus position has changed little since 1945 (as evidenced by the 1945 lichen date within 100 m of the 2000 ice front), a 55-yr period during which most NPI glaciers have seen significant changes (Aniya, 2001). However, several of the western calving outlets of the NPI (San Quintin, San Rafael, Gualas, Reicher) recently exhibited slowed retreat or slight advance following high precipitation in the 1970s and 1980s (Warren, 1993; Winchester and Harrison, 1996; Harrison and Winchester, 1998), and this period of enhanced accumulation may also explain the 1990s readvance of Glaciar León. Again, this would imply synchrony across the icefield, similar to that inferred from LIA dating investigations.

Conclusion

For the first time in Patagonia we have used four complementary dating techniques (cosmogenic isotopes, OSL, dendrochronology and lichenometry) to construct a late-Holocene glacier chronology and believe that this approach deserves to be widely adopted. We show that Glaciar León, a major outlet of the NPI, is unusual amongst Patagonian outlet glaciers. Most of the present ice-contact lakes around the NPI are just a few decades old. During Neoglacial time, therefore, most NPI outlet glaciers have terminated on land and so their response to climate forcing has not been modulated by calving dynamics. By contrast, Lago Leones is likely to have existed for most or all of the last 2500 years, implying that Glaciar León has been calving throughout this time, subject to the peculiar sensitivity to topographic controls that is one of the hallmarks of calving glaciers. This sensitivity is apparent in the glacier's post-LIA fluctuation history: rapid retreat followed by almost 60 years of stability at a sharply defined pinning point. In a similar fashion, given the considerable depth of individual basins within the lake (≤ 360 m), it is likely that Neoglacial fluctuations consisted of a pattern of 'punctuated equilibria', in which topo-climatically defined stillstands were interspersed with relatively short periods of rapid retreat.

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