Palaeogeography, Palaeoclimatology, Palaeoecology 281 (2009) 351–362

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

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

# Little Ice Age fluctuations of small glaciers in the Monte Fitz Roy and Lago del Desierto areas, south Patagonian Andes, Argentina

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ARTICLE INFO

*Article history:*
Received 6 June 2007
Accepted 21 October 2007
Available online 7 September 2008

*Keywords:*
Glacier fluctuations
South Patagonian Andes
Little Ice Age
Dendroglaciology

ABSTRACT

Current knowledge about late Holocene glacier fluctuations in the south Patagonian Andes is mainly based on evidence from large outlet glaciers of the North and South Patagonian Icefields, and few data exist for the smaller glaciers elsewhere in the region. Here we provide dendrogeomorphological evidence for Little Ice Age (LIA) and post-LIA activity for five small glaciers near the northeast margin of the South Patagonian Icefield. The study sites include Glaciar Torre and Piedras Blancas in the Monte Fitz Roy area, and three adjacent glaciers near Lago del Desierto. At these sites the LIA maximum position was identified by massive moraines with mature trees dating to the late 1500s–early 1600s. Several older moraines were observed beyond these limits but could not be precisely dated. Relatively synchronous advances occurred at most glaciers in the early 1700s and were dated using living trees and *in situ*, subfossil material. All glaciers show three to five subsequent advances mostly concentrated between the mid-19th and early 20th centuries. Estimates based on Landsat TM imagery indicate these glaciers lost between 15 and 46% of their LIA areas by 1984 and a further 5–18% by 2005, with the smallest glaciers showing the greatest proportional loss. Paired comparisons of contemporary and the earliest known photography for the glaciers in the Fitz Roy area confirm this mass loss. These results provide important new information on the glacier history of this area but additional, more precisely-dated records are needed from many more sites before we can fully elucidate the complex late Holocene glacial history of this region.

## 1. Introduction

Large outlet glaciers from the North and South Patagonian Icefields (NPI and SPI, respectively) have historically been the foci of most glaciological investigations in Patagonia south of 45°S, and little is known about the smaller glaciers elsewhere in the region (e.g. Mercer, 1965; Röthlisberger, 1986; Wenzens, 1999; Delgado et al., 2002). The studies from the NPI and SPI have supplied most of the evidence for the development of the late Holocene glacier history for this region, which has been used with other multi-proxy climate reconstructions to improve our understanding of Patagonian climate variability during this time frame (see e.g. Glasser et al., 2004, and references therein). However, despite these efforts and the enormous potential for glaciological investigations of this region, current knowledge about past glacier fluctuations and glacier–climate relationships in the south Patagonian Andes remains limited (Warren and Sugden, 1993; Porter, 2000; Luckman and Villalba, 2001; Casassa et al., 2002; Rivera, 2004). Mercer (1965, 1968, 1970) used evidence from six outlet glaciers of the SPI and limited data from the San Lorenzo area and Glaciar Narváez (located to the east of the icefields) to identify three main periods of late Holocene glacier advances in this region at ca. 4700–4200, 2700–2000 $^{14}$C yrs BP and during the past few centuries. Aniya (1995, 1996), working subsequently on three different outlet glaciers of the SPI, proposed a revised Neoglacial glacier chronology with glacier advances ca. 3600, 2300, and 1600–1400 $^{14}$C yrs BP, and during the past few centuries. More recently, Strelin et al. (2002) proposed up to seven Neoglacial advances for the southern tip of South America and the Antarctic Peninsula region.

In this paper we focus on the last Neoglacial event identified in these regional glacier chronologies, namely the widely recognized Little Ice Age (LIA) (Grove, 2004). We develop preliminary LIA and post-LIA glacial chronologies for five glaciers located near the northeast margin of the SPI using dendrogeomorphological techniques plus the analysis of historical documents, aerial photographs and satellite images. The study sites are Glaciar Torre and Glaciar Piedras Blancas in the Monte Fitz Roy area and three small glaciers on the west margin of Lago del Desierto (Fig. 1). There is conspicuous morphological evidence of pre-LIA events at some of these sites but it is not reported in detail here. Although some glacier advances have been identified in the south Patagonian Andes dating from the 12th and 14th centuries (e.g. Glasser et al., 2002), the available evidence suggests that most glaciers reached their LIA maxima between the 17th and 19th centuries (Luckman and Villalba, 2001;

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doi:10.1016/j.palaeo.2007.10.031

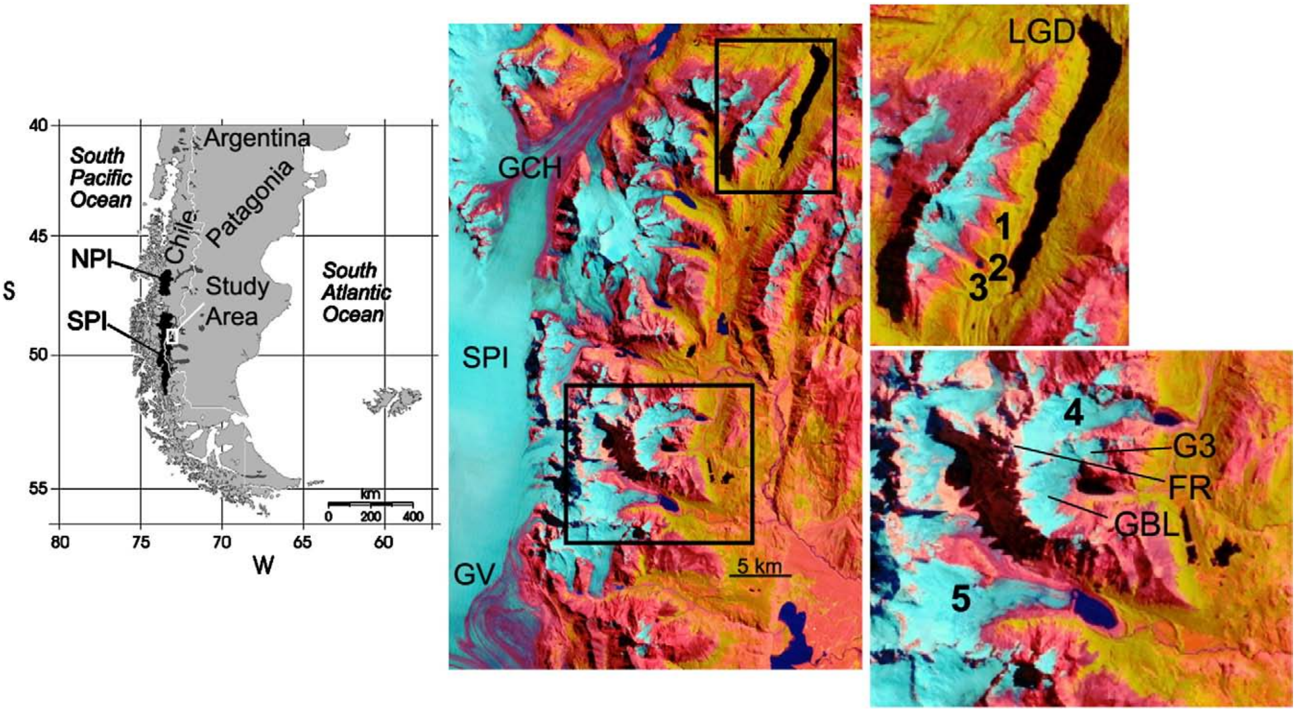

**Fig. 1.** (Left) Location of the study area and the North and South Patagonian Icefields (NPI and SPI). (Center and right) 2005 Landsat TM image showing the location of the glaciers (1–3) studied at the Lago del Desierto (LGD) area, and Glaciar Piedras Blancas (4) and Glaciar Torre (5) in the Monte Fitz Roy (FR) area. Glaciar de los Tres (G3) and Glaciar Río Blanco (GBL) are also indicated. Portions of Glaciar Viedma (GV) and Glaciar Chico (GCH) are shown to illustrate the differences in size between these large SPI outlets and the small glaciers analyzed in this study.

Delgado et al., 2002; Glasser et al., 2004; Koch and Kilian, 2005; Aravena, 2007). However, as few glaciers have been studied in detail, little is known about the timing, number and magnitude of glacier events that occurred in the south Patagonian Andes during this time (see review by Masiokas et al., 2009-this issue). This is unfortunate because the LIA is usually the period with the most abundant, best preserved and most easily dated evidence: it also comprises the period for which other high resolution proxy climate records (e.g. tree rings) are generally available for comparison with the glacier records. The lack of long (>10 yrs) direct glacier mass balance records in this region hampers the paleoclimatic interpretation of the available late Holocene glacial chronologies. In addition, most previous studies are from a few large calving glaciers that tend to have complex responses to climate variations (Warren and Sugden, 1993; Warren and Aniya, 1999). Thus, the detailed study of LIA and post-LIA glacier advances from these smaller glaciers is an important step towards improving our understanding of the influence of climate on glacier behaviour and, therefore, the climatic significance of the glacier events identified in Patagonia.

Many factors control the response of individual glaciers to climate changes (e.g. Oerlemans, 2001). Larger glaciers tend to have longer response times and more complex dynamic responses to climate than small glaciers (Johannesson et al., 1989) and therefore we specifically targeted several small accessible glaciers that we assume would be more sensitive (and respond more immediately) to climate changes. In addition, selecting several glaciers of similar size minimizes differences due to glacier size and allows a better evaluation of the regional response of the glacier system. These data will hopefully facilitate subsequent studies where the climatic significance of the inherently low resolution glacier records will be analyzed together with higher resolution proxy climate records and instrumental climate data from this region (see e.g. Grosjean and Villalba, 2006). The ultimate goal of this and additional ongoing studies at other small glaciers is to develop robust, reliable regional glacial chronologies for the past ~1000 yrs in order to evaluate the main spatio-temporal variability of glacier and climate fluctuations in the Patagonian Andes.

## 2. Study area

Environmental conditions of southwestern Patagonia are largely determined by the interaction between the dominant westerly winds and the north–south orientation of the Patagonian Andes (Miller, 1976; Prohaska, 1976). This results in an extremely steep precipitation gradient ranging from ca. 7000–8000 mm of annual precipitation on the SPI (Escobar et al., 1992) to less than 300 mm within 100 km east of the main divide (Villalba et al., 2003). Temperatures are less variable but exhibit a more maritime (continental) regime on the west (east) side of the Andes, with mean annual temperatures of around 6 °C measured at the few low elevation stations that exist around the SPI (Miller, 1976). Regional studies using the limited long climate records available (rarely >60 yrs) have found a long-term warming trend (Rosenblüth et al., 1997; Villalba et al., 2003; Rivera, 2004). Long-term changes in precipitation are more variable, and although some studies report a negative trend for some stations in the region (Rosenblüth et al., 1995; Rivera, 2004), recent analyses of homogenized precipitation records suggest no trend for this area (Aravena, 2007).

The five glaciers studied here are located a few kilometres east and separate from the SPI. They have a predominantly easterly orientation and are between ca. 1 and 25 km$^2$ in size (Fig. 1 and Table 1). Glaciar Torre is actually formed by three merging tongues referred to as Glaciar Torre, Adela and Grande in Lliboutry (1953b). Glaciar Piedras Blancas is also known as Glaciar Fitz Roy, whereas the three glaciers studied at Lago del Desierto have adjacent accumulation areas and are referred to as Glaciar Laguna del Desierto 8, 9, and 10 in Bertone (1960). For simplicity, they will be called here Glaciar Lago del Desierto I, II, and III. Parts of Glaciar Piedras Blancas and Glaciar Torre are debris-covered and both end in relatively large proglacial lakes confined by recent moraines (Fig. 1). Usually the oldest moraines are densely covered by mature forests, and forest colonization in the forefield allows the tree-ring dating of younger glacier deposits. The dominant tree species colonizing these deposits are *Nothofagus pumilio* (lenga) and *N. betuloides* (coihue), but in some humid places *N. antarctica* (ñire) is also common. Unfortunately, some forested portions

**Table 1**
Data sources used in this study.

| Glacier | Location (elev.) | Approximate area in 2005 | Year of available photographs (reference) | AP | SI |
|---|---|---|---|---|---|
| Torre | 49°19′S<br>73°01′W (660 m) | 24.6 km$^2$ | 1931 (De Agostini, 1945); 1946 (Heim, 1951); 1950s? (Auer, 1956); 1952 (Lliboutry, 1953b); 1950s? (Bertone, 1960); 1960s? (Wilhelmy and Rohmeder, 1963); 1963 (Mercer unpubl.); 1980s? (Clapperton, 1993); 2002; 2005 (Villalba, Masiokas unpubl.). | 1966; 1968; 1981 | 1984; 2000; 2002; 2005 (all glaciers) |
| Piedras Blancas | 49°16′S<br>72°58′W (650 m) | 5.6 km$^2$ | 1931, 1936 (De Agostini, 1945); 1946 (Heim, 1951); 1952 (Lliboutry, 1953b); 1950s? (Bertone, 1960); 2002 (Villalba, Masiokas unpubl.); 2005 (Masiokas, Skvarca unpubl.). | 1966; 1968; 1981 | |
| Lago del Desierto I | 49°03′S<br>72°54′W (1090 m) | 0.83 km$^2$ | 1930s? (De Agostini, 1945); 2004, 2005 (Villalba, Casteller, Masiokas unpubl.). | 1966; 1997 | |
| Lago del Desierto II | 49°04′S<br>72°54′W (850 m) | 1.92 km$^2$ | 2003, 2004, 2005 (Villalba, Casteller, Masiokas unpubl.). | 1966;1997 | |
| Lago del Desierto III | 49°05′S<br>72°55′W (1120 m) | 0.95 km$^2$ | 2004, 2005 (Villalba, Casteller, Masiokas unpubl.). | 1966;1997 | |

Available historical documents, aerial photographs (AP) and satellite images (SI) for each site are listed. Unpublished sources cited are from the personal collections of the named individuals. Glacier areas were derived from available satellite imagery (see text for details).

of the glacier forefields were burned by forest fires associated with the European settlement of this area in the early 20th century.

## 3. Previous studies

The great potential for glaciological research of the study area has been known for decades (e.g. Kölliker et al., 1917; Mercer, 1965). Several descriptive studies and glaciological investigations have been carried out (Heim, 1951; Lliboutry, 1952, 1953a,b, 1993; Bertone, 1960, 1972, Mercer, 1965, 1968; Röthlisberger, 1986; Popovnin et al., 1999; Masiokas et al., 2000, 2001; Rivera, 2004), and the well-defined moraine systems located in front of the present glacier margins have long been recognized as clear evidence of recent glacier activity in this region. However, as most investigations have usually focused either on a Holocene perspective (e.g. Mercer, 1968; Röthlisberger, 1986), or on 20th-century glacier conditions (e.g. Lliboutry, 1953a,b; Aniya et al., 1996, 1997; Rignot et al., 2003), few studies have attempted a precise dating of the conspicuous, relatively recent glacier deposits. Few maps or estimates of LIA moraine ages (e.g. Mercer, 1965; Masiokas et al., 2000) and only one very preliminary glacier inventory (Bertone, 1960) are available for the glaciers studied in this paper.

Lliboutry (1952, 1953a,b, 1993) analyzed aerial and field photographs, historical documents and local sources to provide detailed descriptions of surficial glacier features and recent glacier front variations in the Fitz Roy area (Fig. 1). While a marked retreat was indicated for Glaciar Río Blanco between 1936 and 1952, relatively little change in frontal position was found at Glaciar Piedras Blancas for the same interval (Lliboutry, 1953a). At Glaciar Torre the proglacial lake level dropped by 12–15 m between 1931 and 1952 and the glacier front remained in approximately the same position. However, the calving (northern) portion of Glaciar Torre had receded 700 ± 50 m between 1952 and 1981 (Lliboutry, 1993).

Auer (1956) identified four frontal moraine systems, the youngest of which was still bare and assumed to correspond to the latest glacier readvance of recent centuries. Mercer visited Glaciar Torre in 1963 and described the end moraines in front of the present ice margin (Mercer, 1965). He reported an almost bare moraine damming the proglacial lake and another massive moraine almost immediately downvalley with immature forest cover and living trees up to 170 yrs old on the more sheltered (eastern) slopes. Mercer grouped both ridges as Fitz Roy Moraines IV and identified three older ridges with mature forest cover approximately 100 m, 700 m and 2700 m downvalley as Fitz Roy Moraines III, II, and I. Mercer estimated an ecesis of ca. 100 yrs for this site based on historical pictures showing virtually no change in glacier front position in 30 yrs and the lack of vegetation colonizing the moraine damming the lake. Based on these preliminary estimates, Mercer assigned late 19th-century and late 17th-century ages for the two Fitz Roy Moraines IV. He estimated Moraine III to be older than 800 ± 85 $^{14}$C yrs based on a basal peat date from a site between Moraines II and III where they are only a few metres apart.

Masiokas et al. (2000) and Delgado et al. (2002) presented preliminary tree-ring data from sites on the LIA deposits of Glaciar Piedras Blancas. No ecesis correction values were available for the site, but living 80 yr-old and 250 yr-old trees were used to estimate minimum ages for two massive lateral moraines. Most of the tree-ring samples collected at this glacier were also used to develop a long, well replicated tree-ring width chronology that was utilized to reconstruct regional temperature variability for southern Patagonia during the past four centuries (Villalba et al., 2003). The formation of the moraines identified at Piedras Blancas was tentatively related to two significant cold intervals observed around the mid-17th and 19th centuries in a preliminary version of this reconstruction (Masiokas et al., 2000). The clearly delimited sequence of moraine ridges in front of the small glaciers on the west margin of Lago del Desierto (Fig. 1) has not been studied previously. The only available information for these glaciers is the rough areal estimates and basic geographic data in Bertone (1960), and a poor quality photograph published by De Agostini (1945).

## 4. Methods

### 4.1. Dating the glacier deposits

The development of the LIA glacial history for the five glaciers studied in this paper was primarily based on dendroglaciological

**Table 2**
Evidence and limitations of dendroglaciological dating (modified from Luckman, 2000).

| Evidence | Precision | Information provided | Limitations |
|---|---|---|---|
| 1) Trees growing in the glacier forefield | 5–50 yrs | Age of oldest tree provides minimum age for surface | Ecesis (lag time between moraine stabilization and tree establishment) difficult to estimate. Assumes the oldest tree was sampled |
| 2) Tilted and/or scarred tree | Exact calendar age of damage | Damage date indicates glacier position at a specific time | Moderately rare, dead trees require crossdating |
| 3) Trees killed by glacier advance | a) Exact calendar date of outer ring by crossdating with living trees. Dating precision depends on preservation of wood and loss of outer rings<br>b) approx. date by $^{14}$C dating (±50–100 yrs). | *In situ*: death date indicates position of glacier at a specific time<br>Reworked wood: only provides a limiting date for death | a) Requires crossdating, loss of outermost rings<br>b) low temporal resolution, expensive |
| 4) Trees growing outside glacier forefield | Annual resolution | Reference chronologies, paleoclimatic information | Age of oldest tree. Dead material can extend the chronologies but is difficult to find and usually not well-preserved in this region |

techniques (e.g. Luckman, 1986, 1988; Schweingruber, 1996). The usefulness and inherent limitations of dendroglaciological methods are summarized in Table 2. Minimum ages for recent glacial events were usually determined from the age of the oldest trees growing on these deposits. Increment cores were collected from living trees growing on lateral and terminal moraines, prepared using standard dendrochronological procedures (Stokes and Smiley, 1996) and counted to determine tree age. Where the pith ring was not present pith offset values were estimated based on ring curvature on the oldest candidate trees. Minimum ages for trees with rotten piths were estimated by adding 20 yrs to the date of the innermost countable rings. Cores were taken as close to the root collar as possible to minimize potential errors due to sampling height and most samples were taken between 50 and 100 cm from the tree base. Nine young *N. pumilio* trees growing outside the LIA moraines at Glaciar Piedras Blancas were sampled at the base and at 100 cm height to provide a rough estimate of vertical growth rates. Ring counts indicate that, on average, the trees grew 1 m in 7 yrs, suggesting that the error in estimating basal dates from cores sampled up to 1 m above the root crown probably does not exceed 10 yrs. A similar estimate was obtained from seven trees at Glaciar Torre that grew from 25–40 cm to 100 cm height in 7 yrs. Therefore we used a vertical growth rate of 10 cm/yr to correct for sampling height.

An important limitation in determining moraine ages from trees growing on their surface is to estimate the time interval between the stabilization of the surface and tree seedling establishment (Sigafoos and Heindricks, 1969; McCarthy and Luckman, 1993). This interval (also known as "ecesis") has been shown to vary widely depending on microclimatic conditions, substrate and the species involved. There have been very few detailed ecesis estimates for glacier deposits in the Patagonian Andes (see e.g. Koch and Kilian, 2005). Moreover, the presence of proglacial lakes, the sparse vegetation on the steep bedrock outcrops and the poor temporal coverage of available air photos limited our ability to estimate ecesis correction factors for these glaciers. However, De Agostini (1945) reports on a massive outburst flood that occurred on December 16, 1913 from the proglacial lake of Glaciar Río Blanco (Fig. 1) depositing large amounts of sediments throughout the Río Blanco Valley, including numerous boulders especially to the north of Glaciar Piedras Blancas (or "White Boulders Glacier"). Our examination of the site indicates that this outburst probably originated from Glaciar Piedras Blancas and not from Glaciar Río Blanco (see Fig. 4). In either case, the pith date at the base of the oldest of nine trees sampled on this surface was 1923, suggesting an approximate ecesis of 10 yrs for this site. Additional evidence suggesting a variable ecesis of about 15–30 yrs was found at Glaciar Lago del Desierto II. In front of the most conspicuous southern lateral moraine the kill date of a partially buried, *in situ* stump was precisely dated to 1743 by dendrochronological analysis, providing a maximum date for the formation of this deposit. The base of the oldest tree sampled on top of the distal slope of this moraine was dated to 1758, suggesting it took about 15 yrs for the forest to recolonize this surface. The innermost moraine at this site is formed by coarse material on a steep, unstable bedrock slope and was visible several metres in front of the glacier in 1966 air photographs. However, the only seedling found on this moraine was tree-ring dated to 1994, indicating about 29 yrs of ecesis at this site. These preliminary data suggest that, where pith is present, the combination of ecesis and the sampling height correction factor introduce a range of 2–4 decades when estimating dates of moraine formation from tree ages. Larger ecesis estimates are expected at sites lacking good soil conditions (e.g. the steep bedrock slopes in front of the glaciers at Lago del Desierto). However, given the small sample size and the heterogeneity of sites and conditions observed at the different glacier forefields, we used a 15-yr ecesis estimate unless otherwise noted.

Precise information about past glacier activity can be obtained from trees that have been directly affected by past glacier advances (Table 2). This material can be extremely valuable in providing complementary, limiting calendar dates for past glacial events (e.g. Luckman, 2000). Unfortunately very few damaged or killed trees were found at these study sites. The 400-yr-long Piedras Blancas (*Nothofagus pumilio*) reference chronology (Villalba et al., 2003) was used in crossdating trials of tree-ring series from subfossil material. Mature trees located outside the main LIA moraines were also sampled to provide minimum age estimates of surfaces not directly affected by these glacier events. As most tree species in this region rarely exceed 400 yrs of age, it is difficult to differentiate deposits of older events based solely on the age of the trees colonizing their surface. This limitation, plus forest fire activity and the poor preservation of subfossil wood have usually hampered the dating of glacier fluctuations from the first half of the past millennium in the south Patagonian Andes. In most cases we used complementary evidence such as the health and size of the trees to determine whether the sampling sites were covered by old-growth or first generation forests, but unfortunately some degree of uncertainty will remain until better dating is available.

### *4.2. Estimating glacier area changes since the LIA*

Preliminary estimates of glacier area changes since the LIA maximum and between 1984 and 2005 were derived from the analysis of two Landsat Thematic Mapper (TM) scenes with 28.5 m resolution acquired

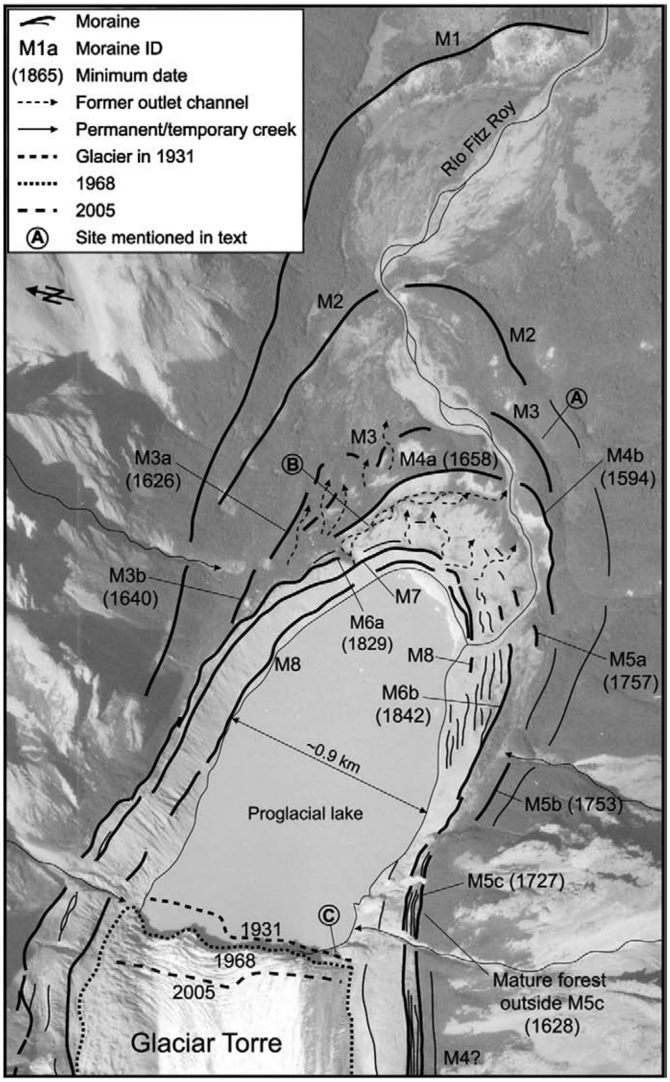

**Fig. 2.** Main features and tree-ring based minimum dates of moraines at Glaciar Torre. The mapping is based on a 1968 air photograph, and the 1931 (2005) glacier frontal position is based on historical documents (field surveys and satellite imagery) (see text for details).

**Table 3**
Dendrochronological dating of moraines at Glaciar Torre.

| Sampling site | Number of trees; innermost ring dates (pith offset and sampling height correction factors) | | Minimum age for surface (ecesis) |
|---|---|---|---|
| | North margin | South margin | |
| M3a (D) | 16 trees; 1674 (20,13), 1683 (20,9), 1687 (20,8) | | 1626 (15) |
| M3b (P) | 14 trees; 1685 (20,10), 1696 (10,5), 1730 (20,5) | | 1640 (15) |
| M4a and M4b (D) | 28 trees; 1690 (10,7), 1705 (10,10), 1708 (20,7) | 10 trees; 1635 (20,6), 1669 (15,11), 1676 (5,6) | M4a: 1658 (15)<br>M4b: 1594 (15) |
| M5a (D) | | 5 trees; 1797 (15,10), 1815* (15,10), 1824* (20,10) | 1757 (15) |
| M5b (P) | | 18 trees; 1783 (0,3), 1792 (20,4), 1792 (5,3) | 1753 (15) |
| M5c (P) | | 27 trees; 1767 (15,10), 1767 (0,4), 1772 (15,13) | 1727 (15) |
| Mature forest outside M5c | | 11 trees; 1664 (15,6), 1710 (20,10), 1722 (20,10) | 1628 (15) |
| M6a and M6b (D) | 20 trees; 1829 (10,5), 1872 (5,5), 1877 (0, 5) | 13 trees; 1842 (2,5), 1854 (10,7), 1882 (0,5) | M6a: 1799 (15)<br>M6b: 1820 (15) |
| M6 (P) | | 7 trees; 1929 (10,2), 1929 (0,8), 1934 (0,8) | 1902 (15) |
| Former channel outside M7 | 9 trees; 1885 (0,4), 1894 (0,6), 1913 (3,6) | | 1866 (15) |

Number of trees and earliest ring dates from the three oldest trees are indicated with the estimated pith offset and sampling height correction factors. Minimum dates for the deposits after accounting for ecesis are shown in the last column. Notes: (D) distal slope of moraine; (P) proximal slope; (*) date obtained after crossdating with living trees (see text for details).

on December 26, 1984 and February 19, 2005. The normal, almost continuous, cloud cover characteristic of the study area and the presence of transient snow on most images hamper the mapping of the true glacier limits and greatly diminish the suitability of most satellite data for analysis. The two images selected were almost entirely cloud free with little transient snow outside the glacier limits and were corrected for geometric and atmospheric distortions (Song et al., 2001; Tucker et al., 2004; SIB, 2005) prior to the delimitation of glacier areas. These images were combined with a 30 m resolution digital elevation model (DEM) derived from Terra ASTER imagery to facilitate the identification of individual glacier basins.

This DEM is processed by The Land Processes Distributed Active Archive Center (LPDAAC), NASA Earth Observing System (EOS). Individual glacier basins were first identified using the HYDRO routine available in ArcInfo and then, based on the visual examination of available satellite imagery, maps and aerial and field photography, corrected manually to exclude minor ice masses and focus only on the main body of selected glaciers. Ratio images of TM bands 4 and 5 (i.e. TM4/TM5) with an interactive examination of different masking thresholds were used to differentiate glacier ice from other surfaces (Paul, 2004). This procedure is considered among the best available for mapping glaciers larger than 0.1 km$^2$ by remote sensing (e.g. Paul et al., 2002) and was supplemented by the manual delineation of debris-covered areas of Glaciar Piedras Blancas and Glaciar Torre. The approximate LIA maximum extent of these glaciers was mapped manually on the 1984 TM scene based on air photo interpretation and field mapping. However, as precise calendar dates often could not be assigned to the LIA maximum, the changes in area should be regarded as approximate and subject to correction as new data become available.

## 5. Results

### 5.1. Glaciar Torre

The main moraine ridges and other relevant features at Glaciar Torre are shown in Fig. 2. No precise dating control is available for the two conspicuous, outermost moraines M1 and M2 (Moraines I and II of Mercer, 1965, see above). These moraine ridges are clearly discernible, especially on the north side of the valley, and can be followed for several hundred metres upvalley providing strong evidence for at least two major, earlier, glacier events at this site. Mercer (1965) located a peat deposit from a site where M2 and M3 (Moraine III of Mercer) are only a few metres apart (site A in Fig. 2). The basal peat date of 800 ± 85 $^{14}$C yrs BP [calibrated to 1050–1400 A.D. (2-sigma probability distribution) using the CALIB radiocarbon calibration program (http://calib.qub.ac.uk/calib/) and the Southern Hemisphere calibration dataset of McCormack et al. (2004)] provides a minimum age for probably both moraines indicating they pre-date the main LIA advances of the past few centuries. The frontal M3 comprises a broad band of ridges that have been extensively modified by fluvioglacial activity at this site. Trees growing on two partially destroyed north lateral ridges that are correlated with this moraine indicate they were formed before the early 1600s (M3ab, Fig. 2 and Table 3). However, the presence of trees of similar or older ages on M4b (see below) implies that M3 pre-dates 1600 and therefore the trees on M3 may not provide closely limiting dates.

A conspicuous, sharp frontal ridge on both sides of Río Fitz Roy (M4ab, Fig. 2) is tentatively interpreted as the LIA maximum at this

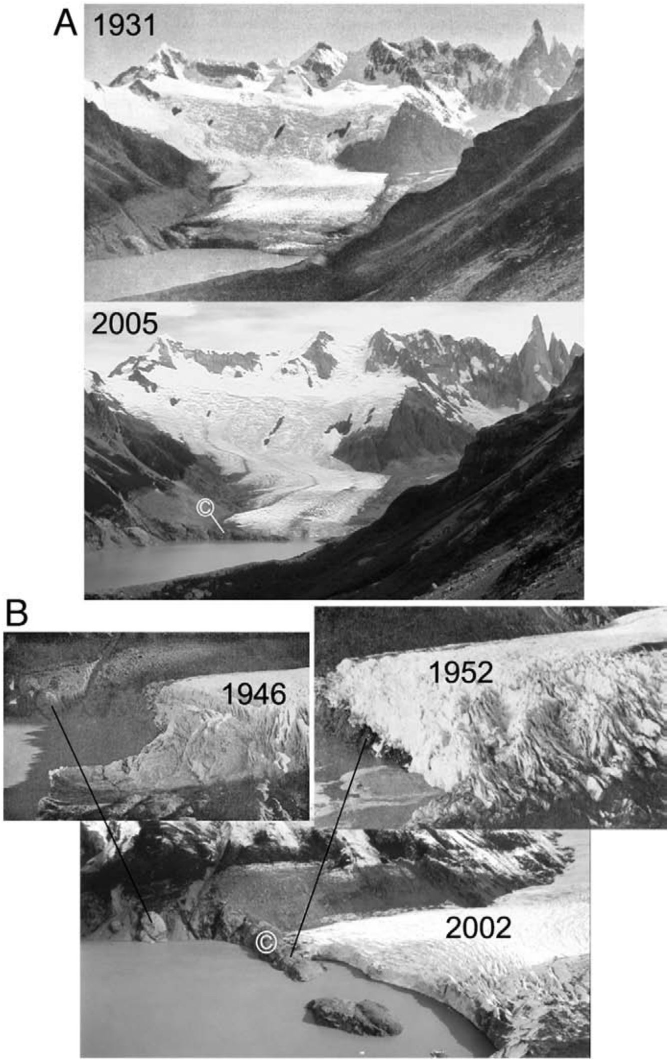

**Fig. 3.** (A). Historical changes of Glaciar Torre between 1931 (De Agostini, 1945) and 2005 (photo R. Villalba). The 1931 view is one of the earliest photographs of this glacier. Note the significant thinning of the glacier tongue. (B) Frontal positions of Glaciar Torre in 1946 (Heim, 1951), 1952 (Liboutry, 1953b) and 2002 (photo R. Villalba). The frontal bedrock ridge (denoted as C here and in Fig. 2) is about 50 m high.

glacier and represents a clear example of the importance of micro-environmental conditions in the establishment of vegetation that is used for the tree-ring dating of a given surface. The samples from the distal, more sheltered slopes of these moraines indicate that these deposits were formed sometime in the late 16th century (Table 3). On the contrary, the proximal unstable slopes of the moraines, constantly exposed to strong westerly winds, remain only barely vegetated. Unfortunately, no evidence has been found yet to provide a maximum, bracketing date for this event.

Evidence for a subsequent glacier advance (M5) comes from the south margin of the glacier where a series of fragmented but conspicuous ridges occurs along the southern slope of the valley (Fig. 2). Although initially assumed to correspond to the M4 frontal moraines, based on morphological continuity, tree-ring dating of numerous trees growing on and immediately outside these ridges indicates that this deposit was formed later, during the early 1700s (M5a–c, Table 3 and Fig. 2). There is no strong morphological evidence for an equivalent event on the north margin of Río Fitz Roy and only a few large boulders and minor ridges remain as a possible indication of the former frontal glacier position of M5 (Fig. 2). The strong fluvio-glacial dissection beyond the former glacier snout has also largely destroyed the frontal moraines associated with the subsequent readvance (M6) of Glaciar Torre. However, the lateral extent of this advance is clearly indicated by two massive lateral moraine ridges at the margins of the proglacial lake (M6ab, Fig. 2). Tree-ring dating from trees growing on the more sheltered, distal slopes of M6 suggest a late 18th-century minimum age for these deposits (Table 3). This determination comes from 20 trees sampled at the eastern end of the north lateral M6 (Fig. 2 and Table 3). However, recent, extensive sampling of *Rhizocarpon geographicum* lichens along the crest of this lateral moraine and in several other sites at this glacier (I. Garibotti, pers. comm.) indicates a minimum age of 1740 for this deposit and suggests that in fact M6 may have not completely obliterated the evidence from the lateral M5 on the north side of the lake. Although preliminary, this complementary information may provide further evidence for the lateral extent and date of formation for M5 at this site. Evidence for at least two major subsequent events (M7 and M8) was identified inside M6, but as the moraines have no tree cover it was not possible to obtain direct minimum ages for the events. However, assuming a 15-yr ecesis, the pith date at the base of the oldest tree sampled along a former outlet channel associated with M7 (site B in Fig. 2) suggests that this moraine was formed before 1866 (Table 3). In addition, the examination of historical documents from 1931 (De Agostini, 1945) indicates that the proglacial lake has remained approximately the same size for at least seven decades (Fig. 3A). Assuming that the trees at site B established only after the outlet channel was abandoned due to glacier front recession, M8 must have been formed only a few decades after M7, probably by the end of the 1800s or the beginning of the 20th century. This implies a subsequent, dramatic glacier front recession (and a concurrent proglacial lake expansion) to the 1931 ice front position shown in Fig. 3A. The proglacial lake covers any evidence of more recent moraines (if they existed), and no evidence was found for subsequent, 20th-century readvances at Glaciar Torre.

Although the limited documentation available indicates that the glacier front has retreated a small distance during recent decades, the main loss of glacier ice at this site in the last 75 yrs has been principally due to a drastic thinning of the glacier tongue (Figs. 2 and 3). Using the conspicuous bedrock ridge in front of the glacier as a reference (denoted as C in Figs. 2 and 3), we estimate that the glacier has thinned by at least 50–60 m since 1952. In recent years the glacier

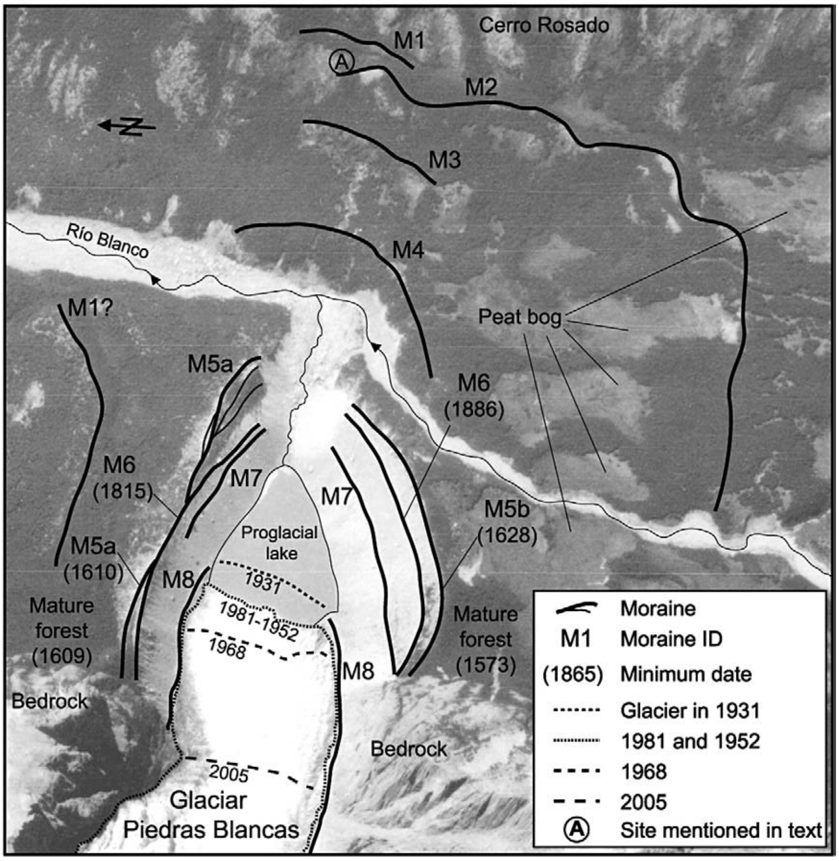

**Fig. 4.** Main features and dendroglaciological dating of moraines at Glaciar Piedras Blancas. The mapping is based on a 1981 air photograph and the widest point in the lake is about 450 m. The 1931 and 1952 glacier frontal positions are derived from photographs in De Agostini (1945) and Lliboutry (1953b), respectively. The 1968 and 2005 positions are based on air photos, field surveys and satellite imagery.

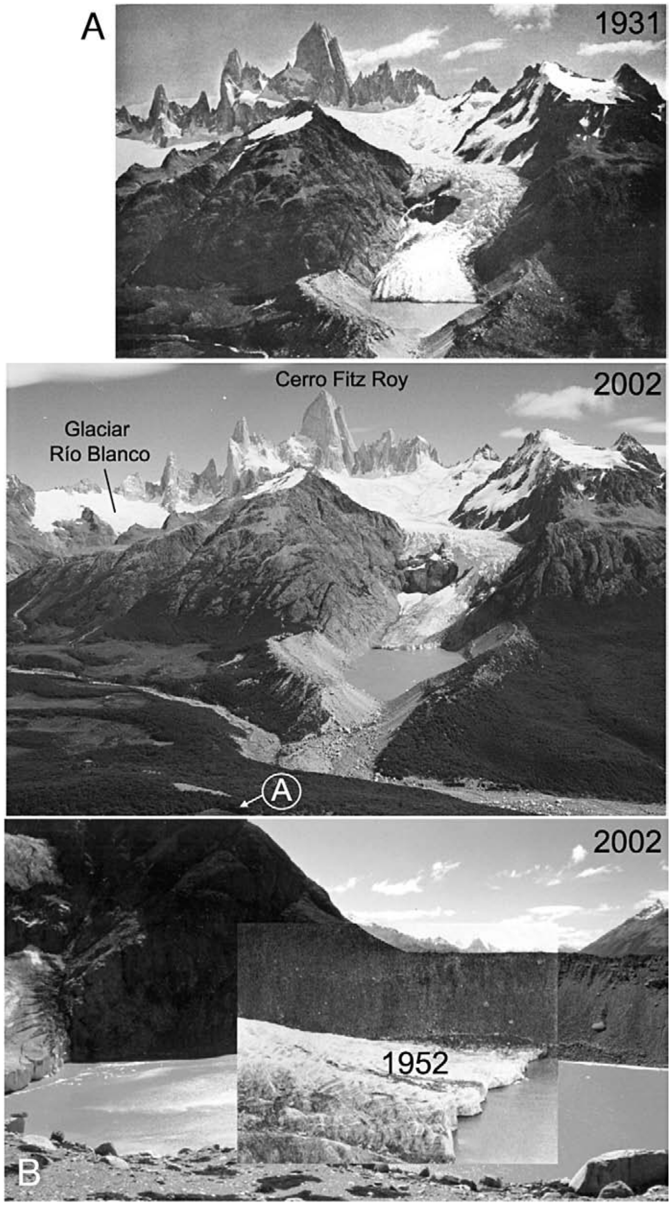

**Fig. 5.** (A) Paired comparison of Glaciar Piedras Blancas between 1931 (De Agostini, 1945) and 2002 (photo M. Masiokas). Monte Fitz Roy and Glaciar Río Blanco are located a few km to the southwest of Glaciar Piedras Blancas. A small moraine-dammed lake with thick organic deposits is denoted as A here and in Fig. 4. (B) Glacier front variations between 1952 (Lliboutry, 1953b) and 2002 (photo R. Villalba). Note the north lateral M8 outside the glacier in 1952.

snout has almost detached from this ridge and the width of the calving front has increased significantly (Fig. 3B). We suggest that this ridge acted as a pinning point that anchored the position of the glacier front for most of the 20th century. However, with recent retreat the snout is no longer protected by this ridge and calving processes will probably accelerate frontal recession in coming years.

### *5.2. Glaciar Piedras Blancas*

Several massive frontal and lateral moraine ridges were identified at Glaciar Piedras Blancas (Fig. 4). On the eastern side of Río Blanco there are at least four possible moraine ridges (M1–4, Fig. 4) built against the steep slopes of Cerro Rosado. Although no dating control is available for these ridges, the small lake with thick organic sediments immediately outside M2 (site A, Figs. 4 and 5A) could potentially provide limiting dates for these features. Additional information may also be obtained from basal dates of the other peat bogs in this area (see Fig 4).

Moraines of at least four glacier advances (M5–M8, Fig. 4) have been identified and formed during the last few centuries. As the forest cover on the eastern portion of the moraines has been affected by forest fires, we concentrated sampling on the western sector of the lateral moraines immediately below a massive bedrock ridge (Fig. 4). Tree-ring dating from the north and south lateral M5 (Table 4) indicates that these ridges were formed during or prior to the early 17th century. Slightly older trees dating to 1573 were cored immediately outside M5 in mature, old-growth forests (Fig. 4). An inner moraine ridge (M6) was assigned an early 19th-century date of formation based on trees growing on the north lateral ridge. However, the low number of trees colonizing this deposit and the wide disparity in ages for the north and south lateral moraines (1815 and 1886, respectively) suggest that this date may not be closely limiting (Table 4). In fact, the oldest tree sampled on a former outlet channel immediately outside the north lateral M6 was dated to 1759. Assuming this channel was active when M6 was formed, this date suggests the channel was abandoned by the mid-1740s (Table 4) and the moraine could date from the mid-18th century.

The remnants of M7 are poorly preserved on the unstable proximal slopes of M6 on both sides of the proglacial lake and lack tree-ring evidence for dating (Fig. 4). The innermost moraines identified at Glaciar Piedras Blancas (M8) mark the lateral limits of a more recent glacier advance during the early 20th century. The glacier front was very close to the M8 position in 1931 (Fig 5A, upper) but below it in 1952 (Fig. 5B, inset). The analysis of aerial photographs from 1968 and 1981 indicates that the glacier advanced again after 1968 and had reached approximately the 1952 position (i.e. stayed within M8 limits, Fig. 5B) by the early 1980s (Fig. 4). After this readvance Glaciar Piedras Blancas has retreated and thinned significantly and as a result, the lower, calving portion of the glacier snout is almost disconnected from the upper glacier (see Fig. 5A).

### *5.3. Glaciar Lago del Desierto I*

The three glaciers investigated at Lago del Desierto all showed a clear sequence of moraines (Fig. 6) but in places the forest has been subject to recent fires. The forest on the outer moraines of the northernmost glacier has been burned but we located several trees that escaped these recent fires and a few well-preserved *in situ*, burned stumps to provide minimum age estimates for some of these moraines. The oldest of nine mature trees sampled in the forest outside the outermost, northern moraine ridge (M1, Fig. 6A) was dated to 1654 (Table 5). Nine trees cored on the distal slope of the south lateral M1 showed similar ages with the oldest tree dating back to 1628. Between this outer moraine and the present glacier front position we identified at least seven moraines

**Table 4**
Same as Table 3, but for Glacier Piedras Blancas.

| Sampling site | Number of trees; innermost ring dates (pith offset and sampling height correction factors) | | Minimum age for surface (ecesis) |
|---|---|---|---|
| | North margin | South margin | |
| Mature forest outside M5 | 17 trees; 1655 (20,11), 1690 (20,5), 1701 (20,10) | 18 trees; 1616 (15,13), 1647 (20,10), 1655 (20,12) | North: 1609 (15)<br>South: 1573 (15) |
| M5a and M5b (D) | 7 trees; 1640 (5,10), 1656 (2,9), 1733 (2,13) | 14 trees; 1672 (20,9), 1686 (0, 10), 1688 (0,12) | M5a: 1610 (15)<br>M5b: 1628 (15) |
| M5a and M5b (P) | 7 trees; 1670 (0,2), 1774 (15,3), 1806 (10,4) | 7 trees; 1750 (20,10), 1777 (20,7), 1803 (20,13) | M5a: 1668 (15)<br>M5b: 1705 (15) |
| Former channel between M5 and M6 | 2 trees; 1783 (20,4), 1812 (20,4) | | 1744 (15) |
| M6 (D) | 4 trees; 1851 (10,11), 1895 (15,10), 1898 (6,4) | | 1815 (15) |
| M6 (P) | | 7 trees; 1931 (20,10), 1945 (4,2), 1946 (9,10) | 1886 (15) |

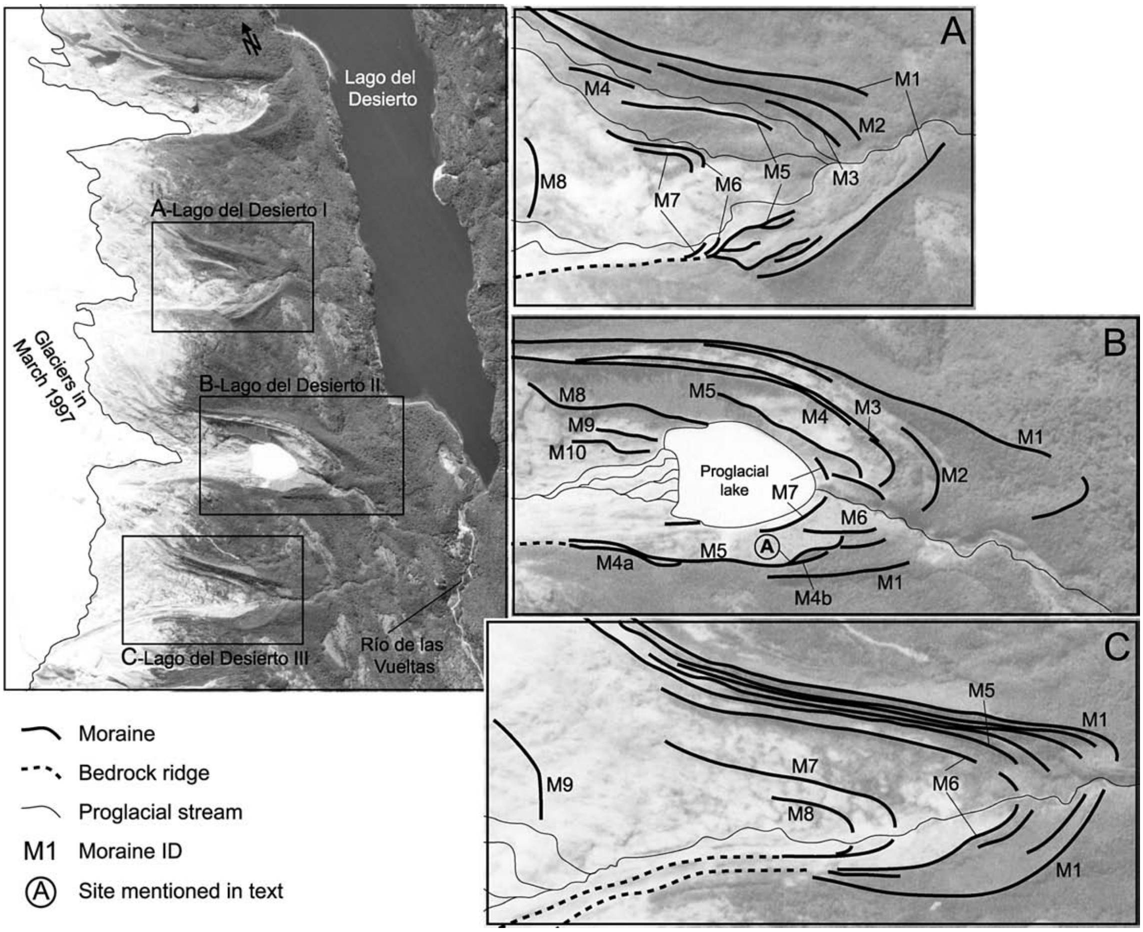

**Fig. 6.** Main features identified at the three glaciers studied in the Lago del Desierto area, identified from north to south as Glaciar Lago del Desierto I, II and III (A, B and C, respectively). The mapping is based on aerial photographs from March 1997 and the lake in front of Glaciar II is about 340 m long. The limit between M5 and older deposits at this same glacier is denoted by A (see text for details).

which were better preserved on the north margin of the glacier (M2–8, Fig. 6A). Four trees (including two *in situ* stumps) cored on the distal side of the north lateral M5 (Fig. 6A) provided a minimum reference date of 1740 for M5 (Table 5). In addition, the oldest tree sampled inside this moraine on the south margin of the central proglacial stream (Fig. 6A) was dated to 1830 (Table 5). A small, 1–1.5 m high ridge of boulders (M6, Fig. 6A) marks the limit of a recent glacier advance at this site, and the innermost ring of the trees inside this moraine was dated to 1901 (Table 5). Another small moraine ridge (M7) occurs a few metres inside M6 with trees of similar size and an innermost ring of 1905 (Table 5). This similarity in tree age and size between M6 and M7 suggests that M7 may have been formed soon after M6 in the late 1800s or early 20th century, probably during a minor advance or pause in glacier recession. These ridges were also identified on the south margin of the southern branch of the proglacial stream (Fig. 6A). A small ridge of boulders (M8), evidence for the most recent advance of this glacier, was found only a few metres in front of the current glacier margin on the steep bedrock slope but no trees had colonized this recently deglaciated surface.

### 5.4. Glaciar Lago del Desierto II

Glaciar Lago del Desierto II (locally known as Glaciar Huemul) is the most easily accessible and is frequently visited by tourists arriving at the southern shores of Lago del Desierto (Fig. 6). This glacier is also the only one with a proglacial lake that has developed between the recent moraines and the steep bedrock outcrop where the glacier snout is presently located. At least ten moraines were identified in front of this glacier and on both sides of the lake (Fig. 6B). This complex glacial history is difficult to elucidate because some moraines have been partially or completely overridden by subsequent, more extensive events and because recent fires have destroyed potential tree-ring sampling sites, especially on the north side of the lake. As a result, a complete glacial chronology is not available, and we currently do not have precise dating control for the three outermost moraines identified at this site (M1–3, Fig 6B). However, on the south margin of the glacier the forest was protected from burning by steep bedrock ridges, and six mature trees cored along the crest and proximal slope of M4 were tree-ring dated to 1615 providing a minimum age estimate for this event (Table 5). Further downglacier, three trees sampled immediately outside M4 were dated to 1528 (Table 5). Although preliminary, these tree ages indicate that moraines M1–M3 pre-date 1528 and that M4 was probably formed in the early 1700th century.

M5 is a sharp, arcuate moraine ridge clearly visible on both sides of the proglacial lake (Fig. 6B). The south lateral M5 has partially overridden the lateral M4, and at the bottom of the distal slope of M5 we found one *in situ* stump that seemed to have been killed during the formation of the moraine and was partially buried by glacier deposits. A 101 yr-long tree-ring width series was developed from this stump and crossdated with the Glaciar Piedras Blancas chronology. The outer ring was dated to 1743. A living tree with its base also buried by glacier deposits was sampled a few metres from the *in situ* snag and the innermost ring was dated to 1725 by simple tree-ring counting. We interpret these data as indicating that the glacier event forming M5 culminated in the 1740s when relatively fine material was being deposited in front of the moraine, killing the *in situ* stump which therefore provides a precise maximum date for this event. The

**Table 5**
Same as Table 3, but for the three glaciers at Lago del Desierto.

| Glacier | Sampling site | Number of trees; innermost ring dates (pith offset and sampling height correction factors) | | Minimum age for surface (ecesis) |
|---|---|---|---|---|
| | | North margin | South margin | |
| Lago del Desierto I | Mature forest outside M1 | 9 trees; 1695 (20,6), 1698 (10,8), 1769 (20,10) | | 1654 (15) |
| | M1 (D) | | 9 trees; 1668 (20,5), 1674 (20,8), 1713 (3,13) | 1628 (15) |
| | M5 (D) | 4 trees; 1788 (20,13), 1805* (20,5), 1819 (20,3) | | 1740 (15) |
| | Inside M5 | 16 trees; 1849 (0,4), 1862 (3,1), 1864 (10,4) | | 1830 (15) |
| | Inside M6 | 9 trees; 1921 (3,2), 1930 (0,1), 1935 (0,1) | | 1901 (15) |
| | Inside M7 | 17 trees; 1924 (0,4), 1936 (5,2), 1940 (5,4) | | 1905 (15) |
| Lago del Desierto II | Mature forest outside M4 | | 3 trees; 1575 (20,12), 1599 (15,10), 1709 (20,15) | 1528 (15) |
| | M4a (P) | | 6 trees; 1645 (5,10), 1670 (10,8), 1672 (20,6) | 1615 (15) |
| | M4b (D) | | 3 trees; 1689 (20,13), 1794 (3,7), 1821 (15,12) | 1656 (15) |
| | M5 (D)# | | 15 trees; 1772 (10,4), 1772 (3,4), 1804 (10,4) | 1743 (15) |
| | M8 (P) | 14 trees; 1931 (0,1), 1941 (0,1), 1945 (0,2) | | 1900 (30) |
| | M9 (P) | 5 trees; 1967 (0,1), 1972 (0,1), 1982 (0,1) | | 1936 (30) |
| | M10 (D) | 1 tree; 1994 (0,0) | | 1964 (30) |
| Lago del Desierto III | M1 (D) | 9 trees; 1581 (20,13), 1591 (10,13), 1631 (0,5) | | 1553 (15) |
| | M1 (P) | 2 trees; 1669 (20,15), 1786 (20,13) | | 1619 (15) |
| | M5 (P) | 4 trees; 1702 (20,12), 1730 (0,10), 1809 (20,10) | | 1655 (15) |
| | M6 (D) | 25 trees; 1755* (0,6), 1759 (10,10), 1766* (10,5) | | 1734 (15) |
| | M6 (C) | 1 tree; 1774 (15,10) | | 1734 (15) |
| | M6a and M6b (P) | 5 trees; 1857 (20,3), 1862 (20,4), 1873 (10,3) | 2 trees; 1930 (20,10), 1949 (20,10) | M6a: 1819 (15)<br>M6b: 1885 (15) |
| | M7 (D) | | 1 tree; 1951 (0,8) | 1928 (15) |
| | M7a and M7b (C) | 2 trees; 1920 (0,2), 1944 (0,2) | 2 trees; 1946 (3,2), 1958 (0,2) | M7a: 1903 (15)<br>M7b: 1926 (15) |
| | M7 (P) | 8 trees; 1900 (0,18), 1904 (0,2), 1927 (10,2) | | 1867 (15) |
| | M8 (P) | 6 trees; 1936 (0,1), 1944 (5,1), 1958 (0,4) | | 1920 (15) |
| | Outside M9 | 3 trees; 1976 (0,1), 1978 (0,1), 1979 (0,1) | | 1945 (30) |
| | M9 (C) | 1 tree; 1985 (0,0) | | 1955 (30) |

Note: (#) The outermost ring of a single *in situ* stump on the distal slope of the south lateral M5 was crossdated to 1743 using a living tree-ring width chronology and provides a maximum age for this event. The innermost ring of another partially buried living tree that apparently survived this event was dated to 1725 (see text for details).

partially buried living tree at this site was probably a small seedling at the time of moraine formation and may have survived this event. The earliest ring of 15 living trees growing on these deposits at the foot of the distal slope was dated to 1758 (Table 5), indicating that deposition from the moraine had ceased by that time. This value also suggests a lag time between moraine stabilization and tree establishment of about 15 yrs at this site.

Further downvalley along this ridge, the morainic material on the distal slope of M5 becomes much coarser and the trees are much older and larger (site A in Fig. 6B). This was interpreted in the field and by re-examination of aerial photographs as the limit between M5 and an older surface (probably M4) that had been partially overridden by M5. The earliest ring of the oldest of three trees sampled on this coarser and apparently older deposit (denoted as M4b in Fig. 6B) was dated to 1656. Unfortunately the forest on M6 and M7 (Fig. 6B) has been seriously affected by forest fires and no tree-ring based age estimations are available for these events. Three additional, more recent moraines (M8–10, Fig. 6B) with no evidence of fire activity are located on the steep bedrock slope between the proglacial lake and the present glacier margin. The basal pith date of the oldest tree sampled inside M8 (M9) was 1930 (1966), and only one tree (with a basal pith dated to 1994, Table 5) was found on the distal slope of the innermost of these moraines (M10). Available air photographs (Table 1) indicate that the glacier front was already several metres behind this moraine by 1966, suggesting that it took at least 29 yrs for this tree to colonize the newly exposed surface. We applied a larger ecesis of 30 yrs to these more recent moraines (M8–10) and preliminarily dated them to 1900, 1936 and 1964, respectively (Table 5).

### 5.5. Glaciar Lago del Desierto III

Glaciar Lago del Desierto III is the southernmost of the glaciers studied in this area (Fig. 6). Detailed examination of the glacier forefield and the available documentation revealed the existence of at least nine distinct moraines (M1–9) that are particularly well-preserved as arcuate ridges on the north side of the proglacial stream (Fig. 6C). However, as extensive portions of these moraines have been affected by forest fires, we focused on those deposits where tree-ring dating was feasible. Several mature trees were sampled on the outermost moraine ridge (M1, Fig. 6C) and indicate that this deposit is at least 450 yrs old (Table 5). Inside these deposits on the proximal slope of M5 two trees that apparently survived the fire were about 350 yrs old. Both living and dead trees (*in situ* stumps killed by recent fires) were sampled along an inner, well-defined moraine ridge with immature forest cover (M6, Fig. 6C). The inner and outermost rings of four of the five burned stumps sampled were successfully crossdated using the Piedras Blancas chronology and indicate they established between 1749 and 1784 and were killed between 1949 and 1968. Together with similar minimum ages obtained from living trees (Table 5), this suggests that this moraine was probably formed during the early 1700s. The three moraines observed within M6 (M7–9, Fig. 6C) showed no evidence of former fires. The age of the oldest tree sampled in association with M7 indicate that this deposit is at least 138 yrs old. The trees inside M8, on the north margin of the proglacial stream, indicate it was formed before 1920 (Table 5). The only seedling found on M9 had a basal date of 1985 and the basal pith of the oldest of three trees immediately outside the moraine was dated to 1975 (Table 5). Since these trees are growing in roughly similar conditions to those at M10 in Glaciar Lago del Desierto II (see above), we assumed a larger, 30-yr ecesis value for this particular site and dated this moraine to about 1945 (Table 5).

### 5.6. Changes in glacier area

Preliminary estimates of glacier area changes since the LIA and between 1984 and 2005 were derived from Landsat TM satellite imagery and represent the first attempt to document long-term glacier changes in the study area. These data will also be valuable reference measures for future monitoring of these sites (Table 6). Glaciar de los Tres and Glaciar Río Blanco, located between Glaciar

**Table 6**
Approximate changes in glacier area (in km$^2$) between the LIA, 1984 and 2005 based on the analysis of Landsat TM satellite imagery (Table 1).

| Glacier | LIA area (approx. date) | Moraine used | 1984 (% change since LIA) | 2005 (% change since 1984) |
|---|---|---|---|---|
| Torre | 30.8 (late 1500s) | M4 | 26.2 (−14.9%) | 24.6 (−6.1%) |
| Río Blanco | N/A | N/A | 4.42 | 4.21 (−4.8%) |
| De los Tres | N/A | N/A | 1.01 | 0.90 (−10.9%) |
| Piedras Blancas | 7.20 (early 1600s) | M5 | 6.02 (−16.4%) | 5.63 (−6.5%) |
| Lago del Desierto I | 1.60 (early 1600s) | M3/4 | 0.87 (−45.6%) | 0.83 (−4.3%) |
| Lago del Desierto II | 3.03 (early 1600s) | M4 | 2.21 (−27.1%) | 1.92 (−13.1%) |
| Lago del Desierto III | 1.79 (early 1600s) | M5 | 1.16 (−35.2%) | 0.95 (−18.1%) |

Maximum extent and dating of LIA advances was based on the location of LIA maximum moraines and tree-ring based estimations (refer to text for details). Area changes between 1984 and 2005 for Glaciar Río Blanco and Glaciar De Los Tres are included for completeness.

Torre and Glaciar Piedras Blancas (Fig. 1), were included for completeness. The 1995–96 area of Glaciar de los Tres (0.976 km$^2$) is known from field measurements (Popovnin et al., 1999) and agrees reasonably well with our estimates for 1984 and 2005 (Table 6), providing an independent validation of our results based on the relatively coarse (~30 m) resolution of Landsat TM sensors. The approximate dates for the LIA maximum at each glacier are based on tree-ring based minimum age estimates from the late 1500s and early 1600s for specific moraines at each site (Table 6). As moraine positions are interpolated in some cases, these areas only provide a rough, minimum estimate of LIA surface area for comparison with present conditions. The results in Table 6 indicate that these glaciers had lost between 20 and 48% of their LIA area by 2005. The smaller glaciers show the highest proportional reductions: the three small glaciers at Lago del Desierto shrank by an average of 44% whereas Glaciar Torre and Piedras Blancas, though losing a greater absolute area, decreased by only ~21%. In the last two decades these glaciers have lost between 5 and 18% of their 1984 areas. The significant downwasting of glacier surfaces since the LIA maximum suggests that glacier mass losses are proportionally greater than these areal estimates indicate.

## 6. Summary and conclusions

The available evidence from the five small glaciers studied in the Fitz Roy and Lago del Desierto areas (Fig. 1) highlights the complex late Holocene glacial history of this region and the existence of numerous glacier advances during the past few centuries (Table 7). In most cases there are at least three or four well-defined older moraine ridges downvalley of early 17th-century LIA moraines but they could not be accurately dated with the available evidence (Figs. 2, 4 and 6). Provisional minimum age estimations from a single $^{14}$C date inside M2 at Glaciar Torre and tree-ring data from this glacier and Glaciar Lago del Desierto II suggest these moraines probably pre-date 1500 A.D. Recent investigations at Glaciar Seco (a small, east facing glacier located ca. 95 km to the south of Glaciar Torre) revealed several massive bouldery lateral moraines with a mature forest cover similar to those seen Lago del Desierto. Radiocarbon dates from subfossil logs preserved beneath the boulders of the outermost of these moraines indicate these boulders were emplaced after 1000 $^{14}$C yrs BP. Given the morphological similarities between the moraine records at these sites, it seems possible that the outermost moraines at Lago del Desierto could be of similar age. Röthlisberger (1986), Luckman and Villalba (2001) and Masiokas et al. (2001) have also reported radiocarbon dates in the 500–1500 $^{14}$C yrs BP time frame from wood recovered from sub-till localities at several glaciers in the vicinity of the study area (see review by Masiokas et al., 2009-this issue). However, correlation of these events will remain problematic until better dating control is available. Future investigations at Glaciar Piedras Blancas could target the small moraine-dammed pond or the peat bogs within the older moraines (see Figs. 4 and 5) that might provide evidence to date some of these earlier advances.

The LIA maximum at these glaciers was tentatively identified as a series of massive moraines that tree-ring dating indicates were formed during or before the late 1500s–early 1600s (Tables 3, 5 and 7). Although no closely limiting dating control is currently available for these events, the examination of the tree-ring samples and the conditions at the sampling sites (i.e. health of the forest, size of trees, etc.) suggest that, even after accounting for the inherent uncertainties of ecesis and other correction factors, the potential error associated with these minimum age estimates is ca. ±20 yrs. Similar dating of moraines from other glaciers in the south Patagonian Andes (e.g. Glasser et al., 2004; Koch and Kilian, 2005; Aravena, 2007) seems to corroborate this preliminary dating and suggests the existence of a major glacier event in this area between the late 16th century and the early 17th century.

The best documented glacier advances in the study area were identified immediately inside the massive ridges of the LIA maxima and occurred in the first decades of the 18th century (Table 7). The clearest evidence for this event comes from Lago del Desierto with the tree-ring dating of M5 at Glaciar II to ca. 1743 and from moraines M5 at Glaciar I and M6 at Glaciar III dating to ca. 1740 and 1734, respectively (Fig. 6 and Table 5). Preliminary analyses of available aerial photographs revealed the existence of apparently similar features in other glaciers immediately to the north of Glaciar Lago del Desierto I (Fig. 6), suggesting that this was probably a widespread (and likely simultaneous) event throughout this area. An event of similar age (M5, Fig. 2 and Table 3) was also observed at Glaciar Torre, and although the associated depositional landforms have been largely modified by later readvances, complementary dendrochronological and lichenometric determinations suggest it was formed in the early 1700s. The evidence for a concurrent event at Glaciar Piedras Blancas is not clear as the (apparently) equivalent moraines (M6, Fig. 3) inside the LIA maximum were dated to the early 1800s based on the few trees found on their surface. However, tree-ring samples along a former outlet channel immediately outside the north lateral M6 (Table 4) suggest that this moraine could in fact have been formed in the first half of the 18th century (see above). In contrast to earlier advances, the moraines of the early 1700s event were dated by bracketing ages from living and

**Table 7**
Summary of tree-ring based minimum (<) and maximum (>) age estimates for the main moraine systems identified at the five glaciers analyzed in this study.

| Period | Glacier | | | | |
|---|---|---|---|---|---|
| | Torre | Piedras Blancas | Lago del Desierto I | Lago del Desierto II | Lago del Desierto III |
| 2000–present | | | | | |
| 1975–99 | | Early 1980s? | | | |
| 1950–74 | | | M8? | <1964 (M10) | |
| 1925–49 | | ~1931 (M8) | | <1936 (M9) | <1945 (M9) |
| 1900–24 | M8? | | <1905 (M7)<br><1901 (M6) | <1900 (M8) | <1920 (M8) |
| 1875–99 | | M7? | | M7–M6? | |
| 1850–74 | <1866 (M7) | | | | <1867 (M7) |
| 1825–49 | | | | | |
| 1800–24 | | <1815 (M6)* | | | |
| 1775–99 | <1799 (M6) | | | | |
| 1750–74 | | | | | |
| 1725–49 | <1727 (M5) | <1744? (M6)* | <1740 (M5) | <1743> (M5) | <1734 (M6) |
| 1700–24 | | | | | |
| 1675–99 | | | | | |
| 1650–74 | | | | | <1655 (M5) |
| 1625–49 | | | M4–M1 | <1645 (M4) | |
| 1600–24 | | <1610 (M5) | | | M4–M1 |
| 1575–99 | <1594 (M4) | | | | |
| Prior to 1574 | M3–M1 | M4–M1 | | M3–M1 | |

Note: (*) see text for details about the preliminary dating of M6 at Glaciar Piedras Blancas.

subfossil trees well within their maximum life span. Since this advance was clearly identifiable at most sites in the study area, it was used here as a relatively well-dated reference event to evaluate the sequence of advances at each site and the relationship with those at other glaciers analyzed in this study (Table 7). For example, the moraine sequence at Glaciar Torre (Fig. 2) shows that there are no major moraines between the early 1700s and the LIA maximum advance of the late 1500s (M5 and M4, respectively). A similar situation can also be observed at Glaciar Piedras Blancas (Fig. 4), and probably applies to other glaciers in the study area, especially those at Lago del Desierto that showed several, poorly dated outer ridges that hampered the identification of the LIA maximum extent (Fig. 7).

We identified three glacial events after the early 1700s at all glaciers studied except for Glaciar Lago del Desierto II, where at least five readvances occurred (M6–10, Fig 6 and Table 7). Although the tree-ring based minimum ages for these events span several decades, they indicate a regional glacier reactivation during the late 19th and early 20th centuries when all glaciers experienced readvances within a few decades (Table 7 and Fig. 7). However, the uncertainties inherent in such dendroglaciological dates prohibit precise evaluation of synchroneity as it is possible that events spaced only a few decades apart could be assigned approximately similar minimum ages (see e.g. M6/M7 at Glaciar Lago del Desierto I, or M8/M9 at Glacier III, Table 7). Future research should, if possible, pay special attention to those sites and situations where evidence could provide more precise, maximum age estimates for these more recent glacier events in the study area.

The analysis of available Landsat TM satellite imagery from the study sites is the first quantitative estimates of the long-term changes in glacier area since the LIA. It also provides important reference material for future studies and complements the evidence from repeat photography of historical documents (Table 6 and Figs. 3 and 5). The results indicate a loss of between 20 and 48% of the LIA glacier area to 2005 with significant recession (5–18%) in the last two decades. Smaller glaciers have suffered proportionally greater loss of area. These figures underestimate volumetric losses as many glaciers have also thinned considerably in the 20th century. This widespread overall pattern of recession agrees with the results from the majority of glacier studies in the region (e.g. Rignot et al., 2003).

In general, our study highlights the importance of analyzing detailed results from single case studies with caution and the need to build a regional database of well-dated records from carefully selected sites before we can fully elucidate the complex late Holocene glacier history of this region. Although these results indicate general patterns of glacier fluctuations, differences between the individual records may reflect real differences in glacier response/behaviour or uncertainties inherent in the dating controls presently available. This was particularly evident at the Lago del Desierto area, where three glaciers of similar size, setting and moraine sequences showed a relatively poor agreement in the tree-ring based estimates of the age of the most recent moraines (see Fig. 6 and Table 7). Although an increased sample of study sites will improve our understanding of the LIA and post-LIA glacier history of this region, they must provide an adequate sample of more precisely-dated histories that may not be possible at every site. Bracketed dating, locating glacier damaged trees and improved ecesis estimates may yield better dendrogeomorphic dates but it is also important to evaluate other dating techniques such as lichenometry, glaciolacustrine sedimentary records and basic stratigraphy to complement dendrogeomorphic techniques. The existence of numerous, additional small valley glaciers surrounded by dense forests neighboring the Patagonian Icefields (see Fig. 1) offers many opportunities for such multi-disciplinary, multi-proxy paleoenvironmental initiatives.

## Acknowledgements

This research was supported by the Argentinean Agency for the Promotion of Science and Technology (grants PICT07-03093 and PICTR02-186) and the Projects CRN03 and CRN2047 from the Inter-American Institute for Global Change Research (IAI). The latter project is funded by grant CRN II # 2060 which is supported by the US National Science Foundation (Grant GEO-0452325). We are grateful to many individuals from IANIGLA (Mendoza), personnel from Parque Nacional Los Glaciares, and other institutions for assistance in the field. J.C. Aravena (CEQUA, Chile) and D. Fernández (El Calafate, Argentina) facilitated access to aerial photographs from Lago del Desierto. Detailed comments by O. Solomina and G. Wiles helped to improve the manuscript and are greatly appreciated.

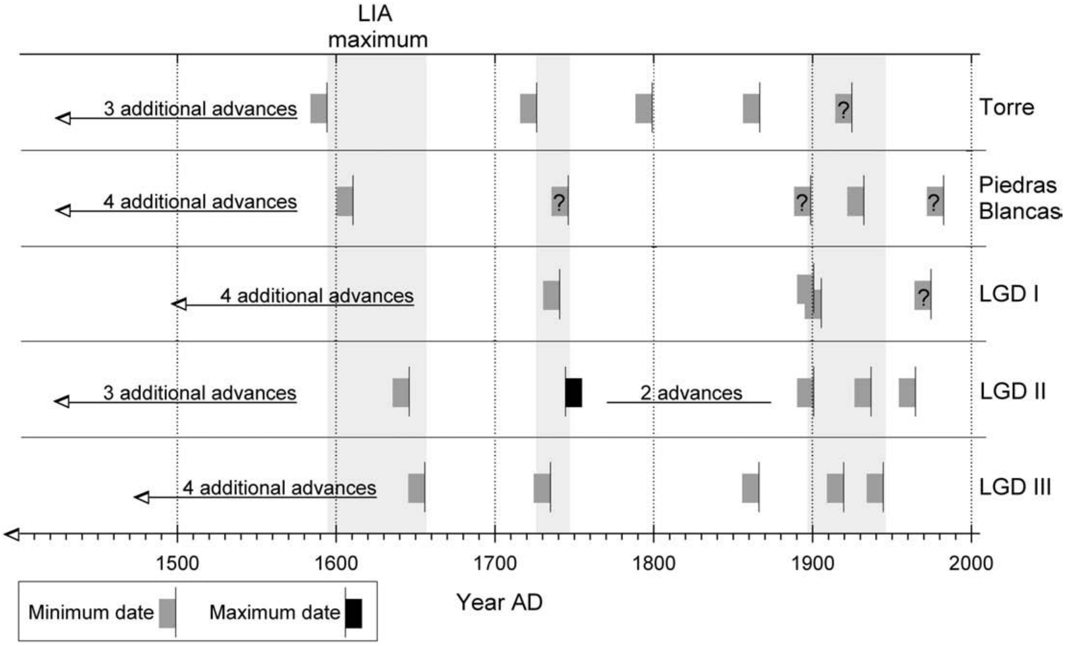

**Fig. 7.** Summary of available age estimates for the main glacier advances identified in the Fitz Roy and Lago del Desierto areas (for details see Table 7). Shaded bars indicate probable ages of major glacier events.

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