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Little Ice Age advances of Glaciar Perito Moreno, Hielo Patagónico Sur, South America

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Abstract

Glaciar Perito Moreno, with an area of 258 km^2, is located on the eastern side of the Hielo Patagónico Sur (Southern Patagonia Icefield) at about 50°29′S and 73°04′W. Currently, it terminates in Lago Argentino, thereby dividing the lake into Canal de los Témpanos to the north and Brazo Rico to the south. The glacier has repeatedly made small advances and retreats in the 20th century; however, it can be regarded as rather stable since the 1920. Based on ^{14}C dating of 22 wood and one organic samples, we inferred that Glaciar Perito Moreno made two Little Ice Age (LIA) advances, one at ca. AD 1650 and the other about AD 1820–50. These two dates fit very well into the general framework of the LIA of the HPS.

Key words: Patagonia Icefield, Glaciar Perito Moreno, Little Ice Age (LIA) advance

1. Introduction

Glaciar Perito Moreno, with its beauty and easy access, is one of the most well known glaciers in Patagonia, and probably the most-studied glacier among more than seventy outlet glaciers in Patagonia. Many of these studies documented and discussed the variation of its terminus in the 20th century (*e.g.*, Reichert, 1917; Heim, 1946; Nichols and Miller, 1952; Raffo *et al.*, 1953; Mercer, 1962; Liss, 1970; Aniya and Skvarca, 1992; Warren, 1994), while recent studies focused more on the glacier dynamics and flow (*e.g.*, Naruse *et al.*, 1992; Naruse *et al.*, 1995; Takeuchi *et al.*, 1996; Skvarca and Naruse, 1997; Rott *et al.*, 1998; Michel and Rignot, 1999; Naruse *et al.*, 2001; Stuefer *et al.*, 2007; Ciappa *et al.*, 2010). Glaciar Perito Moreno started advancing around the turn of the 20th century, and since then it has repeatedly made small advances and retreats, thereby reaching the opposite bank, Peninsula Magallanes, and damming up the southern lake, Brazo Rico (Mercer, 1962). Based on aerial photograph analyses and historical documents, the glacier is regarded to have been more or less stable since the 1920s (Aniya and Skvarca, 1992; Skvarca unpublished).

Mercer (1968), based on ^{14}C dating of wood and peat samples around the glacier, concluded that since ca. 4000 yr BP the glacier cannot have been much further forward than it is today. There is a very distinctive vegetation trimline on both sides of the glacier, above which has developed a dense forest with trees a few hundred years old or more, while below is a predominantly bare till-covered slope. Although it is apparent that this prominent vegetation trimline was formed during a most recent major glacier advance, there has been no definitive study that has attempted to determine its age. Only Aniya and Sato (1995) dated one tree killed by a lateral moraine of the advancing Glaciar Perito Moreno to be 820±90 yr BP (sample NU-355). Also along the shore of Brazo Rico, we can see a very distinctive, level vegetation trimline, below which many large (Diameter at Breast Height - DBH up to ca. 80 cm) dead yet standing trees as well as fallen trees are scattered on fan deltas and gentle slopes covered with soil, whose sizes are similar to those living trees above the trimline.

The LIA advances and subsequent recession of the Patagonian glaciers have been studied at some outlet glaciers. For example, Harrison *et al.* (2007) reviewed LIA studies at eleven outlet glaciers of the Hielo Patagónico Norte (HPN; Northern Patagonia Ice field), concluding that glacier recession from the maximal positions began in the early 1860s–1870s. Masiokas *et al.* (2009) made a comprehensive review of the LIA in Patagonia, both of the HPN and the HPS (Hielo Patagónico Sur; Southern Patagonia Icefield), thereby pointing out a regional contrast: in the HPN the LIA maximum mostly occurred during the 19th century whereas in the HPS it occurred one to three centuries earlier. Some glaciers made two or more LIA advances before the 21st century (*e. g.*, Nichols and Miller, 1951; Mercer, 1965; Marden and Clapperton, 1995; Aniya, 1995, 1996; Aniya and Naruse, 1999; Harrison and Winchester, 2000; Aniya and Shibata, 2001; Aniya *et al.*, 2007). However, we still need more studies at individual glaciers before a complete picture of the LIA advances in Patagonia can be established.

It is the purpose of this study to determine the age of the vegetation trimline and infer the LIA advance (s) of Glaciar Perito Moreno. We took a total of 23 samples for ^{14}C dating, mostly wood pieces from standing or uprooted (in situ) trees that were killed directly or indirectly by the advancing glacier. The conventional radiocarbon age was converted to AD using a calibration curve. Telford *et al.* (2004) criticized the use of the mean only for the interception method with a calibration curve to obtain a single date, quoting an example from 3000–5000 ^{14}C yr BP, because a calibration curve is often multimodal (resulting in multiple interceptions) and the method does not consider the standard deviation. However, when we have many samples from the same area with the similar dates, they can be regarded pointing the same event that directly or indirectly caused sample's occurrence. When there are multiple intercepts, we adopted a date that is similar or close to the others with singular dates, because since they are located very close to each other, it is very probable that they were killed by the same event at a similar time.

2. Study Area: Hielo Patagónico and Glaciar Perito Moreno

The Hielo Patagónico is located at the southwestern end of South America, between the latitudes 46°30′ and 51°30′S along the longitude 73°30′W (Fig. 1, inset). It stretches over ca. 540 km with the width ranging from ca. 8 km to 60 km. At present it comprises two separate ice bodies, HPN with an area of ca. 3950 km^2 (Rivera *et al.*, 2007) and HPS with an area of ca. 12550 km^2 in 2009 (Skvarca, unpublished). Together it is the largest temperate ice body in the Southern Hemisphere.

On the east side of the HPS at around 50°29′S and 73°04′W is located Glaciar Perito Moreno (Fig. 1), with an area of 258 km^2 and an AAR (Accumulation Area Ratio) of 0.73 (Aniya *et al.*, 1996). Currently it has two calving fronts in Lago Argentino, one in Brazo Rico to the south and the other in Canal de los Témpanos to the north (Fig. 2). The behavior of Glaciar Perito Moreno with the repeated advances and subsequent snout collapses during the 20th and 21st centuries (*e.g.*, Mercer, 1962; Aniya and Skvarca, 1992; Stuefer *et al.*, 2007) contrasts strongly with that of Glaciar Ameghino (GA in Fig. 2), a neighboring glacier to the immediate north, which has been steadily retreating although the accumulation area is situated in the same topo-

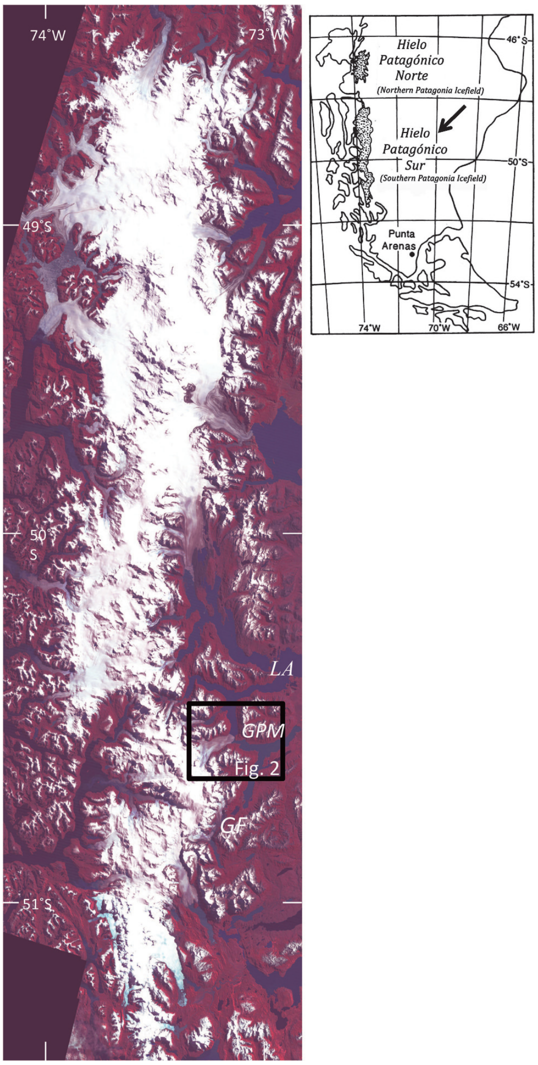

Fig. 1. Landsat TM mosaic of Hielo Patagónico Sur (March 12, 2001) and the location of Glaciar Perito Moreno (GMP), with an inset indicating the location of Hielo Patagónico (Patagonia Icefield). The extent of Fig. 2 is indicated. GF: Glaciar Frias. LA: Lago Argentino.

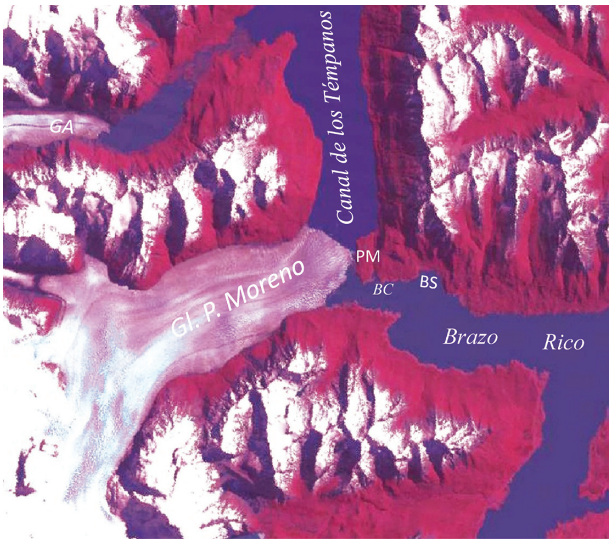

Fig. 2. Study area: Glaciar Perito Moreno, indicated on part of the Landsat TM mosaic of Hielo Patagónico Sur (March 12, 2001). GA: Glaciar Ameghino. PM: Península Magallanes. BS: Bajo de las Sombras. BC: Bahía Catalana.

graphic setting as Glaciar Perito Moreno. The contrasting behaviors of Glaciar Perito Moreno and Glaciar Ameghino have been noted by Nichols and Miller (1952) and Warren (1994). We do not know, however, the reason or cause for such contrasting behaviors, because there is no field measurement at the accumulation areas of these glaciers.

3. Vegetation Trimline around Brazo Rico and Glaciar Perito Moreno

Since we started sampling on the shore of Brazo Rico rather than at the glacier, we describe the trimline around Brazo Rico first.

The prominent vegetation trimline along the shore of Brazo Rico, located at ca. 23.5 m higher than the normal lake level (Fig. 3), was formed during the higher water caused by damming of advancing Glaciar Perito Moreno. The vegetation above the trimline is the wood mainly composed of Nothofagus (Coigüe and Lenga) with a DBH larger than 50 cm, some even reaching around 80 cm. The soil is mostly of eolian origin deposited during the Holocene and ca. 30–40 cm thick on the glaciated bedrock. Because the area below the vegetation trimline is still largely devoid of vegetation, often of bare bedrock, the water must have stayed high for a prolonged time. Although the trimline has probably existed for a long time, its present level was formed during the 1954–56 damming event when the lake level was highest, which was revealed by a comparison of the 1947 and 1968 aerial photographs taken by the Instituto Geográfico Militar (IGM) of Argentina. In some areas below the vegetation trimline where the shore slope is gentle with soil, there are many large dead yet standing trees as well as fallen large tree trunks that were killed by water submersion during the high water.

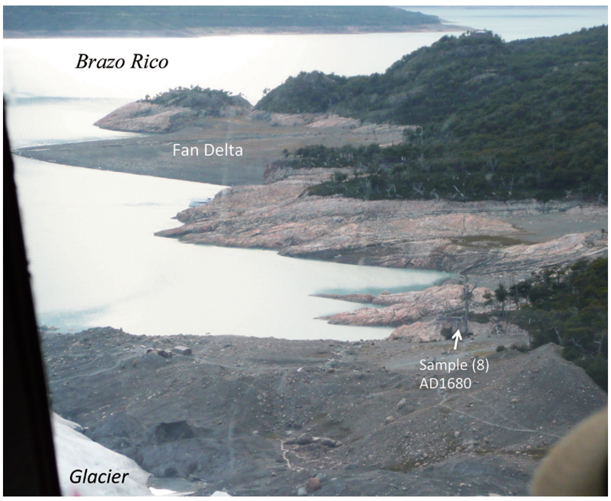

Fig. 3. Vegetation trimline on the southern shore of Brazo Rico and a fan delta where seven samples (#1, 2, 3, 4, 12, 13 and 15) were taken from five dead standing trees. Also shown is the tree of sample #8. (Photo taken from helicopter on Feb. 25, 2010)

Fig. 4. The right valley slope of Glaciar Perito Moreno, showing a prominent vegetation trimline (Photo, Jan. 3, 2009). The dotted white line roughly indicates the boundary between the older and younger moraines.

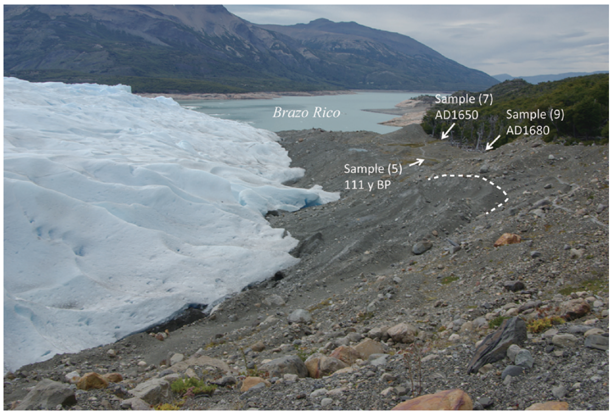

Fig. 5. Vegetation trimline on the right valley slope of Glaciar Perito Moreno. Looking down the area toward Brazo Rico (Photo, Jan. 3, 2009). Some sampling sites with dates are shown with arrows. The two sets of lateral moraines with different materials can be clearly recognized. The lower (younger) one looks young and soft; however, it is weakly indurated, implying its antiquity (crest is indicated with a dotted line).

Fig. 6. Another vegetation (grass) trimline (indicated with dotted red line) located below the prominent vegetation trimline, on the right valley side of Glaciar Perito Moreno, about 6 km up from the snout (Photo, Dec. 26, 2007).

On the valley slope of Glaciar Perito Moreno, there is one distinctive trimline located only several tens of meters above the present glacier surface (Fig. 4). Another, younger lateral moraine can be clearly recognized on the ground that is mostly composed of sand/silt/clay, rather than gravel/boulder of the older lateral moraine which produced the trimline (Fig. 5). The wood above the trimline is very similar to that of Brazo Rico. About 6 km up from the terminus, another trimline, although sporadic, can be discerned, which is marked with grasses at ca. 20 m below the distinctive one (Fig. 6). Thus, there are two trimlines. On the right valley slope near the lake shore where the glacier flows into the lake, we can recognize two types of tills with the different degree of weathering or freshness. These two trimlines, two sets of lateral moraines in general, and the two types of tills indicate two recent advances.

4. Radiocarbon Dating

4.1 Brazo Rico Shore

The first sampling was carried out on a fan delta below the vegetation trimline, where many large dead trees (DHB, up to 80 cm) are still standing among many fallen trees of a similar or larger size (Fig. 7). Four samples were taken in 2007 from dead yet still standing trees with DBH ~80 cm. Three samples (#1, #3 and #4: sample numbers correspond to those in Table 1) out of the four yielded an identical calibrated age, Cal AD 1650 (Table 1), while one sample (#2) yielded an anomalous age [later sampled again (#15), with Cal AD 1660]. The three identical ages suggest that these trees were killed by the same event, that is, water submersion due to high water caused by damming of advancing Glaciar Perito Moreno. Later, in February 2010, two more samples were taken from one tree on this fan delta: one (#12) from the core of the tree and the other (#13) from the surface. Both yielded the same age, Cal AD 1650. A tree (#8) on the lake shore covered with till near the glacier, which was killed by water submersion, is Cal AD 1680 (see Fig. 3).

In order to check these ages, five samples were taken from the northern shore of Brazo Rico in December 2010. Two samples were collected from dead trees at Bajo de las Sombras (see Fig. 2): the sample #19 (DBH ~50 cm) with Cal AD 1650 is about 5 m higher

Table 1. Radiocarbon measurements.

Data ID & Sample no.	Material	Sampling Date	Conventional Radiocarbon Age	Cal AD*	Remarks (site, cause, etc)
β-239794 (1)	wood	Dec 25, '07	260±50	1650	fan delta, killed by WS**
β-239795 (2)	wood	Dec 25, '07	20±60	NA	fan delta, killed by WS sampled again, see (15)
β-239796 (3)	wood	Dec 25, '07	270±70	1650	fan delta, killed by WS
β-239797 (4)	wood	Dec 25, '07	260±60	1650	fan delta, killed by WS
β-255188 (5)	peat	Dec. 30, '08	110.7±0.4pMC		depression formed by gl adv
β-255189 (6)	wood	Dec. 28, '08	101.8±0.5pMC		uprooted by lateral moraine (LM)
β-255190 (7)	wood	Dec. 27, '08	250±40	1650	uprooted by LM
β-255191 (8)	wood	Dec. 31, '08	160±40	**1680** 1740 1800 1940 1950	till flat, killed by WS
β-255192 (9)	wood	Dec. 31, '08	170±40	**1680** 1740 1800 1940 1950	pond formed by LM, killed by WS
β-257818 (10)	wood	Dec. 29, '08	109.7±0.7pMC		depression formed by LM
β-257819 (11)	wood	Dec. 27, '08	100±40	**1710** 1880 1910 1950	uprooted by LM
β-276675 (12)	wood	Feb. 28, '10	250±40	1650	fan delta, killed by WS, core
β-276676 (13)	wood	Feb. 28, '10	250±30	1650	fan delta, killed by WS, surface
β-276677 (14)	wood	Feb. 25, '10	160±40	**1680** 1740 1800 1940 1950	#1, uprooted by LM
β-276678 (15)	wood	Feb. 26, '10	230±40	1660	same tree as (2)
β-276679 (16)	wood	Feb. 27, '10	127.3±0.7pMC		uprooted by LM, 2 m from (6)
β-276680 (17)	wood	Feb. 25, '10	210±40	1660	emerged from gl bottom
β-276681 (18)	wood	Feb. 25, '10	410±40	1450	emerged from gl bottom
β-291043 (19)	wood	Dec. 20, '10	250±50	1650	#2, near shore, killed by WS
β-291044 (20)	wood	Dec. 20, '10	280±40	1640	#2, near VT***, killed by WS
β-291045 (21)	wood	Dec. 20, '10	310±40	1540 **1630**	#3, between bogs, killed by WS?
β-291046 (22)	wood	Dec. 20, '10	260±40	1650	#3, highest pt, killed by WS?
β-291047 (23)	wood	Dec. 20, '10	140±40	**1690** 1730 1810 1930 1950	#3, below VT, killed by WS

* Intercept of CRA with calibration curve. When there are multiple intercepts, the one closest to other single dates was adopted (indicated in Bold)
** water submersion
*** vegetation trimline
#1: This tree stump was sampled in 1990 and measured to be 820±90 BP (NU-355)
#2: Bajo de las Sombras
#3: Bahía Catalana
β-276675 (12) & β-276676 (13) are the same tree

than the present water surface, while the sample #20 (DBH~80 cm) with Cal AD 1640 is 16 m higher than the sample #19. A tree located higher yielded an age 10 years older than that located lower, when both were killed by the rising water: however the difference is well within the error margin. Three samples were collected from the Bahía Catalana and its saddle area, a longitudinal shallow valley leading to Canal de los Témpanos and separating Península Magallanes from the main land (Fig. 8). The sample #23 (Cal AD 1690) is a large tree stump (DBH ~60 cm) located below the trimline at the Bahía Catalana, where numerous small dead trees that were killed during the 1954–56 damming are still standing. The sample #21 (Cal AD 1630) was taken from a standing tree (DBH ~25 cm) between bogs in the Bahía Catalana saddle, while the sample #22 (Cal AD 1650) was taken from a fallen tree (DBH ~80 cm) at the highest point of the Bahía Catalana saddle.

From these ages, it appears reasonable to conclude that water became high ca. AD 1650 for the first time in several hundreds of years during which a mature wood had developed, thereby killing large trees by water submersion.

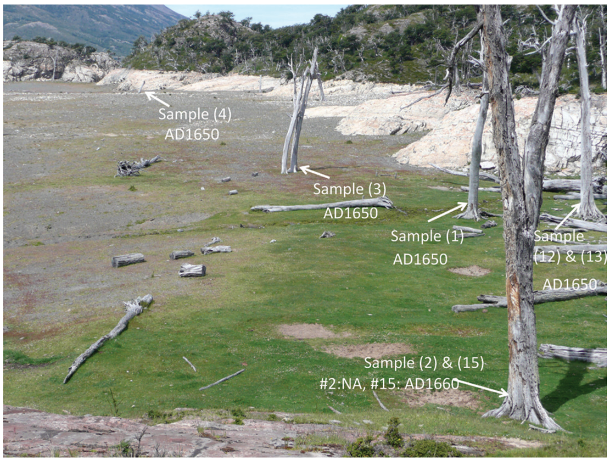

Fig. 7. Sampled standing trees on a fan delta below the vegetation trimline (Photo, Dec. 25, 2007). Samples #2 and #15 were taken from the similar part of the same tree. Samples #12 and #13 were taken from the same tree, but #12 from the core while #13 from the surface. Ages are also indicated.

4.2 Trimlines of Glaciar Perito Moreno

Subsequently, based on the 2007 finding, many more samples were collected in December 2008 and February 2010 to determine the age of the trimline on the right bank of the glacier from those associated with the glacier advance. They are three types. (I) Trees uprooted (in situ) by lateral moraines formed by an advancing glacier, yielded Cal AD 1650 (sample #7), AD 1710 (#11) and AD 1680 (#14). The tree stump of the sample #14 was originally sampled in 1990, from which an age of 820±90 yr BP was obtained (NU355, Aniya and Sato, 1995: Cal AD 1230–70). We have no idea why there is a wide difference of more than 400

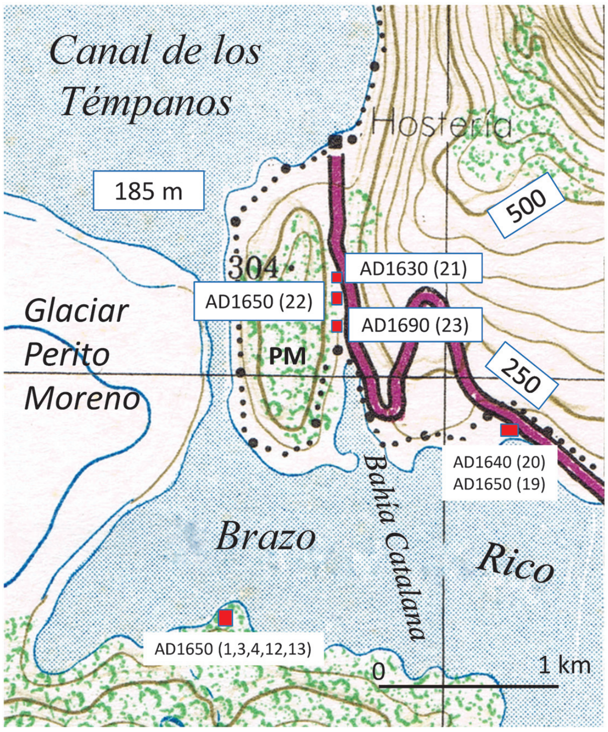

Fig. 8. Map showing the Bahía Catalana saddle area and sampling points with dates and sampling number in parentheses (map taken from 1: 100,000 topographic map 'Glaciar Perito Moreno', published by Argentinean IGM in 1989). Contours in meters. The lake level, 185 m, is given by an Argentinean company for water resources, EVARSA. PM: Península Magallanes. Sample #22 is located at the highest point of the saddle area (elev. ~227 m). The wide red line is the road.

Fig. 9. An example of sample (#9, AD 1680) and sampling site (Photo, Dec. 31, 2008). The pond was formed by a lateral moraine that dammed a stream from the hillside. Some trees are still standing in water. On the left side, there is a younger moraine.

years between these two dating results, which exceeds even a range of 2 σ. In addition, conventional radiocarbon ages of 102 yr BP (#6) and 127 yr BP (#16) were obtained. (II) Water-submerged tree in a pond that was formed by damming of a stream from the hillslope by newly formed lateral moraine, yielded Cal AD 1680 (#9, Figs. 9 & 5). (III) Organic matter deposited and wood piece embedded in ponds that were formed by younger lateral moraines, yielded conventional radiocarbon ages of 110 yr BP (#10) and 111 yr BP (#5, Figs. 10 & 5), respectively.

Two wood pieces were collected from scattered tree litters on a lateral moraine right next to the glacier surface, about 5 km up from the terminus, which were brought to the surface and deposited by thrusting from the glacier bed. Because the tree litters here are very extensive, they were probably killed en masse by the advancing glacier and subsequently incorporated into the glacier body and trans ported sub/en-glacially to the present site before emerging onto the surface by thrusting. Their ages are Cal AD 1660 (#17) and Cal AD 1450 (#18).

Fig. 10. Another example of sample (#5, 111 yr BP) and sampling site (Photo, Dec. 31, 2008), an organic matter collected from a sediment-filled flat on the younger moraine.

5. Discussion and Conclusions

We have obtained two general ages for the trimlines and lateral moraines of Glaciar Perito Moreno (Fig. 11 and Table 1), Cal AD 1650–1710 and 102–127 yr BP (probably equivalent to AD 1823–1848). From many of the samples taken on the lake shore we obtained the age of Cal AD 1650, which is the same as the older age of the glacier trimlines. Since killing of trees by water submersion is rather uniform in timing while uprooting of trees by lateral moraine formation occurs at different times with unknown time lags, it appears reasonable to take Cal AD 1650 as the time of a LIA advance of the glacier. Since we have two trimlines, two sets of lateral moraines, and two types of tills along the glacier, the two ages we obtained are congruent with the field evidences.

At the neighboring Glaciar Ameghino, Nichols and Miller (1951) first identified a LIA advance from the tree ring analysis at AD 1870–80. Then, Aniya (1996) identified two rows of terminal moraines that are damming a proglacial lake, Laguna Ameghino and dated the older one to be 320±80 y BP (NU-659), concluding that an earlier LIA occurred around AD 1600–

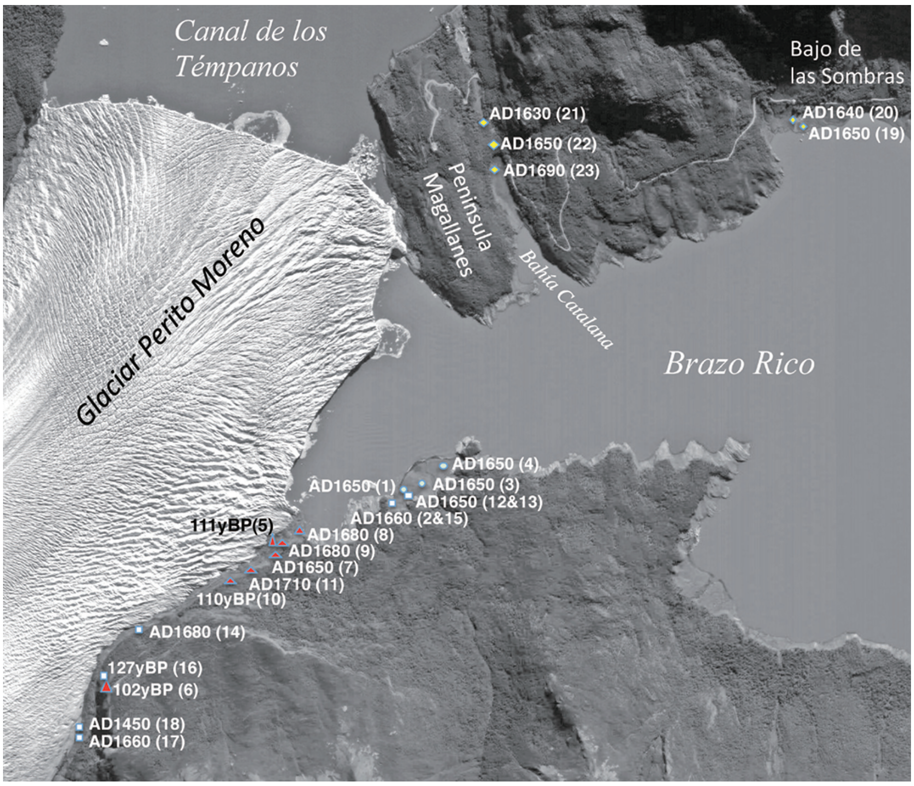

Fig. 11. Location of ^{14}C samplings at and around Glaciar Perito Moreno, with ages (conventional radiocarbon age indicated with y BP). Circles indicate samples taken in Dec. 2007, triangles (red) those in Dec. 2008, squares those in Feb. 2010 and diamonds those in Dec. 2010 (Satellite image, ALOS PRISM, March 28, 2008, courtesy of JAXA). The number in bracket after the age corresponds to that in Table 1.

1700. This age was calibrated using Calib 6.0 (Stuiver and Reimer, 1993: http: //calib.qub.ac.uk/calib/calib.cgi); thereby, Cal AD 1640 was obtained from the calibration curve. This age agrees very well with the older age obtained for Glaciar Perito Moreno in this study. The younger age, ca. AD 1820–1850 at Glaciar Perito Moreno is a little earlier than that at Glaciar Ameghino; however, if we consider the current different behavior of each glacier, this amount of the time lag is quite plausible.

Glaciar Frías, which is located immediately south of Glaciar Perito Moreno (see Fig. 1), has three rows of recent terminal moraines within 1 km of the ice front (Mercer, 1968). From the ages of trees given by Mercer (1968), Masiokas *et al.* (2009) estimated the formation of these three moraines as the mid-19th, early 19th and mid-17th centuries. Of these, the early 19th and the mid-17th century advances coincide with those at Perito Moreno.

The dates we obtained at the Bahía Catalana saddle raise some interesting, but very enigmatic issues about the nature of environment during the LIA. Mercer (1968) asserted that Glaciar Perito Moreno could not have been much larger than today, at least during the last 4000 years, based on the age 3830±115 yr BP of the basal peat in a bog on the Bahía Catalana saddle. Since the basal peat has not been disturbed, he concluded that this area has not been occupied as spillway. The bog from which Mercer (1968) recovered the peat sample has been drying up since then and has now divided into two, and the sample #21 (DBH ~25 cm, see Fig. 8) is one of many dead trees still standing between these separated bogs, yielding a Cal AD 1630. The sample #22 with a Cal AD 1650 is a fallen large tree (DBH ~80 cm) at the highest point of the Bahía Catalana saddle. These two dates indicate that they were killed at the same time as those on the northern and southern shores of Brazo Rico. Therefore, it is probable that the cause of death of those trees located at the saddle was the water submersion. Due to the topography of the saddle area, the water submersion could only have been possible if the water of Brazo Rico spilled through to Canal de los Témpanos when the water level was high due to ice damming by advancing Glaciar Perito Moreno.

We checked the elevation figures of the area given by Mercer (1968), and the height difference from the mean lake level to the saddle area of 42 m was confirmed by the recent measurements. The water level of a dammed Brazo Rico could not have risen more than 42 m in order to spill through the saddle area during the LIA, because a) the vegetation trimline along the glacier margin is not that high, and b), if the water level had risen more than 31 m the water would have spilled to Lago Argentino over the other (east) end (Raffo *et al.*, 1953). Then, why the trees on the saddle area were killed at the same time as those on the shores of Brazo Rico? We could interpret that the bog from which the sample #21 was taken was formed during the LIA, although we do not know how; but the sample #22 was taken from the highest place, which could not have become a pond/bog. If we can identify the cause of their death, a new interpretation might emerge for the environment of Brazo Rico and the surrounding area during the 17th century, and nature of the LIA advance of Glaciar Perito Moreno. The sample #23 taken below the vegetation trimline at the Bahía Catalana yielded a Cal AD 1690, which is later than those located at higher grounds (#21 and 22) or those located at Bajo de las Sombras (#19 and 20), but the difference of 40–60 years is within the error margin.

We conclude that Glaciar Perito Moreno made two LIA advances, at ca. AD 1650 and AD 1820–50, and the environment of the Peninsula Magallanes and the Bahía Catalana saddle area was probably much more complex than previously thought.

Acknowledgments

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