Recent glacier advances at Glaciar Exploradores, Hielo Patagónico Norte, Chile

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Abstract

With the purpose of establishing the recent glacial chronology of the HPN, moraines at Glaciar Exploradores were identified and investigated, thereby collecting samples for ^{14}C dating. In total, three moraine systems were recognized, the Invernada moraine (TM1), main moraine (TM2) and the modern (secondary) moraines (TM3). TM3 was further subdivided into TM3–1 and TM3–2 based on vegetation cover, size, morphology, degree of rock weathering, and development of mosses on rocks. Two samples from TM1, six samples from TM2 and seven samples from TM3 were dated. Also the number of tree rings was counted at TM2 and TM3. Based on these data, four possible scenarios were postulated and examined. The tentative conclusion is that there were two recent glacial advances at Glaciar Exploradores, one sometime between the 12th and 17th century (forming main moraine, TM2) and the other around the early to mid-19th century (TM3–1) and after ca. 1944 (TM3–2). We could not obtain a date that would indicate the age of the Invernada moraine (TM1): however, from the age of TM2, it was speculated that it could be of the Neoglaciation III (1600–1300 BP).

1. Introduction

The Patagonia Icefield is very important to understand the global pattern of the environmental changes, because of its nature (temperate glacier), size and location. In order to elucidate the global pattern of Holocene glaciations, Neoglacial advances of Patagonian glaciers have been studied mostly at the HPS (Hielo Patagónico Sur; southern Patagonia Icefield), first by Mercer (1964, 1968, 1970, 1976, 1982) and later by Aniya (1995, 1996). Mercer identified three Neoglaciations around 4700–4200 BP, 2700–2000 BP, and the Little Ice Age (LIA), whereas Aniya proposed four glaciations around 3600 BP, 2300 BP, 1600–1400 BP, and the LIA. Glasser *et al.* (2004) called this as Mercer type and Aniya type chronology.

On the other hand, at the HPN (Hielo Patagónico Norte; northern Patagonia Icefield) studies on recent glacial chronology are scarce and the glacial chronology of the HPN has not well established yet. The first such study was carried out by Aniya and Naruse (1999) who identified two glacial advances at Glaciar Soler, 1300 BP and the LIA during the 18th century. Later Glasser *et al.* (2002) suggested another advance between AD 1200–1350. Harrison and Winchester (2000), at Glaciares Colonia and Arco, suggested the LIA advance during the 18–19th century from the dendrochronology. Recently, Glasser *et al.* (2005), using ASTER and other satellite images, manually interpreted terminal moraines of the HPN outlet glaciers and identified three advances including the LIA, without assigning ages to the other two earlier advances. Because of the satellite resolution (ASTER, 15 m; Landsat, 30 m), identification of terminal moraines was naturally limited. In their paper, they list the big moraine of Glaciar Exploradores as of the LIA, without giving any concrete evidence or argument. It was probably simply judged so because it is located immediately front of the present glacier snout.

Including Glaciar Exploradores, there is a big terminal moraine in front of the present snout at many outlet glaciers, and some of them have formed a proglacial lake such as Glaciares León, Fiero, Nef and Steffen, to name but a few. Determining the age of this big moraine is an important key for establishing the recent glacial chronology of the HPN. Aniya first thought it is probably of the age around 1600–1300 BP, from the study at Glaciar Soler (Aniya and Naruse, 1999), whereas British groups (*i. e.,* Harrison and Winchester, 2000; Glasser *et al.,* 2005) think it is of the LIA. With this background, we carried out landform investigation in December 2003, December 2004 and August 2005, thereby collecting many samples for ^{14}C dating.

Based upon the moraine distribution and the ages of ^{14}C data, we present our interpretation of the recent glacier advances at Glaciar Exploradores.

2. Study area

Glaciar Exploradores is located at 46°30′S and 73°10′W, on the north side of Monte San Valentin, the highest mountain in Patagonia (3910 m) and is fed principally with snow accumulating on the mountain slope and snow/ice avalanches (Fig. 1). It is not directly connected with the icefield to the south. The glacier has three main sources (Fig. 2), however, two of which are now not contributing to the glacier body in the ablation area, due to prolonged recession (A & C of Fig. 2). The area is ca. 121 km^2, with a length of ca. 20 km and the accumulation area ratio (AAR) of 0.66 (Aniya, 1988). The AAR is the ratio of the accumulation area to the total glacier drainage area, describing one of the important drainage characteristics, and many glaciers have a typical value of around 0.6. It has the largest relief in Patagonia with the highest being 3910 m and the lowest being around 180 m. The width of the ablation area is about 2.5 km, and delimited by prominent lateral moraines on both sides with a relief more than 50 m, which are associated with the main terminal moraine.

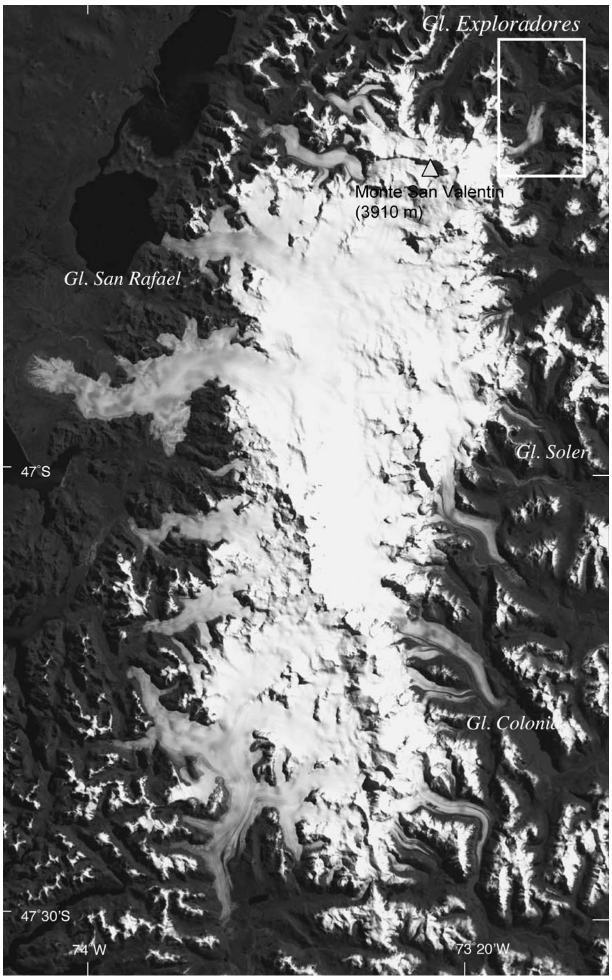

Fig. 1. Landsat image of HPN (March 11, 2001) and the location of Glaciar Exploradores.

3. Distribution of terminal moraines

The moraine systems located just in front of the present snout can be largely divided into two, according to the relative location to each other, morphology, vegetation, and degree of soil development. In addition, about 3 km down the river from these moraine systems, there is an old terminal moraine abut on the mountain slope on the right bank of Río Exploradores. Since the local people call this site “Invernada”, we denote this moraine “Invernada moraine”. Therefore,

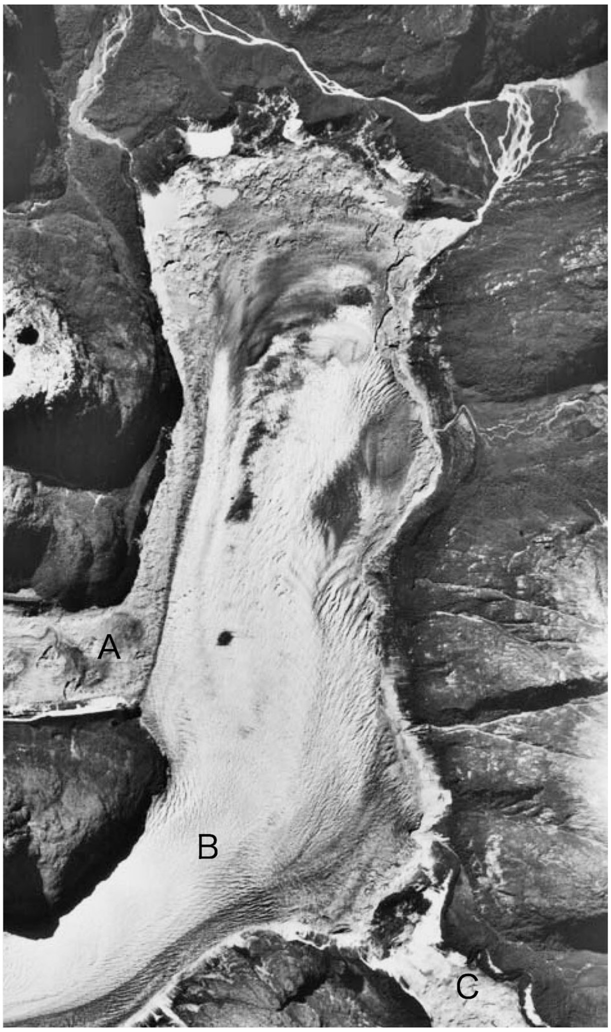

Fig. 2. Vertical aerial photograph of Glaciar Exploradores (March 11, 1997 by SAF, Chile). The glacier has three sources for the lower part of the glacier, the central part (B) being the largest and main body : branch used to join on the east (C) has detached before 1974, while the branch joining on the west that is completely covered with debris has diminished supply of ice for a long time (A). It is now covered with thick debris on which some trees are growing.

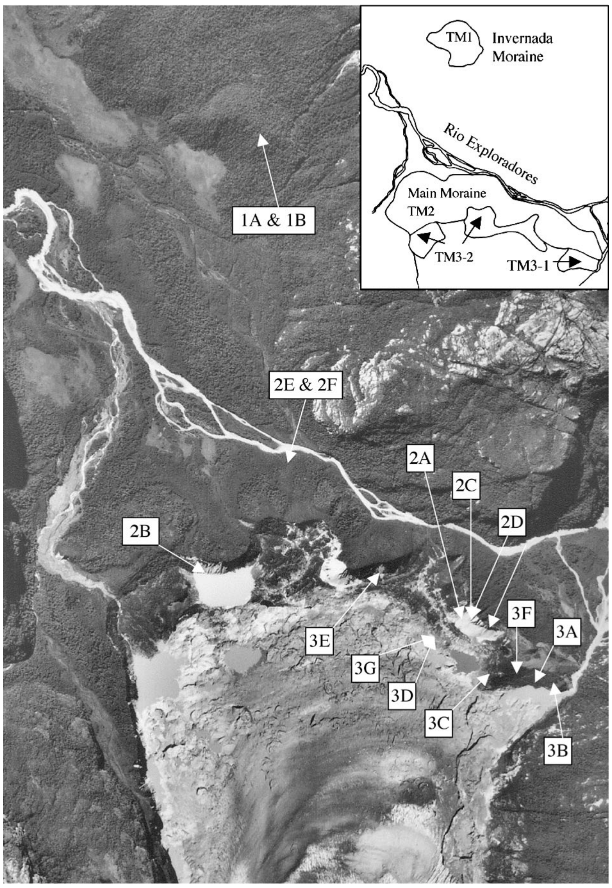

Fig. 3. Terminal moraines and sampling sites for dating materials at Glaciar Exploradores (aerial photo by SAF, Chile, March 11, 1997).

in total, there are three main terminal moraine systems in the area down the snout (Fig. 3).

3.1 Invernada moraine (TM1)

This moraine was first spotted from the road in December 2004, when we tried to walk to the neighbor glacier Grosse, and subsequently checked on the 1997 vertical aerial photographs. In August 2005, we visited this site and confirmed indeed as a terminal moraine (Fig. 4). This is a huge moraine consisting of a single ridge, with a relief from the valley floor exceeding 250 m, length more than 1000 m, and the width at the base about 900 m. The whole hill is covered with dense, large vegetation. There is a gently inclined terrace to the northwest of this moraine, which was formed by huge landslide deposits. Since the ridge of the moraine is separated from the mountain slope, this cannot be a depositional landform produced by huge landslide. Actually, the formation and existence of this moraine seems to owe this terrace, which may have blocked the glacier snout. We call the glacier advance that formed this moraine “Invernada Advance”.

The moraine consists of huge blocks of granites, particularly near the top. Here boulders of more than 5 m long are piled up, and without soil development and dense vegetation cover, it would have been impossible to walk about. From depressions near the top, we collected two samples of organic matters for ^{14}C dating.

Fig. 4. Ground photograph of Invernada moraine (August 3, 2005, by Aniya), looked from the south on the road under construction along Río Exploradores. Note: although it was the middle of winter, the snow cover on the mountain slope was very limited, indicating moderate climate around here even in winter.

Although the moraine is located by the mountain slope, we have judged this moraine a terminal one, from its position on the valley floor and the direction of the main ridge (though not completely transverse to the valley direction). To our enigma, however, we could not recognize any corresponding lateral moraines on either side of the valley, from the field observation of hill slope topography and/or vegetation change on slope, or even from stereoscopic interpretation of the 1997 aerial photographs at about 1: 70000. At present with so much debris supply, the development of lateral moraines is very good. Therefore, it seems difficult to think that lateral moraines were not formed when the Invernada Moraine was deposited. If formed, what would have completely destroyed the lateral moraines of the Invernada advance. One possibility is a glacial lake outburst flood (GLOF). If a GLOF of such magnitude had occurred, the Invernada Moraine should have been affected; however, due to dense vegetation cover such evidence could not possibly be recognized.

3.2 Main terminal moraine (TM2)

Because this terminal moraine system is most prominent and important in this area and therefore is a subject of age estimation of this project, we call it “main moraine” (Fig. 5). This moraine encircles the present snout almost completely with one active outlet stream on the eastern edge and three old, dried-out outlets that break the continuation of the moraine ridge. There are distinctive lateral moraines on either side of the glacier, which are associated with the main moraine. On the 1944 Trimetrogon aerial photograph, at least three active outlets were recognized (Fig. 6). Since then, the central ones were dried out, and on the 1974 aerial photographs two active outlet

Fig. 5. The main terminal moraine of Glaciar Exploradores (July 26, 2004, by Aniya), looked from the northeast, with perfect reflection in Lago Bayo. The mirror-like lake surface indicates that there was absolutely no wind, which was not unusual during winter. The peak at the top left is Monte San Valentin (3910 m), the highest mountain in Patagonia. Since the elevation of Lago Bayo is about 180 m, the relief in this photograph is more than 3700 m.

Fig. 6. Trimetrogon aerial photograph of Glaciar Exploradores, taken in 1944. A is a branch joining on the west, which was completely covered with debris. B is the main body.

streams are recognized at the western and eastern edges, while on the 1997 aerial photographs the western outlet stream was dried out due to surface lowering. When we visited the wind gap at the western edge in December 2004, the lake level on the glacier side was about 20 m lower than the wind gap.

A relief of the moraine on the proximal side is up to 80 m, while on the distal side it is 140–200 m from Río Exploradores. The moraine is extensively covered with trees, particularly on the distal side due to mild climate with abundant rain; however, it is still ice-cored at many sites. The evidence for ice-cores includes: (1) seepage of water from the proximal base of the moraine (even in winter); (2) exposure of ice-core at the base due to erosion; and (3) bulging of the proximal slope, flowage of surficial rubbles and tilting of trees on them due to core-ice melting. For this reason, much of the proximal side is devoid of vegetation or with fallen trees of 10–15 cm thick, while the distal side is covered with thick soils and dense trees (many conifers) with the diameter at breast height (DBH) of 50–60 cm.

The proximal slope of the eastern part of the moraine ridge is totally devoid of vegetation, on which rock fall is very active, particularly when it is raining. Abundant water seepage from the base of this part, including winter time, indicates that a large core-ice still exists inside this part. The nature of sediments is totally different between the upper and the lower part. The upper part consists of fine material that has slightly indurated with weak stratification, inclining toward the distal side, and the proximal slope is more than 50°, while the lower part consists mainly of gravel of loose materials resting at the angle of repose, some of which are subrounded or subangular indicating the influence of running water. Many fallen rocks originate from the lower slope. A lot of wood pieces are seen embedded here on both the upper and lower parts.

3.3 Modern terminal moraines (TM3)

These moraines are located between the main moraine (TM2) and the present snout. At places, there are proglacial lakes between TM3 and the snout. From the fieldwork and the aerial photographic interpretation, this moraine system can be further divided into two types (see Fig. 3 inset), according to vegetation cover, size, morphology, degree of rock weathering, and development of mosses on rocks.

3.3.1 TM3–1

This moraine system is located near the eastern edge, in front of a water pool for the outlet stream. This system comprises several small moraine ridges transverse to the glacier flow direction and two kettle ponds developed here. Nothofagus found on this moraine system are large, with the DBH ranging up to 40–50 cm near the water pool. The present snout abuts on this system, with striking contrast in appearance. The area (rocks) without vegetation is covered with extensive mosses. Boulders include many limestones, which cannot be found elsewhere on the moraine.

3.3.2 TM3–2

This system is located on the proximal side of the Main moraine (TM2). In many places, active proglacial lakes are located between this system and the present snout. In contrast to TM3–1, the topography of this moraine system is generally flat, with some hummocky areas. Invasion of vegetation is fairly well, and at places Nothofagus trees with the DBH of 15–20 cm are found. There exist extensive ice cores beneath the soil of about 30 cm thick. Recent melting of core ice is very striking, with trees falling, ponds enlarging, and steps on the surface formed due to differential melting (Aniya *et al.,* 2005).

4. ^{14}C Samples and dating results

Sampling sites are shown in Figure 3, and the following dates were obtained for each moraine system.

1) Invernada Moraine: two organic samples were collected from two depressions near the top, which yielded the following ages.

1A, ca. 106 BP: 1B, ca. 100 BP.

2) Main Moraine: six wood samples were collected from this moraine, with the following ages.

2A, 9250±50 BP; 2B, 1900±50 BP; 2C, 1400±40 BP; 2D, 1050±54 BP; 2E, 870±50 BP, and 2F, 820±60 BP.

3) Modern Moraines: seven samples were dated.

3A, ca. 108 BP (plant); 3B, ca. 109 BP (organic matter); 3C, ca. 115 BP (wood); 3D, ca. 121 BP (wood); 3E, 123 BP (organic matter); 3F, ca. 134 BP (plant); 3G, ca. 147 BP (organic matter).

4.1 Interpretation of ^{14}C data

A sample for ^{14}C data is normally a piece of wood that was embedded in a moraine or destroyed by a glacier advance, or organic matters/plant remains found in a depression that was supposedly formed by a glacier advance. Interpretation of these data is totally different though. In case of a piece of wood, the age of a sample indicates that the glacial advance was later than that age (maximum possible age). On the other hand, the age of organic matter or plant remains found in a depression indicates that the glacier advance was well before the age of such samples (minimum possible age). As for a wood sample, we normally do not know its origin and transportation processes until its deposition. As for the organic matters, we are usually not sure how long it took for the organic matter to be formed in a depression that was formed by a glacier advance. It is not difficult to suppose that this decomposition/sedimentation process is very different under different climate conditions and nature of sediments (gravelly or clayey/silty), and in Patagonia it is inferred to range from 100 to more than 2000 years (Mercer, 1976). Therefore, interpretation of the ^{14}C age must be carefully done, considering the nature and the environment of samples.

4.1.1 Samples from Invernada moraine

Samples 1A and 1B both yielded a modern age of ca. 100 BP. Although these samples were collected from a layer just above the gravel in depressions near the top of the moraine, this cannot be indicative of the age of the moraine formation, judged from the circumstance and the environment of the moraine.

4.1.2 Samples from the main moraine

Ages of these samples are wide spread, ranging from 9250 BP to 820 BP. Of these samples, 2A (9250±50 BP), 2B (1900±50 BP), 2C (1400±40 BP), 2D (1050±54 BP) were collected from the proximal slope of the moraine. The age of sample 2A is very different and from the general circumstance of the icefield it is very likely that it was reworked many times before being embedded in the moraine. Therefore, we can safely exclude this sample from our subsequent discussion.

The age of 1900 BP of sample 2B was obtained with a piece of wood that was embedded in the proximal slope by a proglacial lake near the western edge of the main moraine. The piece of wood was chipped from a tree trunk of about 30 cm thick, which was one of the piled-up tree trunks. From the size of tree trunks and the way they are clustered, it is unlikely that these were subglacially transported and subsequently brought up onto the surface by thrusting. It seems rather that these tree trunks were mostly transported supraglacially. Around this sampling site, which is about 10 m above the present proglacial lake level, there is a weak-bedding structure on the slope, indicating a higher level of the old proglacial lake. From these circumstances, we interpret that the formation of the main moraine was after this date, 1900 BP.

One of the distinctive characteristics of the main moraine is that the ridge near the eastern edge has a bedding structure, although weak, that inclines toward the distal side. Samples 2C (1400±40 BP) and 2D (1050±54 BP) were collected from the proximal side of this bedded part. Because the age of samples becomes progressively older from the top (Fig. 7), it is possible to interpret that the formation of this moraine started around 1400 BP and culminated around 1050 BP. This interpretation is close to the Aniya and Naruse's (1999).

It is difficult, however, to suppose that such structure was formed in random deposits of supraglacial debris, because the bedding structure is normally found in sediments that were deposited in water. It is therefore natural to suppose that either these are subglacial sediments by subglacial streams that were brought up by thrust, or sediments in a proglacial lake. These strata contain a lot of subround or subangular gravel, indicating strong effect of running water. Because the thickness of these strata is more than 20 m, it seems unlikely that this was brought up by thrust and we interpret that this strata was sediments in a proglacial lake. Varved clay layers that are normally recognized in sediments in still-standing water cannot be found in this sediment though. The reason may be that at Glaciar Exploradores, there is no strong contrast in melting between summer and winter, and the volume of the outlet stream does not fluctuate much without lake freezing. From this interpretation of the nature of this layer, it is probable that wood pieces originated somewhere upstream where Nothfagus are abundant. Fallen trees were probably subglacially transported and near the snout were brought up onto the surface by thrust and then deposited in a proglacial lake. From these data, the moraine formation was probably later than 1050 BP.

Samples 2E (870±50 BP) and 2F (820±60 BP) were collected at the same site on the distal side of the moraine (Fig. 8). There are horizontal strata here in which tree remains with 30–40 cm thick were embedded. Since the tree remains were laid down, its origin cannot be ascertained; if they were washed into a lake after being killed somewhere else, or if they were killed and buried in situ by impounding water due to moraine formation or glacial advance. According to their origin, the interpretation would be totally opposite. If the interpretation is the former, the glacial advance took later than 820 BC, or if the latter, the

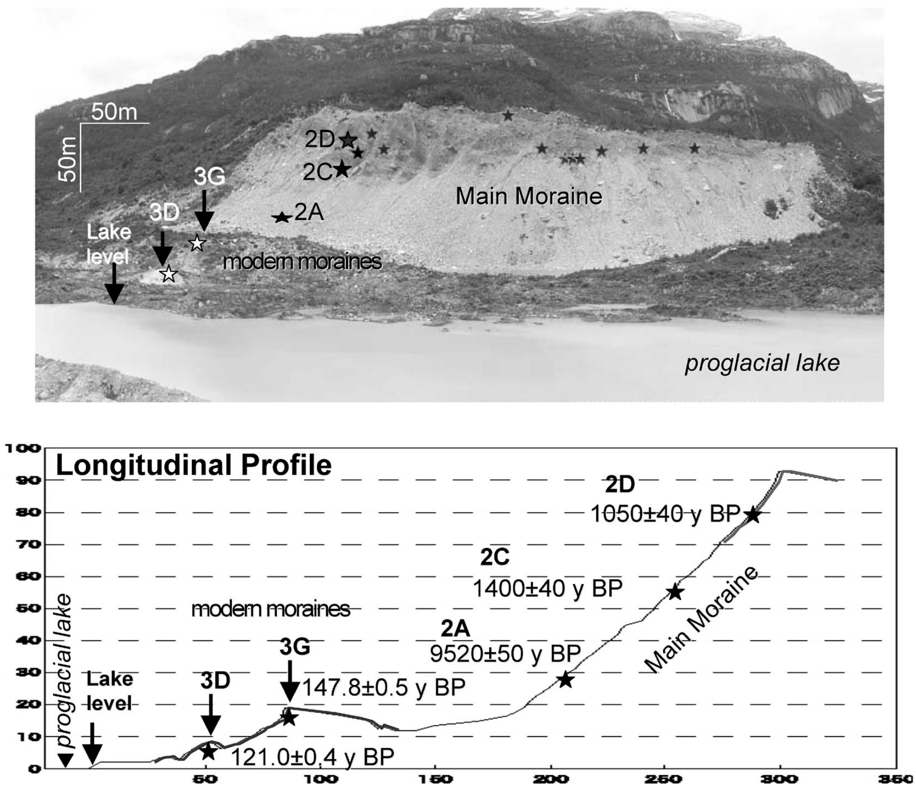

Fig. 7. Sampling sites on the eastern part of the main moraine (TM2) and their dates. Compare with Figure 3 for the location.

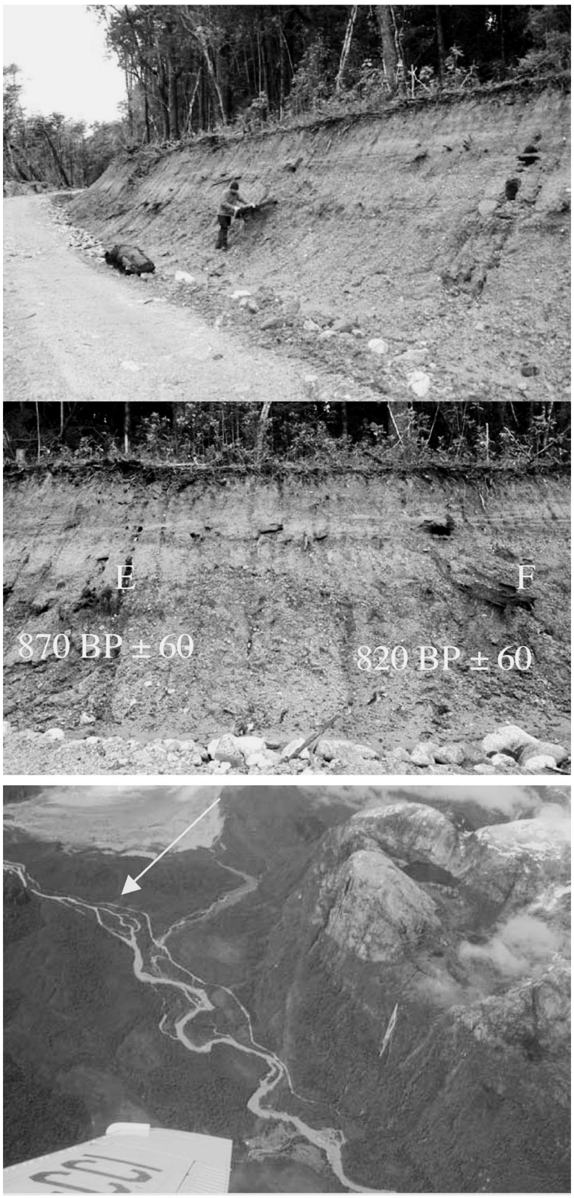

Fig. 8. Sites of samples 2E and 2F on the distal side of the main moraine (TM2), showing the bedding structure (about 2 m thick), near the bottom of which samples were located. Before ca. AD 1100, it was warm enough to support a forest of large trees here.

glacial advance occurred before 820 BC. Here, considering the result of the tree ring analysis in the following section, it is interpreted that the glacial advance or moraine formation took later that 820 BP.

5. Tree ring analysis

5.1 TM2

The number of tree rings was roughly counted on a tree section that was cut and left by the road for the road construction. We counted roughly 200 rings on the section with a diameter of about 40 cm. The largest tree in this area is about 50–60 cm at DBH and if we simply extrapolate the growth rate (5 years/cm), we obtain a maximum age of about 250–300 years. The development of vegetation and soil is very well in this area, because of mild, temperate climate; however, in comparison to those at the Invernada Moraine, they look much younger.

5.2 TM3

By a proglacial lake behind TM3–2, we found several fallen trees due to the recent melting of the core ice, and cut one of them for tree ring count. About 30 cm above the root, 20 rings were counted at the section with a diameter of 15 cm. This area was debris-covered glacier in 1944 (see Fig. 6). So trees started growing 20–30 years later and in about 20 years it grew to a height of around 5 m. Such rapid invasion of trees and subsequent rapid growth are probably due to thick debris, mild climate and abundant precipitation.

6. Postulation of moraine formation ages and recent glacier advances

6.1 Main moraine (TM2)

From the preceding discussion of interpretation of ^{14}C data, indicating the maximum age of ca. 820 BP, and the tree ring count (2–300 years) and the time elapsed before plant invasion (not known for sure, but probably less than 50 years from TM3–2), it appears best to suppose that the moraine was formed sometime between the 12–17th century, that is, the Medieval warm period to the LIA.

6.2 Modern moraines (TM3)

Ages obtained from organic matters and plant remains range from ca. 150 BP to 100 BP. Wood samples 3D and 3G were collected from sediments on top of the ice-cored moraines, which were probably brought up by thrust. This area was still debris-covered part of the glacier in 1944. Considering the time required for algae and plants to grow in a pond on the ice-cored moraine, it seems reasonable to suppose that the formation of TM3–1 was sometime between the mid- and the late19th century. Glacial advance at this time was recognized at Glaciar Colonia of the HPN (Harrison and Winchester, 2000). The manual interpretation of the Trimetrogon aerial photograph indicates that TM3–2 was formed after 1944.

TM3 moraines were divided into two types, TM3–1 and TM3–2. Then we can postulate several scenarios for glacial advance and retreat that produced TM 3–1 and TM3–2, because the sources of glacier bodies that produced these moraines are likely different. Some of them are as follows.

(1) After forming the main moraine sometime between the 12th and 17th century, the glacier retreated. Then the glacier bodies that formed both TM3–1 and

TM3-2 advanced at the same time around the early 19 th century. The glacier body that formed TM3-1 started retreating earlier than the other part, and during the slow retreat the glacier formed a series of recessional moraines (mid- to late 19th century). Meanwhile, the large part of the glacier that subsequently formed TM3-2 had been stationary for a long time, being blocked by the large main moraine. It was only ca. 1940s when that part started receding after a prolonged period of surface lowering. Because of long stagnation (about 100 years?), a mantle of thick debris has been developed, which facilitated easy plant invasion along with the mild climate.

(2) After forming the main moraine, the glacier became stagnant for a while. Because of diminished accumulation, the glacier surface gradually lowered, thereby accumulating thick debris cover and eventually started receding. In this process, the eastern part (TM3-1) started receding earlier than the western part (TM3-2), forming a series of recessional moraine ridges.

(3) After forming TM2, the glacier receded. Then the glacier advanced at the whole front in the early to mid-19th century, and the glacier receded at the whole front, thereby forming a series of recessional moraines. The TM3-2 part advanced again, destroying the recessional moraine, and remained abutting on the TM2 until around the 1940s before starting recession again.

(4) Only the TM3-1 part advanced during the early to mid-19th century, and receded by the late 19th century, thereby leaving recessional moraines. The TM3-2 part advanced independently around the beginning of the 20th century and started losing mass of ice from the mid-20th century.

Of these four scenarios, either (1) or (2) seems most plausible for the following reason. The proximal side of TM3-1 is a water pool for the only outlet stream at present, and the recession of ice on this part is conspicuous, compared with the other parts of the front. This is because the glacier body (branch) that used to join the main body and come down to this part no longer joins the main body since the 1940s (see C in Fig. 2). Therefore, after the 19th century advance, the glacier part that was fed with this branch could have started earlier retreat than the TM3-2 part. Although the appearance and characteristics of TM3-1 and TM3-2 are quite different, these are basically the products of the same glacier advance, and the difference in stagnation period and the nature of debris materials have caused such apparent difference.

If we take the scenario (1), Glaciar Exploradores made two LIA advances. In case of the scenario (2), there was only one LIA advance. We do not have decisive data yet. However, in Patagonia, at Glaciar Ameghino of the HPS two LIA advances are recognized at 16-17th century and the late 19th century (Aniya, 1996), and at a moraine-dammed lake near Glaciar Soler of HPN, two LIA dates were obtained for the double moraine ridges (Aniya and Shibata, 2001). Therefore, it appears that the scenario (1) is most plausible.

As the tentative conclusion for the recent glacier advance, we propose that Glaciar Exploradores advanced sometime between the 12th and17th centuries, thereby forming the main, big moraine. In addition the glacier made another advance around the beginning of the 19th century, thereby producing the secondary moraines. We have no data to infer the glacier advance that produced the Invernada moraine; however, from the studies at Glaciar Soler (Aniya and Naruse, 1999; Aniya and Shibata, 2001), and the appearance of the moraine, it could be of the Neoglaciation III (Aniya, 1995), that is, sometime between 1600-1300 BP, from the date of the main moraine.

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