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Overview of glaciological research project in Patagonia in 1998 and 1999: Holocene glacier variations and their mechanisms

Masamu Aniya[1] and Renji Naruse[2]
1 Institute of Geoscience, University of Tsukuba, Ibaraki 305-8571 Japan
2 Institute of Low Temperature Science, Hokkaido University, Sapporo 060-0819 Japan

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Abstract

The Patagonia Icefield (Hielos Patagōnicos) comprises Hielo Patagōnico Norte (HPN) and Hielo Patagōnico Sur (HPS) and is the largest temperate ice body in the Southern Hemisphere with the combined area of 17,200 km^2. Glaciological research project in Patagonia was carried out in 1998 and 1999, with the two main objectives; (1) to elucidate the Holocene glacier variations of HPN, and (2) to drill in the accumulation area of Glaciar Tyndall of HPS. The other research topics included; (1) glaciological, meteorological and hydrological resurveys at Glaciar Soler of HPN, (2) study of snow/ice biology (insects and algae) at Glaciar Tyndall of HPS, (3) ice calving observation and measurements of Glaciar Perito Moreno of HPS, (4) bathymetric survey of Brazo Upsala of Lago Argentino in HPS, and (5) aerial survey of Glaciar Soler and HPN outlet glaciers. The background of the project is presented, and field work and some of the major results are described.

1. Introduction

After five years of hiatus since 1993, Glaciological Research Project in Patagonia (GRPP) was resumed for 1998 and 1999 with the two main objectives;
(1) to elucidate the Holocene glacier variations of Hielo Patagōnico Norte (HPN), and (2) to drill in the accumulation area of Glaciar Tyndall of Hielo Patagōnico Sur (HPS) in order to estimate the annual accumulation rate as well as to carry out chemical analyses of ice core samples for detecting environmental changes.

The other research topics included; (1) glaciological, meteorological and hydrological resurveys at Glaciar Soler of HPN, (2) study of snow/ice biology (insect and algae) at Glaciar Tyndall of HPS, (3) ice calving observation and measurements of Glaciar Perito Moreno of HPS, (4) bathymetric survey of Brazo Upsala of Lago Argentino in HPS, and (5) aerial survey of Glaciar Soler and outlet glaciers of HPN.

The Patagonia Icefield (Hielos Patagōnicos) is located between latitudes of 46°30′S and 51°30′S along longitude of 73°30′W. It stretches nearly 500 km north-south, with the width varying from 8 km to 45 km. It comprises Hielo Patagōnico Norte (or Northern Patagonia Icefield) with an area of 4200 km^2 (Fig. 1) and Hielo Patagōnico Sur (or Southern Patagonia Icefield) with an area of 13,000 km^2 (Fig. 2). Together they comprise the largest temperate ice body in the Southern Hemisphere where land mass is scarce; thus the location of the Patagonia Icefield is very important to elucidate the global picture of the environmental changes. The Patagonian glaciers are characterized by large amounts of accumulation and ablation. In fact, the annual accumulation is estimated to be around 10,000 mm on the icefield from hydrological data (Escobar *et al.,* 1992).

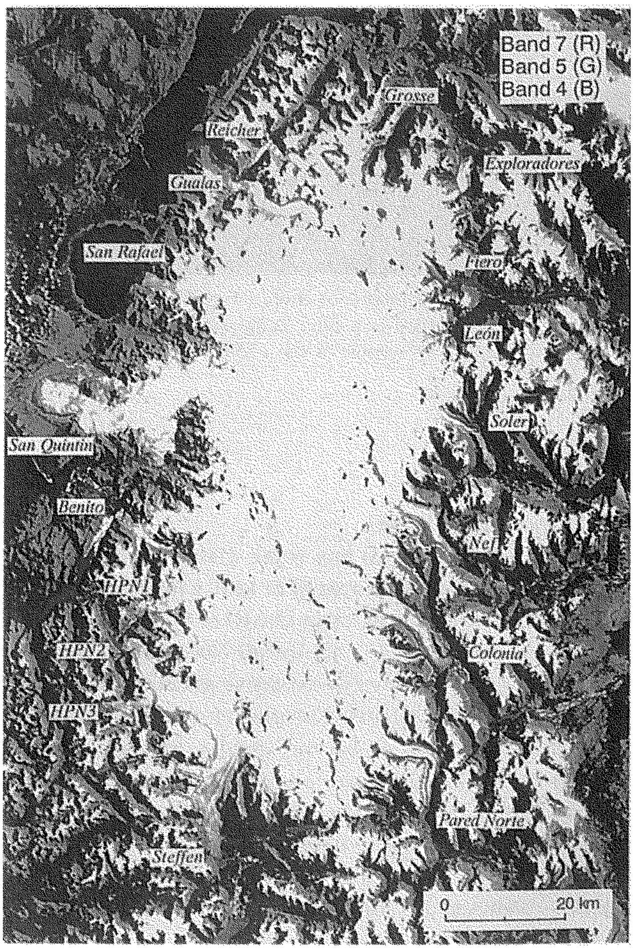

Fig. 1. Landsat MSS mosaic of Hielo Patagōnico Norte (Feb. 9, 1987). The original is a color composite image. The white area in the center is the icefield.

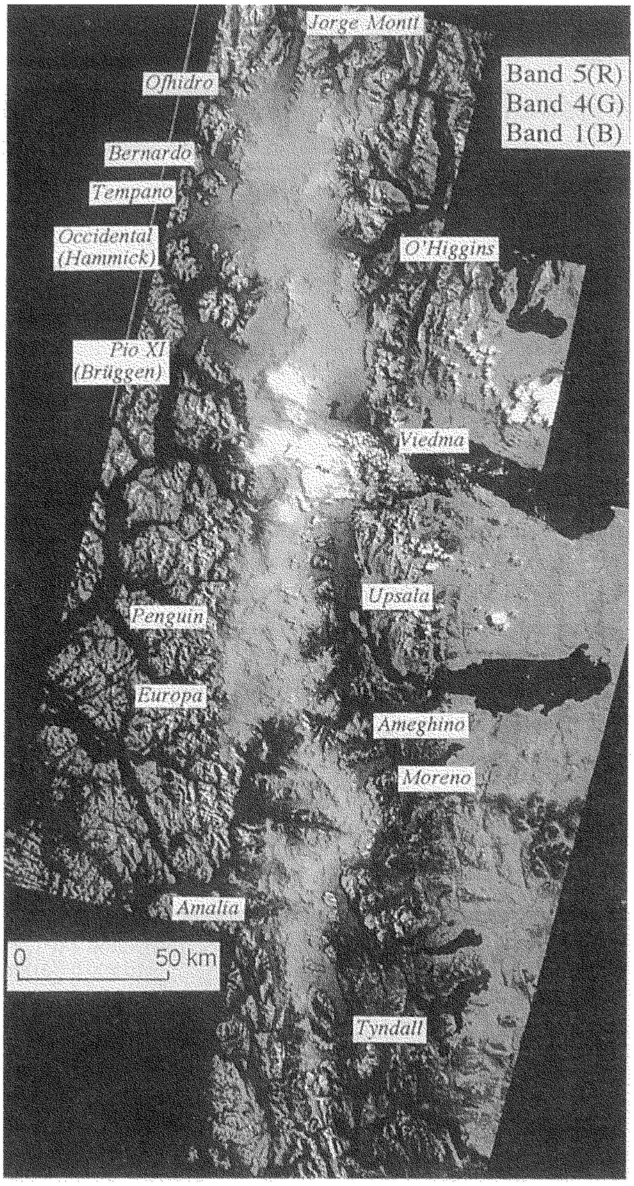

Fig. 2. Landsat TM mosaic of Hielo Patagónico Sur (Jan. 14, 1986). The original is a color composite image. The light gray area in the center is the icefield. White specs are clouds.

2. Study sites

2.1. Glaciar Soler (1998)

Glaciar Soler (Fig. 3) is a small glacier located on the east side of HPN, with an area of 51 km^2, a length of 16.6 km, and an accumulation area ratio (AAR) of 0.71 (Aniya, 1988). The ablation area below a big icefall (700 m high) from the icefield has been subjected to extensive glaciological studies during the 1980s by GRPP. The glacier thickness was estimated to be 200-600 m by the gravity anomaly method (Casassa, 1987). A proglacial lake was formed around 1990, and calving commenced, although it does not appear active yet. Ice supply from the icefield has considerably diminished during the last 15 years or so, from observation of the exposed bedrock in the big icefall. In 1998 the same glaciological and meteorological measurements were carried out in order to compare with those of the earlier ones.

2.2. The valley of Río Soler (1998)

Río Soler flows almost west-east, is roughly 30 km long

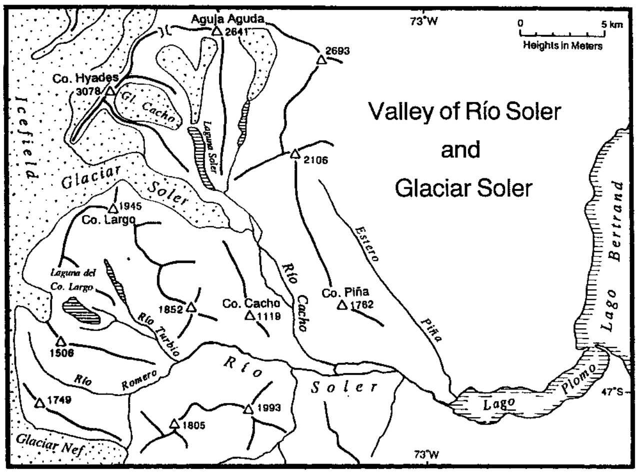

Fig. 3. Map showing the vicinity of the valley of Río Soler and Glaciar Soler, HPN.

and empties into Lago Plomo (elevation about 200 m a.s.l.), which is separated by terminal moraines from Lago Bertrand (Fig. 3). Its head is located near the accumulation area of Glaciar Nef at the elevation of around 1300 m. About 10 km from the mouth, Río Cacho, the biggest tributary, joins from the north, draining Glaciar Soler, Laguna Soler (Glaciar Cacho and an unnamed glacier) and an unnamed glacier. Another major tributary joining from the north is Río Turbio (local name). One of the two moraine-dammed source lakes, Laguna del Co. Largo, outburst in 1989 (or 1987), which was probably caused by ice avalanche (s) from the southern flank of Co. Largo, causing a catastrophic debris flow in Río Turbio and flood in Río Soler. The upstream of the main stream from this confluence is called Río Romero by local people. A small tributary, draining a small marginal lake of Glaciar Nef, joins from the south Río Romero .

In this valley, landforms, in particular identifying moraines, were investigated, collecting ^{14}C dating materials in order to elucidate the Holocene glacial chronology.

2.3. Glaciar Tyndall (1999)

This glacier is located near the southern end of HPS, with an area of 339 km^2, a length of 32 km, and AAR of 0.64 (Naruse *et al.,* 1987). It had been steadily retreating since 1944 until 1986 (Aniya *et al.,* 1997), however, it retreated a maximum of 1.6 km between 1986 and 1994, losing an area of 4.47 km^2 (Aniya *et al.,* 2000). GRPP was carried out here in 1985, 1990 and 1993, focusing primarily on measuring surface profiles (Naruse *et al.,* 1987; Kadota *et al.,* 1992; Nishida *et al.,* 1995). The glacier thickness was also measured with an ice radar, for the first time in Patagonia, revealing that a maximum is more than 600 m thick (Casassa, 1992). Since access to this glacier from the Paine National Park Headquarters is relatively easy, the accumulation area of this glacier is chosen for a drilling site.

2.4. Glaciar Perito Moreno (1999)

This glacier is commonly called just "Glaciar Moreno", and has an area of 257 km^2 with a length of 30 km. AAR is 0.73, and the hypsometry of the drainage area suggests that the glacier is not susceptible to ELA (Equilibrium Line Altitude) shift (Aniya and Skvarca, 1992). This glacier is one of the two glaciers in HPS which have not retreated during the last 50 years, the other being Pío XI, the largest glacier in South America. This glacier is well-known for repeated damming of Brazo Rico by reaching the opposite bank of the lake. Since 1947, the snout oscillated and the glacier was considered in the equilibrium (Aniya and Skvarca, 1992; Naruse *et al.*, 1995). Since access to this glacier is easy, relatively many glaciological studies have been carried out here including GRPP 90 and 93, among which the one by Rott *et al.* (1998) is most comprehensive. In order to estimate the annual mass balance, the evaluation of calving was found to be essential.

2.5. Brazo Upsala and Glaciar Upsala (1999)

Brazo Upsala is a branch of Lago Argentino, in which Glaciar Upsala calves. Glaciar Upsala is the third largest glacier in South America, with an area of 857 km^2 and a length of 60 km. AAR is 0.68 and the hypsometry of the drainage area suggests that the glacier is susceptible to ELA shift (Aniya and Skvarca, 1992). After temporary advance between 1968 and 1977, this glacier commenced rapid recession with large-scale calving (Aniya and Skvarca, 1992; Aniya *et al.*, 2000). Naruse and Skvarca (2000) explained these phenomena of extensive calving by glacier stretching and thinning. Brazo Upsala has a maximum depth exceeding 600 m. It was noted in November 1999 that the left margin was terminating on land and no longer calving in the lake. After GRPP 90 and 93 one of the members, Pedro Skvarca, Instituto Antártico Argentino, went back there on his own several times to locate the snout position as well as measuring the depth of the lake. From these experience, it was understood that the complete bathymetry of Brazo Upsala was essential to understand the retreat mechanism of the glacier.

3. Background of GRPP

GRPP was initiated in 1983-84, and carried out in 1985-86 in HPN (Nakajima, 1985; 1987), and in 1990 and 1992 in HPS (Naruse and Aniya, 1992; 1995).

3.1. HPN

In HPN, Glaciar San Rafael on the west side of the icefield and Glaciar Soler on the east side of the icefield were chosen for comparative studies in meteorology along with other observation/measurements such as glacier flow, hydrology, snow insects, and aerial photographic survey. From these studies, the strong east-west contrast of meteorology and steep climate gradient were elucidated (Kobayashi and Saito, 1985; Ohata *et al.*, 1985a, b). It was in this project that the flow speed of Glaciar San Rafael was found to exceed 17 m/d at the calving snout during the summer (Naruse, 1985).

At three glaciers of HPN, Glaciar San Rafael, Soler, and Nef, Kohshima (1985) found snow insects, stonefly (*Plecoptera, Gripopterygida*) and snow flea (*Collembola, Isotoma sp.*), for the first time in Patagonia. This is the first report of such insects outside of the Himalaya.

Over Glaciar Soler, semi-vertical aerial photography with a format of 6 x 6 cm was flown in 1984 and 1986 and the surface structure of the glacier was mapped and studied (Aniya and Naruse, 1985, 1986, 1987). Naruse (1985, 1987) measured flow speed of Glacier Soler, as well as the surface profile and obtained a thinning of about 10 m in two years at the lower reach of the glacier. Casassa (1987) estimated thickness of the glacier with gravity anomaly measurements, and using the surface profile he inferred the bedrock profile. Combining these data, interrelationships between the surface structure, flow data, and surface and bedrock topography were discussed (Aniya *et al.*, 1988). At Glaciar Soler, ice avalanches from Co. Hyades (3087 m) were recorded using a time lapse 8 mm film camera (Kobayashi and Naruse, 1987). Hydrology was also measured to discuss the relationship with meteorology and glacier flow (Saito and Kobayashi, 1985; Fukami and Escobar, 1987; Naruse *et al*, 1992).

In 1985, the first drilling was accomplished in Patagonia at the accumulation area of Glaciar San Rafael, which succeeded to bore 34 m deep (Yamada, 1987). From this drilling, the annual net accumulation was for the first time in Patagonia estimated to be 3.45 m (water equivalent) for the year 1984/85.

After completing two field seasons, Aniya (1988) completed an inventory of 28 outlet glaciers, including estimates of the ELAs. He also elucidated the variation of these outlet glaciers since 1944/45 and has been updating (Aniya, 1992; Wada and Aniya, 1995; Aniya and Wakao, 1997; Aniya, 1999; Aniya, 2001). In addition to those official GRPP, Aniya went back to Glaciar Soler on his own in 1995 and collected ^{14}C dating materials, based on which Aniya and Naruse (1999) identified two latest neoglaciations (1300 BC and 16th century). These data are the first of its kind in HPN and suggest some synchrony of the Holocene glaciations between HPN and HPS. Also Matsuoka went to the accumulation area of Glaciar Nef in 1996 and drilled at the elevation of 1500 m down to 14.5 m and estimated the annual net accumulation of 2.2 m (w.e.) in 1996 (Matsuoka and Naruse, 1999).

3.2. HPS

GRPP 1990 and 1993 were concentrated in HPS, at Glaciar Upsala, Perito Moreno and Tyndall, and in Ameghino valley. The main theme was surface profile changes (Naruse and Aniya, 1992; 1995). Thinning of Glaciar Upsala between 1990 and 1993 was 11 m/a, by far the largest in the world (Skvarca *et al.*, 1995). Thinning of Glaciar Tyndall was 4.0 m/a for 1985-90 (Kadota *et al.*, 1992) and 3.1 m/a for 1990-93 (Nishida *et al.*, 1995). On the other hand, the surface profile remained unchanged at Glaciar Perito Moreno (Naruse *et al.*, 1995). By identifying moraines and with ^{14}C datings, the Holocene glacial chronology was elucidated for Glaciar Upsala, Tyndall and Ameghino, and four Neoglaciations were proposed for HPS (Aniya, 1995, 1996).

Using Landsat TM data and aerial photographs, Aniya *et al.* (1996) made a comprehensive inventory of HPS, in which they identified 48 outlet glaciers with estimates of ELAs. At the same time Aniya *et al.* (1997) elucidated variations of these glaciers between 1945 and 1986, using various remotely sensed data. Apart from our study, Aristarain and Delmas (1993) drilled 13.2 m at the accumulation area of Glaciar Perito Moreno, finding 1.2 m w.e. of a mean annual net accumulation for the year 1981-86.

As the results of these studies in HPN and HPS, it has become apparent that drilling in HPS is necessary in order to estimate the annual net accumulation, and calving is very important to understand glacier dynamics of Patagonian glaciers and to obtain an estimate of the annual mass balance. Out of more than 70 outlet glaciers of HPN and HPS, only three are not calving. The rest is calving in lakes on the east and in fjord on the west of the icefield. Another important topic is the Holocene glacier variations of HPN. Although four major neoglaciations have been established in HPS (Aniya, 1995), only the latest two have been identified in HPN. Therefore it is obvious that much more field studies on the glacial landforms and datings are needed in HPN.

4. Field work and major findings

4.1. 1998 activities

Field work was concentrated at Glaciar Soler and in the valley of Río Soler of HPN in 1998.

4.1.1. Glaciar Soler

At Glaciar Soler the subjects of the measurements and observations are as follows;
(1) surface profile,
(2) flow speed,
(3) strain rate,
(4) ablations,
(5) meteorology and heat budget,
(6) hydrology of runoff stream, and
(7) observation of ice avalanches.

Naruse, Yamaguchi, Matsumoto and Ohno measured temperature, precipitation, albedo, and wind from Nov. 15 to Dec. 10 at the base camp and on the glacier, as well as measuring surface profile, flow speed, and strain rate. Stream runoff was measured several times between Nov. 18 and Dec. 10. These measurements are compared to those measured in 1984 and 1986. Izumi recorded ice avalanche activities by a video camera from Nov. 26 to Dec. 9, which can be compared with the data Kobayashi and Naruse (1987) recorded in 1984 and 1985. The surface lowering from 1985 to 1998 was found to be 42 m $\pm$ 5 m, i.e. 3.2 $\pm$ 5 m/a (Naruse *et al.*, 2000). Flow speed decreased almost linearly from about 0.6 m/d in the mid-reach of the ablation area to 0.25 m/d near the snout, and fluctuated as much as three times day by day (Yamaguchi *et al.*, in preparation). The proglacial lake has been steadily enlarging since around 1990, and the snout tip could barely be reached from the front in 1998 (Fig. 4; in Feb. 2000, it was detached from the land; pers. comm. Neil Glasser, June 2000).

Fig. 4. Glaciar Soler in November 1999 (Photo by M. Aniya; Nov. 23, 1999). The glacier surface of the frontal area has become very flat and smooth due to stagnation of ice and melting.

4.1.2. The valley of Río Soler

Aniya, with the help of Cesar Acuña and Gregory Kay, worked on identifying and mapping glacial landforms distributed in the valley of Río Soler from the entrance of Lago Plomo all the way up to near the head. He identified several terminal moraines and managed to collect 18 samples for ^{14}C dating, although carbon materials were extremely scarce there. The obtained dates suggest that the samples are probably contaminated by modern roots.

Two moraine-dammed lakes located at the heads of Río Turbio were visited and mapped for moraine distribution. The moraine damming Laguna del Co. Largo which burst out in 1989 (or 1987) was found to consist of two closely spaced terminal moraines (the Little Ice Age and earlier ?) (Fig. 5). Due to this outburst, the valley floor of Río Turbio was completely devastated by the deposition of huge boulders (long axis exceeding 10 m), and the valley of Río Soler was completely washed out almost to the confluence of Río Cacho valley. The rough survey indicates that the lake level was dropped by 97 m and has lost 0.176 km^3 of water, eroding roughly 325 x 10^4 m^3 of morainic materials. According to the local inhabitants living at the mouth of Río Soler, some 25 km down stream, the flood was up to the level of eaves of their houses, about 3-4 m higher than the normal level.

Fig. 5. Laguna del Co. Largo and the devastated valley floor due to an outburst flood (Photo by M. Aniya; Nov. 29, 1999). The moraine damming the lake appears one system due to heavy vegetation cover; however, in the field it was found out that two closely spaced ridges, thus probably representing two advances, constitute this moraine. The lake to the right is unnamed.

4.1.3. Aerial survey

As part of the continuing project, Aniya made an aerial survey of outlet glaciers of HPN on November 30, 1998, for a study of the glacier variation. Unfortunately, the weather was not good on the western side of the icefield, in particular southwestern side of the icefield. Consequently, only 15 out of 21 outlet glaciers which have been continuously monitored for variation since 1944 were photographed for study. It was found out that Glaciar San Rafael had advanced some 350 m between 1995/96 and 1998/99.

4.2. 1999 activities

4.2.1. Glaciar Tyndall

The drilling was planned to bore 100 m in the accumulation area of Glaciar Tyndall. After waiting for two weeks in Punta Arenas and at the Paine Park Headquarters due to inclement weather conditions, three Japanese (Kohshima, Shiraiwa and Kubota) and three Chileans (Quinteros, Godoi, and Arevalo) were flown in by a helicopter operated by Chilean Air Force on November 29, and the drilling camp was established at the elevation of 1756 m (Fig. 6). The weather in Patagonia during November and December 1999 was extremely bad, and the delay forced them to quit drilling operation at the depth of 46 m on December 9. The in-coming helicopter flight to get them out of the icefield was forced to wait until December 23 after two weeks of stand-by. Even on this day, the cloud ceiling was about 1300 m, which prevented the helicopter coming onto the camp site directly. Two Chilean members (Casassa and Rivera) took a skidoo in the helicopter which landed near 1300 m. From there they drove it to the camp site to get the drilling team out of the icefield. The drilling party had to abandon most of their valuable equipment including drilling apparatus, and part of the ice cores they retrieved. While at the drilling site for three weeks, the snow accumulation amounted to some 4 m in thickness. This experience itself provides a rare data on snow accumulation and drilling operation in the future.

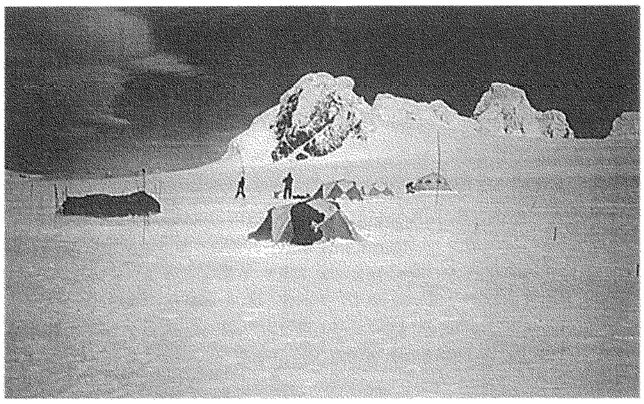

Fig. 6. Drilling camp site at the accumulation area of Glaciar Tyndall, HPS (Photo by T. Shiraiwa; December 1999). Looking southward at the elevation of 1756 m.

In the ablation area, Takeuchi worked on snow/glacier biology, collecting insects and algaes.

4.2.2. Glaciar Perito Moreno

Naruse and Kobayashi independently worked on measuring and observing calving events. Naruse analyzed the snout changes by calving activities with stereo ground photographs from the southwestern shore. Since calving causes a series of waves which may be captured by a water level gauge, Kobayashi recorded calving events by setting a water level gauge at the southwestern shore (Fig. 7).

4.2.3. Brazo Upsala

Skvarca worked on the bathymetry of Brazo Upsala, with the help of Miguel Beizuela from National Hydrographic Services from December 8 to 16. Glaciar Upsala commenced rapid retreat in the early 1980s and continues drastic retreat due to extensive calving once in a few to several years. Therefore, it is most important to know the depth of the lake in order to understand the retreat mechanism of Glaciar Upsala. However, again due to unusually bad weather in December 1999, he could work only two and a half days out of eight days. Strong winds make waves high and dangerously choppy, and icebergs choked the lake water

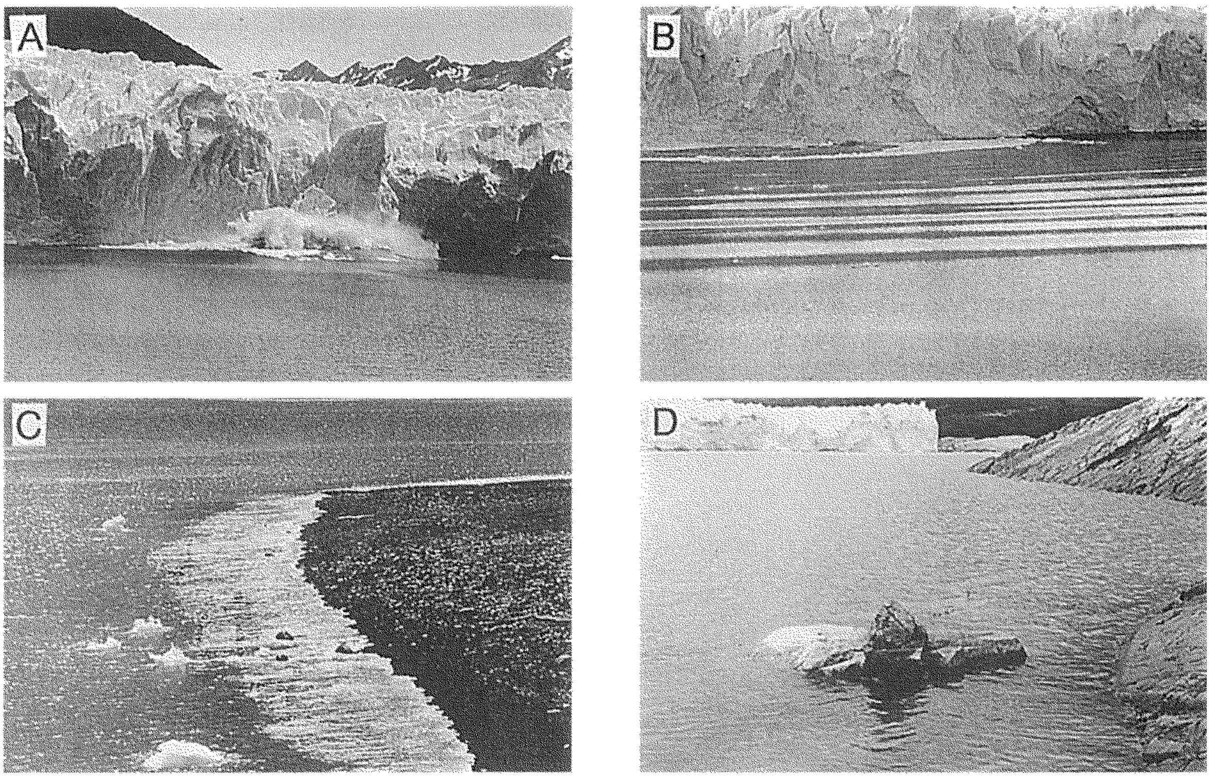

Fig. 7. Calving at Glaciar Perito Moreno, HPS (Photos by S. Kobayashi; Dec. 5, 1999). A: a large calving, about 40–50 m high. B: a series of waves caused by calving. C: waves washing the shore. D: water level gauge setting. It was put on metal angles which were set into water with two stones as weight, each weighing about 30 kg. The backround is the snout of the glacier.

(Fig. 8).

Aniya joined the Skvarca's party at Brazo Upsala and investigated glacial landforms of the Valle de las Americas (or Vacas), a tributary valley of Brazo Upsala. He also investigated Pearson I lateral moraine (*ca.* 1600 BP, Aniya, 1995) on the right bank of Brazo Upsala, collecting some dating samples.

4.2.4. Aerial surveys

Aniya made aerial surveys in HPN. First, he flew over Glaciar Soler on November 29, 1999, taking vertical photographs with a 6 x 6 cm format camera (Fig. 9), from which he assembled a mosaic to study the surface structure of the glacier and compared it with those made in 1984 and 1986. He also made a circumferential flight of HPN on November 30, 1999, taking oblique aerial photographs of the snout of the outlet glaciers for glacier variation studies. The weather was very good on this day, and he could take very good photographs of glaciers, together with skillful flight by the pilot. It was found that Glaciar San Rafael, which had been advancing since around 1992, retreated between 1998/99 and 1999/2000. Enlargement of proglacial lakes of Glaciar San Quintin and Grosse is notable.

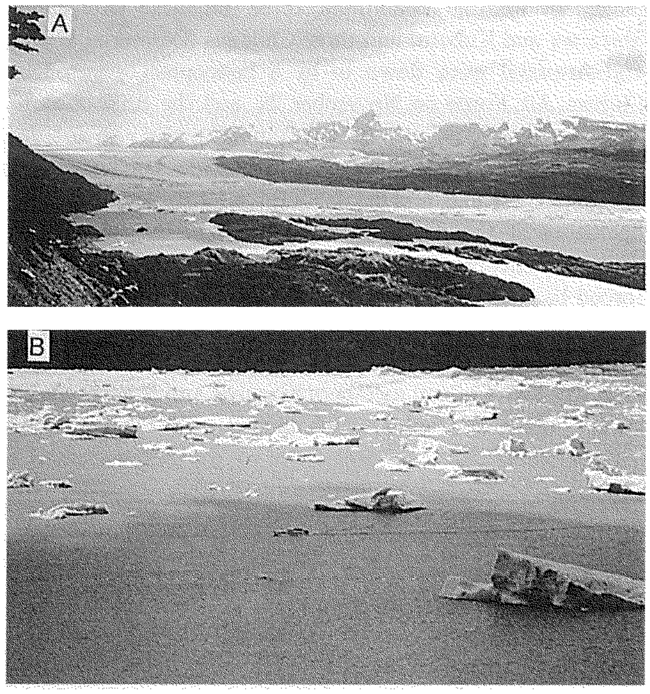

Fig. 8. Brazo Upsala and Glaciar Upsala (Photos by M. Aniya; Dec. 12, 1999). A: upper left is the glacier and a white strip of icebergs is blocking the lake. Whiteness at the lower right is the reflection of water. B: a tourist boat (in the middle) trying to penetrate into the maze of channels choked by icebergs.

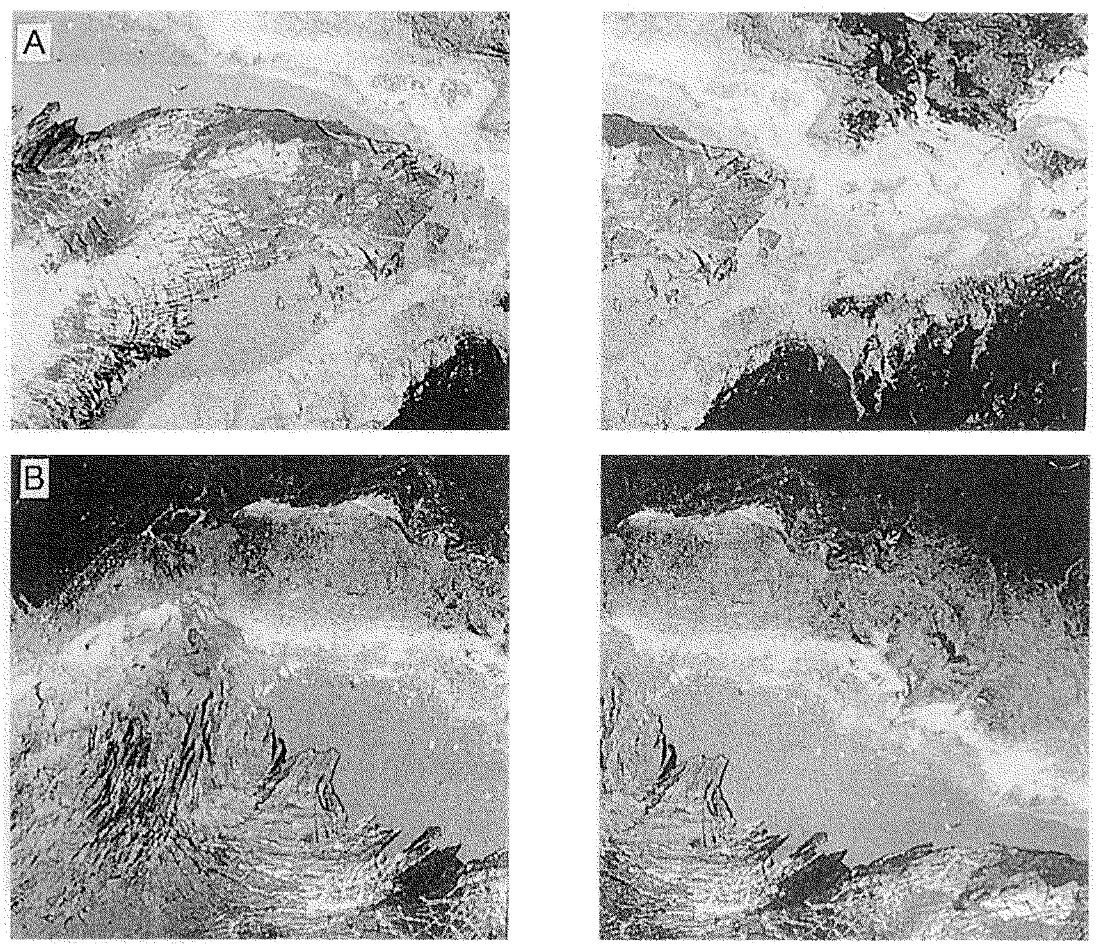

Fig. 9. Stereograms of the snout of Glaciar Soler, HPN (Photos by M. Aniya; Nov. 29, 1999). A: showing the tip of the snout, barely touching the land. B: left side extension of A, showing the enlarged proglacial lake with a few icebergs. White strip in front of the lake is the position of the glacier front around 1990.

5. Members of the project

The affiliation and title are those at the time of participation.

Field Leader

Renji Naruse: Dr. (Glaciologist), Associate professor, Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan.

Masamu Aniya: Dr. (Geomorphologist), Professor, Institute of Geoscience, University of Tsukuba, Ibaraki, Japan.

Deputy Leader

Pedro Skvarca: Ing. (Glaciologist), Head of Glaciology Division,
Instituto Antârtico Argentino, Buenos Aires, Argentina.

Gino Casassa: Dr. (Glaciologist), Associate professor, Area de Geociencias, Instituto de la Patagonia, Universidad de Magallanes, Punta Arenas, Chile.

Shiro Kohshima: Dr. (Biologist), Associate professor, Faculty of Bioscience and Biotechnology, Tokyo Institute of Technology, Tokyo, Japan.

Research Members

Shun'ichi Kobayashi: Dr. (Glaciologist), Professor, Research Institute for Hazards in Snowy Areas, Niigata University, Niigata, Japan.

Kaoru Izumi: Dr. (Glaciologist) Associate professor, Research Institute for Hazards in Snowy Areas, Niigata University, Niigata, apan.

Takayuki Shiraiwa: Dr. (Glaciologist), Assistant professor, Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan.

Andrês Rivera: MS (Geographer), Assistant professor, Departamento de Geografîa, Universidad de Chile, Santiago, Chile.

Satoru Yamaguchi: MS (Glaciologist), Ph.D. student, Graduate School of Earth Environmental Sciences, Hokkaido University, Sapporo, Japan.

Takane Matsumoto: MS (Hydrologist), Ph.D. student, Graduate School of Earth Environmental Sciences, Hokkaido University, Sapporo, Japan.

Hiroshi Ohno: (Glaciologist), MS student, Graduate School of Earth Environmental Sciences, Hokkaido University, Sapporo, Japan.

Nozomi Takeuchi: Dr. (Biologist), Research student, Faculty of Bioscience and Biotechnology, Tokyo Institute of Technology, Tokyo, Japan.

Keiji Kubota: (Meteorologist), MS student, Graduate School of Earth Environmental Sciences, Hokkaido University, Sapporo, Japan.

Field Assistants

Teodoro Toconâs: Surveyor, Gendarmerîa Nacional, Buenos Aires, Argentina.

Jorge Quinteros: Technician, Direcciôn General de Aguas, Santiago, Chile.

Maria A. Godoi: Biologist, Universidad de Magallanes, Punta Arenas, Chile.

Marcelo G. Arevalo: Andenista, Universidad de Magallanes, Punta Arenas, Chile.

Miguel A. Beizuela: Hydrographer, National Hydrographic Service, Buenos Aires, Argentina.

Cesar Acuña: Student, Departamento de Geografîa, Universidad de Chile, Santiago, Chile.

Gregory Kay: Graduate student, Graduate School of Environmental Sciences, University of Tsukuba, Ibaraki, Japan.

Cooperative Investigators

Rodolfo del Valle: Vice director, Instituto Antârtico Argentino, Buenos Aires, Argentina.

Fernando Escobar: Research scientist, Direcciôn General de Aguas, Ministerio de Obras Pûblicas, Santiago, Chile.

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