ICE THICKNESS MEASUREMENTS ON THE SOUTHERN PATAGONIA ICEFIELD

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1. ABSTRACT

The first detailed ice thickness measurements in the accumulation area of the Southern Patagonia Icefield have been obtained with a radio-echo sounding system, revealing a complex subglacial topography and internal reflection pattern.

A ground-based digital impulse radar system at 2.5 MHz was used to obtain continuous profiles of the subglacial topography. The system was mounted on sledges that were pulled by a snowmobile, allowing for coverage of extensive areas in short periods of time.

Two GPS receivers were used simultaneously and a differential correction method was applied for obtaining a precise geographic position at each thickness measurement.

2. INTRODUCTION

The Southern Patagonia Icefield (SPI), with an area of 13,000 km^2 (Aniya *et al.,* 1996), is the largest ice mass in the Southern Hemisphere outside of Antarctica. SPI has a length of 370 km (48-51° S) and an average width of 35 km (Figure 1), with 48 major outlet glaciers. Most of these glaciers have shown high retreat rates during the last decades, in response to the regional climate change (Aniya *et al.,* 1997). The glacier retreat is responsible for producing large amounts of meltwater which contributes significantly to the rise in sea level (Aniya, 1999). In spite of the generalized retreat, a few glaciers have shown strong advances during the last decades (Rivera *et al.,* 1997).

The observed changes of the SPI glaciers have been restricted mainly to the lower parts, the frontal and areal variations of the main glacier tongues. The accumulation area has been scarcely visited, due to logistic restrictions and harsh climatic conditions (Casassa *et al.,* 2002; Chapter 7). Ice thickness is one of the basic glaciological

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The Patagonian Icefields: A Unique Natural Laboratory for Environmental and Climate Change Studies.
Edited by Gino Casassa et al., Kluwer Academic /Plenum Publishers, 2002.

parameters needed for characterizing the glaciers. However, thickness data for the SPI are very limited, especially in the accumulation area.

This paper presents a review of the ice thickness methods and measurements carried out in Chile, as well as preliminary results of ice thickness and internal structure of the ice on the upper part of the SPI, by means of a radio-echo sounding system. The results are useful for a variety of scientific objectives, such as paleoclimate reconstruction, glacier modeling, and glacial geology, among others.

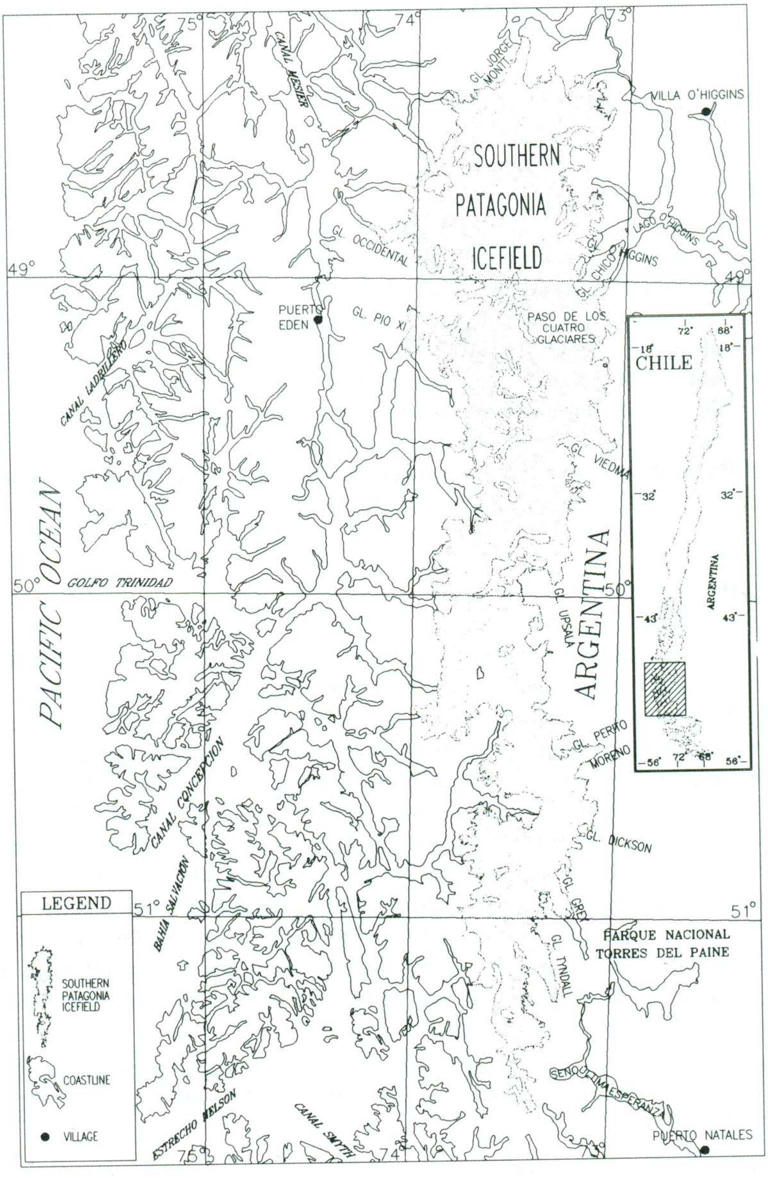

Figure 1. Location map of Southern Patagonia Icefield.

3. ICE THICKNESS METHODS

Two methods for detecting ice thickness have been applied in Chile:

3.1. Gravity Method

This method allows for determination of ice thickness based upon the deficiency of the vertical component of gravity observed on the surface of a glacier. This deficiency is generated by the smaller ice density with respect to the density of the underlying rock. Ice has a maximum density of 0.9 g/cm^3 (Paterson, 1994), while the density of the underlying rock is larger than 2.6 g/cm^3.

To convert the observed gravity to ice thickness values, it is first necessary to convert gravity data to a common reference value, such as mean sea level, obtaining in this way gravity anomalies (known as Bouguer anomalies) on ice. At the same time, it is necessary to measure gravity at rock outcrops surrounding the ice, to determine local and regional Bouguer anomalies due to varying geological conditions in the area. For example, intrusive rocks compose the "Patagonian Batholith", one of the most important units in the western margin of the SPI (Forsythe and Mpodozis, 1983). The differences between Bouguer anomalies on rock and ice result in residual anomalies due exclusively to the presence of the ice. Ice thickness is calculated applying an inverse model to the ice residual anomalies (Casassa, 1987).

The advantages of the gravity method are mainly logistic, due to the light weight of the equipment, little time required for each measurement and the unlimited maximum penetration range of the system. The limitation of this method is its great uncertainty (about 20% of the ice thickness) because the measured surface gravity value is in fact an areal average gravity of the underlying material for each station, which produces a smoothing of the complex subglacial topography.

3.2. Radio-Echo Sounding

Detection of ice thickness and internal structure of glaciers using radar, or radio-echo sounding, is also known as radioglaciology. This method is based on the same principle as sonar, frequently used in navigation and marine prospecting, and the seismic method, used in oil prospecting.

In essence, radio-echo sounding consists of the transmission of a signal into the glacier, which is reflected at the glacier bed, returning to the ice surface, where it is captured by a receiver. Ice thickness is determined based upon the so-called "two-way travel time", or time needed for the signal to travel from the transmitter to the glacier bed, and back to the receiver.

Different radio-echo sounding systems have been used to date, most of them working at frequencies between 30 and 700 MHz (Bogorodsky *et al.,* 1985). At this frequency range, cold ice is transparent to the penetration of electromagnetic waves. However, for temperate ice, that is ice at melting point, where water coexists with ice, radio signals with frequencies larger than 30 MHz are scattered by water bodies within the ice, and are also strongly attenuated by absorption, thus preventing wave penetration.

The first to suggest the construction of a radar for temperate ice were Watts and England (1976), who recommended frequencies lower than 10 MHz, where the scattering of the signal should theoretically be significantly reduced. Based on this principle, Vickers and Bollen (1974) built the first radar for temperate ice, successfully probing the South Cascade glacier in Washington, USA. The transmitter was an impulse model type, generating a monopulse signal, which is transmitted using resistively-loaded dipole antennas.

At present, radio-echo sounding is widely used because it is the most accurate method (1-10%), which combines powerful data collection capabilities and field versatility.

4. RADIO-ECHO SOUNDING SYSTEMS USED IN CHILE

4.1. Analogue Radar

The first radar system used in Chile consisted of a transmitter with an amplitude of a few hundred Volts and an analogue receiver composed of a CRT oscilloscope, taking photographs of the screen for obtaining the data (Casassa, 1992). This system allowed for collection of discrete measurements.

4.2. Portable Digital Radar

To eliminate the technical problems arising from the need to photograph the oscilloscope screen, a second radar system was designed, composed of a transmitter with an output signal amplitude of 680 Vpp and a digital oscilloscope receiver with connection to a PC via RS232 interface (Casassa and Rivera, 1998). This system allowed for discrete measurements.

At present, the digital system is used, with antennas connected to fibreglass fishing poles of 8 m length, which are transported by two people, one at the receiver and one at the transmitter, using backpacks. This system allows for data collection while walking on the surface of the glacier, generating a continuous profile of subglacial returns. Due to its profiling nature, the method has improved the interpretation of subglacial returns and has been especially useful when applied to crevassed ablation areas, in high altitude glaciers, or accumulation areas with limited access (Rivera *et al.,* 2000a).

4.3. Snowmobile-Based Digital Profiling Radar

To measure ice thickness in extensive areas, a profiling system was designed, which allows for collection of ice thickness data every two seconds, creating a continuous profile of subglacial returns (Casassa *et al.,* 1998a).

In this profiling system, the transmitter and the digital receiver are mounted on sledges, pulled by a snowmobile. A 20 m half-dipole antenna length has been used, with the receiver and the transmitter being located 40 m and 100 m respectively behind the snowmobile. In this system the separation between the receiver and transmitter is 60 m (Figure 2).

The antennas are connected to an impulse transmitter with an output amplitude signal of 1600 Vpp. In the receiver, the antennas are connected through a balun to a digital oscilloscope. The data are recorded on the hard disk of a notebook computer. The receiver and transmitter systems are powered by 12 V batteries.

Ice thickness measurements are positioned with topographic data collected by either geodetic or topographic-quality GPS (Global Positioning System) receivers, using a differential correction method, which permits fixing positions every five seconds. In the portable system, a GPS receiver is installed on the backpack, whilst in the profiling system, a GPS receiver is mounted on the snowmobile (Casassa *et al.,* 1998b). The precision of the measurements depends on the GPS signal quality, which can reach sub-meter accuracy when geodetic-quality GPS receivers are used.

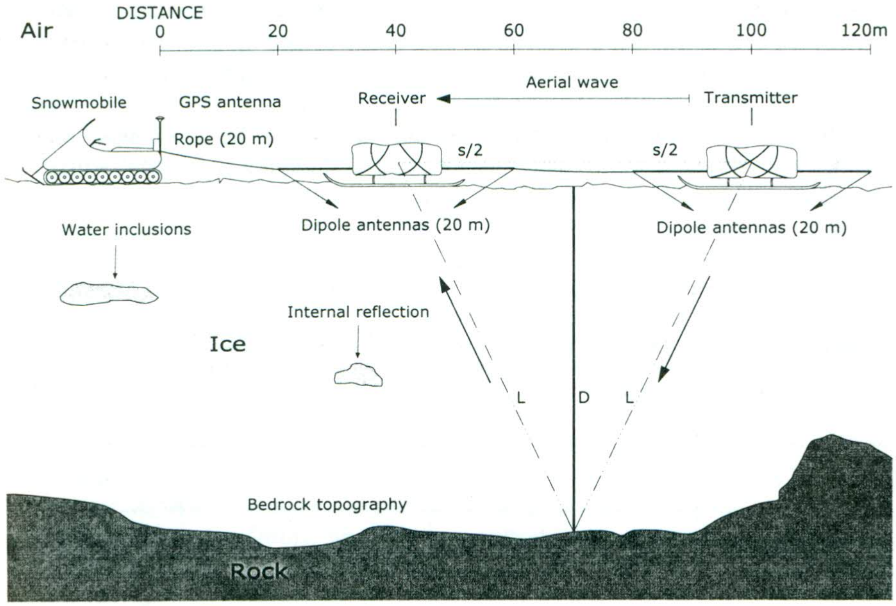

Figure 2. Snowmobile-based radio-echo sounding system. S/2 = 20 m is the half-dipole length of the antennas. The upper scale shows horizontal distance.

4.4. Helicopter-Borne Radar

Helicopter-borne and airplane-borne radio-echo sounding systems have been developed in Scandinavia, Russia, Germany, U.K., Italy, Japan, and the USA, among other countries. These systems have the advantage of rapid and effective measurement of remote glacier areas.

A Norwegian helicopter-borne radar has been used successfully in Svaritsen (Kennet *et al.,* 1993), consisting of an impulse transmitter with half-dipoles of 8 m and a central frequency of 6 MHz which can measure a thickness of 300 m of temperate ice. A similar system for temperate ice is being built at the University of Magallanes, Chile.

In polar ice, a 150 MHz German radar system has been used successfully to probe 2000 m of ice in Antarctica. The antenna is a corner reflector, consisting of two plane reflectors mounted at an angle of 90 degrees on the antenna frame, which is made of fiberglass tubes, all of which hangs from a helicopter. This system has been used recently in Chile (Damm *et al.,* 1999). Results show that its performance in temperate ice of Patagonia is very poor, compared to the good results obtained on clean ice in Antarctica and in the Alps.

4.5. Transmitters

Four different transmitters have been used in the radar systems of Universidad de Chile-Universidad de Magallanes, which are shown in Table 1.

The Bristol transmitter was designed by University of Bristol (UK), and has been used with success by Gilbert *et al.,* (1996) in southern Chile. The Narod/Clarke transmitter was designed by Barry Narod and Garry Clarke (Narod and Clarke, 1994), and tested by Cárdenas (1998) in Patagonia. The O.S.U. transmitter (Huffman, 1993) was designed by the Ohio State University, USA, and used successfully in cold and temperate glaciers by Thompson *et al.,* (1982) and Thompson *et al.* (1988). The Modified-O.S.U. transmitter was designed by Cárdenas (1998), nearly doubling the output voltage of the original O.S.U. transmitter, tested in Antarctica.

Table 1. Transmitters used by Universidad de Chile-Universidad de Magallanes.

Transmitter	Peak output power (kW)	Peak output voltage (V)	Output resistive load (Ω)	Rise Time (ns)	Consumption in Amperes (A)	Pulse repetition rate (pps)	Dimensions (mm³)	Weight (kg)
Bristol	9	680	50	< 5	60 mA	?	13x13x12	0,7
Narod/Clarke	24	1100	50	< 2	180 mA	512	102x75x30	0,1
O.S.U.	51	1600	50	≈ 100	0,59 A	200/400/800	200x120x58	0,7
O.S.U. Modified	168	3000	50	≈ 100	0,8 A	200/400/800	200x120x58	0,7

4.6. Oscilloscopes

Different oscilloscopes have been used as part of the radar system of Universidad de Chile-Universidad de Magallanes:

- Hitachi V-209 analogue oscilloscope, with a bandwidth of 20 MHz
- Tektronics digital storage oscilloscope, model TekScope THS 720, with a 100 MHz bandwidth
- Fluke digital storage oscilloscope, model PM97, with a 50 MHz bandwidth
- Hitachi digital storage oscilloscope, model VC-6045A, with a bandwidth of 20 MHz
- Lecroy digital storage oscilloscope, model 9310-A, with a 400 MHz bandwidth.

5. ICE THICKNESS MEASUREMENTS IN CHILE

In the Antarctic Peninsula, the gravity method was applied by Chileans on Anvers Island ice cap in 1982 (Casassa, 1989) using precise measurements of gravity and station coordinates collected by German geodesists.

The first published measurements of ice thickness in Chile were carried out using the gravity method at the Northern Patagonia Icefield (NPI) by Casassa (1987), who estimated a maximum thickness of 1460 m on the accumulation area of San Quintín glacier, determining a subglacial topography under sea level.

In 1990, during the Japanese Glaciological Research Project in Patagonia (Naruse and Aniya, 1992), ice thickness at the ablation area of Tyndall Glacier (Figure 1) was measured with an analogue radio-echo sounding system (Casassa, 1992). The maximum penetration was 616 m near the center line at the ablation area of Tyndall Glacier. The high attenuation and absorption of the radar signals due to the presence of water inclusions in that part of the glacier, prevent the penetration of thicker ice. The maximum thickness of this part of the glacier could exceed 1000 m.

In 1992, a team of geologists from the University of Bristol, together with geologists from SERNAGEOMIN (National Mining and Geology Service, Chile) and a geographer of the University of Chile (Andrés Rivera), carried out measurements of ice thickness at the glacier located inside the caldera of Nevados de Sollipulli (38°59' S/71°31' W). The maximum ice thickness measured was 650 m, which was obtained using a combined system of radar sounding and gravity data (Gilbert *et al.*, 1996). The radar system was digital with PC connection through a serial port.

In 1993, the ablation area of Tyndall Glacier was measured again by a Japanese-Chilean team, but this time a digital radar system was used. The ice thickness results obtained were somewhat smaller than those of the previous 1990 campaign, presumably due to thinning of the ice during the three-year period (Casassa and Rivera, 1998).

In 1999 and 2000, a digital radio-echo sounding system was used by researchers from the University of Washington (Raymond *et al.*, 2000) to probe ca. 600 m thick ice at Tyndall Glacier, Patagonia. The radar system used is potentially capable of sounding ca. 1000 m of temperate ice.

In Patriot Hills, located at 80° S in the Antarctic interior, radar measurements have been carried out by Chilean expeditions in 1995, 1996 and 1997, using a system pulled by a snowmobile. The early measurements of 1995 were performed with a discrete digital radar system, and a maximum penetration of ca. 300 m (Cárdenas, 1998). In 1996 and 1997, a profiling radar system was used and an ice thickness of up to 1320 m of cold ice could be detected at Patriot Hills (Rivera *et al.*, 1998; Casassa *et al.*, 1998a and 1998b). In the vicinity of Patriot Hills, seismic studies indicated a maximum ice thickness of approximately 2 km.

In central Chile, most of the glaciers are smaller than those in Patagonia, but the surface topography is more complex and generally crevassed. For this reason, it is not possible to use a snowmobile profiling system. Instead, we have used a profiling system mounted on 8 m fiberglass poles and transported on backpacks by two people walking on the ice surface. This system was successfully used at the glacier of cerro Tapado (Rivera *et al.*, 2000a), Juncal Norte, San Francisco, and cerro Plomo. In all these cases, penetration was successful, allowing detection of the full subglacial topography. A maximum ice thickness of 225 m was detected at the ablation area of Juncal Norte Glacier (Rivera *et al.*, 2000b).

In 1999 the first helicopter-borne measurements of ice thickness were performed at Tyndall and Dickson Glaciers in Torres del Paine National Park, in addition to several high altitude glaciers of central Chile (Figure 1). Preliminary results are presented by Damm *et al.,* 1999.

6. RADIO-ECHO SOUNDING MEASUREMENTS IN PASO DE LOS CUATRO GLACIARES, SOUTHERN PATAGONIA ICEFIELD

During the Hielo Azul III operation of the Chilean Air Force (FACH) of 1997, we carried out several ice thickness measurements on the upper part of the SPI. These are the first measurements published for the accumulation area of SPI (Rivera and Casassa, 2000).

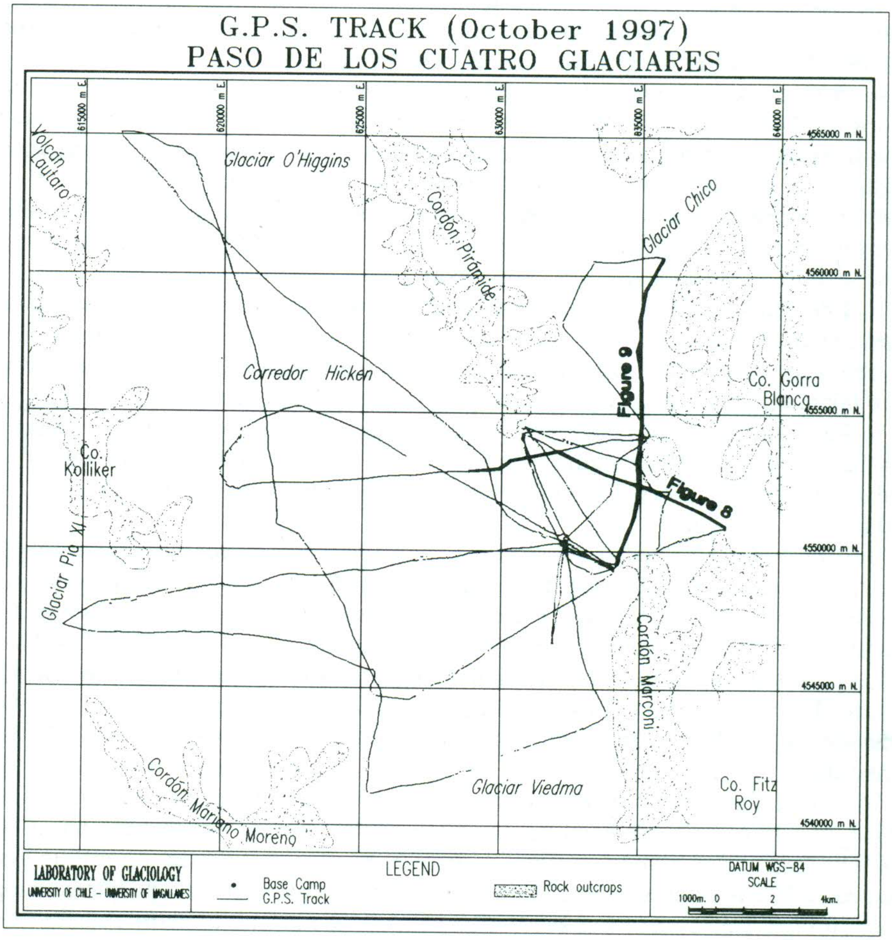

Figure 3. GPS tracks (dotted lines) on paso de los Cuatro Glaciares. The heavy lines correspond to the topographic profiles of Figures 8 and 9.

During the field campaign, base camp was located at 1450 m above sea level on the accumulation area of Chico Glacier, one of the outlet glaciers of the paso de los Cuatro Glaciares (Figures 1 and 3).

From this plateau, several glacier tongues discharge ice in different directions: Viedma Glacier flows toward the south; Chico Glacier flows to the northeast; O'Higgins Glacier flows to the north; Pío XI Glacier flows toward the west and Marconi Glacier flows to the east. This large area extends from the vicinities of monte Fitz Roy to the south to volcán Lautaro to the north.

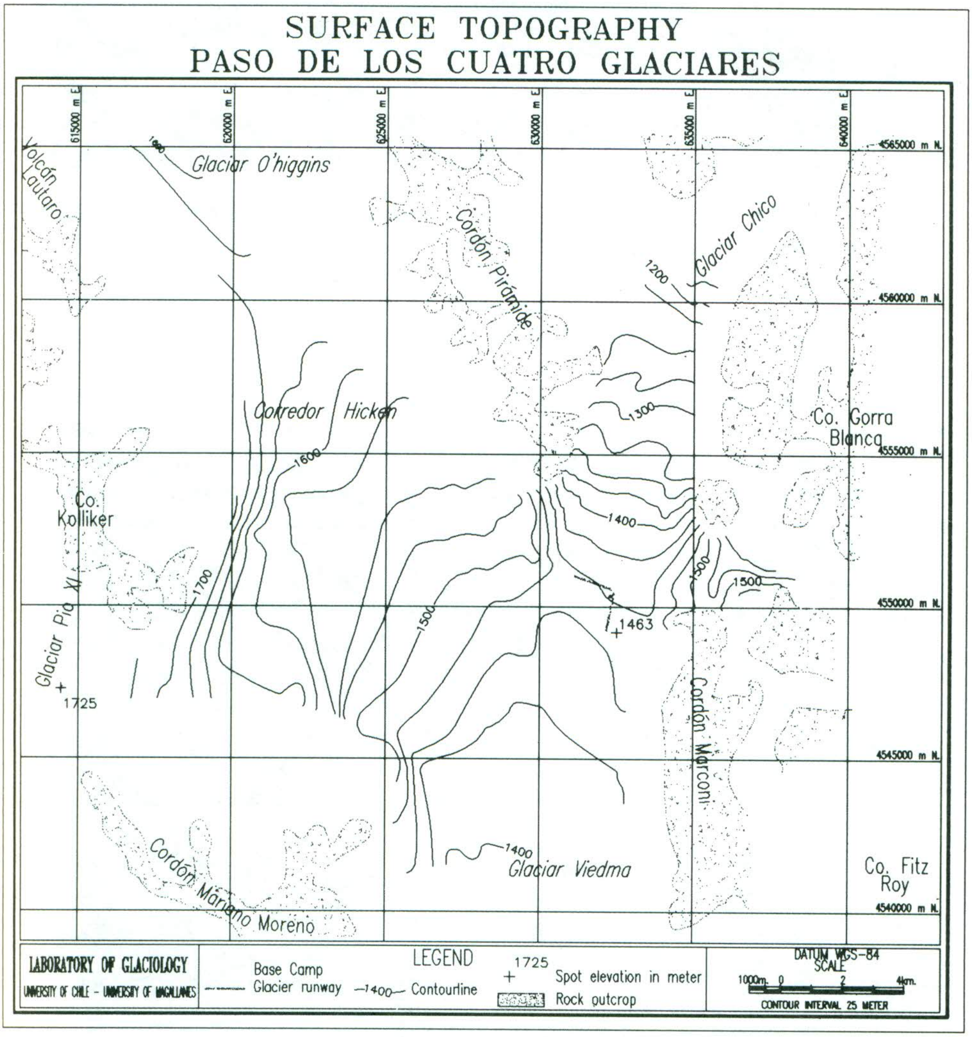

Figure 4. Surface topography of paso de los Cuatro Glaciares. The map has been adapted from Carta Preliminar 1:250,000 of Instituto Geográfico Militar de Chile. Elevation data collected in the field by the authors with GPS receivers have been used to compile contour lines at an interval of 25 m.

The recent behavior of glaciers of paso de los Cuatro Glaciares is contrasting. For example, Pío XI Glacier advanced 9 km in 50 years (Rivera *et al.,* 1997), O'Higgins Glacier retreated 15 km in 100 years (Casassa *et al.,* 1997) and Chico and Viedma Glaciers have retreated at slower rates (Rivera and Casassa, 2000 and Aniya *et al.,* 1997, respectively).

In the paso de los Cuatro Glaciares area, more than 25 radar profiles were measured (Figure 3). Each profile contains ice thickness measurements taken every two seconds.

To locate each measurement, we used one GPS receiver mounted on the snowmobile, which allows recording of one position every 5 seconds. Another GPS receiver was installed simultaneously at base camp, applying later a differential correction procedure to obtain surface topography with an accuracy better than 5 m on a horizontal scale and 10 m on a vertical scale.

Each ice thickness measurement was collected at the receiver and stored in real time by a PC, where a simultaneous log file with precise time was recorded. This information was necessary to combine the radar measurements with the GPS data, in order to locate each ice thickness data.

With the GPS position corrected, a surface topography map was produced (Figure 4). The contour lines have an interval of 25 m and their distribution shows a flat relief in the vicinity of the study area. The subglacial returns have been interpreted as the first significant and consistent increase of amplitude of the signal, after the end of the aerial wave. No migration or inversion procedures were applied to correct the bottom reflections.

By analyzing each radar profile with PC-based software, we could determine the subglacial topography for most of the profiles. In a few cases, the signal was too noisy, due to interference from the portable radio equipment used for personal communication. In other profiles, the signal was lost due to problems in the antenna connectors. Examples of ice thickness profiles are shown in Figures 5, 6, and 7.

Figure 5 shows the subglacial topography at the accumulation area of Chico Glacier from cordón Pirámide at the western side of the glacier (left) to cerro Gorra Blanca, and cordón Marconi at the eastern side of the glacier (right). In the central part of the main valley of Chico Glacier, deep ice not penetrated by our radar system can be observed. At the right side of this profile (cordón Marconi) it is possible to distinguish the rough subglacial topography, including one section where we believe a small subglacial lake may exist, at the site of a possible geologic fault.

Figure 6 shows another subglacial profile located at the accumulation area of Chico Glacier from cerro Gorra Blanca (left) to the Equilibrium Line Altitude (ELA) of Chico Glacier (right).

Figure 7 shows a radar profile close to volcán Lautaro at corredor Hicken. This profile contains two strong internal reflectors, at a depth of 296 m and 406 m. These reflectors have been interpreted as ash deposition layers produced by eruptions of the nearby volcán Lautaro, an active volcano. Its last eruption occurred in 1979 (Lliboutry, 1998) and several other eruptions have previously been reported during recent decades, in 1959, 1960, 1972 and 1978 (Martinic, 1988).

Figures 8 and 9 present two topographic profiles of the accumulation area of Chico Glacier, compiled partly from the radar profiles shown in Figures 5 and 6. The topographic profiles include both the subglacial and surface topography of the glacier. The location of both profiles is indicated in Figure 3.

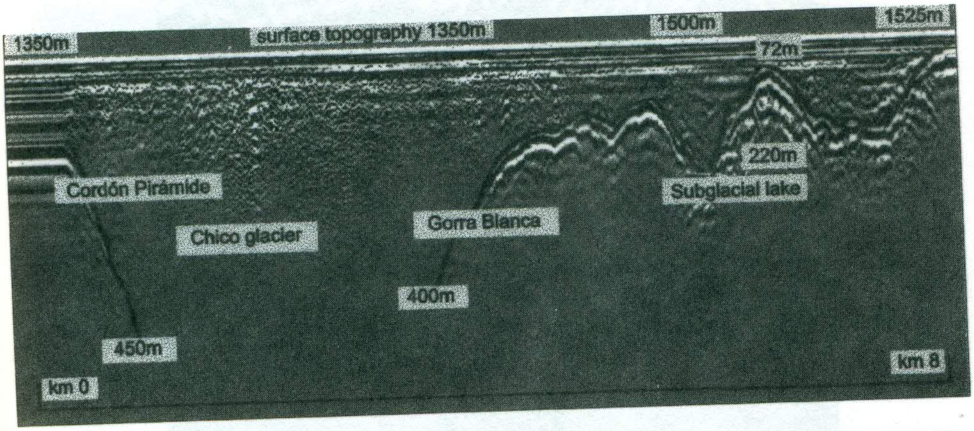

Figure 5. East-west radar profile of Chico Glacier. 72 m is the ice thickness above the subglacial nunatak. 220 m is the ice thickness above the feature interpreted as a subglacial lake.

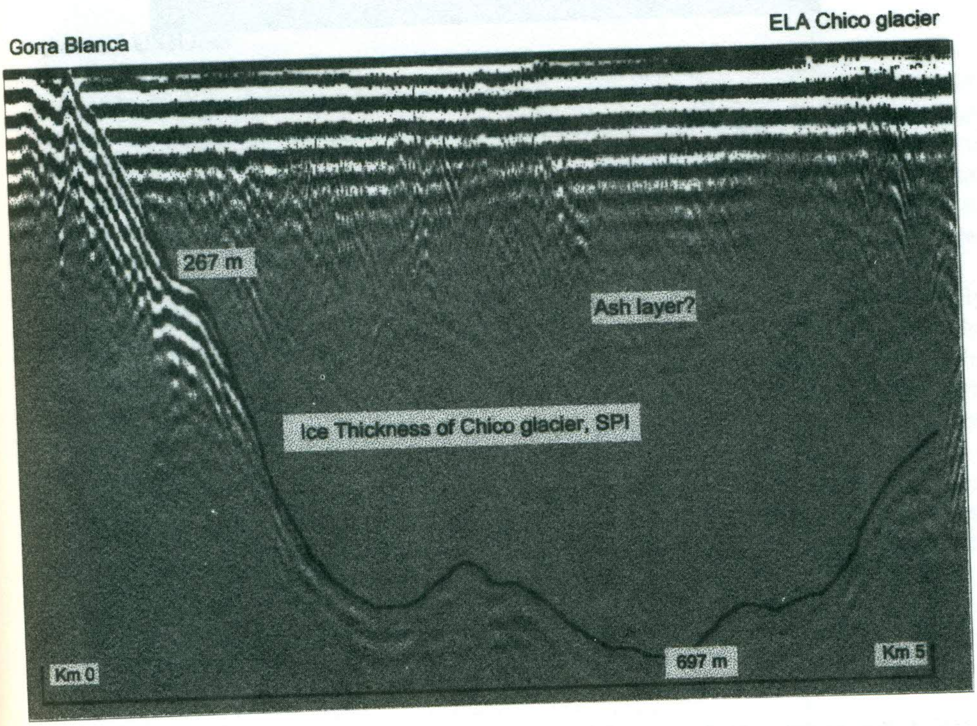

Figure 6. South-north radar profile of Chico Glacier. Numbers indicate ice thickness.

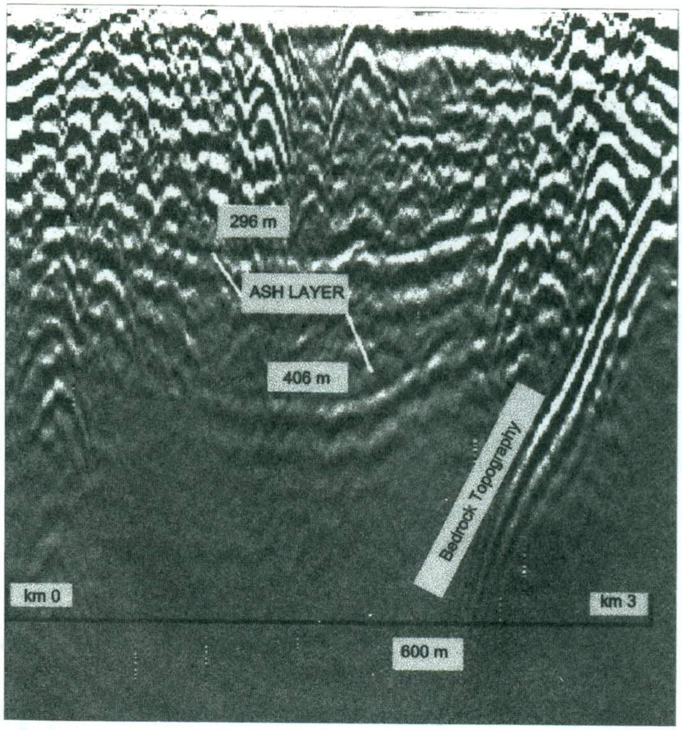

Figure 7. Radar profile at corredor Hicken. Numbers indicate ice thickness.

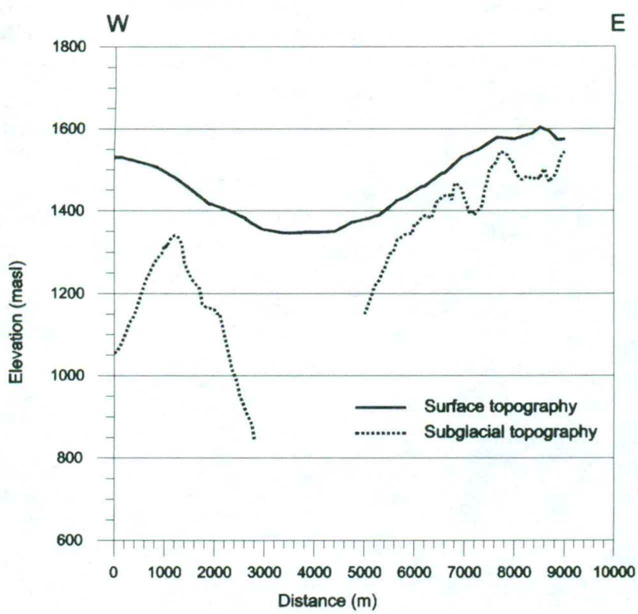

Figure 8. Topographic profile from west to east at the accumulation area of Chico Glacier. Note 7.5:1 vertical exaggeration.

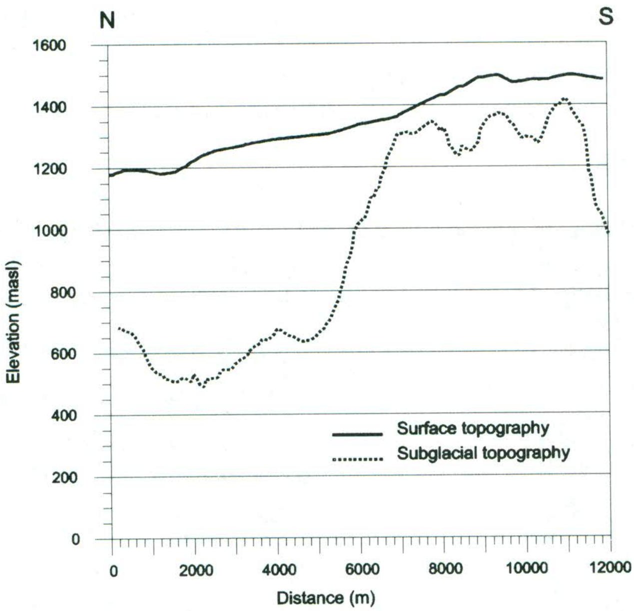

Figure 9. Topographic profile from north to south at Chico Glacier. Note 7.5:1 vertical exaggeration.

7. CONCLUSIONS

In spite of the progress made in ice thickness measurements over the last few years, it has been impossible to penetrate temperate ice deeper than 800 m in Patagonia. In this kind of temperate ice, the attenuation, absorption and scattering from water inclusions and internal reflectors, prevent collection of better results with the current system. Several modifications are being tested to improve the radar system range, such as increasing the amplitude of the transmitter signal, averaging a larger number of traces, and enhancing the signal strength by means of PC-based software.

The subglacial topography of paso de los Cuatro Glaciares cannot be completely detected with our system. Particularly difficult to probe, are the deep areas located in the central part of the main valleys. The interpretation of the subglacial returns could be improved by using a migration method, able to correct the returns from lateral reflectors, which are very important in areas where the bedrock topography is rough and steep, such as in Patagonia.

The internal structure of the ice needs to be better interpreted. At least two internal reflectors parallel to the surface topography have been detected at corredor Hicken. These reflectors suggest the presence of layers of volcanic ash deposited during one of the several eruptions of volcán Lautaro, located within the study area.

8. ACKNOWLEDGMENTS

This work has been carried out with financial support from project FONDECYT 1980293. The Chilean Air Force provided logistic support for the Hielo Azul operation.

Thanks are expressed to Cesar Acuña, for drawing the figures, Heiner Lange, for collaborating with the GPS data analyses and Carlos Cárdenas, for compiling Table 1. Comments from Al Rasmussen are acknowledged.

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