

DIGITAL RADIO-ECHO SOUNDING AT TYNDALL GLACIER, PATAGONIA

SONDAJE DE RADAR DIGITAL EN EL GLACIAR TYNDALL, PATAGONIA.

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ABSTRACT

Radar data collected in 1993 with a portable digital system at Tyndall Glacier, Southern Patagonia Icefield are analyzed. Point measurements were carried out along a transverse profile on the ablation area of the glacier, which is 8 km wide in this section. Clear bottom returns were received on the glacier to a point about 2.9 km from the margin. No return could be received beyond that point. Ice thicknesses range from 70 m to 569 m, increasing near-parabolically. The data are in the lower range of ice thicknesses collected with an analog radar system using the same transmitter in 1990. The inability of the radar to penetrate deeper ice is probably due to absorption and scattering produced by water bodies within the ice.

RESUMEN

Se analizan datos de radar recolectados en 1993 en el glaciar Tyndall, Hielo Patagónico Sur, con un sistema digital portátil. Las mediciones puntuales se realizaron a lo largo de un perfil transversal en la zona de ablación del glaciar, el cual tiene 8 km de ancho en esta sección. Se obtuvo claros retornos del fondo del glaciar hasta un punto ubicado a 2,9 km del margen, pero no fue posible obtener retornos del fondo más hacia el centro del glaciar. Los espesores de hielo obtenidos fluctuaron entre 70 m y 569 m, aumentando casi parabólicamente hacia el centro del glaciar. Estos datos están en el rango inferior de espesor de hielo medido en 1990 con un sistema análogo de radar que incorpora el mismo transmisor utilizado en 1993. La limitación para penetrar hielo más profundo se debe probablemente a la absorción y dispersión producida por cuerpos de agua presentes dentro del hielo.

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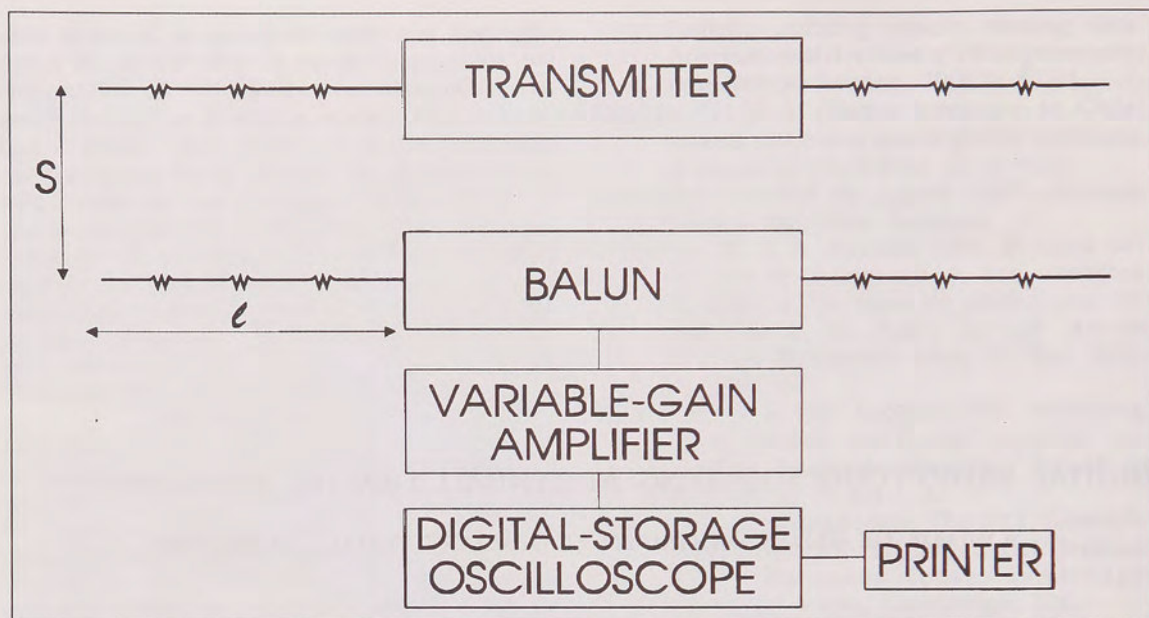


Fig. 1. Schematic of the digital radar system.

INTRODUCTION

Radar soundings to determine ice thickness have been carried out in 1990 at the upper ablation area of Tyndall Glacier, Southern Patagonia Icefield (Casassa 1992). Those measurements, collected with an analog system, constitute the first radar soundings in Patagonia. A maximum ice thickness of about 600 m at 2.9 km from the margin was obtained in 1990 and no bottom return could be received beyond that point. At that time it was concluded that the dynamic range of the radar was insufficient to penetrate deeper temperate ice as found in Patagonia. One alternative to increase the range is to use a more powerful transmitter. A simpler option, described in this paper, is to measure with the same low-power transmitter and use a digital oscilloscope averaging (stacking) several waveforms over time. In addition to stacking, a variable-gain amplifier was also used, effectively increasing the gain.

Digital Radar System

Unlike polar glaciers, abundant meltwater is present in the temperate glaciers of Patagonia. Water bodies within a glacier

range typically from a few centimeters to a few tens of meters and thus produce large scattering if radar wavelengths of less than about 30 m are used, *i.e.* frequencies larger than about 10 MHz (Watts & England 1976). However, scattering decreases rapidly at smaller frequencies, as has been demonstrated successfully for sounding temperate ice (Watts & Wright 1981).

The transmitter used here was constructed at The Ohio State University (OSU) and is the same as the OSU transmitter used in 1990 at Tyndall Glacier (Casassa 1992) and in 1995 at Patriot Hills, Antarctica (Casassa *et al.*, in press). It is powered by a 12 V battery and produces a short-pulse signal of a few hundred volts in amplitude which is radiated using resistively-loaded dipole antennas. In 1990 a Hitachi-V209 oscilloscope was used, with a simple mount for taking pictures off the screen. The digital system described here uses a Philips Scopemeter 97 digital storage oscilloscope, with a bandwidth of 50 MHz and a maximum sensitivity of 1 mV/div, stacking capacity of up to 256 traces and a storage capacity of 8 waveforms. Data were stored in the oscilloscope, and downloaded at base camp every day to a

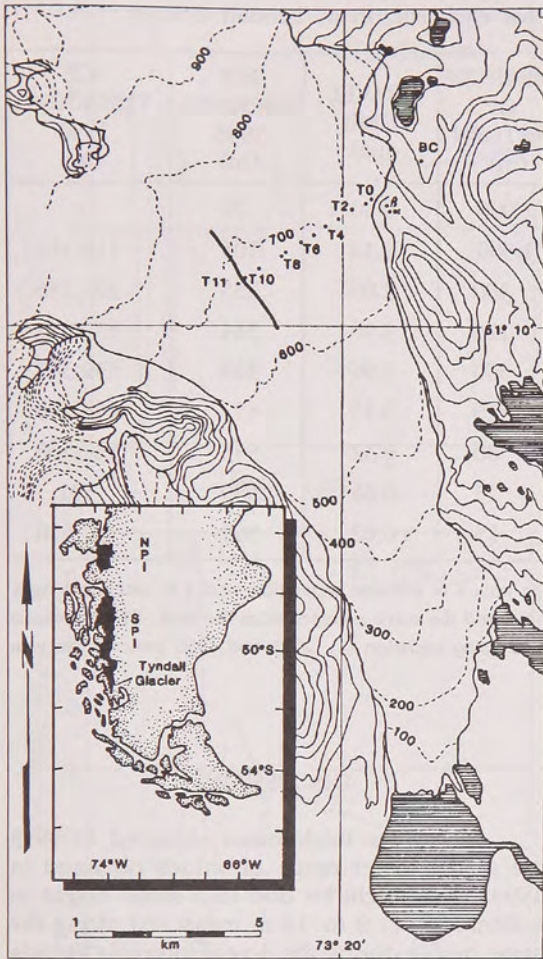


Fig. 2. Map of Tyndall Glacier (source: 1:100,000 scale map Parque Nacional Torres del Paine, Sociedad Turística Kaoniken Ltda. 1990). α and β are ground control points. BC is Base Camp. Bed reflections could only be obtained from station T0 to T7. The medial moraine at station T10 is indicated with a thick line.

portable computer. In the field, the data were also printed out as well using a small thermal printer. In addition to stacking, a variable-gain amplifier designed at OSU was used. This amplifier increases the receiver gain, compensating for weaker signals produced from deeper returns. The gain, which is adjustable, is about 0 dB before the transmitted pulse is detected, increasing to about 25 dB in 20 μ s. A balun was used for coupling the variable-gain amplifier to the receiving antenna. Antenna separations of 10 to 80 m were used, together with

half-dipole lengths (l) of 10 to 40 m. The field layout of the radar system is shown in Fig. 1.

The center frequency of the transmitted signal can be calculated using the empirical expression (Hodge 1978):

$$f = 50/l,$$

where f is the frequency in MHz and l is in meters. Frequencies of 5 and 1.25 MHz are obtained for half-dipole lengths of 10 and 40 m, respectively.

RESULTS

Measurements were carried out from December 9 to 14, 1993 at stations T0 to T11 on the upper ablation area of Tyndall Glacier (Fig. 2). At stations T0 and T1, where ice is only about 100 m deep, smaller antenna lengths were used so that the higher frequency of the signal would shorten the pulse length and enable to separate better the surface and reflected waves. From stations T0 to T3 the variable-gain amplifier (VGA) was not needed and a clear bed return was observed, although the signal was increasingly weaker away from the margin (Table 1).

From station T4 to T7 the VGA was necessary for detecting a bed return. No bed return could be observed beyond station T7. Ideally, the surface wave is a monopulse. In practice, several attenuated pulses are transmitted as well. The same is true with the reflected wave, where a train of attenuated surface pulses appear. The two first pulses are most prominent, as can be seen on the waveforms obtained at T0 and T1, shown in Fig. 3. The first two peaks of the transmitted wave are labeled 1 and 2 in Figs. 3, 4 and 5, and the corresponding peaks of the reflected wave are shown as 1' and 2'. The travel times are calculated as an average of the time intervals between peaks 1-1' and 2-2' ($\Delta t_{11'}$ and $\Delta t_{22'}$ respectively).

For the cases where no VGA was used, $\Delta t_{11'}$ and $\Delta t_{22'}$ are nearly equal. However, when using the VGA (Figs. 4 and 5) both the surface and the reflected waves were distorted, the surface one becoming weaker and the reflected one being amplified, resulting in a waveform difficult to interpret. In spite of this, after careful inspection the surface and

TABLE 1. Radar measurements and ice thickness for each station at Tyndall Glacier.

ST.	VGA	S (m)	l (m)	PHASE SHIFT (deg)	AMPLITUDE OF RETURN (mV)	TRAVEL TIME (μ s)	ICE THICKNESS 1993 (m)	ICE THICKNESS 1990 (m)
T0	NO	10	10	0	2,000	0.80	70	-
T1	NO	40	20	180	1,500	1.12	104	119-162
T2	NO	40	40	180	300	2.07	185	162-246
T3	NO	40	40	180	125	3.96	344	339-347
T3	YES	40	40	180	500	3.96	344	339-347
T4	YES	80	40	180	125	5.18	457	448-490
T5	YES	40	40	180	80	6.32	543	532-566
T6	YES	40	40	180	25	6.86	589	591
T7	YES	40	40	180	25	6.62	569	582-616

VGA indicates whether the variable-gain amplifier was used or not. S is antenna separation and l is antenna length. Phase shift refers to the phase difference between the surface wave and the wave reflected from the bed. The amplitude is expressed as a peak-to-peak value. Ice thickness is calculated using equation (1). 1993 and 1990 indicate the year when the data were collected in the field.

reflected waves could be identified.

Unlike the data collected without VGA, when using the VGA the wavelength of the reflected wave became larger than that of the surface wave. This wavelength increase is regarded to be introduced by the VGA and not related to any physical properties of the surface-ice-bed system. Therefore, when using the VGA the travel time is taken to be the interval between peaks 1 and 1', and peaks 2 and 2' are disregarded. Ice thickness (D) was computed using the expression (Watts & Isherwood 1978):

$$D = (t + s/c)^2 c^2 / 4\epsilon_i - s^2 / 4 \quad (1)$$

where t is the travel time in μ s, s is the antenna separation in m, ϵ_i is the dielectric permittivity of the ice (3.17) and c is the speed of light in vacuum (3×10^8 m/s).

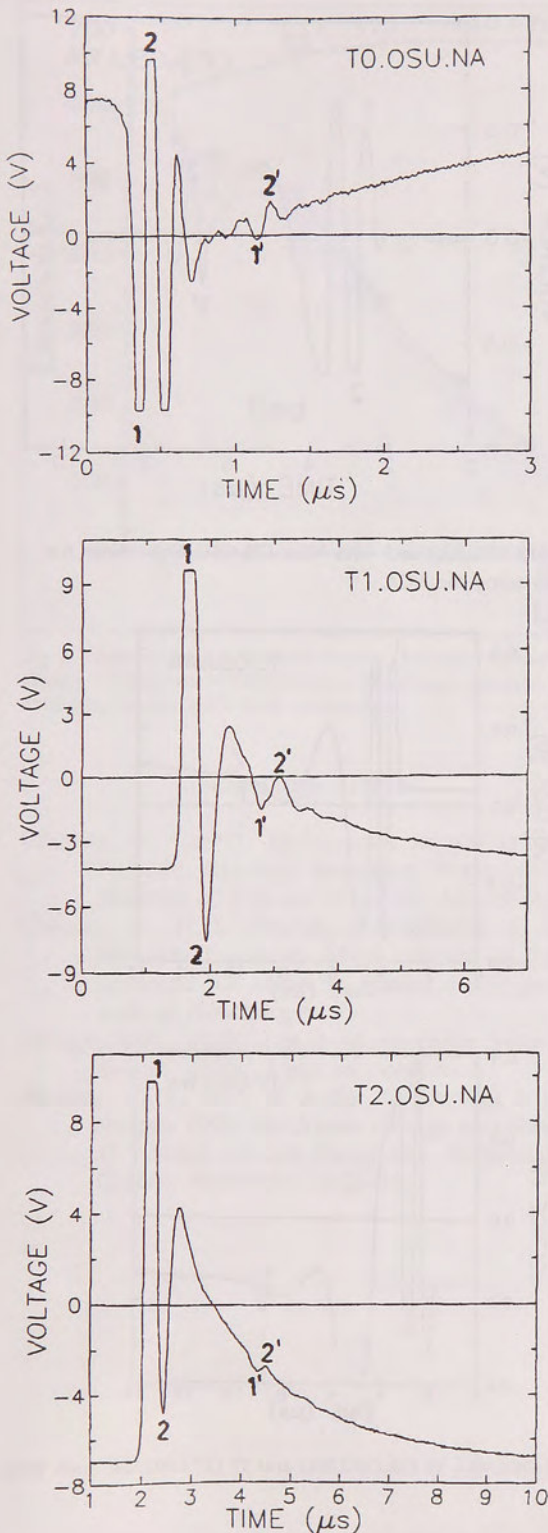
The results are summarized in Table 1, which also shows 1990 data obtained with the analog radar system. Ice thicknesses are plotted in Fig. 6, which show a near-parabolic profile with the deepest ice occurring at T6.

DISCUSSION

Ice thicknesses obtained in 1993 are in the lower range of values obtained in 1990. This might be due to a small extent to a thinning of 9 to 14 m measured along the same profile during the 3-year interval (Nishida *et al.* 1995), but is thought to be mainly due to the better accuracy of the digital data as compared with the analog data.

The advantage of using the VGA can be clearly seen in the waveforms obtained at station T3 with and without VGA (Fig. 4). The peak-to-peak amplitude of the reflected peak is 125 mV without amplifier, whereas with amplifier the amplitude of the return increases to 500 mV (Table 1). The advantages of the VGA are also seen at station T7, where the peak-to-peak amplitude of the reflected peak is 25 mV, as compared to 2 mV obtained in 1990 without amplifier.

In spite of stacking and using the VGA, beyond station T7 no bed reflection was observed. This was also the case with the analog radar system used in 1990. Beyond station T7, which is about 1 km away from the



center of the glacier, the ice could be deeper. If this is true, then the radar system is unable to penetrate ice deeper than 600 m. Alternatively, ice thicknesses might not increase, as suggested by the cross profile of Fig. 6, but water inclusions within the ice might become more relevant toward the center of the glacier, resulting in greater scattering which prevents detecting any bed return.

In either case, *i.e.* ice deeper than 600 m or high amount of water inclusions, the digital radar configuration used showed that stacking or amplifying the signal was not the solution. Instead, increasing the output power of the transmitter, optimizing the coupling with the antennas and increasing the gain of the antennas should be tried for obtaining a larger dynamic range. For this, a new transmitter and antennas should be designed and tried in combination with a digital receiving system.

ACKNOWLEDGMENTS

In the field, the assistance of Jorge Quinteros from Dirección General de Aguas, Santiago, is greatly appreciated. Kenro Nishida also helped in the field. Pedro Skvarca from Instituto Antártico Argentino kindly provided the OSU radar, antennas, balun and batteries. The transmitter and antennas were constructed by Frank Huffman from The Ohio State University, USA, who provided valuable advice. The Project of Volcanic Risk of Servicio Nacional de Geología y Minería, Santiago, kindly provided the digital storage oscilloscope, which was donated by the University of Bristol, UK. This study was supported by a grant on International Scientific Research Program (N° 05041049: Principal Investigator Dr. R. Naruse) of the Ministry of Education, Science and Culture of Japan.

Fig. 3. Waveform obtained at stations T0 (T0.OSU.NA), T1 (T1.OSU.NA) and T2 (T2.OSU.NA) without variable-gain amplifier (VGA). 1 and 2 indicate peaks of the surface wave, while 1' and 2' show peaks of the bed return. The same notation is used in Figs. 4 and 5.

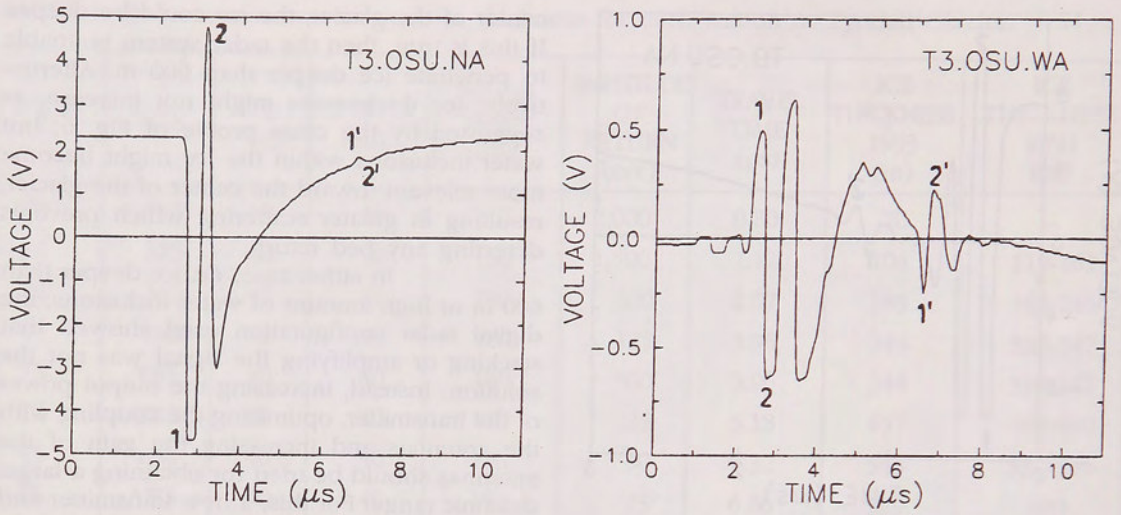


Fig. 4. Waveforms obtained at station T3 without VGA (T3.OSU.NA) and with VGA (T3.OSU.WA). Note the amplified return when using the VGA.

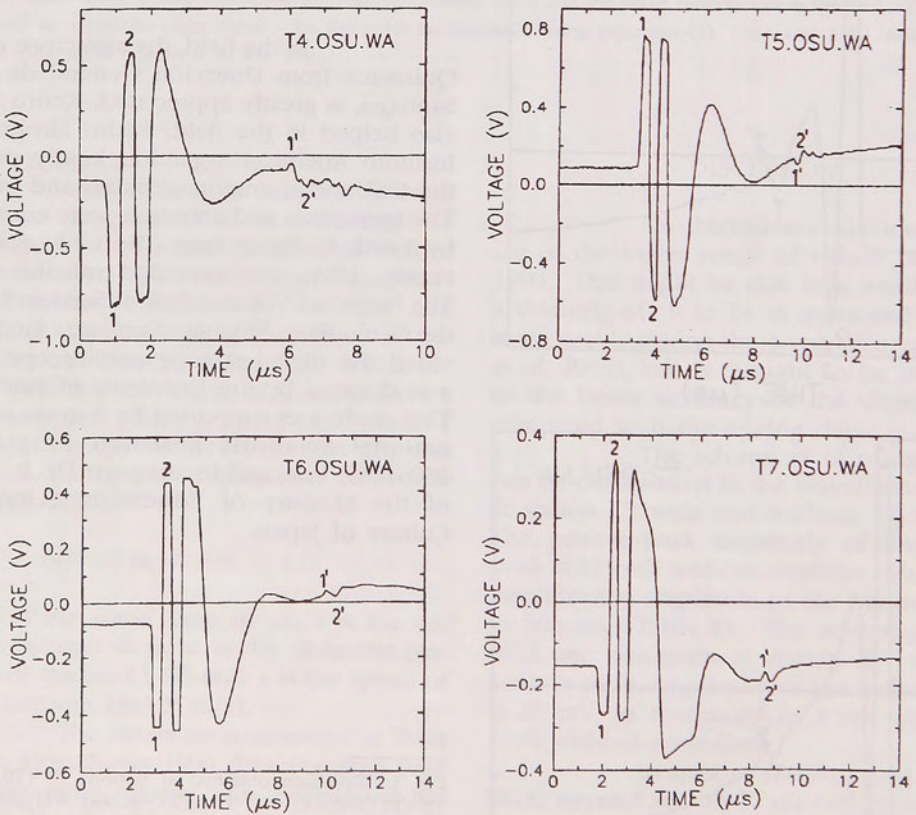


Fig. 5. Waveforms obtained at stations T4 (T4.OSU.WA), T5 (T5.OSU.WA), T6 (T6.OSU.WA) and T7 (T7.OSU.WA) with VGA.

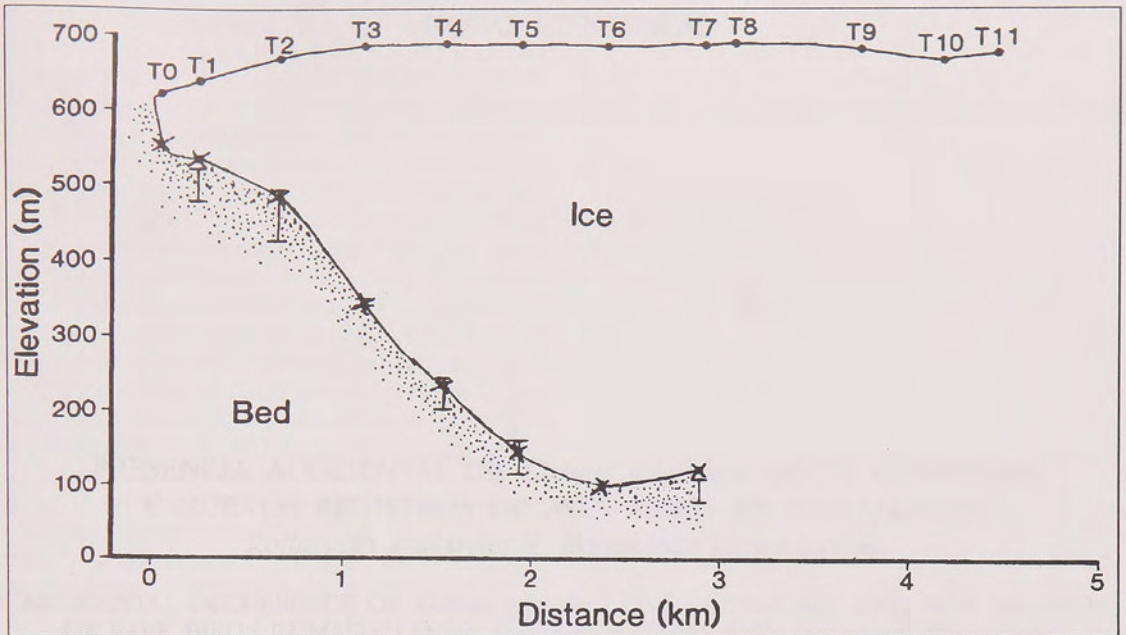


Fig. 6. Cross section of Tyndall Glacier. Crosses represent thickness data obtained in 1993 with the digital radar system. Vertical bars represent ice thickness data range obtained in 1990 with the analog radar system. The ice surface is drawn according to the 1990 field survey data.

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