THE APPLICATION OF GROUND-PENETRATING RADAR TO THE STUDY OF GLACIAL HYDROLOGY

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ABSTRACT

A major problem in the study of glacial hydrology has always been determining the exact location and interconnections of englacial and subglacial drainage networks. Advances in ground-penetrating radar (GPR) technology makes this possible.

A PulseEKKO IV GPR system was used to survey the accumulation area and the termini of two high arctic glaciers, and a proglacial icing. Near-surface detail was best imaged using a 200 MHz/400 V configuration, while the 50 MHz/1000V configuration imaged through thicker ice.

While minor variations in ice properties were not imaged, major changes in ice character were detected and large air, water, and sediment inclusions were mapped with gridded surveys. Pulse phase modeling was used to differentiate air-filled from water-filled voids. The low attenuation and decreased directivity of the radar signal in ice resulted in the generation of very long diffraction tails (>30 m) from point source reflectors within the ice. This enabled the determination of the precise location of these reflectors by interpolating their position between survey lines. As a result, the three dimensional position of drainage tunnels within the ice was mapped.

Key words: ground penetrating radar, glaciology, hydrology

INTRODUCTION

The study of glacial hydrology is complicated by the complex surface and subsurface variability of glacial drainage networks. An example of this is the formation of icings at the terminii of glaciers as a result of the freezing of subglacial or englacial water when it comes to the surface. The process of icing development and destruction in the proglacial environment is still poorly understood because of the inaccessibility of much of this hydrological system. Thus an effective method for remotely studying the structure and hydrological systems within and beneath glaciers and icings is required.

Over the last three decades, radio echo devices and radar systems have been developed for a variety of large scale glaciological applications (eg. Davis et al., 1973; Weber and. Andrieux, 1970; Koerner, 1977; Bentley et al., 1979). However, until recently these systems tended to be very bulky, and operating them in the rugged terrain around a glacier terminus was difficult to impossible.

Radar systems operated from aircraft have provided some subsurface data, but the strong reflection from the air/ground interface dramatically limits the amount of energy entering the ice and thus the depth of penetration (Arcone et al., 1995).

The most recently developed GPR systems, designed for general geomorphologic and geotechnical work, are backpack portable and have technical specifications appropriate to glaciological work. However, they have yet to be extensively utilized to study the glacial/proglacial environment.

The purpose of this project was to assess the feasibility of using ground penetrating radar to study the structural and hydrological network within glaciers and icings.

STUDY AREA

A portion of southern Bylot Island in the Canadian Arctic was the focus of this research (see Figure 1). The two glaciers in the study area have very different morphologies and hydrological systems, enabling the evaluation of GPR in a variety of scenarios.

Winter runoff from these glaciers form large braidplain icings. Warm air temperatures, solar radiation and summer runoff are responsible for the partial destruction of the icings each summer. A portion of the icing in front of Fountain Glacier has existed since the first aerial photograph of the area was taken in 1948.

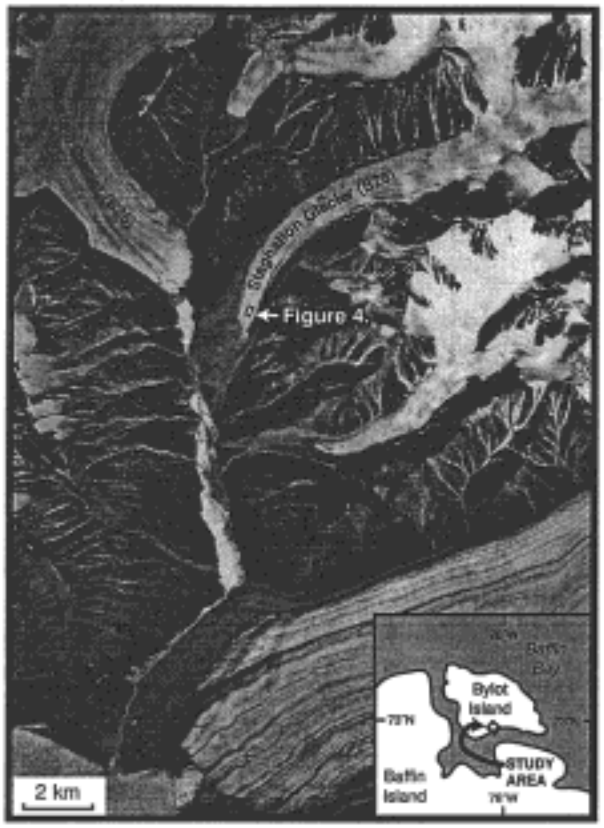

Figure 1. Location of glaciers and icings studied on Bylot Island.

METHODS

The large contrast in the dielectric constant between ice, water, and air makes ground penetrating radar well suited for studying glacial hydrology.

A pulseEKKO IV radar system, employing antennas with center frequencies of 25, 50, 100, and 200 MHz, was tested with both 400 V and 1000 V transmitters. It was found that 50 MHz antennas with a 1000 V transmitter was optimal for surveying thick glacier ice and 200 MHz antennas with a 400 V transmitter was best used to image complex stratigraphy in ice that is less than 20 m thick.

The minimum vertical resolution was estimated through computer modelling and verified with field measurements to be about 0.5 m at 200 MHz and 1 m at 50 MHz. Although the size of objects smaller than this cannot be resolved, they can still be detected by the GPR system and appear as point source reflections on the profiles. While the 200 MHz configuration offers better resolution, the lower frequency and higher power output of the 50 MHz setup enables structures to be observed to greater depths (see Figure 2).

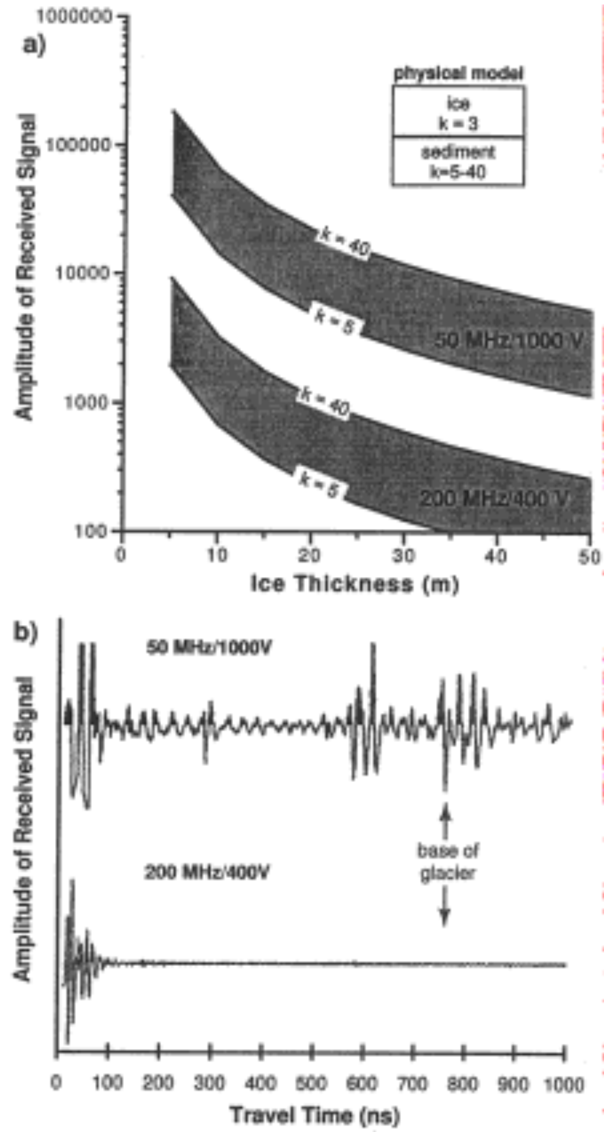

Figure 2. In a), modelled reflection amplitudes for the 50 MHz and 200 MHz configurations show an order of magnitude difference in the reflection strength when profiling a glacier. This is graphically displayed in b) where a sample trace from a 50 MHz profile containing a reflection from the bottom of Stagnation Glacier has a signal to noise ratio of 2.4 while the 200 MHz example at the same location has a signal to noise ratio of less than 1.

RESULTS AND DISCUSSION

In order to determine the depth of reflectors, the propagation velocity was measured in two ways; 1) common mid-point velocity surveys, and 2) point source reflection analysis. The distinctive geometry and lateral extent of reflection patterns generated by point source reflectors in ice enables the determination of the average propagation velocity of the ice above the reflector using the normal move-out equation. The travel time equation for normal move-out:

$$t^2 = \frac{x^2}{V^2} + t_o^2$$

where x is the antenna separation in a velocity survey or the lateral offset from the point source reflector in a profile, V is the propagation velocity, t_o is the one-way travel time at zero separation/offset, can be rearranged to calculate velocity:

$$V = \sqrt{\frac{x^2}{t^2 - t_o^2}}$$

The range in measured velocities represents variations in the air and water content of the ice (see Table 1). The ice velocity measurements made near the terminus of Stagnation Glacier were uniformly 0.17 m ns^{-1}. This is consistent with values observed by others (e.g. Bjornsson, 1986) for homogenous glacier ice. In the accumulation area of the glaciers, the dry firn, which had a larger proportion of air bubbles, yielded a higher near surface velocity of 0.19 m ns^{-1}.

Firn and Ice Density

The propagation velocity of a GPR signal through an electrically resistive medium, such as a glacier, is dominantly a function of the bulk dielectric constant of the material. The velocity is given by:

$$V = \frac{c}{\sqrt{\varepsilon}}$$

where c is the speed of light (0.3 m ns^{-1}) and ε is the effective (bulk) relative dielectric constant of the material. Kovacs et al. (1995) showed that:

$$\varepsilon = (1 + 0.845\rho)^2$$

in polar firn (i.e., composed of ice and air with no liquid water content), where ρ is the bulk density of the firn. For these conditions the two equations can be merged and the velocity can be expressed as:

$$V = \frac{c}{1+0.845\rho}$$

And thus the density of dry firn can be determined by:

$$\rho = \frac{(\frac{c}{V} - 1)}{0.845}$$

From this equation the density of the upper portions of the firn in the accumulation area and the glacier ice near the terminus was calculated to be 0.68 g cm^{-3} and 0.90 g cm^{-3}, respectively. The bulk density of a sample of the ice from near the terminus of Stagnation Glacier was gravimetrically determined to be 0.90 g cm^{-3}.

Table 1. Averages of GPR propagation velocities measured on glaciers and icings.

location	velocity (m/ns)	# of values
accumulation area (snow/firn)	0.19	3
terminus (white to blue ice)	0.17	27
icing (wet slush to bubbly ice)	0.12-0.17	35

Glacier Character

In general, glacier ice is relatively transparent to radar, resulting in few reflections being generated from within it. However, in the accumulation area, the coarse stratigraphy of the snow and firn appears on the GPR profiles. In profiles from the terminus, layering within the ice could not be identified.

The relative transparency of ice simplifies the detection of anomalous features within it. Several anomalous features were detected in the vicinity of the terminus of Stagnation Glacier.

As Arcone et al. (1995) discuss, by examining the polarity of the reflections, the dielectric constant (k) of the target relative to the ice can be determined. The strong reflection from the ice (k=3) to sediment (k 25) interface at the base of the glacier shows a distinctive +-+ polarity. Thus, targets within the ice with the same polarity are expected to have a higher dielectric constant than ice. Most geologic materials including water have a higher dielectric constant than ice, while air has a lower dielectric constant than ice. Thus air filled voids would be expected to generate a reflection with a -+- polarity.

Two anomalies within the glacier, at the 255 m and 369 m positions in the GPR profile shown in Figure 3, have a -+- polarity and are interpreted as air filled voids. The size of these voids cannot be determined as they are smaller than the resolution of the GPR and act as simple point source reflectors. The diffraction patterns have been eliminated by migrating the data, but the inset in Figure 3 shows the appearance of the returns prior to migration. The migration routine used amplifies the return from the apex of the diffraction pattern thus enhancing the positive component of the -+- wavelet, but does not alter the polarity. The location of four other air filled voids are shown in Figure 4. Extrapolation of the diffraction tails to surrounding GPR profiles using the method described by Moorman (1998) indicated that these voids are not connected. It is likely that they are remnant air cavities from when crevasses closed on the surface. There are several heavily crevassed areas up glacier from the study area.

Several of the reflections from within Stagnation Glacier have the same +-+ polarity as the base of the glacier, indicating that the reflectors have a higher dielectric constant than the ice (eg., water or sediment). The lateral extent of the two reflectors displayed on the profile in Figure 3 is resolved. The source of these reflections is likely a water filled englacial drainage tunnel that crossed the GPR survey line at an acute angle. From interpolating between the GPR profiles surveyed in the grid on Stagnation Glacier, the route of the tunnel was mapped (see Figure 4). The tunnel is aligned with the location of where a marginal stream disapears into the glacier in the up ice direction and reappears down ice.

Icing Character

Unlike glaciers, icings are composed of ice layers with dramatically different bubble content and crystal structure. These variations in physical properties enabled the imaging of the internal structure of the icings.

The GPR profiles from the icing contain many strong continuous reflections within the top 6 m of the ice (see Figures 5 and 6). Those reflections were confirmed in drill cores which showed the upper portion of the icing containing alternating “bubbly” and “clear” ice units. Below a depth of 6 m, the layers were thicker and more uniformly bubble-rich. This is represented on the GPR profiles by a reflection free zone. Unfortunately the icing contained an appreciable liquid water content so the velocity analysis could not be used to quantify the density (or bubble content).

Depressions and mounds are prevalent in the tabular structure of the icings. The depressions were observed to be relatively localized. They are interpreted as abandoned drainage channels that have since filled with ice. Crystallographic evidence from ice samples support this theory.

The mounds observed on the GPR profiles extended for distances of as much as 60 m in the down valley direction and across the entire width of the seasonal icing. Their top and bottom contacts were generally undulating (see Figure 6). The conformable nature of the contacts suggests that these mound structures are ice injection features or aggradational frazzle ice units. This type of feature was also observed in exposures at the side of the icing.

The profiles in Figures 5 and 6 were not migrated so the diffraction patterns indicate the location of drainage tunnels within or below the icing (see Figure 4).

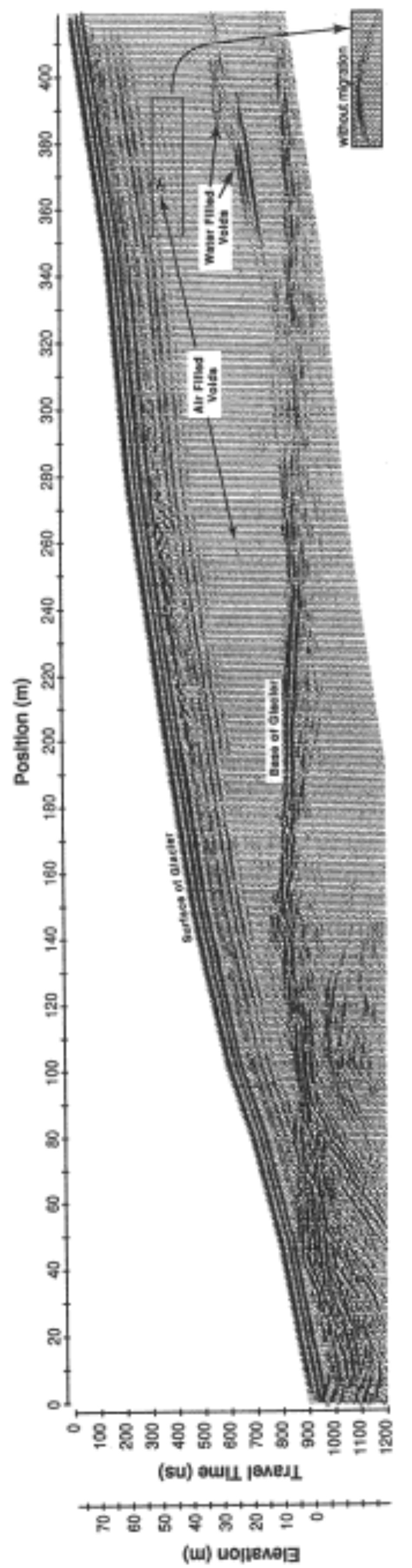

Figure 3. GPR profile up the central axis of Stagnation Glacier starting at the terminus.

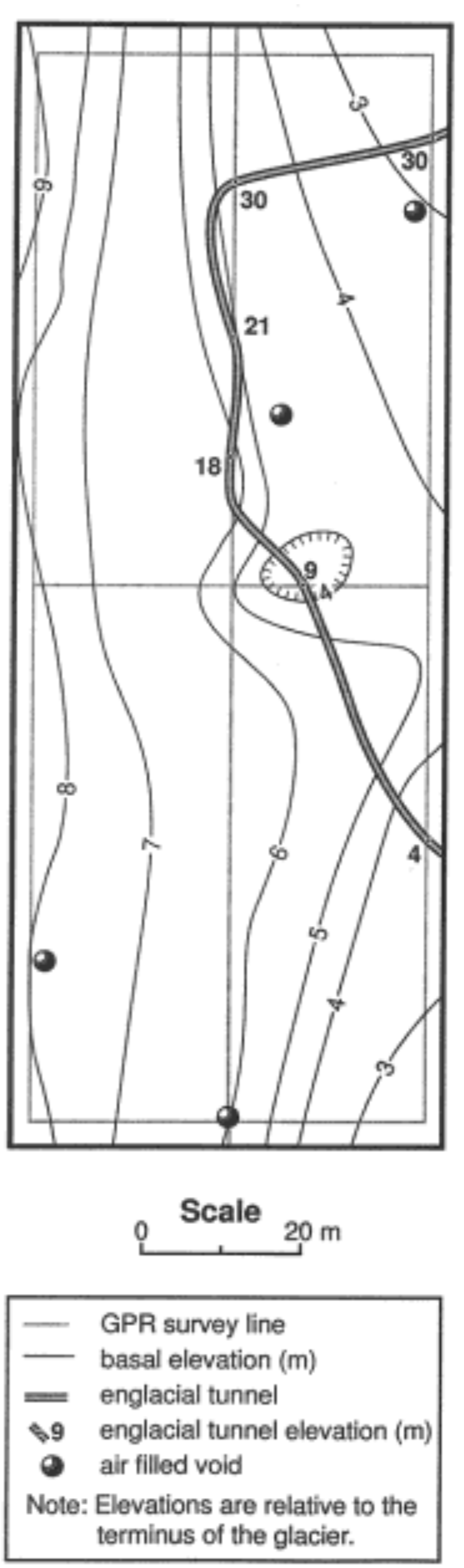

Figure 4. A portion of Stagnation Glacier containing an englacial drainage tunnel.

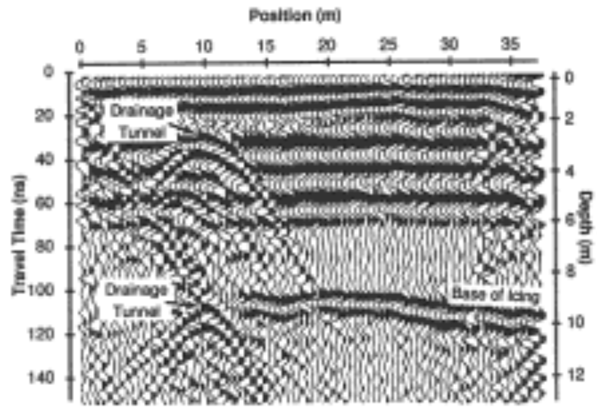

Figure 5. A portion of the GPR profile perpendicular to the long axis of the icing in front of Fountain Glacier.

CONCLUSIONS

The GPR profiles displayed in this paper demonstrate that this technology is very effective for surveying the hydrological network around the termini of glaciers and icings. Specifically, findings include:

- Measured GPR propagation velocities can be used to estimate the density of “dry” snow and firn.
- The long diffraction tails generated within ice can be used in interpolating the precise position of objects between profiles.
- With the aid of a reflection from a known interface, the polarity of other reflections can be used to determine dielectric constant relative to the ice, and thus the nature of reflector (eg. air or water).
- Stagnation Glacier has numerous isolated air filled voids as well as active englacial drainage tunnels.
- Fountain Glacier Icing also has channelized drainage within the ice.
- Drainage channels within the ice that had dimensions considerably less than the resolution of the GPR system were detected.
- General layering within the icing was imaged, revealing ice types indicative of different formational processes
- From the radar data it is apparent that the icing formed from both slush accumulations, and injection of water between existing ice layers.

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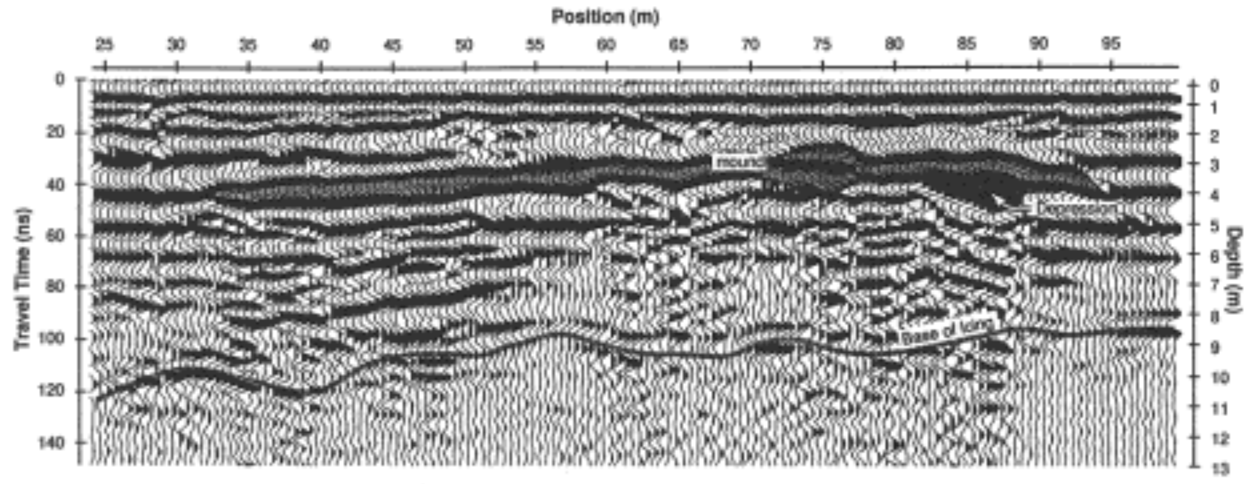

Figure 6. A portion of the GPR profile parallel to the long axis of the icing in front of Fountain Glacier.

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