Bedrock Topography and Isochrone Mapping of Five Glaciers in Victoria Land, Antarctica

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Abstract - Ground Penetrating Radar (GPR) has been used extensively as a reconnaissance tool to determine the optimum sites for ice core retrieval in the New Zealand contribution to the International Trans Antarctic Scientific Expedition (ITASE). Between 2000 and 2007 five glaciers situated in Victoria Land, Antarctica, have been investigated using GPR. Continuous long distances traverses were recorded in a convoy, with the GPR equipment mounted on a central sledge towed between two skidoos for crevasse safety.

A 50MHz antenna was used to provide total ice thickness measurements and also simultaneous high resolution imaging of isochrones. Higher frequency antennae were used for crevasse definition. Typically, 30km of GPR transects in a grid pattern were completed each survey day at a acquisition speed of 10km/hr. Strong bedrock reflections were obtained to a depth of up to 600m (range of 8,000ns) and isochrone reflections from seasonal firn layers to approximately 120m depth.

Keywords – GPR, glacier, Antarctica, isochrone, bedrock, ITASE, ice cores, climate change, global warming.

I. INTRODUCTION

New Zealand’s contribution to the International Trans Antarctic Scientific Expedition (ITASE) program focuses on the investigation of coastal glacier sites, predominantly consisting of low elevation, local ice domes. The overall objective of this project is to collect and analyse ice cores to improve our understanding of the major southern hemisphere climate drivers causing high frequency climate variability. In particular, these are the El Nino Southern Oscillation, the Antarctic Oscillation and the Antarctica Circumpolar Wave, as well as the drivers and feedback mechanisms causing abrupt climate change. High resolution sub-annual records of ice stratigraphy are essential to capture the high frequency variability of these drivers.

GPR has been used extensively during the ITASE project to map bedrock topography, glacial isochrones and provide shallow firn (old snow) stratigraphy for correlation between ice cores (Arcone, 2002A and 2002B).

The accurate selection of ice drilling sites to maximise the scientific benefit obtained from each ice core is crucial, as the costs required to deploy drilling rigs to very remote locations in Antarctica are extremely high. The requirements for good drilling sites are:

- Sufficient ice thickness for drilling to the required depth and with no unusual bedrock rises.
- Very flat isochrones (annual layers of ice) with a continuous chronological record of at least 200 years, but preferably > 2,000 years.
- Areas of minimal glacial flow, or a location where the glacial flow dynamics can be well understood.

GPR measurements have been undertaken at the following sites, as shown on Figure 1.

- Victoria Lower Glacier (2000)
- Mt Erebus (2003)
- Whitehall Glacier (2006)

Figure 1. The location of GPR surveys conducted at the New Zealand ITASE sites is represented by the yellow dots. (http://www2.umaine.edu/itase/)
II. METHODOLOGY

Three different GSSI GPR systems were used for the glacial measurements; a SIR-10A (highly modified and upgraded), SIR-20 and SIR-3000. These instruments were successfully operated in temperatures as low as minus 40°C from field camps (tents) with very limited facilities. All personnel and equipment had to be deployed by either helicopter or Twin Otter ski plane.

Figure 2. Nansen sledge with towed array of bistatic 50MHz antennae (on left) and also 500MHz antenna (on right) for crevasse detection.

Figure 3. 50MHz bistatic antennae mounted on rubber car inner tubes with PVC frame.

The GPR acquisition set up consisted of a control unit mounted on a wooden (Nansen) sledge, which was towed between two skidoos. All three vehicles were roped together, to minimise risk and loss should a vehicle fall through a snow bridge and into a crevasse. For these surveys we carried special crevasse safety equipment and were trained in crevasse rescue. Typically, up to 30km of GPR transects in a grid pattern could be completed each survey day at a maximum acquisition speed of 10km/hr.

Modified Radarteam resistively loaded bistatic antennae with a nominal centre frequency of 35MHz were used (Figure 2). The typical centre frequency of the received signal from these antennae on glacial ice was found to be approximately 50MHz (Figure 12). The antennae were fitted with a high power transmitter (1,000 Volt) and dual stage receiver electronics to increase sensitivity. A fibre-optic pulse trigger was used to reduce antenna ringing. The antennae were air-launched at 10-20cm above the surface on a frame fabricated from PVC pipe and car inner tubes (Figure 3). Often the surface of the glaciers was very rough with sastrugi (wind blown ice ridges), so the inner tubes provided the necessary cushioning when towing across the surface. Flexibility of the frame at minus 40°C was also essential, so that it could twist and flex over the rough ice.

At some of the glacier sites, higher frequency antennae (100MHz, 200MHz, 500MHz and 400MHz) have also been used. While providing higher resolution data, results recorded with these antennae have not matched the ability of the 50MHz antennae to image isochrones to depths of up to 120m and also simultaneously to image strong bedrock reflections within the same time window. Using just one antenna for the traverses saves valuable time, effort and fuel resources. In Antarctica there is often a very limited weather window in which to collect GPR data, so minimising the set up and acquisition time is very important.

All GPR data acquisition was time based, using the maximum possible sampling parameters selected for the respective GPR to provide good definition of annual isochronal layers. A sampling rate of 2,048 samples per scan was utilised on the SIR-10 and SIR-20 control units, and 8,192 samples per scan on the SIR-3000 systems. The GPR acquisition time was synchronised with differential GPS unit. A Trimble RTK system was used for all surveys, providing sub-metre accuracy in position.

The recording time windows needed to be selected carefully to position the bedrock reflection at about 75% down the window. Initially however, when no information was available about ice thickness, a test GPR survey was conducted using the maximum time range of the instrument; 10,000ns for the SIR-10 or 8,000ns for the SIR-20 and SIR-3000 systems. Visually identifying the reflection on the screen while surveying can be very difficult, due to the vertical compression of the samples necessary to fit the entire waveform onto a small LCD panel. At maximum sampling levels, the sampling rate is very slow. Depending on the particular time window set, it was only be possible to acquire one trace every two seconds (0.5Hz).

When operating in Antarctic conditions, it was essential to maintain a stable temperature range for the electronic equipment (typically between minus 10°C and plus 10°C). This was a serious challenge when operating from a tent in temperatures as low as minus 40°C. Sudden changes in
temperature had to be avoided or they would lead to equipment breakdown. For example, we found that the GPR control systems needed to remain powered up for the entire time they are on the sledge, which generally involved the use of a small generator. At subzero temperatures, battery life was be less than 50% of the normal duration and more importantly, at cold temperatures batteries fail to charge to maximum capacity.

Cables required very special attention, as some plastic coatings and internal wiring became brittle and was prone to fracture. Generally, cables needed be kept warm in storage until they were ready to be positioned onto the sledge or antenna frame and once positioned, they had to be firmly tied down immediately and do not moved until the end of the survey. Bubble wrap around the antenna and cables was used to reduce the wind chill factor especially at higher altitudes.

Post processing of GPR data was conducted using RADAN software and involved stacking, bandpass frequency filtering, background removal, distance normalisation, elevation correction, migration and deconvolution. Particular features on the final processed images were then digitised manually using the stratigraphic layer-picking module in RADAN. This provided an X,Y,Z ascii file which could be used to generate a grid file for 3D surface projection. The images were then used to determine glacial flow orientation and select optimum core drilling sites.

Generally, bedrock reflections at depths of 200m to 300m were very strong at all five sites. The maximum depth that reflections were obtained from the bedrock was observed at Skinner Saddle (600m depth at 8,000ns time range), which was the maximum time range possible for the SIR-3000 system. At some of the sites bedrock reflections were not observed either because they occurred beyond the 8,000ns maximum time range, or due to surface roughness degrading data quality. More difficulty in achieving consistent bedrock reflections was observed in the northern sites (Whitehall Glacier, Evans Piedmont Glacier) than the southern sites (e.g. Skinner Glacier). This may be partially due to the warmer conditions and higher conductivity levels in the northern sites. These parameters will be evaluated when ice core data analysis becomes available.


The Victoria Lower Glacier is situated between the Dry Valleys and the Wilson Piedmont Glacier. Fifty kilometres of GPR profiles across the glacier revealed a typical U-shaped valley with strong bedrock reflections to a depth of 250m (Watson, 2002, Bertler 2003). An interesting bedrock rise with strongly diffracted surface reflections was observed along the southern side of the glacier. Isochrones were visible to a depth of 120-140m. The 50MHz antenna also produced strong diffraction hyperbole from crevasses at the junction with the Baldwin Glacier (Figure 5).

Typically we used a 400MHz or 500MHz antenna to identify crevasses, but after applying strong horizontal filtering to the 50MHz data, it was possible to reduce the isochrone reflections and thus observe diffraction hyperbolae from the crevasses on the lower frequency data (Figure 5).
Mt Erebus (2003)

GPR measurements were carried out in the 2,460 m (8,000 ft) saddle between Mt Erebus and Mt Terra Nova. This required man-hauling the GPR sledge and accessory equipment as it was not possible to deploy the skidoos in this terrain. Ice thickness was found to be approximately 220m. Some unusually strong internal reflections were initially interpreted as volcanic debris layers. However, when the 200m ice core was retrieved in 2003, there were no visible ash or debris bands at the depths indicated by the GPR. (Figure 6).


GPR measurements at this site revealed a complex bed topography with ice thicknesses of up to 300m. Heavy sastrugi conditions were experienced, which reduced data quality in some areas. Due to technical problems and breakages in cold conditions, only one 50MHz antenna was operational for part of the survey, so the antenna was used in monostatic mode with a transceiver electronics board. The maximum penetration depth achieved in monostatic mode was less, but clear bedrock reflections to 250m were obtained using the single antenna. There appeared to be no reduction in depth of isochrone reflections (Figure 7).

Figure 6. GPR data from Mt Erebus, showing strong internal reflections at between 400ns and 700ns as indicated by arrows.

Figure 7. Bedrock reflections and isochrones on the Evans Piedmont Glacier recorded using a monostatic 50MHz antenna. Orientation of this GPR transect A – B is shown in the insert.

The Whitehall Glacier is a small East Antarctic Ice Sheet, located about 5km from the coast and 500m above sea level, which is moving independently from other adjoining ice masses. This was the northern-most site we examined with GPR, with much warmer summer temperatures. Isochrones were visible to a depth of approximately 1,000ns. Bedrock was visible only near the edges of the glacier and penetration was insufficient to reach the deeper bedrock in the middle sections of the glacier (Figure 8).

Independent 5MHz radio echo sounding equipment that we carried indicated 700-800m ice thickness. Although the GPR failed to map bedrock topography, the internal structure was well defined and a good ice coring location was found, which was subsequently drilled in 2006. An abrupt discontinuity of isochrones was observed at the edge of this glacier, which is possibly the division between active and stagnant ice.


Approximately 60km of GPR data were collected at this site, with bedrock reflections visible to over 600m (8,000ns) and isochrones to 1200ns. An example of the typical GPR data recorded is shown in Figure 9, with an enlargement showing the compression of the isochrones over a bedrock rise presented in Figure 10.

Sample traces are shown for two locations (A and B) along this particular profile which indicate the relative amplitudes of reflectors (Figure 11). The frequency spectrum indicates that the dominant reflection frequencies are found between 25 and 80MHz for this antenna (Figure 12).
IV. FUTURE RESEARCH

Current and future research in this program is aimed at:

- Correlation of GPR results with ice cores.
- Development of new low frequency antennae which are optimised for coupling with the ice surface.
- Increasing transmitter power and increasing receiver performance, whilst reducing system ringing.
- Increasing the scanning speed of the control units when used at very long time ranges (10,000ns).
- Reducing operating power requirements for the radar systems, so that they do not have to be supported with generator power in the field.

V. SUMMARY

We have shown that it is possible to obtain detailed high resolution isochrone structure and also bedrock measurements in the same data record using low frequency (50MHz) GPR. With this system, bedrock reflections up to 8,000ns (the limit of our equipment time window) were recorded and isochrone reflections were typically observed to 1000ns. The data collected at these sites has been successfully used to plan the optimum drilling locations for ice core retrieval.

Correlation between the GPR data and ice cores is being conducted as an ongoing process, which will assist in our understanding of the relationship between radar reflections and ice density, conductivity and dielectric permittivity. In turn, these ice cores provide a detailed and accurate record.
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REFERENCES


[4] ITASE Website: http://www2.umaine.edu/itase/