Geophysical Investigation of Icy Debris Fans With Ground Penetrating Radar, Southern Alps, New Zealand

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GEOPHYSICAL INVESTIGATION OF ICY DEBRIS FANS WITH GROUND PENETRATING RADAR, SOUTHERN ALPS, NEW ZEALAND

By

Erica May Rubino

A Thesis

Presented to the Faculty of Bucknell University
In Partial Fulfillment of the Requirements for the Degree of Bachelor of Science with Honors in Geology
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ABSTRACT

Degradation of ice caps has begun to alter alpine periglacial regions, resulting in the exposure of bedrock escarpments, and in the occurrences of mass-flow processes. These mass wasting processes include ice avalanches, rockfalls, slushflows, and icy debris flows, and can result in the development of poorly understood landforms known as icy debris fans. Icy debris fans are formed at the base of escarpments along the margins of valley glaciers. According to a 2013 study in New Zealand, fan surfaces are dominated by ice and lithic material derived from ice avalanches, which constitute >90% of mass flows annually. Depositional processes over 8-9 months range from 15-300 events per fan. Subsurface information on icy debris fans has allowed for the relationship of these mass-wasting landforms and their underlying valley glacier to be better understood.

Ground penetrating radar (GPR) profiles allow subsurface geometries and architectures to be interpreted, which in turn allows estimates of fan volumes to be made, as well as provides a better understanding of icy debris fans’ process evolution over time—all important in understanding their contribution to valley glacier budgets.

Noninvasive GPR profiles, including common mid-point (CMP) soundings, were used to characterize the subsurface architecture of four icy debris fans along the La Perouse and Douglas Glaciers in the Southern Alps of New Zealand. RTK-GPS coordinate and elevation data was used to document the surface topography of icy debris fans. Interpretation of GPR surveys provides information on the sedimentary architecture of the fans, which can be compared to surface deposits. Integrating surface
measurements with subsurface information allows documentation of the volume of fan deposits through time.

Six CMPs and 15 profiles ranging between 25-210 m long were collected in the distal half of four fans along the La Perouse and Douglas Glaciers. Semblance analyses of CMP soundings on the East Fan of La Perouse Glacier indicate the GPR signal velocity is 0.162 m/ns above a reflector at a depth of ~16 m, consistent with the presence of dominantly icy materials to this depth, similar to those observed at the surface. This velocity and concurrent elevations allows for the interpretation of elevations for subsurface stratigraphic interfaces, and cross-sectional analysis of reflections.

The GPR data indicates that ~25-75 m thick packages of lenticular fan deposits thin toward the perimeter of the icy debris fans. Multiple packages of reflectors with varying geometries indicate complex fan histories. GPR interpretations indicate a transition area between the presence of valley glacier underlying the icy debris fans at depths increasing from 0 m at the toe of the fan to package thicknesses of >75 m in the center of fans. This transition area occurs beneath the package of primary reflectors in GPR profiles, where subsurface material is more homogenous in nature, and indicates a transition to glacial ice.

GPR studies are important in understanding how icy debris fans contribute ice and lithic material annually to the glacial budget. These investigations provide subsurface geometries to be interpreted, allowing estimates of fan volumes to be made. These estimates may be very significant, especially for glaciers that are not connected to upslope glaciers. Understanding of fans’ contributions to valley glacier budgets is also
important as icy debris fans serve a method for monitoring study sites that will likely degrade if climate change progresses as forecasted.
INTRODUCTION

In recent decades, deglaciating alpine regions have been evolving rapidly through mass wasting processes. Degradation of high-level ice caps has exposed major bedrock escarpments, resulting in ice avalanches, rockfalls, icy debris flows, and slushflows (Kochel and Trop, 2008, 2012). This period of exceptional instability on the alpine slopes immediately following deglaciation is known as a paraglacial interval (Ryder, 1971; Church & Ryder, 1972).

These mass wasting processes, especially when channeled through narrow catchments to specific discharge points (icy debris fan apexes), produce mass wasting landforms at the base of the escarpments, which have been recently identified as icy debris fans (Kochel and Trop, 2008, 2012) (Figure 1). Icy debris fans are a poorly understood and under-described mass wasting landform that develop along valley glaciers during periods of deglaciation. This type of mass wasting landform varies in composition, and includes snow, ice, and lithic deposits.

Recent ice avalanche and icy debris flow deposits on the surface of icy debris fans have dimensions of hundreds of meters long, tens of meters wide, and up to several meters thick (Kochel and Trop, 2012). On the surface of icy debris fans, rapid ablation occurs on the deposits delivered to icy debris fans during winter months. Ablation decreases the albedo of the deposits, and causes an increase in the concentration of lithic material in fan deposits, which later gets buried by subsequent avalanche, icy debris flow, slushflow, and rockfall events. The material from these fans that does not get ablated accumulates on the icy debris fans, transitions into ice in the subsurface after burial, and
contributes unknown quantities of ice and lithic deposits to underlying valley glaciers and their glacial budgets. One of the primary objectives of this study is to improve the understanding of the transition of icy debris fans into the underlying valley glacier after deposits accumulate and ablate on the surface.

Surface studies regarding mass wasting landforms such as alluvial fans and talus cones have been explored and studied in paraglacial regions (Ryder, 1971; Iturrizaga, 2008), yet characteristics of icy debris fans remain widely unknown, especially their subsurface architecture. Initial studies on icy debris fans conducted by Kochel and Trop (2008, 2012) recorded active geomorphic processes that occurred on the surface of icy debris fans. Interpretations of the internal architecture and geometry of icy debris fans were made based on surface observations and preliminary GPR data, represented by Figure 2 (Kochel and Trop, 2012). This image is a modified schematic cross section of an icy debris fan, created after surface observations were analyzed. The fan deposits are interpreted to directly overlie the valley glacier, and take on a planar and parallel geometry in relation to the surface of the icy debris fan.

While data for this study was collected, further geomorphic investigations were also conducted analyzed for icy debris fans on the La Perouse and Douglas Glaciers (located in the Southern Alps of New Zealand), including direct field measurements for 10 deposits, and eight months of time-lapse imagery for 225 deposits (Reid, 2015). Surface observations record the minimum deposit widths to be 15 m through field measurements, and 11 m through time-lapse imagery, and the maximum deposit widths to be 72 m through field measurements, and 103 m through time-lapse imagery. The
average deposit widths for both field measurements and time-lapse imagery is 38 m, and
the average deposit thickness is ~2 m, recorded by field measurements (Reid, 2015). It is
a key goal of this study to better document the subsurface architectures and geometries of
icy debris fans and compare measurements to surface measurements.

The ability to understand icy debris fan subsurface orientations and geometries
also contributes to better understanding the transitory nature of icy debris fans into
underlying valley glaciers. One hypothesis regarding the subsurface of icy debris fans
includes the valley glacier abutting against the bedrock wall of the valley; another
possibility would be the bedrock dipping into the valley, so that the surface of the icy
debris fan lies nearly parallel to that of the underlying bedrock, giving the fan its shape
and geometry. A third hypothesis includes the theory that icy debris fans act similar to
glaciers; the deposits of the icy debris fans may convert into ice at depth, and flow within
the subsurface (as well as on the surface) into the underlying valley glaciers. The initial
purpose of collecting geophysical data on icy debris fans was to investigate these
hypotheses, and to determine whether or not the interpretations regarding the subsurface
of icy debris fans needed to be updated in the schematic provided in Figure 2.

In order to better investigate boundaries, materials, and discontinuities of
subsurface features on icy debris fans in a noninvasive way, the GPR geophysical system
was used. The GPR geophysical system uses electromagnetic (EM) pulses in order to
determine velocity changes in the subsurface, allowing subsurface geometries to be
interpreted noninvasively. Characteristics of the subsurface, including ice content, liquid
water content, lithologic content, and chemistry of the material through which EM is traveling determines the travel time and magnitude of EM pulses (Annan, 2009).

GPR studies on paraglacial landforms other than icy debris fans have been previously conducted. In the studies of Ékes and Hicken (2001) and Ékes and Friele (2003), GPR was able to reliably distinguish between alluvial fan sediments, non-alluvial fan sediments, as well as underlying bedrock. Studies conducted on debris flow and rockfall-dominated talus slopes, such as those by Otto and Sass (2006) and Sass and Krautblatter (2007), show the ability of GPR to investigate the sediment structures of talus cones, including the detail of pronounced stratification in the subsurface. Watson, Yelf, and Bertler (2008) were able to collect GPR data supporting bedrock reflections to a depth of 600 m using 50 MHZ antennas on continental glaciers. Lastly, rock glaciers were explored with GPR by Degenhardt (2003) and Morrier et al (2009). Degenhardt’s GPR results show the interior of rock glaciers is composed of a permafrost mixture of ice, sediment, and ice lenses, while data collected by Morrier et al. show the ability to image stratigraphy in rock glaciers.

GPR studies by Smith (2014) and Kochel and Trop (2008) from the McCarthy Glacier in Alaska were the first to demonstrate how GPR can provide high-resolution data in order to interpret subsurface characteristics of icy debris fans in Alaska. Reconnaissance GPR data for the subsurface of the icy debris fans was collected on the Douglas Glacier, New Zealand in 2013 (Kochel et al.). This preliminary data shows the ability of GPR to image lobate geometries of buried avalanches and icy debris flow deposits, as well as provides basic characteristics of the fan’s subsurface architectures.
and dimensions. While the 2013 study in New Zealand focused on the scale of the icy debris fans, the data collected was neither able to be used in order to further investigate the vertical and horizontal positioning of icy debris fans on Earth’s surface, nor to be used to investigate the variation of topography on the icy debris fans.

This thesis details the results of multiple GPR profiles, including CMP soundings, as well as RTK-GPS data in order to fully understand the icy debris fans in New Zealand. The comprehensive GPR dataset, collected in 2014, on the subsurface stratigraphic characteristics of icy debris fans on the La Perouse and Douglas Glaciers in the Southern Alps of New Zealand is the first systematic approach of geophysical investigations for icy debris fans in New Zealand (Figure 3). Overall goals for this study include the analysis of the collected GPR data in order to better document and characterize the subsurface architecture of icy debris fans, the improvement of understanding of icy debris dimensional boundaries, including the transition into the underlying valley glacier, which would provide the thicknesses of fan deposits, as well as the determination of evolution of these mass wasting landforms over time.
Figure 1. Image of the La Perouse Névé (icecap), which contributes material to the East and Middle icy debris fans. Fans eventually contribute to the underlying valley glacier.
Figure 2. Schematic cross section view of icy debris fan transition from overlaying icecap to underlaying valley glacier (Adapted from Kochel and Trop, 2012). Red line A-A’ is an example of the location of one GPR traverse on the East fan of the La Perouse Glacier.
Figure 3. Area map of the location of the La Perouse and Douglas Glaciers in the Southern Alps. The study took place on the west coast of the south island of New Zealand.
METHODS

GPR systems respond to velocity changes in the subsurface, allowing subsurface geometries to be interpreted, while also making it necessary to distinguish between vertical and horizontal velocity changes. The system uses two antennas—a transmitter (Tx) and a receiver (Rx) (Figure 4). The transmitter sends high frequency electromagnetic signals to a receiver, which records the travel time and magnitude of the EM signals.

Physical features in the subsurface can cause a reflection, refraction, or diffraction as the signal incident on the boundaries between different features. Such features include planar interfaces, discrete point objects, and continuous objects. Steeply dipping reflectors or point reflectors present artifacts such as diffraction hyperbolas, which may be used as a guide for finding sharp reflectors (Burger et al., 2006). The propagation of EM signals is based on the relationship between Maxwell’s equations and constitutive equations that describe a medium’s response to an EM field. The velocity that the EM waves travel through the subsurface is dependent on the material’s electric permittivity, conductivity, and magnetic permeability. These parameters are subject to variation depending on different subsurface characteristics including ice content, liquid water content, lithologic content, and the chemistry of the material (Table 1).
### Typical Properties of Common Icy Debris Fan Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Velocity (m/μs)</th>
<th>Attenuation Constant (dB/m)</th>
<th>Relative Permittivity</th>
<th>Conductivity (mS/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.30</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Ice</td>
<td>0.16-0.17</td>
<td>0.01</td>
<td>3-4</td>
<td>0.01</td>
</tr>
<tr>
<td>Damp Rock</td>
<td>0.100</td>
<td>~0.01-100</td>
<td>~6</td>
<td>10</td>
</tr>
<tr>
<td>Fresh Water</td>
<td>0.033</td>
<td>0.1</td>
<td>80</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 1. Typical velocities, attenuations, permittivities, and conductivities of common materials expected to be found in the subsurface of icy debris fans (After Burger, 2006).
The use of GPR systems to investigate glaciers is effective because ice with little
water content is a low-signal-loss medium, or a medium where very little attenuation of
EM signal occurs. The presence or absence of water in material within the 10-1000 MHz
frequency range dominates GPR behavior. Water is invariably present in pore space of
geologic materials, and has a dominant effect on electrical properties, and is often the
dominant factor in determining bulk material electrical conductivity (Annan, 2009). This
is important, as fresh water is observed to flow along the bedrock separating the
overlying icecap and underlying icy debris fan, and interpreted to flow down underneath
the surface of the icy debris fans. Significant ablation is also observed on the surface of
icy debris fans, and interpreted to migrate into the subsurface. It is inferred that fresh
water collects in the subsurface in the form of meltwater ponds, such as the one depicted
in Figure 2.

For icy debris fans, magnetic permeability does not need to be taken into
consideration because most soils and sediments are only slightly magnetic. Icy debris
fans consist of ice and lithic rock fragments, deposited through mass wasting processes
including ice avalanches, slushflows, debris flows, and rockfalls. Changes in the ratio of
lithic content to ice content between mass wasting events are expected to cause changes
in EM velocity of the subsurface of icy debris fans (Table 1).

The data for this study was collected using unshielded Sensors and Software Pulse
Ekko antennas. The Tx and Rx antennas used by GPR systems create and detect
significant EM fields (Annan, 2009). Antennas may be held in either parallel (TE), or
perpendicular (TM) broadside orientation. TE mode makes the electric field transverse to
the plane normal to a subsurface interface, and TM endfire orientation makes the magnetic field transverse to the plane normal to a subsurface interface (Annan, 2009). Energy propagates away from the Tx antenna, and the changes of the EM pulses over time is translated and recorded by the Rx antenna. The Tx-Rx offset is important in collected GPR data, as it plays a factor in the depth that EM pulses propagate into the subsurface.

The frequency of the GPR system’s antennas controls the resolution of the data, as well as the record of an object’s geometrical attributes. Lower frequency antennas send longer wavelengths and penetrate deeper into the subsurface, but are not able to resolve a high level of detail on the centimeter scale. Higher frequency antennas send shorter wavelengths and show better resolution of structures on the centimeter scale, but are not able to penetrate deeply into the subsurface. Wavelengths for both low and high frequencies assume a constant velocity. Penetration was more important than resolution for this research, since the goal was to detect the overall subsurface structure of icy debris fans. Therefore, low frequency antennas were used.

The direct air phase is a linear signal, and the first GPR signal to arrive to the system of all observed signals. The direct ground phase is the second GPR signal to arrive to the system. The direct ground phase is also linear, but with a steeper slope than the direct air phase. The underlying reflectors are a result of the change in velocity in the subsurface where material interfaces are located (Figure 5).
Common-offset Surveys

In common-offset surveys, the distance between the Tx and Rx antennas is fixed, and traces are collected at regular intervals. Unedited GPR profiles show horizontal position (m) versus two-way travel time (ns) on the respective x and y-axes. Reflection data from common-offset surveys lack radar signal velocity needed to determine subsurface materials, as well as depth to reflections. The general travel time equation that relates velocity to depth is:

\[ t = \frac{d}{v} \]  

Eq. 1

Where \( t \) is time; \( d \) is distance or path length; and \( v \) is velocity. In this study, GPR profiles were collected parallel and perpendicular to the axes of the fans, and are referred to as axial and transverse profiles respectively.

The original GPR and GPS data collected is regarded as raw and required editing and processing in order to make analyses and interpretations. GPR profiles and CMP soundings were plotted, edited, processed and analyzed using the Ekko View Deluxe software processing program. Ekko View Deluxe uses a spreadsheet approach to display GPR data such as Start Position, Number of Traces, Time Window Length, etc.

Common Midpoint Soundings (CMPs)

In order to determine the velocity of subsurface materials, a CMP sounding may be collected. In CMP soundings, the Tx-Rx offset is increased in predetermined increments from a primary mid-point (Figure 6). This allows the EM signals sent into the subsurface to intersect the same reflection point, but along different paths of increasing
length while passing through the same material (Annan, 2009). CMP soundings show Tx-Rx offset (m) along the horizontal x-axis, and two-way travel time along the vertical y-axis (ns). A second y-axis displaying depth (m) into the subsurface can be calculated after finding the average velocity of subsurface materials.

The orientation of Tx and Rx relative to the subsurface interfaces affects any reflected phases, hence by collecting CMP soundings with the long axis of antennas perpendicular and parallel to the axial and transverse direction of the fans provides a better understanding of the subsurface. Collecting multiple CMPs at different sites on the La Perouse and Douglas icy debris fans not only allowed analyses of subsurface velocities to be explored at different parts of the fans, but also allowed velocities to be analyzed at different times after mass wasting events had occurred.

The velocity of the subsurface material versus the depth may be found using the equation:

$$v_1 = \frac{\sqrt{(2d^2 + x^2)}}{T(x)} \quad \text{Eq. 2}$$

where $d=$depth; $v=$velocity, and $x=$Tx-Rx offset. This equation does not apply to direct air or refraction data.

Benefits of CMPs include improving signal-to-noise ratio through stacking (Fisher et al., 1992, Annan, 2009), and configuring a full velocity cross section (Greaves et al., 1996, Annan, 2009). CMP surveys collected translate travel time in the GPR profiles into velocity, allowing the depth to vertical changes in the subsurface material to be determined for each profile.
Processing of CMP soundings, including stacking data traces at various velocities, can be achieved using the Ekko View Deluxe software program. Traces stacked at incorrect velocities will destructively interfere and produce low amplitudes, while traces stacked at correct velocities will constructively add together and produce high amplitudes (Sensors & Software Inc., 2003). Once the data is stacked, the highest amplitudes correspond with a velocity value through semblance analysis, which can then be used to find depth using Eq. 2.

A semblance analysis may be processed from CMP soundings in order to translate travel time to average radar velocity. This processing estimates normal moveout (NMO) velocity as a function of zero-offset time. Semblance is a normalized coherency coefficient, that emphasizes terms in a calculation that are sensitive to changes in velocity (Luo and Hale, 2012). The value of semblance reflects how well the moveout path fits the moveout of signal in the CMP data. Good fits produce peaks in the semblance spectrum, while poor fits produce semblance values closer to zero (Luo and Hale, 2012). Once GPR profiles are edited to show horizontal position versus depth, the position of reflections may be observed and analyzed to determine subsurface features.

Real Time Kinematics, Global Positioning System (RTK-GPS)

A Trimble R8 GNSS RTK-GPS (Real Time Kinematics, Global Positioning System) was also used to locate the GPR traces relative to the surface topography of the icy debris fans, and thus the variation of the topography along the GPR profiles. This type of GPS system uses two receivers, a base and a rover, and provides relative
horizontal and vertical positions of the rover compared to the base station with an accuracy of $\leq 0.01$ m (Trimble). The base was stationed away from the fans on top of a large rock on each respective glacier. The GPS base receiver continuously records GPS positioning based on available satellites. This time-series of GPS locations is used to improve the positional accuracy of the base receiver to $<0.01$ m. GPS data was collected while the rover was mounted in a backpack above and slightly behind the operating GPR antennas (Figure 7). This data acquisition setup generates increased error between the position of the GPS rover and the horizontal and vertical position of the GPR traces, approximately $<0.3$ m.

**Data Collection**

The data for this study was collected over four field days along the La Perouse and Douglas Glaciers in the Southern Alps of New Zealand, between March 9-15, 2014. GPR profiles, CMP soundings, and concurrent GPS spatial data were collected on the distal half of four icy debris fans. Fifteen GPR profiles, ranging between ~25-210 m long, and six CMPs were collected in total. At the La Perouse study site there were ten profiles and four CMPs collected over three days on the East and Middle fans (Figure 8). At the Douglas study site there were five profiles and two CMPs collected over one day on Fans 4 and 5 (Figure 9).
La Perouse Glacier

The ten GPR profiles collected on the distal half of the East and Middle fans along the La Perouse Glacier are labeled Lines A-J (Figure 8). These profiles are also referred to as axial and transverse profiles respective to their collection position on the icy debris fan.

In order to assess the velocities of prominent reflections in the subsurface, four CMPs were collected at this site. The location of where these CMPs were collected lies approximately at the middle of Line C on the East Fan. These CMPs are labeled Lines 05, 11, 12, and 13. Three of the four CMPs had antenna positions in TE orientation, excluding Line 12 which recorded data using TM antenna orientation. The purpose of collecting CMP data was to assess the velocities of prominent reflections in the subsurface.

Douglas Glacier

The five GPR profiles collected on the distal half of Fans 4 and 5 along the Douglas Glacier are labeled Lines A-E (Figure 9). These profiles are also referred to as axial and transverse profiles respectively.

One of the two CMPs collected at this site was at the toe of Fan 4, where the icy debris fan and underlying valley glacier meet on the surface, perpendicular to Line A. The other CMP collected along the Douglas Glacier was located along Line E on Fan 4.
GPS

The data acquired from the GPS system was the first data set to be corrected. The latitude and longitude of the GPS data first were formatted to the correct coordinate system, to make sure that the survey locations were accurately recorded. In order to do this, the raw GPS data were sent electronically to Geoscience Australia, through the Australian Government (AUSPOS), who in turn processed the GPS data using International GNSS Service (IGS) products in order to compute coordinates in ITRF on Earth and GDA94 within Australia (AUSPOS, 2014). Processing reports for both the La Perouse and Douglas sites were returned with computed coordinates based on the ITRF2008 reference frame.

Raw GPS data for both the La Perouse and Douglas sites included trace numbers, name of the profile (that it was given during field work), and elevation. La Perouse coordinates were displayed as northing and easting (Figure 10), whereas Douglas coordinates were displayed in decimal degrees (Figure 11).

Using the AUSPOS report, the La Perouse coordinates were converted and corrected to Okarito Circuit 2000 coordination, and the Douglas coordinates corrected into decimal degrees. Coordinates were plotted on graphs in Microsoft Excel, and each was matched to its corresponding line of continuous GPS measurements. The lengths of the lines plotted on each graph were calculated using the average between each recorded GPS measurement, in order to compare the lengths recorded for GPR profiles to the GPS coordinate data. GPS data was then applied to GPR profiles by merging .top files composed of GPS elevation vs. distance from zero (length of GPS line) tables in Ekko.
View Deluxe. The GPS data collected ultimately allowed each GPR profile to accurately depict fan elevation and topographic relief.

**GPR**

Eleven GPR profiles and five CMP soundings used 100 MHz unshielded antennas. Four profiles and one CMP collected on the La Perouse icy debris fans used 200 MHz antennas. The GPR system was set with temporal sampling intervals of 0.4 ns for the 200 MHz, and 0.8 ns for the 100 MHz antenna frequency, step size between data traces varied between 0.2 m, and 0.3 m (according to GPS), and the time window was set to 2000 ns. The large data collection time allowed the Rx antenna to collect larger traveltimes from deeper reflectors in the subsurface of the icy debris fans. For each GPR profile, the antennas were oriented in parallel broadside mode.

GPR corrections applied to each profile included Dewow filters in Ekko View Deluxe. Dewow filters are used to remove the low frequency “wow” which is superimposed on the high frequency reflections on each trace (Sensors & Software Inc., 2003). This time-varying component causes the base level of the received signal to either bow up or down (Annan, 2009). Corrections of GPR profiles also included editing and merging of profiles that were meant to be continuous, but were interrupted during data acquisition. Interruptions included falling incidents and receiver errors most likely due to fiber optic cable issues. Various profiles were also reversed so that the direction of data observed correlated to images of GPR profile transects superimposed on images of the La Perouse and Douglas collection sites (Figures 8 & 9).
CMP soundings did not need to be corrected, but were processed using semblance analyses so that radar wave velocities could be measured and average velocities of subsurface materials could be calculated. Once average velocity was applied to each profile, changes in EM travel time to reflections were attributed only to changes in depth (m). Interpretations and analyses on reflections in GPR profiles were made in confidence after elevation, instrument noise, and velocity were sufficiently processed and corrected.
Figure 4. Cartoon of GPR system using transmitter and receiver antennas to investigate subsurface boundaries through electromagnetic reflections (Hermance, 2003).
Figure 5. Generic CMP sounding displaying Direct Air phase, Direct Ground phase, and the curved shape of the first reflector, which is a result of Tx-Rx offset during data acquisition (Hermance, 2003).
Figure 6. Cartoon of CMP sounding where transmitter and receiver offset is increased in predetermined increments from a primary midpoint (Hermance, 2003).
Figure 7. GPR and GPS equipment collecting a GPR profile.
Figure 8. Image of the East and Middle icy debris fans (from left to right) along the La Perouse Glacier. Figure circled in lower right corner is 1.9 m for scale. The yellow lines represent the approximate locations of the 10 GPR profile lines collected on top of the fans, while the blue dot represents the approximate location of the 4 CMP sounding locations.
Figure 9. Image of icy debris Fans 5 and 4 (from left to right) along the Douglas Glacier. Recent avalanches are light colored, while the ablated deposits are dark colored. The yellow lines represent the approximate locations of the 5 GPR profile lines collected on the distal half of fans.
Figure 10. GPS data imaged over Google Earth image using GIS software for the East and Middle icy debris fans (from left to right) along the La Perouse Glacier. The maroon lines represent the GPS locations of the 10 GPR profile lines collected on top of the fans. Imaged has been flipped to show similar perspective of La Perouse icy debris fans displayed in Figure 8.
Figure 11. GPS data imaged over Google Earth image using GIS software for Fans 5 and 4 (from left to right) along the Douglas Glacier. The pink lines represent the GPS locations of the 5 GPR profile lines collected on top of the fans.
RESULTS

CMP Characterization

The calculated average of the velocities in the CMP soundings (excluding the CMP Line 05 from La Perouse for reasons further explained in section “GPR INTERPRETATIONS”) is 0.162 m/ns above a reflector at 189 ns (~16 m depth). This velocity is consistent with the presence of dominantly icy materials (which have a velocity of 0.16-0.17 m/ns) to this depth, similar to materials observed at the surface. The 0.162 m/ns velocity was applied to each GPR profile to correct for the spatial relationships between reflections in raw GPR data.

Profile Characterization

Two prominent and distinctive reflection patterns dominate the subsurface architecture of the La Perouse and Douglas icy debris fans. Layered lenticular to subhorizontal packages of reflections are the first distinctive pattern, found exclusively in the transverse profiles (Figures 13, 18). Out of 32 measured subsurface lenticular lenses, widths vary from 4 m to 34 m, with an average width of 12 m. The top of these lenses are convex, with a flat base, similar to surface observations of new deposits. The average thickness of the subsurface lenses is less than ~2 m, whereas surface observations average the thickness of new deposits to be ~2 m.

Parallel to subparallel laterally extensive reflections are the second dominant reflection pattern, found in both axial and transverse profiles. These extensive reflections are surrounded by chaotic packages of reflections and hyperbolic signatures. Chaotic
packages are found throughout both the axial and transverse profiles, in both the shallow to deep subsurface architecture. These packages are classified chaotic due to their discontinuous nature of strong reflections, and lack of lateral continuity along the profile direction.

The packages of primary reflectors are observed where chaotic packages are prominent, and vary in thickness between ~25-75m. With depth, these chaotic packages transition to lighter colored reflections, where a gradual decrease of prominent reflections occurs. In addition, there are few reflections from depths greater than 75 m. This loss of signal is caused by a change in subsurface properties; either more lossy material, such as an increase in conductivity due to bedrock or water, or more homogeneous material with gradual changes between material with different EM velocities. If the material in the subsurface of icy debris fans becomes homogeneous at depth, a lack of primary reflectors would be expected. This would occur as no boundary would exist for the EM pulses to reflect back to the Rx antenna.
GPR INTERPRETATIONS

The layered lenticular to subhorizontal packages of reflections observed in the transverse profiles resemble the lobate geometries of new fan deposits on the surface. Within the packages of primary reflections, layered reflection horizons suggest multiple deposits episodically. The sub-parallel interfaces to the surface topography are attributed to annual freeze-thaw cycles, where mass wasting processes aggrade and ablate.

Individual spots where chaotic reflections are observed are interpreted to be point scatters, hyperbolic reflections, and other discontinuous reflections, due to a change in subsurface material. Individual air pockets or water cavities are possible reasons for these individual chaotic reflection spots. Large lithic clasts are not generally interpreted for these chaotic reflection spots, due to field observations where the subsurface of icy debris fans is exposed by crevasses. Within these crevasses, it is observed that most of the subsurface material is ice, and not as much lithic material gets incorporated into the fans. Larger lithic clasts are interpreted to slough off by pedestal melting, and roll to the base of the icy debris fans.

The parallel to nearly-parallel laterally extensive reflections found in both axial and transverse profiles have various GPR interpretations, founded both on the geometries and architectures of the reflections, as well as surface observations where profiles were collected. Interpretations for laterally extensive reflections include: lithic-rich deposits, buried by overlying icy debris fans deposits; approximate fan boundaries; prominent underlying glacial reflectors; or new icy deposits.
As ablation causes ice deposits to degrade, concentrated lithic material is left on the surface of icy debris fans. This concentrated lithic material is covered by subsequent mass wasting events, which may be one cause of the laterally extensive reflections interpreted to be lithic-rich deposits. An alternate process that could generate lithic-rich deposits on the surface of the fan would be individual rockfall events, later covered by more recent ice avalanche and icy debris flow type mass wasting deposits. Lithic-rich deposits are represented by the yellow dashed lines in La Perouse Lines A, G, and I, as well as Douglas Lines A, and C (Figures 13, 17).

Approximate fan boundaries are another laterally extensive reflection interpretation. These reflections are interpreted to be fan boundaries coincident with observations on the surface where profiles were collected. At the Douglas Glacier site, Line E was collected along the toe of Fan 4, along the margin of the underlying glacier. Two nearly parallel, laterally extensive reflectors are observed starting ~20 ns and ~200 ns at position 0 m. These reflectors are interpreted to be different interfaces within the icy debris fan, with the reflector with a greater reflection time to be an approximate fan boundary. The fan boundary approximations are represented by purple dashed lines in this profile, and it is observed that fan deposits are thinner in profiles with approximate fan boundaries (Figure 18).

An approximate fan boundary is also seen in part of the Line I profile from the La Perouse study site, represented by the purple dashed lines (Figure 13). This profile was collected over the boundary between the Middle and East fans, where the two are interpreted to coalesce in the subsurface. In the area of the profile that was collected
between the two fans, there is a bulge where the prominent reflections are diminished, which continues at depth. The gradually lighter chaotic reflection packages found deep in the subsurface are interpreted to be older fan deposits that are transitioning into the underlying valley glacier. Ice deposited on the surface of the fan gradually becomes more dense and homogeneous as it transitions and compacts toward the underlying glacier, which would cause a lack of primary reflectors. Because this transition is gradual, there is no distinct change in material velocity; therefore there are no prominent reflections deeper into the subsurface. This transition zone is interpreted to be where the base of the icy debris fan begins to flow along with the underlying valley glacier. The homogenous, ice-rich material becomes indistinguishable from the underlying valley glacier, making it difficult to observe a distinctive base of the fan versus the underlying glacier the further away from the toe the profiles are collected. The observations and interpretations for diminished reflecting horizons and chaotic zones relative to depth into the subsurface of icy debris fans occur throughout most of the GPR profiles collected.

Line J along the La Perouse Glacier is also near a fan margin, but instead of valley glacier, it is interpreted that bedrock is dipping underneath the surface of the East icy debris fan. Overlying bedrock located to the east of the East Fan is interpreted to dip ~45° W based on surface observations (Figure 15). Line J was collected on an area of the eastern-most part of the East Fan that was safe to traverse. The GPR Profile of Line J displays a prominent, laterally extensive reflection dipping approximately ~45° across the 40 m of data collection, represented by the yellow dashed line. This reflection is interpreted to be the boundary between the icy debris fan, and the underlying dipping
bedrock (Figure 16). The thickest area of the East Fan recorded in this profile is 32 m, at position 40 m.

Although one would expect bedrock to be homogenous, and thus expect GPR reflections to diminish after signals enter the bedrock, reflections are observed under the primary reflection that is interpreted to be the surface of the bedrock (Figure 16). It is interpreted that fractures are located throughout the underlying bedrock, and that these fractures have been infiltrated by liquid water due to the shallow thickness of the fan, and close proximity to the exposed bedrock. As distance from the exposed bedrock surface increases and thickness of the fan increases, water in these fractures would be subsequently frozen, instead of remaining in liquid form. The reflections beneath the surface of bedrock would therefore be stronger closer to the exposed bedrock surface (left side of Figure 16), caused by difference in velocity between the bedrock and the ice-filled fractures. As icy debris fans continue to thicken over underlying bedrock, reflections diminish due to the gradual transition between ice from the fans to the ice contained within the bedrock. The transition from ice to damp bedrock would also mark a conductivity increase (Table 1), causing signal attenuation to decrease with depth.

An alternative interpretation would be that the bedrock does not continue to dip underneath the entirety of the East Fan, but rather transitions to a nearly vertical face at a position of ~40 m on Line J (Figure 16), where the 45º dipping reflection diminishes. This interpretation also accounts for the lack of bedrock reflections interpreted in any other profile collected at the La Perouse and Douglas Glacier sites. The hypothesis of a slow change in liquid to ice ratio in bedrock also supports a primarily ice-composed
subsurface, that would have the thicknesses capable of transitioning icy debris fan deposits into the underlying valley glacier.

Prominent glacial reflectors are the third laterally extensive reflections interpreted for the GPR profiles collected. The first prominent glacial reflection was interpreted in Douglas Line A, represented by the pink dashed line (Figure 17). The collection of this profile began on the glacier. In the profile, it can be observed at position ~40 m topography changes, as the toe of the fan is traversed, and elevation begins to increase more steadily. This profile continues axially up Fan 4.

Douglas Line E also shows prominent glacial reflections. As previously stated, this profile was collected along the toe of Fan 4, along the margin of the underlying glacier. Underneath this fan boundary, two prominent reflectors with nearly inverse slopes are observed, and interpreted to be glacial reflections (Figure 18). These glacial reflectors are represented by the pink dashed lines.

New icy deposits are the last laterally extensive reflector interpretation. These reflections in the subsurface are due to surface observations made while collecting profile surveys. An example of this would be Line I of La Perouse, where a package of new ice-rich deposits was traversed from ~25-50 m along the profile (Figure 12). It should be noted that Figure 8 does not show this fresh deposit traversed for Line I, as the image for the figure was taken six days prior to the collection of Line I, before the deposition event occurred.

Surface measurements record new icy deposits to have an average thickness of ~2 m, which correlates to the shallow lenses observed at small travel times (ns) on GPR
Profiles, where data was collected over recent deposits. Icy deposits are represented by orange dashed lines (Figure 13).

Further data collected over recent icy avalanche deposits includes the CMP Line 05, taken on the East Fan at La Perouse (Figure 14). The results of this CMP sounding differ than the other three soundings taken in approximately the same location. Semblance analysis of Line 05 shows subsurface materials have an average velocity between 0.15-0.30 m/ns for time less than ~200 ns. This average velocity is higher than the previously discussed average velocity of 0.162 m/ns used to topographically correct GPR profiles. The interpretation of these higher velocities is due to the greater presence of air in recent icy debris fan deposits. The average velocity of air is 0.30 m/ns (Table 1).

Past GPR Studies

Previous GPR studies on icy debris fans include the work by Smith on the West, Middle, and East fans of the McCarthy Glacier in Alaska (2014). GPR profiles on the West and Middle Fans along the margins of the McCarthy glacier show prominent lenticular reflections in the shallow subsurface of the icy debris fans, similar to those found in the transverse profiles taken on the La Perouse and Douglas Glaciers in New Zealand.

Transverse profiles collected on icy debris fans along the McCarthy Glacier provide data interpreted to show lenses ranging from 3-10 m thick, 40-60 m wide, and 150-200 m long (Smith, 2014). The widths of the lenses interpreted in this New Zealand study have thicknesses within the range of the data collected in Alaska, with lens
thicknesses averaging ~2 m. The widths of the New Zealand lenses are more variable, with ranges from 4-34 m wide. One reason why the widths of the subsurface lenticular reflections may vary between the Alaska data and the New Zealand data may correlate to the area where the GPR profiles were collected. Due to the hazardous conditions including mass wasting events on the icy debris fans, data could only be collected on the distal half of fans. The overall lengths of the fans studied in Alaska compared to the fans studied in New Zealand differ from the apex to the toe, which would mean we could expect the average widths of deposits would differ relative to the position on each fan.

The data collected along the McCarthy Glacier has been observed to have packages of primary reflectors between 8-70 m thick (Smith, 2014). These packages are interpreted to be fan deposits. These thicknesses are similar, but thinner, than the observed 25-75 m thick packages in the New Zealand data. This difference in thicknesses suggests that the icy debris fans in New Zealand are larger in size and volume, and are receiving a higher volume of deposits compared to icy debris fans along the McCarthy Glacier.

Data collected on the Middle and East Fans of the McCarthy Glacier suggest coalescing of the two fans at depth (Smith, 2014). This is similar to the data collected on Line I at the La Perouse Glacier, where coalescing is also interpreted, particularly the Middle and East Fans. An important aspect of the fans coalescing at depth that was not discussed by Smith was the indication that the lack of primary reflectors between the two fans is due to the gradual transition to the underlying valley glacier. Smith 2014 mentions that the deposits may have been deformed due to compressional and tensional
forces at depth, but not that this compaction of the icy debris fan deposits is causing the gradual transition into the underlying valley glacier.

Prominent bedrock reflections were interpreted by Smith in the subsurface of the West Fan, while weaker bedrock reflections were interpreted in the subsurface of the Middle and East Fans. In New Zealand, the only clear interpretation of underlying bedrock beneath an icy debris fan is on the eastern most side of the East Fan at the La Perouse site. Both studies support the interpretation that the interface between bedrock fan deposits may be too gradual to display a prominent reflection using the GPR equipment, while the New Zealand study speculates the cause of this gradual transition between bedrock and icy debris fan would likely be due to bedrock fractures filled with ice.
Figure 12. Image of data being collected over ~25 m of new deposits on Line I of the Middle fan above the La Perouse Glacier. Image circled is ~1.6 m.
Figure 13. GPR profile of Line I of the Middle fan above the La Perouse Glacier, represented by I-I’ in Figure 8. The depth of the package of primary reflectors reaches ~40 m when topographically corrected. From left to right on the profile, the East Fan is interpreted to coalesce with the Middle Fan. A package of new ice-rich deposits was traversed from position ~25-50 m, as outlined by the orange dashed line. The green dashed line represents estimated topographic data, as the GPS could not connect to satellites at this position.
Figure 14. Velocities of the upper subsurface of the East fan of La Perouse are inconsistent on newer ice avalanche material according to one of the CMPs collected, represented by the blue dot in Figure 8. (left) CMP for Line 05 (right) Semblance Analysis for Line 05. Velocity of material in subsurface reads between 0.15-0.30 m/ns at times less than ~200 ns.
Figure 15. Image of the eastern side of the East fan of La Perouse, where a large crevasse is located. Bedrock is exposed above the icy debris fan, dipping to the west at ~45°. The thicknesses of fan deposits were estimated to be ~30 m out in the field.
Figure 16. Topography-corrected GPR profile of ~41 m long Line J of the East fan of La Perouse, represented by J-J’ in Figure 8. The package of primary reflectors that slopes downward from ~220 ns to ~550 ns is interpreted to be bedrock dipping to the west at ~45°. Above the underlying bedrock is icy debris fan deposits, which reaches ~32 m thick at position ~40 m, similar to the ~30 m estimated thickness of the fan deposits made out in the field.
Figure 17. GPR profile of Line A up the apex of Fan 4 above the Douglas Glacier, represented by A-A’ in Figure 9. The depth of the package of primary reflectors reaches ~50 m when topographically corrected. This beginning of this line was collected on the glacier, and a prominent glacial reflector is represented by the pink dashed line.
Figure 18. GPR profile of Line E along the toe of Fan 4 above the Douglas Glacier, represented by E-E’ in Figure 9. Purple dashed lines represent fan boundaries, while pink dashed lines represent prominent glacial reflections.
CONCLUSIONS

Icy debris fans are unique mass wasting landforms, dominated by ice avalanches, which form along the margins of valley glaciers. These fans are created due to the decoupling of overlying icecaps and subsequent mass wasting of the icecaps. As recent studies used geomorphic, sedimentological, geophysical, and remote sensing techniques on the La Perouse and Douglas Glaciers in New Zealand, the subsurface of these recently studied periglacial landform remained widely unknown. Geophysical techniques, such as GPR, provide the ability to study the subsurface architecture and geometries of icy debris fans noninvasively. The 2014 study on the La Perouse and Douglas Glaciers was the first of its kind to systematically approach the collection of GPR data in New Zealand in order to determine stratigraphic characteristics. This study provides improved understanding of icy debris fans’ dimensional boundaries and transition into the underlying valley glacier, better documentation and characterization of the subsurface architecture of these mass wasting landforms, determinations of fan deposits’ thicknesses and contributions to valley glacier budgets, as well as evaluations of the evolution of icy debris fans over time.

In order to collect data to provide this information, a total of six CMPs were taken between two fans, and fifteen axial and transverse GPR profiles were taken on the distal half of four fans at the La Perouse and Douglas Glaciers study sites. CMP soundings provide an average subsurface velocity of the four icy debris fans studied in New Zealand to be 0.162 m/ns. This velocity correlates to the velocity of ice, which is observed on the surface of the fans, and so is expected in the subsurface of icy debris fans.
GPR profiles demonstrate that the package of primary reflectors ranges between ~25-75 m thick. Lenticular deposits buried in the subsurface may be seen in transverse profiles, and range from ~4-34 m width, which are well within the range of widths measured in the field for recent ice avalanche deposits. Deeper into the subsurface of icy debris fans, reflections diminish. One place this occurs is where bedrock is observed to be dipping under the subsurface of icy debris fans, such as Line J on the East Fan of the La Perouse Glacier. Here it is interpreted that fractures in the bedrock fill with water and then freeze, causing subsurface ice reflections to mix with bedrock reflection features (Figure 19). As icy debris fans thicken on top of underlying bedrock, reflections diminish due to the gradual transition between ice from the fans to the ice contained within the bedrock.

In areas where it is interpreted that bedrock does not underlie icy debris fans, the fans thicken on top of the valley glaciers, and gradually transitions into the underlying valley glacier. In these cases, GPR reflections also diminish. It is interpreted that primary reflections are not as prominent due to the gradual thickening of ice content in icy debris fans, versus a clear boundary between icy debris fan content and underlying valley glacier. This gradual transitional boundary is caused by subsurface icy material becoming more compacted and homogenous in nature. The gradual transition into underlying glacial ice supports the interpretation that as icy debris fan deposits thicken, subsurface ice begins to flow along with the underlying valley glacier. It is in this way that icy debris fans contribute ice and sediment into valley glaciers (Figure 20).
Figure 19. Schematic cross section view of the subsurface of the La Perouse East Icy Debris Fan transitioning from overlaying névé to underlaying valley glacier. Bedrock is interpreted to be dipping under the subsurface of the icy debris fan, but the boundary between the bedrock and the fan is unknown.
Figure 20. Schematic cross section view of the subsurface of the La Perouse Middle Icy Debris Fan transitioning from overlaying névé to underlaying valley glacier. Ice deposited on the surface of the fan gradually becomes more dense as it transitions and compacts toward the underlying glacier. It should be noted that it is interpreted that the ice within the fan is from this compaction, and that the ice would not be from the underlying glacial ice flowing upward. It is interpreted that subsurface ice and lithic-rich deposits from the fan begin to flow at depth with underlying glacier.
**FUTURE WORK**

Interpretations of icy debris fans surface and subsurface processes has greatly improved since studies began in 2006, but further investigations would greatly benefit the pursuit of better understanding these periglacial mass wasting landforms. Future work dedicated to studying the subsurface architecture of icy debris fans, as well as the transition into underlying valley glaciers, would include further GPR profiles and CMP soundings. Data collection taken both at the La Perouse and Douglas Glaciers sites, as well as other icy debris fan locations around the world, would be of great value in understanding icy debris fans’ characteristics.

 Longer GPR profiles extending across multiple fans at the La Perouse and Douglas Glaciers study sites would allow the transition from one fan to the next in the subsurface to be better understood. Increasing the data collection of axial and transverse profiles taken, in a grid that has smaller profile intervals, could also help distinguish the subsurface boundaries between fans, as well as between fans and underlying glacier.

 A greater number of CMP soundings at both sites, taken in various locations on the fan/glacier boundary would also provide the ability to refine subsurface velocities in order to determine subsurface materials and material boundaries. A CMP sounding taken where bedrock is confidently interpreted to be underlying icy debris fan deposits (such as Line J at the La Perouse Glacier) would be particularly of great value. Comparisons between subsurface velocities obtained from CMPs taken over newer versus older icy debris fan deposits may also provide interesting findings, if time is the only dependent variable in the collection of CMP data.
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- Lithic-Rich Reflections
- New Icy Deposits
- Lenses
- Approximate Fan Boundary
- Prominent Glacial Reflector