A Research Application of Lessons Learned During the 2003 Glacio-Euro Course

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INTRODUCTION

Glaciology is a rapidly changing branch of earth science that has benefited from the development of several key geophysical instruments including the global positioning system (GPS), ground-penetrating radar (GPR), and dielectric profiling (DEP) systems. Despite their common usage, there are few opportunities for scientists to get hands on training and field experience using these geophysical instruments except during research missions. The 2003 Glacio-Euro course offered lab instruction on the theory behind each of these instruments. Students had the opportunity to use each instrument on Storglacieren and were taught how to process the raw data. The purpose of this paper is to demonstrate how applicable the lessons taught during the Glacio-Euro course are to glaciological research missions.

This report outlines a field plan for data collection at the Allan Hills, East Antarctica scheduled for January 2004. We will measure ice flow, mass balance, and topography with GPS. We will track the internal layers with GPR to derive accumulation rates. We will also map stratigraphic layers outcropping on the blue ice surface using DEP. The primary objectives of this project are to determine the ice flow and mass balance of the region and to identify a suitable profile for future collection of a horizontal ice core.

PRIMER ON STUDY AREA

There are areas in Antarctica where old ice (up to 2.8 Ma; Harvey *et al.*, 1998) outcrops on the surface of the ice sheet. These remarkable areas, known as blue ice areas or ice fields, not only represent old ice that is exposed at the surface, but they often serve as stranding surfaces for Antarctic meteorites (Whillans and Cassidy, 1983; Cassidy *et al.*, 1992). The exact age of exposed blue ice is difficult to determine using traditional ice dating techniques (e.g. counting annual layers or dating of radiogenic isotopes in the ice and tephra layers), but dated meteorites can be used to estimate the age of the ice beneath them (Whillans and Cassidy, 1983; Cassidy *et al.*, 1992). Evidence for the direct correlation between ice and meteorite ages comes from an ice flow and mass balance study at the Allan Hills (Spikes, 2000). The model predicts that ice ages across one ice field are approximately the same as meteorite ages and that the source region for the snow and meteorites is local (within ~4 km). These results suggest that continuous sampling of exposed ice (i.e. horizontal ice core) at the Allan Hills will produce a paleoclimate record (up to 2.8 Ma) that has not been severely disrupted by ice flow.

Three ice fields just west of the Allan Hills nunatak are the focus of this study (Fig. 1). Together, the Main Ice Field (MIF), Near-Western Ice field

(NWIF), and Mid-Western Ice Field (MWIF) consist of ~190 km^2 of exposed blue ice, which are separated by zones of accumulation called snow plains. These ice fields are located between two outlet glaciers and are very close to a local ice divide.

TARFALA LESSONS APPLIED

Surveying with GPS

Differential GPS surveys will primarily be used to map topography and measure ice flow. This work will build on a previous study of ice flow through the Allan Hills region (Spikes, 2000). In the previous study, a network of steel poles was installed that starts near the base of the Allan Hills nunatak and stretches out 40 km to the west (Fig. 1). Precise geodetic GPS equipment mounted on snowmobiles was used to survey the positions of each pole and to map the topography along the line of poles. Elevations derived from GPS were combined with a continental-scale digital elevation model (DEM) (Liu *et al*., 2001) to produce the contours in Figure 1. Although the spatial resolution of the DEM is ~8 km (Hamilton and Spikes, 2003), it does provide the location of an ice divide and helps control the gridding away from surveyed lines. During the upcoming field season, we will use more snowmobile-based GPS surveys to improve this topographic map and verify the earlier ice flow measurements.

We will survey the region in Figure 1 (white box) using a carefully designed grid. Spacing between parallel survey lines will be ~1 km on the MIF and ~5 km throughout the rest of the box. This survey resolution should be sufficient to capture the topographic features that are relevant to ice flow and therefore will allow us to accurately identify flowlines. We will resurvey existing poles to verify earlier results and to monitor any changes that have occurred since the poles were last surveyed in 1999. We will also install new poles along a flowline (e.g. Fig. 1) starting at the ice flow divide and ending at the down-glacier side of the MIF.

Surveying the subsurface using GPR

As we learned during the Glacio-Euro course, GPR has many uses in the field of glaciology. For example, high-frequency radar systems (200–2000 MHz) systems have been used to determine snow accumulation rates (e.g. Kohler *et al*., 1997; Spikes *et al*., 2003), mid-frequency (50-200 MHz) systems have been used to interpret the history of ice flow dynamics of an ice stream (Retzlaff and Bentley, 1993), and low-frequency (2-50 MHz) systems have been used map bedrock topography (e.g. Faure, 1990; Delisle and Sievers, 1991). For this project, we will use low-frequency GPR datasets to map the bedrock topography and a mid-frequency system to determine historical accumulation rates.

Measurements of ice thickness in the vicinity of the Allan Hills were made using radar (Faure, 1990; Delisle and Sievers, 1991). Peaks that rise up as much as 800 meters from the surrounding bedrock greatly reduce ice thickness under each blue ice surface. The presence of subglacial peaks and ridges is reflected in the ice surface topography (Fig. 1). The ice in this region has an average thickness of ~400 meters (Delisle, 2001), though ice thickness increases to >1300m between the NWIF and the MIF where there is a deep bedrock trough (Delisle and Sievers, 1991). To produce the map of bedrock elevations in Figure 2a, ice thickness data have been subtracted from the surface elevations in Figure 1. Bed elevations were then gridded using a low resolution continental-scale map of bedrock topography (Lythe *et al*., 2000) as a control for points more than 1 km away from surveyed lines, which explains the apparent change in bedrock roughness across Figure 2a.

The mass balance of the Allan Hills region is a prime concern of this project. The submergence velocity technique (Hamilton *et al.,* 1998) has been used to calculate the average mass balance of this region (Table 1) (Spikes, 2000). These results indicate that the region is thinning, but there is spatial variability in the mass balance measurements related to variability in accumulation/ablation rates. Accumulation/ablation rates have been determined using repeat pole height measurements (Table 1; Fig. 2b) (Faure, 1990; Spikes, 2000). Despite these previous studies, accumulation rates between ice fields have not been adequately measured, which causes mass balance estimates of these areas to have large uncertainties (Table 1).

In the upcoming field season, we will tow a sled-mounted 400 MHz short-pulse radar system behind a snowmobile along the profiles indicated in Figure 2b. The continuous horizons within these radar profiles will be used to determine historical accumulation rates using the methods described in (Spikes *et al*., 2003). To use this technique, an ice core must be collected and sampled at ~20 cm resolution to develop density and depth/age profiles for a point along a flowline (e.g. Fig. 2b). Radar-derived accumulation rates will be included in the updated mass balance estimate for this region.

Tracking isochrones on blue ice surface using DEP

Dielectric profiling can be used to identify isochronal layers in ice (e.g. Eisen *et al*., 2003). We will use DEP to correlate isochronal layers that outcrop on the MIF, such as the tephra/dust layers shown in Figure 1 (Harvey *et al*., 1998). Many more isochronal layers outcrop on the blue ice surface, but because they do not contain large amounts of volcanic debris or dust, they are not visible. These layers are related to changes in the dielectric properties of the ice and can therefore be identified in DEP profiles (Eisen *et al*., 2003). An example of a DEP profile collected on Storglacieren is shown in Figure 3. Presumably, each of the spikes in Figure 3 is related to a change in the dielectric properties of the ice. We will use GPS to precisely geolocate a series of parallel DEP profiles, separated by tens of meters, and oriented perpendicular to ice flow. We will then map the spatial distribution of isochronal layers by correlating peaks between adjacent DEP profiles. The range of ice ages between consecutive layers will be estimated using meteorite ages (described below).

METEORITES AND A HORIZONTAL ICE CORE

Data collected in the field were used as input for an ice flow model that predicts the age and origin of ice that makes up the NWIF (Spikes, 2000). Model results show that the maximum age of ice at the NWIF is $130{,}000 \pm 65{,}000$ years (Fig. 4). The maximum terrestrial age of any meteorite found on the NWIF so far is $180{,}000 \pm 20{,}000$ years (Kunihiko Nishiizumi, unpublished data). The agreement between these ages suggests that meteorites can be used to estimate ice ages.

Assuming the model results from the NWIF apply to other ice fields, the maximum age of ice at the MIF is at least 1 Ma (Nishiizumi *et al*., 1999) and could be 2.8 Ma (Harvey *et al*., 1998). We will use dated meteorites found along a flowline to estimate the age of exposed ice between consecutive isochronal layers identified using the DEP approach discussed earlier. To insure that the meteorite ages are representative of the ice on which they rest, we will only use dates from specimens with a mass >100 gm, because they are less likely to have been moved by wind (Cassidy *et al*., 1992). Using detailed topographic and ice flow analysis, we will also eliminate meteorites that may have slid down steep ice ramps or fallen into crevasses (Delisle and Sievers, 1991).

The development of a horizontal age scale across the MIF will enable us to pick a suitable profile along which a horizontal ice core can be collected. Using ice flow and mass balance measurements, we will deconvolve the deformation history of the ice along this profile. It is very likely that a horizontal core collected at the Allan Hills will be continuous for many hundreds of thousands of years, and possibly millions of years. If the record extends beyond 420,000 years (Petit *et al*., 1999), it would be the longest continuous climate record ever recovered from a glacier or ice sheet.

CONCLUSIONS

Geophysical instruments will be used to study a portion of the East Antarctic ice sheet near the Allan Hills. Lessons from the Glacio-Euro course have proven to be very useful in planning this field measurement program. In particular, instructions on the use of GPS, GPR, and DEP for glaciological applications have been most beneficial.

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Tables and Figures

Ice Facies	*Avg. accumulation rate (m a^{-1})*	*Average Mass Balance*
Blue ice	-0.025 ± 0.012	-0.03 ± 0.011
Firn	-0.015 ± 0.003	-0.035 ± 0.015

Snow	0.084 ± 0.04	0.016 ± 0.026

Table 1. Average accumulation/ablation rates and mass balance results from the network of ice flow stakes shown in Figure 1 (Spikes, 2000). Uncertainties are expressed as the standard deviation from the mean.

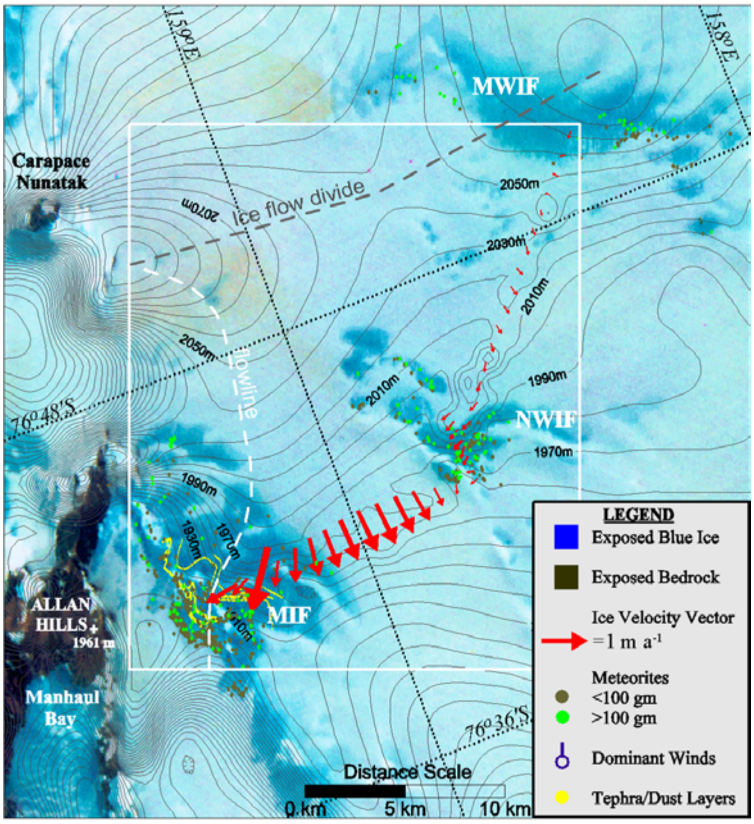

Figure 1. Elevation contours from kinematic GPS surveys and a DEM (Liu et al., 2001) superimposed on a Landsat image of the Allan Hills region. Ice flow vectors are based on repeat GPS surveys of markers in ice. The white box indicates the region that will be the focus of the 2004 field program. The ice flow divide and flowline are based on surface contours. Meteorite locations taken from Cassidy et al. (1992). Tephra layers taken from Harvey et al. (1998).

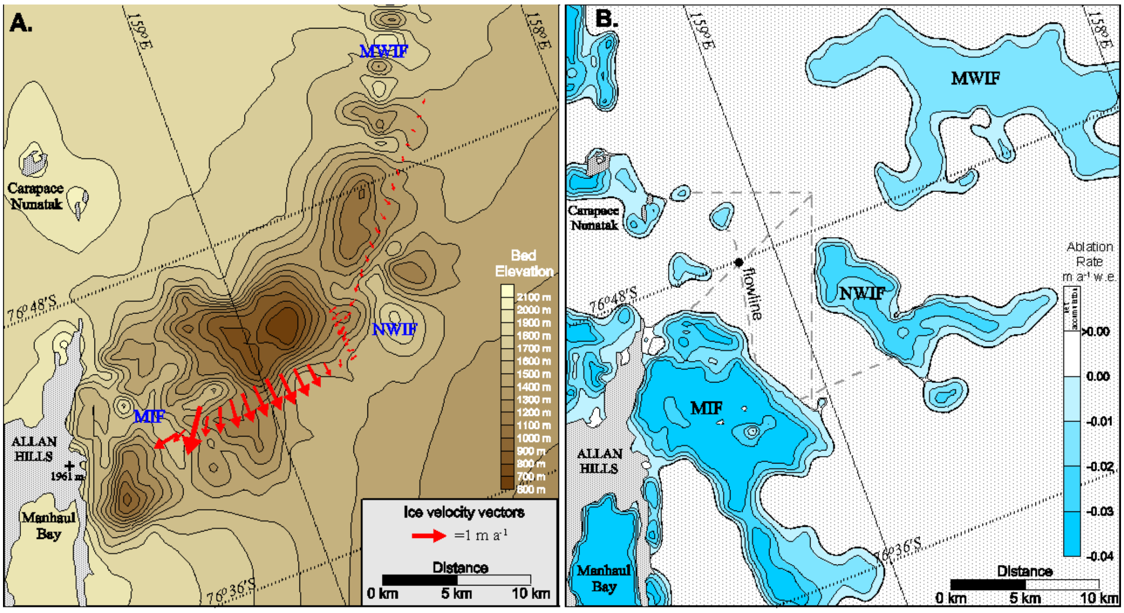

Figure 2. A) Bedrock topography near the Allan Hills (Lythe et al., 2000; Delisle and Sievers, 1991). B) Estimated ablation rates for the MIF, NWIF, and MWIF. Accumulation rates will be determined using radar along the indicated profiles (dashed gray lines). An ice core (black dot) will be collected to develop a density profile and to date radar horizons.

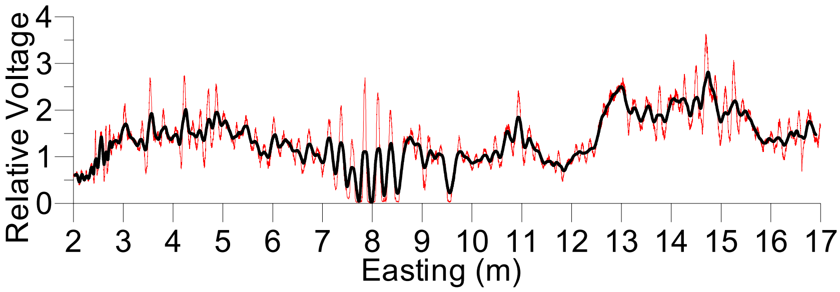

Figure 3. DEP profile from Storglacieren as sampled (red line) and smoothed using a running average of 100 measurements (black line).

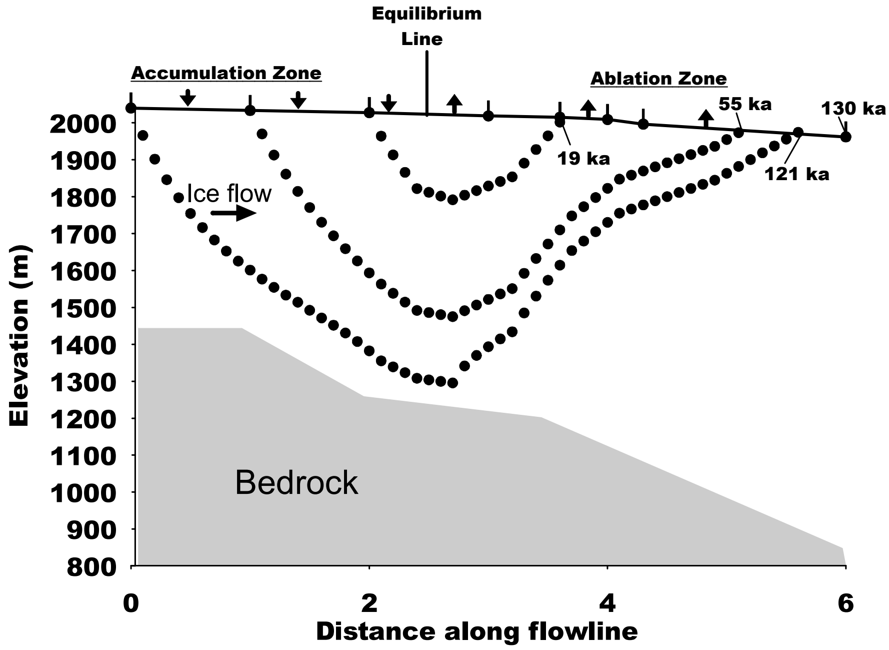

Figure 4. Steady-state ice flow trajectories for ice at the NWIF (Spikes, 2000). Each dot represents 100 m of horizontal movement. Accumulation/ablation rates, ice velocities, and bedrock elevations (Delisle and Sievers, 1991) are based on field measurements.